Characterising the Structure of Molecular Clouds

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Doctor of Philosophy
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Dedication

In memory of Frank J. Wong, Arthur and Carol Wong.
It all started when I was an undergraduate student in a computer security unit. An Associate Professor, managed to persuade everyone in the lecture theatre to attend a barbecue discussing about enrolling into honours and talk about different research topics. After some discussion, I was given an opportunity to do some research before enrolling - that work ended up becoming a part of my honours research. With honours completed, the important question was asked - do you want to do a PhD? Well Miroslav (or Professor), I hope you do not regret asking me that question, because now I present my PhD thesis (who would have guessed)!

Firstly, my thanks goes to Dr. Nicholas F. N. Tothill, whose open door policy and patience have allowed me to learn and grow as an academic, also for sending me to places which I would have least expected. Prof. Miroslav D. Filipović, for giving me opportunities like outreach, as well his encouragement and support from the moment when I first started my research career (he is also the person who may have a lot to answer for). Dr. James A. Green, who helped organise the much needed field trips to the Canberra Deep Space Communication Complex (CDSCC), and took time out of his busy schedule to meet with me. Lastly from my supervisory panel (yes, I had four supervisors): a major component of this work could have not been achieved if it wasn’t for Dr. Shinji Hourichi, who allowed me to gain access to the DSS43 and computer systems at the CDSCC.

I greatly appreciate the efforts made by my supervisors in securing funding, and support in handling the unbelievable ‘red tape’ at the various times of this work. In that respect, Nick and Miroslav in particular were able to lend their voice of support when I was confronted with ‘interesting’ administration problems. I am grateful to the then - University of Western Sydney (UWS) who awarded the Australian Postgraduate Award and the UWS top-up scholarship to me. In addition, I am grateful to CSIRO Astronomy and Space Science, and CDSCC for awarding me a studentship, in particular I thank the director of CDSCC, Dr. E. Kruzins for travel support and hospitality while part of this work was conducted.

My thanks are extended to the families of my supervisors and apologies if you had to endure any complaints in regards about me. Frank and Heather Stootman, in particular Frank, who went out of their way and took the time to help shape my thesis.

I stand on the shoulders of giants, and this work could have succeeded without the
support of the community. Therefore I would like to thank Prof. Michael G. Burton, Dr. Catherine Braiding, and Dr. David L. Robolleo for their assistance with collaborative projects using the Mopra and NANTEN2 telescopes. NANTEN2 is owned by Nagoya University and I would like to thank the team that support the telescope. In addition, I thank Dr. R. Higgins, Dr. C. Buckender, and Dr. R. Simon for their support with the SMART receiver, from a different time zone.

Although not directly related to my work, I have had the honour of being a part of some wonderful collaborations/projects (see appendix for details). I thank the collaborators who have been a part of my work, or allowed me to be a part of their work. Dr. Ain de Horta and Dr. Evan J. Crawford, I have been learning from you since undergrad, thank you for your support.

A special thanks to Rocky and the technical staff at SCEM, for their technical support for numerous times my computer decided to give up at inconvenient times - I swear it was not because of me!

During the time of this thesis I have gained many friends and been a part of some interesting groups, so thank you to the following groups: Team Mopra, ‘RAFP’, Team ‘Ozsome’, and people in the Cosmic data laboratory. To the people who I have left off the list, my apologies, and thank you.

The Tidbinbilla 70-m Radio Telescope (DSS-43) is part of the Canberra Deep Space Communication Complex (CDSCC), which is managed by CSIRO Astronomy and Space Science. CASA is developed at NRAO and under NRAO management with major contributions from ESO and NAOJ.

Finally, I would like to thank my family: G. W. Wong and G. J. Wong.
The work presented in this thesis is, to the best of my knowledge and belief, original except as acknowledged in the text.

I hereby declare that I have not submitted this material, either in full or in part, for a degree at this or any other institution.

..............................................................
Graeme Francis Wong       March 31, 2016
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Abstract

The Interstellar Medium contains the building blocks of matter in our Galaxy and plays a vital role in the evolution of low mass star formation. The poorly studied molecular clouds of Lupus and Chamaeleon contain ongoing low mass star formation, and are in close proximity to our Solar System. While on the other hand the Carina molecular cloud, poorly observed in radio wavelength, is an active region of star formation and host some of the brightest stars known within our Galaxy. Using tracers like carbon monoxide, atomic neutral carbon, and ammonia, we are able to measure the temperature and density of the gas cloud. This information allows us to understand the initial conditions of the formation of low mass stars.

Observations conducted with the 22-m Mopra radio telescope (located at the edge of the Warrumbungle Mountains near Coonabarabran), in the Carbon monoxide (CO) isotopologues $^{12}$CO, $^{13}$CO, C$^{17}$O, and C$^{18}$O (1–0) transitions, have mapped the Chamaeleon II cloud, an intermediate mass cloud within the Chamaeleon. Through the sub-arcminute maps, comparisons have been made to previous low resolution ($2.5'$) maps which have been to resolve some of the dense clumps previously identified. Optical depth, column density, and excitation temperature derived from the CO maps, are consistent with previous results. A detailed comparison between identified C$^{18}$O clumps have shown the different conditions occurring within the clumps, some of which contain or are located near a population of young stellar objects.

The Northern region of the Carina Nebular Complex, was observed with NANTEN2, a 4-m radio telescope (located in the Chilean Atacama desert), in the $^{12}$CO (4–3) and [C\textsc{i}] $^3P_1–^3P_0$ emission lines. Previous observations towards this region has either been at poor resolution or had limited coverage. The presented observations, strike a balance between the two; observing in sub-arcmin resolution (0.6') and with an area of $0.9^\circ \times 0.5^\circ$ mapped. Excitation temperature of the $^{12}$CO (4–3) and column density of [C\textsc{i}] $^3P_1–^3P_0$ have been derived. Discussions have been made of the complex morphology of the Northern Carina Nebular Complex region, compared to optical features, and supported the assertion of the H\textsc{ii} region (Car I) expanding into the molecular cloud.

The selected areas within the Lupus molecular clouds (regions I, III and IV) were observed with the DSS43 (also known as Tid-70m), the largest steerable single dish radio telescope (70-m) in the Southern Hemisphere located at Canberra Deep Space Communication Complex (CDSCC) near Canberra, in the ammonia transitions (1,1) and (2,2). Due to the observation modes and limited amount of time available for
the Astronomical community, the targeted areas were mapped in a series of position-switching strips. Column density, kinetic and rotation temperatures were derived, which were compared and analysed to low-resolution maps towards the dense clumps.

As Tid-70m had limited observing capabilities, this project has been able to improve the observation capabilities by implementing on-the-fly (OTF) mapping. With its size and unique capabilities, implementing OTF mapping will increase the efficiency of observations. Test observations were carried out towards the well known sources of Orion A, and Sagittarius A through the newly implemented OTF observing mode. Analysis and comparison of Orion A and Sagittarius A, shows consistency with the new maps produced.
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<td>2MASS</td>
<td>Two Micron All-Sky Survey</td>
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<tr>
<td>ACS</td>
<td>Advanced Camera for Surveys</td>
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<tr>
<td>AIPS</td>
<td>Astronomical Image Processing System</td>
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<tr>
<td>ALMA</td>
<td>Atacama Large Millimetre Array</td>
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<tr>
<td>AOS</td>
<td>acousto-optical spectrometer</td>
</tr>
<tr>
<td>APEX</td>
<td>Atacama Pathfinder Experiment</td>
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<tr>
<td>ASAP</td>
<td>ATNF Spectral Analysis Package</td>
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<tr>
<td>ASCII</td>
<td>American Standard Code for Information Interchange</td>
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<tr>
<td>AST/RO</td>
<td>Antarctic Submillimeter Telescope and Remote Observatory</td>
</tr>
<tr>
<td>ATCA</td>
<td>Australia Telescope Compact Array</td>
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<td>ATNF</td>
<td>Australia Telescope National Facility</td>
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<tr>
<td>c2d</td>
<td>cores to disk</td>
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<tr>
<td>CASA</td>
<td>Common Astronomy Software Applications</td>
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<tr>
<td>CASS</td>
<td>CSIRO Astronomy and Space Science</td>
</tr>
<tr>
<td>CDMS</td>
<td>Cologne Database for Molecular Spectroscopy</td>
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<tr>
<td>CDSCC</td>
<td>Canberra Deep Space Communication Complex</td>
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<td>CLASS</td>
<td>Continuum and Line Analysis Single-dish Software</td>
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<tr>
<td>CMB</td>
<td>Cosmic Microwave Background</td>
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<tr>
<td>CNC</td>
<td>Carina Nebular Complex</td>
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<tr>
<td>CNM</td>
<td>Cold Neutral Medium</td>
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<td>CO</td>
<td>Carbon Monoxide</td>
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<td>CSIRO</td>
<td>Commonwealth Science and Industrial Research Organisation</td>
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<tr>
<td>CTTS</td>
<td>Classical T Tauri Star</td>
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<td>DENIS</td>
<td>Deep Near Infrared Survey of the Southern Sky</td>
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<td>DSN</td>
<td>Deep Space Network</td>
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<td>DSS</td>
<td>Deep Space Station</td>
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<td>Flexible Image Transport System</td>
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<td>fast-on-the-fly</td>
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<td>HIM</td>
<td>Hot Interstellar Medium</td>
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<td>HST</td>
<td>Hubble space telescope</td>
</tr>
<tr>
<td>IDL</td>
<td>Interactive Data Language</td>
</tr>
<tr>
<td>IF</td>
<td>intermediate frequency</td>
</tr>
<tr>
<td>IR</td>
<td>Infra-Red</td>
</tr>
<tr>
<td>IRAS</td>
<td>infrared astronomical satellite</td>
</tr>
<tr>
<td>IRSA</td>
<td>NASA/IPAC InfraRed science archive</td>
</tr>
<tr>
<td>ISM</td>
<td>Interstellar Medium</td>
</tr>
<tr>
<td>JPL</td>
<td>Jet Propulsion Laboratory</td>
</tr>
<tr>
<td>KOSMA</td>
<td>Kölners Observatorium für SubMillimeter Astronomie</td>
</tr>
<tr>
<td>LMC</td>
<td>Large Magellanic Cloud</td>
</tr>
<tr>
<td>LO</td>
<td>Local Oscillator</td>
</tr>
<tr>
<td>LSR</td>
<td>Local Standard of Rest</td>
</tr>
<tr>
<td>LSRK</td>
<td>Local Standard of Rest Kinematic</td>
</tr>
<tr>
<td>LST</td>
<td>Local Sidereal Time</td>
</tr>
<tr>
<td>LTE</td>
<td>Local Thermodynamic Equilibrium</td>
</tr>
<tr>
<td>HI</td>
<td>Neutral Hydrogen</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>MOPS</td>
<td>Mopra Spectrometer</td>
</tr>
<tr>
<td>MSX</td>
<td>Midcourse Space Experiment</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>NMC</td>
<td>network monitor and control</td>
</tr>
<tr>
<td>NRAO</td>
<td>National Radio Astronomy Observatory</td>
</tr>
<tr>
<td>OTF</td>
<td>on-the-fly</td>
</tr>
<tr>
<td>PDR</td>
<td>Photo-dissociation region</td>
</tr>
<tr>
<td>PMS</td>
<td>Pre-Main-Sequence</td>
</tr>
<tr>
<td>PWV</td>
<td>Precipitable Water Vapor</td>
</tr>
<tr>
<td>RA</td>
<td>Right Ascension</td>
</tr>
<tr>
<td>RAC</td>
<td>radio astronomy controller</td>
</tr>
<tr>
<td>RFI</td>
<td>radio frequency interference</td>
</tr>
<tr>
<td>RHS</td>
<td>right hand side</td>
</tr>
<tr>
<td>RMS</td>
<td>root mean square</td>
</tr>
<tr>
<td>RPFITS</td>
<td>Radio Physics Flexible Image Transport System</td>
</tr>
<tr>
<td>RRL</td>
<td>Radio Recombination Line</td>
</tr>
<tr>
<td>SDFITS</td>
<td>Single Dish Flexible Image Transport System</td>
</tr>
<tr>
<td>SED</td>
<td>spectral energy distributions</td>
</tr>
<tr>
<td>SEST</td>
<td>Swedish-ESO Sumillimetre Telescope</td>
</tr>
<tr>
<td>SIS</td>
<td>Superconductor Insulator Superconductor</td>
</tr>
<tr>
<td>SMART</td>
<td>Sub-Millimeter Array Receiver for Two frequencies</td>
</tr>
<tr>
<td>SMC</td>
<td>Small Magellanic Cloud</td>
</tr>
<tr>
<td>SNR</td>
<td>supernova remnant</td>
</tr>
<tr>
<td>TCS</td>
<td>Telescope Control System</td>
</tr>
<tr>
<td>TTSs</td>
<td>T Tauri stars</td>
</tr>
<tr>
<td>UNSW</td>
<td>University of New South Wales</td>
</tr>
<tr>
<td>UV</td>
<td>Ultraviolet</td>
</tr>
<tr>
<td>VISTA</td>
<td>Visible and Infrared Survey Telescope for Astronomy</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>VLBI</td>
<td>Very-Long-Baseline Interferometry</td>
</tr>
<tr>
<td>WFC</td>
<td>Wide field camera</td>
</tr>
<tr>
<td>WNM</td>
<td>Warm Neutral Medium</td>
</tr>
<tr>
<td>WIM</td>
<td>Warm Ionized Medium</td>
</tr>
<tr>
<td>WTTS</td>
<td>Weak-line T Tauri Star</td>
</tr>
<tr>
<td>XFFTS</td>
<td>extended bandwidth Fast Fourier Transform Spectrometer</td>
</tr>
<tr>
<td>YSO</td>
<td>Young Stellar Objects</td>
</tr>
</tbody>
</table>
Chapter 1

Overview

1.1 Motivation

Clouds of molecular gas in interstellar space play a vital role in the evolution of matter in our Galaxy — they are the birthplaces of new generations of stars and planets. Understanding their physical conditions and chemical evolution is crucial to our knowledge of the Universe. The molecular gas that comprises these clouds is largely invisible, but emits radio waves at specific frequencies defined by the quantum mechanics of the molecules that make up the gas (referred to as ‘spectral lines’). This emission is generally found to have frequencies of tens to hundreds of GHz.

Figure 1.1 shows a common tracer of molecular gas ($^{12}$CO 1–0) mapped along the line of sight towards the Milky Way, labelled with different regions. These clouds are important regions of star formation. Many of the clouds that require closer study but have been mapped in a limited fashion (Heyer and Dame, 2015). Better mapping of the clouds would greatly enhance future high resolution studies using an instrument like Atacama Large Millimetre Array (ALMA).

In this thesis, two regions of molecular clouds are studied at high resolution. The first using the Mopra radio telescope (in Coonabarabran) at 109–115 GHz to observe the Carbon Monoxide (CO) isotopologue spectral lines in the Chamaeleon II region, $-56^\circ < l < -60^\circ$ and $-12^\circ < b < -16^\circ$. The second was using the NANTEN2 telescope (in Chile) at 460 GHz and 492 GHz to observe the CO and atomic Carbon spectral lines in the Carina Nebular Complex (CNC) region at, $-71^\circ < l < -76^\circ$ and $-0.3^\circ < b < -1^\circ$.

Ammonia (NH$_3$) spectral lines are also important to the study of molecular clouds. High spatial resolution spectral lines at 23 GHz can be observed with a radio telescope having a large diameter and with a suitable receiver for example: Mopra is 22-m and NANTEN2 is 4-m. For higher resolution at 23 GHz it would be ideal to increase the diameter over that the two above mentioned telescopes. The 70-m diameter Tidbinbilla telescope (DSS3) located near Canberra, Australia, is the largest single dish telescope in the Southern Hemisphere and has receivers capable of observing the NH$_3$ spectral lines. Thus a major part of this thesis has been to modify the control software on this telescope to improve the instruments capability to study the NH$_3$ spectral lines. Preliminary observations have been taken on these lines towards parts of the Lupus
region between \((-8^\circ < l < -26^\circ, +5^\circ < b < +25^\circ)\) of the Galaxy; these show promise for future work.

1.2 Interstellar Medium

The Interstellar Medium (ISM) can be simply defined as the material that exists in the space between star systems within a galaxy. The mass of the ISM consists of around 70% Hydrogen (H), 28% Helium (He), and 2% heavier elements \(\text{Klessen and Glover, 2014}\). Material in the ISM is made up of ionic, atomic, and molecular gas together with dust particles and cosmic rays, which can form the building blocks for objects like molecular clouds, stars, regions of ionised Hydrogen (H\(\text{ii}\) regions) and supernova remnants (SNRs). Temperatures and densities in the ISM can range from very cold dense material at temperatures of \(\sim 10 - 100 \text{ K}\) (densities \(> 10 \text{ cm}^{-3}\)), to the very hot tenuous gases in SNRs at \(\sim 10^6 \text{ K}\) (densities 0.1 to 1 \text{ cm}^{-3}\).

The ISM are categorised as components, or phases \(\text{Cox, 2005}\). These phases coexist in pressure equilibrium, where the pressure is proportional to the number of density particles and temperature: \(P \propto nT\). This means that material that is in a hot tenuous form may have the same pressure as that in a cold dense form.

The first model of the ISM was created by Field et al. \(1969\), who suggested an ISM made up of two phases. The model consisted of a cold dense phase \((T < 300 \text{ K})\) made up of clouds of neutral and molecular hydrogen, and a warm intercloud phase \((T \sim 10^6 \text{ K})\) consisting of rarefied neutral and ionised gas. This was updated by McKee and Ostriker \(1977\), who presented the popular three-phase model of the ISM dominated by supernova explosions. The model by McKee and Ostriker \(1977\) has the three phases: Hot Interstellar Medium (HIM); the Warm Interstellar Medium which is broken into two subphases: Warm Neutral Medium (WNM) and Warm Ionized Medium (WIM); and the Cold Neutral Medium (CNM). Table 1.1 \(\text{Klessen and Glover, 2014}\) is an overview of the main physical properties of three different phases.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Component</th>
<th>Temperature (K)</th>
<th>Density (cm(^{-3}))</th>
<th>Fractional ionization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold</td>
<td>CNM</td>
<td>50 – 100</td>
<td>20 50</td>
<td>(\sim 10^4)</td>
</tr>
<tr>
<td>Warm</td>
<td>WNM</td>
<td>6000 – 10000</td>
<td>0.2 – 0.5</td>
<td>(\sim 0.1)</td>
</tr>
<tr>
<td>Warm</td>
<td>WIM</td>
<td>(\sim 8000)</td>
<td>0.2 – 0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Hot</td>
<td>HIM</td>
<td>(\sim 10^6)</td>
<td>(\sim 10^{-2})</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 1.1: Phases of the ISM \(\text{Klessen and Glover, 2014}\), adapted from Ferrière et al. \(2007\); Caselli et al. \(1998\); Wolfire et al. \(2003\), and Jenkins \(2009\).

The \(\text{CNM}\) (cold HI\(^1\) or diffuse clouds) has temperatures below 100 K and densities above about \(10 \text{ cm}^{-3}\). The \(\text{WIM}\) which consists of partially neutral or ionised cloud envelopes, has temperatures of several thousand K and a density range of 0.1 to \(1 \text{ cm}^{-3}\).

\(^1\text{Atomic hydrogen}\)
Figure 1.1: Location of the major molecular clouds that can be found along the plane of the Milky Way. The regions of particular interest in this thesis: Chamaeleon (red box) located at Galactic Longitude $-56^\circ < l < -60^\circ$; Carina Nebular Complex (blue box) located between $-71^\circ < l < -76^\circ$; Lupus (green box) located at Galactic Longitudes $-8^\circ < l < -26^\circ$. The purple boxes are selected regions, Sagittarius A and Orion A, targeted for OTF development. Telescopes located on the Southern Hemisphere can observe towards regions within Galactic Longitude $20^\circ < l < 160^\circ$, and the region between $-20^\circ < l < -100^\circ$ can only observed from the Southern Hemisphere. Image reproduced from Dame et al. (2001).
Lastly the HIM has temperatures in excess of $10^6$ K and densities below about 0.01 cm$^{-3}$, and can be found in the hot, low density cavities of SNR. Cox (2005) suggested adding a fourth phase to describe the ISM sometimes called dark clouds with temperatures $10–20$ K, with particle density $>10^2$ cm$^{-3}$. The high density and low temperature indicate possible star forming regions.

Dark clouds are primarily made up of Hydrogen, the most abundant element in the universe. However, the hydrogen is in the form of molecular hydrogen (H$_2$), which does not emit or absorb radiation at these temperatures, making this molecule difficult to detect and H$_2$ emission is from light radiation. Therefore, to understand the conditions that are occurring in the dark clouds, tracers need to be relied upon. Tracers are chemical compounds that make up a small portion of the clouds but are easy to detect. These complex molecules can be developed (in dense gas) without being broken apart by the ultraviolet radiation in space. CO and its various isotopologues are the most prominent of these tracers. Although $^{12}$C$^{16}$O at low transitions of $J=1\rightarrow0$ (often referred to as $^{12}$CO) is the most abundant, it is often optically thick and cannot be used to trace the dense emission of the whole cloud (Klessen and Glover 2014). Therefore, isotopologues which are less abundant and have a lower optical depth, such as $^{13}$C$^{16}$O (often referred as $^{12}$CO) and $^{12}$C$^{18}$O (often known as C$^{18}$O), are utilized. These tracers provide a less biased view of the properties of the molecular cloud. The underlining limitation, which is described by Klessen and Glover (2014), is that the lowest rotation for isotopologues ($J=1\rightarrow0$ transition) has a critical density of only $n_{cr}=1.1 \times 10^3$ particles per cm$^3$, which is larger than the typical mean density of a molecular cloud. This means that these tracers are ideal for understanding the properties of the cloud at densities close to the mean density, but little information is gained on underdense regions.

Tracers used to probe high density regions are somewhat less complicated, the most popular being HCN, NH$_3$, HCO$^+$ and N$_2$H$^+$. Figure 1.2 illustrate some of the tracers, and the range of temperature and density they are most suitable for.

From figure 1.2 it can be seen that the molecular lines chosen for study in this thesis, CO and the isotopologues of Carbon, as well as NH$_3$, are all within “dark” molecular clouds, or a fourth stage as suggested by Klessen and Glover (2014).
Figure 1.2: Plot describing the ranges of temperature and density for various tracers used to probe molecular cloud structure and dynamics. Reproduction of figure 8 from Klessen and Glover (2014).
1.3 Background theory

1.3.1 Black Body Radiation

One of the great advances in physics was the discovery by Max Planck of a formula that describes the spectrum of power radiated per unit area per unit frequency per unit solid angle from a body in Local Thermodynamic Equilibrium (LTE). This is the so-called Black Body radiation spectrum. In some ways Black Body is a misnomer because the body does not need to be ‘black’ in colour but in other ways it’s good. Depending on the temperature of the body it can be any colour visible or invisible to the eye. The Black Body spectral intensity $B_\nu$ (as a function of frequency $\nu$) is described by the following formula:

$$B_\nu(T) = \frac{2\hbar\nu^3}{c^2} \left[ \frac{1}{\exp(\frac{\hbar\nu}{kT}) - 1} \right],$$  \hspace{1cm} (1.1)

where $B_\nu(T)$ has the units Wm$^{-2}$Hz$^{-1}$sr$^{-1}$, $\hbar = 6.62607004 \times 10^{-34}$ m$^2$kgs$^{-1}$ is Planck’s constant, $k = 1.38064852 \times 10^{-23}$ m$^2$kgs$^{-2}$K$^{-1}$ is the Boltzmann constant, $c = 29979246$ ms$^{-1}$ is the velocity of light, and $T$ the temperature of the body in Kelvin.

It is sometimes convenient to express the spectral intensity as a function of wavelength. A little care needs to be taken to convert $B_\nu(T)$ to $B_\lambda(T)$, as need to have the same units on both sides, i.e., W/m$^2$/sr. Thus, noting that over an infinitesimal increase in frequency there is a corresponding infinitesimal decrease in wavelength, and using $c = \nu\lambda$, we can write:

$$B_\nu(T)d\nu = -B_\lambda(T)d\lambda.$$  \hspace{1cm} (1.2)

Solving for $B_\lambda$ gives the differential equation:

$$B_\lambda(T) = -B_\nu(T)\frac{d\nu}{d\lambda} = B_\nu(T)\frac{c}{\lambda^2},$$  \hspace{1cm} (1.3)

and so,

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5} \left[ \frac{1}{\exp(\frac{hc}{kT}) - 1} \right].$$  \hspace{1cm} (1.4)

Several results follow immediately from equation (1.1). If $\hbar\nu/kT$ is small we can expand the exponential in the denominator to first order and obtain the Rayleigh-Jeans Formula, which is a linear relation between spectral power and temperature,

$$B_\nu(T) = \frac{2\hbar\nu^3}{c^2} \left[ \frac{kT}{\hbar\nu} \right] = \frac{2k}{\lambda^2} T.$$  \hspace{1cm} (1.5)

If we integrate equation (1.1) over all frequencies we end up with the power radiated per m$^2$ per sterad. This leads to the Stefan-Boltzmann Law. It is convenient to
substitute \( x = h\nu/kT \) to obtain:

\[
P = \frac{2\hbar}{c^2} \left( \frac{kT}{\hbar} \right)^4 \int_0^\infty \left[ \frac{x^3}{\exp(x) - 1} \right] dx \tag{1.6}
\]

The integral has an exact value, in other words, \( \pi^4/15 \):

\[
P = \frac{2\pi^4 k^4}{15 c^2 h^3 T^4} \tag{1.7}
\]

Substituting for all the constants yields:

\[
P = 1.80493 \times 10^{-8} T^4. \tag{1.8}
\]

If we differentiate equation 1.1 to find the frequency at which maximum power per \( m^2 \) per sterad is radiated we get the **Wien Displacement Rule**:\[
\frac{dB_\nu(T)}{d\nu} = 3 \left( \exp \left( \frac{h\nu}{kT} \right) - 1 \right) - \frac{h\nu}{kT} \exp \left( \frac{h\nu}{kT} \right) = 0 \tag{1.9}
\]

Equation 1.9 can once again (using the substitution \( x = h\nu/kT \)) be conveniently written:

\[
3(e^x - 1) - xe^x = 0 \tag{1.10}
\]

This equation has to be solved numerically to find the roots. Giving the value:

\[
\nu_{\text{max}} = 5.87892 \times 10^{10} T \tag{1.11}
\]

A similar exercise can be done using equation 1.4 by setting \( dB_\lambda(T)/d\lambda = 0 \); it is then possible to calculate \( \lambda_{\text{max}} \).

### 1.3.2 Non-thermal Radiation

Suppose a radiation Intensity \( I_\nu \) enters a cloud of thickness \( s \). There will then be a change in \( I_\nu \) as it traverses the cloud with both absorption and re-emission of spectral energy. Conventionally we define three quantities to describe this. Firstly an absorption co-efficient \( \kappa_\nu \), then an emission co-efficient \( \epsilon_\nu \), and lastly the optical depth of the cloud defined as follows:

\[
\tau_\nu = \int_0^s -\kappa_\nu ds. \tag{1.12}
\]

We expect then:

\[
dI_\nu = -\kappa I_\nu ds + \epsilon_\nu ds \tag{1.13}
\]

and:

\[
-\frac{1}{\kappa_\nu} \frac{dI_\nu}{ds} = I_\nu - \frac{\epsilon_\nu}{\kappa_\nu}. \tag{1.14}
\]
At LTE \(dI_\nu/ds = 0\) (absorption and emission processes are in equilibrium), and can represent the cloud as a simple black body at some temperature \(T\) where:

\[
I_\nu = B_\nu(T) = \frac{\epsilon_\nu}{\kappa_\nu} \tag{1.15}
\]

Strictly, when a telescope measurement is made of the cloud we do so towards the cloud (also known as an on source scan) and also away from the cloud (we refer to this as reference scan). Since the temperatures of the clouds are expected to be low we should also include the radiation of a blackbody at 2.725 K. Included is the molecular excitation temperature \(T_{Ex}\) representing the effective black body cloud temperature at equilibrium. Hence:

\[
B_\nu(T) = B_\nu(T_{Ex}) - B_\nu(2.725) \tag{1.16}
\]

The Rayleigh-Jeans Formula (equation 1.15) relates the temperature \(T\) to the spectral power radiated at some frequency \(\nu\) provided \(h\nu/kT\) is small. Rewriting and making \(T\) the subject leads to:

\[
T = \frac{\lambda^2}{2k}B_\nu(T) = \frac{c^2}{2k\nu^2}B_\nu(T) \tag{1.17}
\]

It is trivial to show that, from equations 1.16 & 1.17 and substituting equation 1.1, at the cloud and Cosmic Microwave Background (CMB) temperatures, that under the Rayleigh-Jeans condition at LTE, equation 1.16 reduces to:

\[
T = T_{Ex} - 2.725 \tag{1.18}
\]

Equation 1.14 can be solved as follows to obtain a more general expression for \(T\) which includes the optical depth \(\tau_\nu\) defined in equation 1.12. Rewriting equation 1.14 and integrating gives:

\[
\int_0^s \frac{dI_\nu}{I_\nu - B_\nu(T)} = \int_0^s -K_\nu ds = \int_0^\tau d\tau_\nu \tag{1.19}
\]

Note that \(s\) and \(\tau_\nu\) run in opposite directions since as \(s\) increases from the back of the cloud to the front of the cloud, the optical depth \(\tau_\nu\) decreases from \(\tau\) to 0. Equation 1.19 has the solution

\[
[\ln(I_\nu - B_\nu(T))]_0^s = -\tau \tag{1.20}
\]

Simplifying and assuming that \(I_\nu = 0\) at \(s = 0\), since that is defined to be the back of the cloud, and also that \(B_\nu(T)\) is a constant:

\[
I_\nu(s) = B_\nu(T)(1 - e^{-\tau}) \tag{1.21}
\]

From equation 1.16 this leads to a final expression,

\[
I_\nu(s) = (1 - e^{-\tau})[B_\nu(T_{Ex}) - B_\nu(2.725)] \tag{1.22}
\]
Applying the Rayleigh-Jeans formula we can write the net brightness temperature \( T_B \) as the result of an average molecular excitation temperature \( T_{Ex} \) producing the line spectrum at \( \nu \), and, the CMB radiation at a temperature of 2.725 K, as follows,

\[
T_B = \frac{e^2}{2k\nu^2}(1 - e^{-\tau})[B_\nu(T_{Ex}) - B_\nu(2.725)]
\]

(1.23)

or again on source,

\[
T_B = \frac{h\nu}{k}(1 - e^{-\tau}) \left[ \frac{1}{\exp\left(\frac{h\nu}{kT_{Ex}}\right) - 1} - \frac{1}{\exp\left(\frac{h\nu}{2.725k}\right) - 1} \right]
\]

(1.24)

Once again equation (1.24) leads to an augmented on source antenna temperature \( T_B \) which includes the optical thickness \( \tau_\nu \) for small \( h\nu/kT \) of

\[
T_B = (1 - e^{-\tau})[T_{Ex} - 2.725]
\]

(1.25)

To make \( T_{Ex} \) the subject using equation (1.24) This, after some algebraic manipulation, leads to the general expression

\[
T_{Ex} = \frac{h\nu/k}{\ln \left[ 1 + \frac{h\nu/k}{1 - \frac{h\nu/k}{\exp\left(\frac{h\nu}{kT_{Ex}}\right) - 1}} \right]}
\]

(1.26)

The above expression is useful if the optical thickness \( \tau \) is large and \( \exp(\tau) \to 0 \), because then there are no unknowns on the left hand side of equation (1.26). We can also make the optical thickness \( \tau \) the subject of the formula, should we know the excitation temperature \( T_{Ex} \) of the cloud. Again after some algebraic manipulation,

\[
\tau = -\ln \left[ 1 - \frac{T_B k/h\nu}{(\exp(h\nu/kT_{Ex}) - 1)^{-1} - (\exp(h\nu/2.725k) - 1)^{-1}} \right].
\]

(1.27)

### 1.3.3 Column Density

Column density may be thought of as squashing a cylinder along the axis of observation to the cloud. The number of absorbers per unit surface area of the cross section of the cylinder is called the column density \( N \).

Consider two atomic levels separated by an energy \( \Delta E = h\nu_0 \), where \( \nu_0 \) is the transition photon frequency. If we use the symbol ‘\( u \)’ to represent the upper state and the symbol ‘\( l \)’ to represent the lower state then the number of electrons in the upper state \( N_u \) is given by the Boltzmann equation:

\[
N_u = \frac{g_u N_l}{g_l} \exp \left( \frac{h\nu_0}{kT} \right)
\]

(1.28)

In the above \( g_l \) and \( g_u \) are the energy degeneracies of the lower and upper levels. By energy degeneracy we mean the levels with different quantum numbers and yet with the same energy. For angular momentum we often use the symbols \( J \) and \( K \) to distinguish
between different momentum states. These different momentum states can have the same energy level associated with them.

If \( A_{ul} \) is the emission co-efficient, \( B_{ul} \) is the stimulated emission coefficient and \( B_{lu} \) is the absorption coefficient, and \( U \) is the input spectral energy density, we can write

\[
N_u[A_{ul} + B_{ul}U] = B_{lu}U
\]  

(1.29)

This leads to the following using equation 1.28

\[
U = \frac{A_{ul}}{N_u B_{lu} - B_{ul}} = \frac{A_{ul}}{\frac{N_u}{N_l} B_{lu} - B_{ul}}
\]  

(1.30)

\( U \) is the radiated spectral energy density and has the units \( \text{J m}^{-3} \text{Hz}^{-1} \). At \( \text{LTE} \) the spectral power is given by \( B_\nu \) and has the units \( \text{W m}^{-2} \text{Hz}^{-1} \text{sr}^{-1} \). If the spectral power is radiated into \( 4\pi \) steradians at a velocity of \( c \) then we can write

\[
U = \frac{4\pi}{c} B_\nu(T) = \frac{8\pi h\nu_0^3}{c^3} \left[ \frac{1}{\exp\left(\frac{h\nu_0}{kT}\right)} - 1 \right]
\]  

(1.31)

Comparing equations 1.30 & 1.31 leads to the following for \( \text{LTE} \)

\[
A_{ul} = \frac{8\pi h\nu_0^3}{c^3} B_{ul}
\]  

(1.32)

and

\[
g_l B_{lu} = g_u B_{ul}.
\]  

(1.33)

Equation 1.30 can be rearranged using equations 1.32 and 1.33 so that only an emission term on top and an absorption term at the bottom. Therefore at \( \text{LTE} \)

\[
U = \frac{N_u A_{ul}}{N_l B_{lu} \left[ 1 - g_l N_u g_u N_l \right]}
\]  

(1.34)

From equations 1.15, 1.33 & 1.34 can be written as:

\[
\frac{4\pi \epsilon_\nu}{c} \kappa_\nu = \frac{N_u A_{ul}}{N_l B_{lu} \left[ 1 - g_l N_u \right]} = \frac{N_u A_{ul}}{N_l B_{lu} \left[ 1 - \exp\left(-\frac{h\nu_0}{kT}\right)\right]}
\]  

(1.35)

Equation 1.35 is convenient for it can be split into two separate equations. Introducing an emission spectrum of shape \( \phi(\nu) \) such that,

\[
\epsilon_\nu = C_1 N_u A_{ul} \phi(\nu)
\]  

(1.36)

and,

\[
\kappa_\nu = C_2 N_l B_{lu} \left[ 1 - \frac{g_l N_u}{g_u N_l} \right] \phi(\nu)
\]  

(1.37)
where,

\[
\frac{C_1}{C_2} = \frac{e}{4\pi}
\]  

(1.38)

From the definition in equation 1.13, \( \epsilon_\nu \) and \( \kappa_\nu \) have different units, thus writing for consistency \( C_1 = h\nu_0/4\pi \) and \( C_2 = h\nu_0/c \) yielding finally,

\[
\epsilon_\nu = \frac{h\nu_0}{c} N_u A_{ul} \phi(\nu)
\]  

(1.39)

and, substituting for \( B_{lu} \),

\[
\kappa_\nu = \frac{c^2}{8\pi \nu_0^2} \frac{g_u}{g_l} \frac{N_l}{N_u} \left[ 1 - \frac{g_l N_u}{g_u N_l} \right] \phi(\nu)
\]  

(1.40)

or,

\[
\kappa_\nu = \frac{c^2}{8\pi \nu_0^2} N_u A_{ul} \left[ \exp \left( \frac{h\nu_0}{kT} \right) - 1 \right] \phi(\nu)
\]  

(1.41)

The optical depth is then,

\[
\tau_\nu = -\int_0^\infty \kappa ds = -\frac{c^2}{8\pi \nu_0^2} A_{ul} \left[ \exp \left( \frac{h\nu_0}{kT} \right) - 1 \right] \phi(\nu) \int_0^\infty N_u ds
\]  

(1.42)

The upper radiating column density \( D_u = \int_0^\infty N_u ds \), hence also integrating over \( \nu \):

\[
\int_0^\infty \tau_\nu d\nu = -\frac{c^2}{8\pi \nu_0^2} A_{ul} \left[ \exp \left( \frac{h\nu_0}{kT} \right) - 1 \right] D_u \int_0^\infty \phi(\nu) d\nu
\]  

(1.43)

Making \( D_u \) the subject and normalising \( \int_0^\infty \phi(\nu) d\nu = 1 \) a general expression for the upper level column density can be written as,

\[
D_u = \frac{8\pi \nu_0^2}{c^2} \frac{1}{A_{ul}} \int_0^\infty \frac{\tau(\nu) d\nu}{1 - \exp \left( \frac{h\nu_0}{kT} \right)}
\]  

(1.44)

Converting the frequency spectrum into a velocity spectrum:

\[
\frac{d\nu}{\nu_0} = -\frac{dv}{c}
\]  

(1.45)

Equation 1.44 becomes

\[
D_u = \frac{8\pi \nu_0^3}{c^3} \frac{1}{A_{ul}} \int_0^\infty \frac{\tau(v) dv}{\exp \left( \frac{h\nu_0}{kT} \right) - 1}
\]  

(1.46)

Equation 1.46 is a general expression for the number column density of the line at a frequency \( \nu_0 \). The emission coefficient \( A_{ul} \) is related to the dipole moment (Wilson et al., 2009; Mangum and Shirley, 2015). The exact expression depends on the unit system being used. For the (outdated) cgs system and using Debye (\( \equiv 1 \) statC.cm) as

\(^2\)centimetre gram second
the unit for the dipole moment, can be obtained:

$$A_{ul} = \frac{64\pi^4}{3hc^3}\nu_0^3|\mu_{ul}|^2$$  \hspace{1cm} (1.47)

The same expression in the S.I. system would use the mks (Metre-Kilogram-Second) system and C.m for the dipole moment.

$$A_{ul} = \frac{1}{4\pi\varepsilon_0}\frac{64\pi^4}{3hc^3}\nu_0^3|\mu_{ul}|^2$$  \hspace{1cm} (1.48)

Substituting equation 1.47 into 1.46 yields a general result for the column density of the excited upper state, which radiates the ISM spectral line at $\nu_0$

$$D_u = \frac{3h}{8\pi^3|\mu_{ul}|^2} \int_0^\infty \tau(v) dv \left[ \exp\left(\frac{h\nu_0}{kT_{Ex}}\right) - 1 \right]$$  \hspace{1cm} (1.49)

The total column density $D_t$ which is related to a summed Boltzmann distribution over all energy levels. Following Mangum and Shirley (2015) and noting that the inversion of equation 1.28 forces the minus sign to disappear,

$$\frac{D_t}{D_u} = \frac{Q}{g_u} \exp\left[\frac{E_u}{kT_{Ex}}\right] = \frac{Q}{g_u} \exp\left[\frac{h\nu_0}{kT_{Ex}}\right]$$  \hspace{1cm} (1.50)

where $Q$ is the sum over all energy levels $E_n$ with degeneracy $g_n$,

$$Q = \sum_n g_n \exp\left[-\frac{h\nu_n}{kT_{Ex}}\right]$$  \hspace{1cm} (1.51)

Substituting equations 1.50 and 1.51 into equation 1.49 and note that $|\mu_{ul}|^2 = S|\mu|^2$, where $S$ is called the line strength. Mangum and Shirley (2015) show how to calculate $S$ and estimate $Q$ for various molecular transitions using quantum numbers $J$ and $K$. Also $|\mu|$ can be obtained for various molecules. Thus all the variables in equation 1.53 in order to estimate total column densities for molecules with a given line transition at a frequency $\nu_0$

$$D_t = \frac{3h}{8\pi^3S|\mu|^2} \frac{Q}{g_u} \exp\left[\frac{h\nu_0}{kT_{Ex}}\right] \int_0^\infty \tau(v) dv \left[ \exp\left(\frac{h\nu_0}{kT_{Ex}}\right) - 1 \right]$$  \hspace{1cm} (1.52)

or,

$$D_t = \frac{3h}{8\pi^3S|\mu|^2} \frac{Q}{g_u} \int_0^\infty \tau(v) dv \left[ 1 - \exp\left(-\frac{h\nu_0}{kT_{Ex}}\right) \right]$$  \hspace{1cm} (1.53)

It is very important to note that because the optical depth is integrated with respect to velocity which has units km/s that in order to get the column density to have units cm$^{-2}$ a factor of $10^5$ is included on the right hand side since 1 km/s = $10^5$ cm/s

\^3Taken from tables at [http://spec.jpl.nasa.gov](http://spec.jpl.nasa.gov)
1.4 Carbon Monoxide

Carbon Monoxide (CO) is widely distributed throughout the Milky Way and is found in dark clouds, dense clouds near H\textsubscript{II} regions, and more diffuse regions (Oppenheimer and Dalgarno, 1975). As H\textsubscript{2} cannot be directly observed in the millimetre-wavelength, to trace these regions, tracers like CO are needed to determine the molecular mass (van Dishoeck et al., 1992; van Dishoeck and Blake, 1998). The primary CO rotational transitions can be detected within the millimetre- and submillimetre-wave bands when using ground-based telescopes (Heyer and Dame, 2015). Table 1.2 provides a summary of the CO isotopes and transitions used within this thesis.

<table>
<thead>
<tr>
<th>Isotopologue</th>
<th>Transition</th>
<th>Rest Frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}$C$^{16}$O</td>
<td>(1→0)</td>
<td>115.271202</td>
</tr>
<tr>
<td>$^{12}$C$^{16}$O</td>
<td>(4→3)</td>
<td>461.040768</td>
</tr>
<tr>
<td>$^{12}$C$^{17}$O</td>
<td>(1→0)</td>
<td>112.358988</td>
</tr>
<tr>
<td>$^{12}$C$^{18}$O</td>
<td>(1→0)</td>
<td>109.782176</td>
</tr>
<tr>
<td>$^{13}$C$^{16}$O</td>
<td>(1→0)</td>
<td>110.201354</td>
</tr>
</tbody>
</table>

Table 1.2: Summary of CO isotopes, their transitions, and rest frequency used in this thesis.

CO has a rotational transition which are changes in the molecule’s angular momentum ($J$), where changes of $\Delta J = \pm 1$ are allowed. The notation of rotational transition is shown as e.g. ($J=1\rightarrow0$), such as $^{12}$CO ($1\rightarrow0$) or ($1\rightarrow0$). Molecules possessing this transition require a permanent electric dipole moment for the electromagnetic waves to be able to couple to the angular momentum; without this, molecules cannot be observed in purely rotational transitions. The energy states depend on the rotational level of $J$: $\Delta E \propto J (J + 1)$. The frequency of the emitted photon is determined by the energy difference between the two levels.

Bialy and Sternberg (2015) have illustrated the formation-destruction reactions and pathways of CO. From figure 1.3, a few pathways to form CO can be seen. The first are the CO production pathways via OH,

$$C + OH \rightarrow CO + H \; , \quad (1.54)$$

or

$$C^+ + OH \rightarrow CO^+ + H \; , \quad (1.55)$$
$$CO^+ + H \rightarrow CO + H^+ \; , \quad (1.56)$$

and

$$CO^+ + H_2 \rightarrow HCO^+ + H \; , \quad (1.57)$$
$$HCO^+ + e \rightarrow CO + H \; . \quad (1.58)$$
Production through CH or O$_2$ can also form CO

$$\text{HCO}^+ + e \rightarrow \text{CO} + \text{H} \quad (1.59)$$

$$\text{O}_2 + \text{C} \rightarrow \text{CO} + \text{O} \quad (1.60)$$

Heyer and Dame (2015) describe the optical depths of CO and the isotopes. Due to the low critical density ($\sim 2000 \text{ cm}^{-2}$ for the J = 10 transition), CO is highly abundant at low densities, and as a result column density for this line is generally optically thick. The $^{13}$CO isotope at 110 GHz is described as having moderate optical depth, because it is less abundant than CO by factors of 25100 in the Milky Way (Heyer and Dame 2015). As this line is well correlated with dust extinction, it is used to provide an indirect link to H$_2$ column densities. C$^{17}$O and C$^{18}$O are less abundant, compared to the previously mentioned $^{12}$CO or $^{13}$CO and is generally optically thin.
1.4.1 CO Analysis

The $^{12}$CO transition for $J = 1 \rightarrow 0$ has a line rest frequency of 115.271202 GHz. Assuming this line comes from an optically thick cloud then equation (1.26) becomes, on substitution of the constants:

$$T_{Ex} = \frac{5.53215}{\ln \left[ 1 + \frac{5.53215}{T_B^{\infty} + 0.836279} \right]}.$$  

(1.61)

For the same molecule the $J = 4 \rightarrow 3$ transition has a line rest frequency of 461.040768 GHz (see table 1.2). On substitution of the constants and assuming an optically thick cloud, equation (1.26) becomes:

$$T_{Ex} = \frac{22.1265}{\ln \left[ 1 + \frac{22.1265}{T_B^{\infty} + 0.00658649} \right]}.$$  

(1.62)

There is a small difference between equations (1.12) and (1.13) to the expression given by Wilson et al. (2009) simply because of the updated CMB temperature of 2.725 K whereas they have used 2.7 K. It should be noted that the number of significant figures have been retained in this section for illustration purposes only, to demonstrate how others obtained the approximations used.

1.4.2 $^{13}$CO

Using the excitation temperature derived from $^{12}$CO $J = 1 \rightarrow 0$ or $J = 4 \rightarrow 3$ and calculating the optical thickness for the $^{13}$CO molecule with a line frequency of 110.201354 GHz for the transition $J = 1 \rightarrow 0$ the following can be obtained through substituting into equation (1.27):

$$\tau^{13}\text{CO} = -\ln \left[ 1 - \frac{T_{\text{Ex}}^{13}\text{CO}}{5.28883} \right].$$  

(1.63)

Column density can be calculated using equation (1.53). For $^{13}$CO using Mangum and Shirley (2015) for the $J = 1 \rightarrow 0$ transition, and the Jet Propulsion Laboratory (JPL) website\(^4\):

$$S = \frac{1}{3}$$

$$\mu = 1.1046 \times 10^{-19} \text{ esu cm}$$

$$Q \approx \frac{kT_{\text{Ex}}}{hB_0} + \frac{1}{3}$$

$$B_0 = 55101.011 \text{ MHz}$$

$$g_u = 3$$

$$\nu_0 = 110.201354 \text{ GHz}$$

\(^4\)http://spec.jpl.nasa.gov
\[ D_{13}^{13\text{CO}} = 2.48368 \times 10^{14}(T_{Ex} + 0.881477) \frac{\int_0^{\infty} \tau(v)dv}{1 - \exp\left(-\frac{5.28883}{T_{Ex}}\right)} \] (1.64)

If \( T_{Ex} \) is larger than the constant factor in the equation then it reduces to the form reported by Wilson et al. (2009):

\[ D_{13}^{13\text{CO}} = 2.48 \times 10^{14}T_{Ex} \frac{\int_0^{\infty} \tau(v)dv}{1 - \exp\left(-\frac{5.29}{T_{Ex}}\right)} \] (1.65)

1.4.3 \text{C}^{17}\text{O}

The \text{C}^{17}\text{O} (1−0) with a line frequency of 112.358988 GHz the following can be obtained by substitution into equation 1.27:

\[ \tau_{\text{C}^{17}\text{O}} = -\ln \left[ 1 - \frac{T_{\text{B}^{17}\text{CO}}}{5.39238} \frac{1}{(5.39238/T_{Ex} - 1)^{-1} - 0.160399} \right] \] (1.66)

The column density for \text{C}^{17}\text{O} with parameters obtained as above,

\[ \mu = 1.1034 \times 10^{-19}\text{esu cm} \]
\[ B_0 = 56179.990 \text{ MHz} \]
\[ \nu_0 = 112.358988 \text{ GHz} \]

\[ D_{t}^{17\text{CO}} = 2.44128 \times 10^{14}(T_{Ex} + 0.898738) \frac{\int_0^{\infty} \tau(v)dv}{1 - \exp\left(-\frac{5.39238}{T_{Ex}}\right)} \] (1.67)

For relatively large \( T_{Ex} \) this reduces to

\[ D_{t}^{17\text{CO}} = 2.44 \times 10^{14}T_{Ex} \frac{\int_0^{\infty} \tau(v)dv}{1 - \exp\left(-\frac{5.39}{T_{Ex}}\right)} \] (1.68)

1.4.4 \text{C}^{18}\text{O}

For the \text{C}^{18}\text{O} \( J = 1 \rightarrow 0 \) transition with a line frequency of 109.782176 GHz the following can be obtained through substitution of equation 1.27:

\[ \tau_{\text{C}^{18}\text{O}} = -\ln \left[ 1 - \frac{T_{\text{B}^{18}\text{CO}}}{5.26872} \frac{1}{(5.26872/T_{Ex} - 1)^{-1} - 0.169105} \right] \] (1.69)

The column density for \text{C}^{18}\text{O} with the following parameters:

\[ \mu = 1.1079 \times 10^{-19}\text{esu cm} \]
\[ B_0 = 54891.420 \text{ MHz} \]
\[ \nu_0 = 109.782176 \text{ GHz} \]
\[ D_{l}^{18\text{CO}} = 2.47833 \times 10^{14}(T_{Ex} + 0.878125) \left[ \frac{\int_{0}^{\infty} \tau(v)dv}{1 - \exp \left( \frac{-5.26872}{T_{Ex}} \right)} \right]. \]  \hspace{1cm} (1.70)

For relatively large \( T_{Ex} \) this reduces to

\[ D_{l}^{18\text{CO}} = 2.48 \times 10^{14}T_{Ex} \left[ \frac{\int_{0}^{\infty} \tau(v)dv}{1 - \exp \left( \frac{-5.27}{T_{Ex}} \right)} \right]. \]  \hspace{1cm} (1.71)
1.5 Neutral Atomic Carbon

Our understanding of molecular cloud’s physical conditions can be improved through studying the transition from ionized carbon $\text{C}^+$ to $\text{CO}$ via its neutral atomic carbon state (Heithausen et al., 2001). Tatematsu et al. (1999) describe neutral atomic Carbon (hereafter $[\text{C}\,\text{i}]$) as an important coolant for the interstellar medium, whose abundance may reflect the physical structure of molecular clouds. $[\text{C}\,\text{i}]$ exists in regions of low dust extinction and strong radiation (such as found in star forming regions), where $\text{CO}$ will photodissociate into neutral carbon and oxygen (Lo et al., 2014). It has been suggested that a newly-forming cloud will be expected to have a large abundance of $[\text{C}\,\text{i}]$ for the first $\sim 10^6$ years (Phillips and Huggins, 1981).

The rest frequency of $[\text{C}\,\text{i}]$ is $\sim 492$ GHz. It is virtually unobservable apart from at sites which are at high altitudes and dry, since this line lies in a relatively opaque region of the Earth’s atmospheric spectrum (Phillips and Huggins, 1981). The first detection by Phillips et al. (1980) used the NASA Kuiper Airborne Observatory telescope, which carried a 91.5 cm telescope to altitudes of 12-km. The new generation of ground based telescopes, like ALMA which are capable of mapping at submillimeter wavelengths, allow the idea of utilizing $[\text{C}\,\text{i}]$ as a tracer of column density at higher resolution (Lo et al., 2014). Large scale observations towards the galactic cloud has shown $[\text{C}\,\text{i}]$ emission coincident with that of $\text{CO}$ emission (Kramer et al., 2008). Hence, the fine line structure of $[\text{C}\,\text{i}]$ is an ideal tracer of cooling transitions of the ISM (Kramer et al., 2008). $[\text{C}\,\text{i}]$ was initially detected by Phillips and Huggins (1981) towards interstellar clouds, since then it has been found in a number of local systems which have been summarised by Alaghband-Zadeh et al. (2013). This tracer has been used towards on-going star formation regions in the Galactic plane (Jakob et al., 2007; Fixsen et al., 1999; Phillips et al., 1980; Gerin and Phillips, 2000) and external galaxies (Bayet et al., 2006; Kramer et al., 2005; Weiß et al., 2003) to trace the ISM transiting to a cooler phase.

The critical density of $[\text{C}\,\text{i}]$ is the same as $^{12}\text{CO}$ (1–0) (1–0) at $n_{cr} \approx 10^3 \text{ cm}^{-3}$ (Walter et al., 2011). Beuther et al. (2014) has described two pathways showing the sequence of $\text{C}^+/\text{C}^0/\text{CO}$

- During cloud formation, the diffused and ionized medium recombines and becomes partly neutral; at this stage lines of ionized $\text{C}^+$ ($[\text{C}\,\text{ii}]$) and neutral carbon $\text{C}^0$ ($[\text{C}\,\text{i}]$) can be observed. Then with increasing densities, molecular $\text{H}_2$ and $\text{CO}$ are formed.

- $\text{CO}$ can dissociate, if exposed to strong ultraviolet radiation, to form atomic and ionized carbon.

The formation of $[\text{C}\,\text{i}]$ has been explained by Beuther et al. (2014) and Bialy and Sternberg (2015), showing different ways that $[\text{C}\,\text{i}]$ (represented as C) can be created through the photodissociation (shown as crxp) of $\text{CO}$ into Carbon and Oxygen:

$$\text{CO} + \text{crxp} \rightarrow \text{C} + \text{O}$$
radiative recombination can strip an ion form C⁺, 

\[ C^+ + e \rightarrow C + \nu; \]

or charge transfer to C⁺, 

\[ C^+ + S \rightarrow C + S^+ \]
\[ C^+ + Si \rightarrow C + Si^+ \]

via radiative association.

1.5.1 [CI] Analysis

Neutral Carbon is a particularly important tracer because it allows us to understand the interaction between Ultraviolet (UV) radiation from starlight and the ISM. Spectroscopic notation of neutral carbon in the ground state is \(1s^2 2s^2 2p^2\) \(P_0\). Hyperfine splitting occurs because of LS spin-orbit coupling, with \(P_0\) splitting into a triplet state \(3P_{0,1,2}\) (Jackson et al., 1998). The transition \(3P_1 \rightarrow 3P_0\) occurs at \(\nu_0 = 492.16065 \text{ GHz}\) and is particularly difficult to observe because of water vapour so Jackson et al. (1998) used the Antarctic Submillimeter Telescope and Remote Observatory (AST/RO) telescope at the South Pole, where it is relatively dry, to detect the hyperfine transition.

The Einstein ‘A’ co-efficient is obtained from the Cologne Database for Molecular Spectroscopy (CDMS) and for this transition it has the value \(A_{ul} = -7.0972 \, \text{s}^{-1}\). Substituting this and the transition frequency in equation 1.46 we obtain for the column density:

\[
D_{CI}^{CI} = 1.57 \times 10^{15} \int_0^\infty \frac{\tau(v)dv}{1 - \exp\left(-\frac{23.62}{T_{Ex}}\right)}. \quad (1.72)
\]

(a factor of \(10^5\) has to be included to get the column density with units \(\text{cm}^{-2}\)). \(T_{Ex}\) is needed in equation 1.72 but this not easily calculated from first principles using equation 1.26. For optically thin clouds we need to know the optical depth in order to derive \(T_{Ex}\) from this equation. A potential solution is to assume that the excitation temperature of neutral Carbon is similar (at least within 10 K) to the excitation temperature of \(^{12}\)CO (Okada et al., 2015). This value is substituted instead into equation 1.72 in order to obtain an estimate of the column density of neutral Carbon. In addition, the excitation temperature derived from \(^{12}\)CO can be used to calculate the optical depth for [CI], which can be obtained through substituting into equation 1.27

\[
\tau_{CI} = -\ln \left[1 - \frac{T_B^{CI}}{23.62/(23.62/T_{Ex} - 1) - 0.00017}\right]. \quad (1.73)
\]
1.6 Ammonia

Ammonia NH$_3$ is one of the best kinetic temperature probes, due to the number of transitions, sensitive to a wide range of excitation conditions. NH$_3$ has been located in a variety of environments, from cool dark clouds to hot molecular cores. Myers and Benson (1983) and Benson and Myers (1989) found NH$_3$ to be one of the most suitable molecules for studying the cool, dense molecular cores where stars form. Initially discovered by Cheung et al. (1968), NH$_3$ was the first polyatomic molecule found in the ISM. NH$_3$ has a few important properties that make this tracer particularly interesting: inversion motion of the molecule, and the hyperfine structure (Ho and Townes, 1983). The molecular structure of NH$_3$ is a pyramid with three identical N – H bonds, a symmetric top with inversion. The structure of NH$_3$ is well understood by laboratory spectroscopy (Townes and Schawlow, 1955).

The formation mechanism generally proposed for interstellar NH$_3$ is shown by (Ho and Townes, 1983):

\[ \text{NH}_3^+ + e^- \rightarrow \text{NH}_3 + \text{H} \]

The principal dissociation mechanisms are:

\[ \text{NCO}^+ + \text{NH}_3 \rightarrow \text{NH}_3^+ + \text{CO} \]
\[ \text{H}_3^+ + \text{NH}_3 \rightarrow \text{NH}_3^+ + \text{H}_2 \]
\[ \text{N}_3^+ + \text{NH}_3 \rightarrow \text{NH}_3^3 + \text{H}_2 + \text{H} \]

Individual rotational spectral lines are split into five hyperfine components, the relative amplitudes of which can be used to derive the optical depth in the gas. In addition, the collisional rates with molecular hydrogen have been extensively modelled and the link between the excitation of NH$_3$ and the kinetic temperature of the gas is well understood.

The hyperfine lines of NH$_3$ (1,1) often exhibit anomalous intensity ratios towards star forming regions. Park (2001) investigated the effect using radiative transfer codes and concluded that the skewness of the spectrum could be a good probe of systematic motions inside dense cores with high optical depths.

The transitions of NH$_3$ are excited in comparatively dense material, and direct estimation of the temperature, optical depth, and column density of the molecular cloud. Subsection 1.6.1 explains the method for calculating kinetic temperatures.

NH$_3$ has two principal quantum numbers (J,K), which describe the total rotational energy of the molecule. The quantum numbers refer to the total angular momentum (J) and its projection along the molecular axis (K). The molecule has an electric dipole moment only along the molecular axis (Ho and Townes, 1983). The dipole selection rules are $\Delta K = 0$, $\Delta J = 0$, ±1. The transitions between K-ladders (states with the same value of K) are normally forbidden.
1.6.1 NH$_3$ analysis

Ammonia is a symmetric top molecule structured like a triangular pyramid with the Nitrogen and three Hydrogen atoms occupying each vertex. The Nitrogen can move along the centre line of the NH$_3$ molecule through the Hydrogen atoms and this inversion process — stimulated by an electric dipole moment — using quantum mechanical tunnelling produces symmetric inversion splitting of the energy levels.

There are three such symmetric splitting below 100 K. In ($J,K$) notation these are (1,1) at approximately 23.694 GHz, (2,2) at approximately 23.722 GHz, and (2,1) at 23.099 GHz [Mangum and Shirley 2015, see their Figure 11]. The symmetric splitting does not alter the (J,K) values, that is, $\Delta J = 0$ and $\Delta K = 0$. The symmetric energy levels to created are designated

$$(J,K)^+ \leftrightarrow (J,K)^-.$$  \hspace{1cm} (1.74)

Because the molecule is complex and can be excited in many modes we need to develop equation 53 into component parts. Firstly we can write:

$$g_u = g_J g_K g_I$$  \hspace{1cm} (1.75)

Here $g_J$ is the energy degeneracy associated with the $J$ quantum number and is simply $(2J+1)$, $g_K$ the energy degeneracy associated with the $K$ quantum number and is equal to 2 for symmetric top molecules like ammonia [Mangum and Shirley 2015], and lastly $g_I$ is the energy degeneracy associated with the nuclear spin given by:

$$g_I = \frac{g_{\text{nuclear}}}{(2I+1)^\sigma}$$  \hspace{1cm} (1.76)

This leads to $g_{\text{nuclear}} = 2$ for the three opposing identical Hydrogen atoms in Ammonia (Mangum and Shirley 2015), $I = 1/2$, and $\sigma = 3$ because of the three Hydrogen atoms, resulting in $g_I = 2/8 = 1/4$.

The $Q$ parameter in equation 1.53 also takes on a more complicated form for the NH$_3$ molecule:

$$Q = \sum_{J=0}^{\infty} \sum_{K=-J}^{J} g_K g_I g_J \exp \left( -\frac{E_{JK}}{kT} \right)$$  \hspace{1cm} (1.77)

the energy term in the above equation is given by,

$$E_{JK} = h(B_0j(j+1) + s_0k^2) + \text{higher order terms}$$  \hspace{1cm} (1.78)

where $s_0 \equiv A_0 - B_0$ for prolate rotor molecules, or $s_0 \equiv C_0 - B_0$ for oblate molecules. Data for $A_0$, $B_0$, $C_0$ are given at JPL website[^6] which gives $A_0 = B_0$ for NH$_3$ and shows

[^6]: http://spec.jpl.nasa.gov
Table 1.3: Values used to calculate Optical Depth & Column Density for NH$_3$ for the three symmetric energy levels under 100 K.

<table>
<thead>
<tr>
<th>(J,K) Parameter</th>
<th>(1,1)</th>
<th>(2,2)</th>
<th>(2,1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S = \frac{K^2}{J(J+1)}$</td>
<td>$\frac{1}{2}$</td>
<td>$\frac{2}{3}$</td>
<td>$\frac{1}{6}$</td>
</tr>
<tr>
<td>$\mu$ eau.cm</td>
<td>$1.468 \times 10^{-18}$</td>
<td>$1.468 \times 10^{-18}$</td>
<td>$1.468 \times 10^{-18}$</td>
</tr>
<tr>
<td>$g_u = g_J g_K g_l$</td>
<td>$\frac{3}{2}$</td>
<td>$\frac{5}{2}$</td>
<td>$\frac{5}{2}$</td>
</tr>
<tr>
<td>$v_0$ (GHz)</td>
<td>23.6944955</td>
<td>23.7226334</td>
<td>23.0988190</td>
</tr>
<tr>
<td>$S g_u$</td>
<td>$\frac{3}{4}$</td>
<td>$\frac{10}{6}$</td>
<td>$\frac{5}{12}$</td>
</tr>
</tbody>
</table>

It is interesting to note that the essential difference between equations 1.82 and 1.84 is the leading constant multiplied by the respective integrated optical depth and that the ratio of the column densities reduces approximately to the ratio of these factors (if we assume $T_{Ex}$ is essentially the same for all three symmetric modes).
As an example,

\[
\frac{D^{(1,1)}}{D^{(2,2)}} \approx \frac{6.84 \int_0^\infty \tau^{(1,1)}(\nu) d\nu}{3.08 \int_0^\infty \tau^{(2,2)}(\nu) d\nu}
\]

(1.85)

It should be noted from equation 1.23 and assuming that the excitation temperature is the same for two symmetric modes, say (1,1) and (2,2), and that their transition frequency is almost the same, that the following ratio approximately applies,

\[
\frac{T_B^{(1,1)}}{T_B^{(2,2)}} \approx \frac{1 - e^{-\tau^{(1,1)}}}{1 - e^{-\tau^{(2,2)}}} \approx \frac{\tau^{(1,1)}}{\tau^{(2,2)}}.
\]

(1.86)

This is the same relationship (Mangum et al. 1992, equation A3) arrive at. Rearranging the equation we can get the optical depth relationship as

\[
\tau^{(2,2)} = \ln \left[ \frac{1 - T_B^{(2,2)}}{T_B^{(1,1)}} \left( 1 - e^{-\tau^{(1,1)}} \right) \right]
\]

(1.87)

The above equation may be solved if \( \tau^{(1,1)} \) is known. This may be done using the hyperfine splitting of the main (1,1) line which produces a satellite adjacent line. The \( J \) and \( K \) quantum number are augmented with an \( F \) quantum number. The main \((J = 1, K = 1)\) line splits into a hyperfine triplet of satellite lines with values \( F=0 \), 1, 2. The relative ratio of intensities of the main and satellite lines \( R \) are summarised in Table 1.3 for Ammonia.

Table 1.4: This summarises hyperfine splitting of NH\(_3\). After Mangum et al. (1992), also Mangum and Shirley (2015).

<table>
<thead>
<tr>
<th>( J )</th>
<th>( K )</th>
<th>( F )</th>
<th>( R ) (Ratio of line intensities ( s/m ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0.22222</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.27778</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.06281</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.06520</td>
</tr>
</tbody>
</table>

Assuming similar beam filling factors and an approximately equal excitation temperature, equation 1.86 for the main (denoted \( m \)) and satellite lines (denoted \( s \)) becomes:

\[
\frac{T_B^{(1,1,m)}}{T_B^{(1,1,s)}} \approx \frac{1 - e^{-\tau^{(1,1,m)}}}{1 - e^{-R\tau^{(1,1,m)}}}
\]

(1.88)

Equation 1.88 needs to be solved numerically. Substituting \( x = \exp(-\tau^{(1,1,m)}) \) then the equation takes on the form,

\[
x^R - \left( \frac{T_B^{(1,1,s)}}{T_B^{(1,1,m)}} \right) x + \left( \frac{T_B^{(1,1,s)}}{T_B^{(1,1,m)}} \right) - 1 = 0
\]

(1.89)

The roots can be found with a computer program like Mathematica and will yield an
optical depth for the main (1,1) line.

1.6.2 Rotation Temperature of Ammonia

The main transition from the (1,1) to (2,2) line in ammonia is governed by both collision and radiation. This transition yields a rotation temperature \( T_{Ro} \) which includes collisions produced by a kinetic temperature \( T_{Ki} \), as the Ammonia molecules jostle each other, together with a radiative transfer at a temperature \( T_B \). Estimates of both \( T_{Ro} \) and \( T_{Ki} \) of the cloud can be obtained. Let \( N^{(1,1)} \) and \( N^{(2,2)} \) represent the number densities of the (1,1) and (2,2) states of the ammonia molecule in the cloud. Applying a Boltzmann distribution and assuming the transition energy between these levels is \( \Delta E \):

\[
\frac{N^{(2,2)}}{N^{(1,1)}} = \frac{g^{(2,2)}}{g^{(1,1)}} \exp \left( -\frac{\Delta E}{kT_{Ro}} \right), \tag{1.90}
\]

This ratio is equal to the column density ratio derived from equation [1.49] for the upper (2,2) and lower (1,1) levels.

\[
\frac{D^{(2,2)}}{D^{(1,1)}} = S^{(1,1)} \left( \exp \left( \frac{h\nu^{(1,1)}}{kT} \right) - 1 \right) \int_0^\infty \tau^{(2,2)}(v)dv \over S^{(2,2)} \left( \exp \left( \frac{h\nu^{(2,2)}}{kT} \right) - 1 \right) \int_0^\infty \tau^{(1,1)}(v)dv \tag{1.91}
\]

Substituting values from Table 1.3 for \( S^{(1,1)}/S^{(2,2)} \) and recognising \( \nu^{(1,1)} \approx \nu^{(2,2)} \), the above equation reduces to:

\[
\frac{D^{(2,2)}}{D^{(1,1)}} = 3 \int_0^\infty \tau^{(2,2)}(v)dv \over 4 \int_0^\infty \tau^{(1,1)}(v)dv \tag{1.92}
\]

Equating equations 1.90 and 1.92 leads to:

\[
\frac{g^{(2,2)}}{g^{(1,1)}} \exp \left( -\frac{\Delta E}{kT_{Ro}} \right) = 3 \int_0^\infty \tau^{(2,2)}(v)dv \over 4 \int_0^\infty \tau^{(1,1)}(v)dv \tag{1.93}
\]

Substituting for \( g^{(2,2)}/g^{(1,1)} \) from table 1.3 this becomes,

\[
\frac{\Delta E}{kT_{Ro}} = -\ln \left[ \frac{9}{20} \int_0^\infty \tau^{(2,2)}(v)dv \over \int_0^\infty \tau^{(1,1)}(v)dv \right] \tag{1.94}
\]

Mangum and Shirley [2015] and also Mangum et al. [1992], relate the overall optical density \( \tau^{(J,K)} \) to the the main line optical density \( \tau^{(J,K,m)} \) and obtain:

\[
\tau^{(1,1)} = 2.0\tau^{(1,1,m)} \tag{1.95}
\]
\[
\tau^{(2,2)} = 1.256\tau^{(2,2,m)} \tag{1.96}
\]

The transition energy, expressed as an equivalent temperature, is \( \Delta E/k = 64.20 - 23.21 = 40.99K \) (from Mangum and Shirley Table 9 - the literature incorrectly gives the temperature as 41.5 K. Ungerechts et al. quote it correctly). Substituting equations 1.95
and \[1.96\] into equation \[1.94\], obtaining:

\[
\frac{\Delta E}{kT_{Ro}} = -\ln \left[ \frac{0.2826}{\int_0^\infty \tau (2,2,m)(v)dv} \right] - 1
\]

(1.97)

\[
T_{Ro} = -40.99 - \ln \left[ \frac{0.2826}{\int_0^\infty \tau (1,1,m)(v)dv} \right]^{-1}
\]

(1.98)

\[
T_{Ro} = -40.99 - \ln \left[ \frac{0.2826}{\tau (1,1,m)} \ln \left[ 1 - \frac{T_B (2,2,m)}{T_B (1,1,m)} \right] \left(1 - e^{-\tau (1,1,m)}\right) \right]^{-1}
\]

(1.99)

Using equation \[1.87\] in equation \[1.98\] to get the final result for the Rotation Temperature \(T_{Ro}\) between the \((2,2) \leftrightarrow (1,1)\) transitions. Again noting that the \((1,1)\) and \((2,2)\) symmetric splitting frequencies are approximately the same, the result is in complete accordance with the literature.

### 1.6.3 Kinetic Temperature

In the case of the Ammonia molecular transitions caused by collisions also contribute to the rotational transitions as well as transitions caused by radiation. The transitions caused by collisions can be thought of as motivated by the Kinetic Temperature \(T_{Ki}\) of the Ammonia cloud. Therefore, collision excitation is included in the analysis of rotational transitions. For LTE conditions the following total equation for upper to lower or vice versa transitions of ammonia can be written:

\[
N_l(B_{lu} + C_{lu}) = N_u(A_{ul} + B_{ul}I_\nu + C_{ul})
\]

(1.100)

Here \(A_{ul}\), \(B_{ul}\), and \(B_{lu}\) are the Einstein coefficients we used before in equation \[1.29\] and, \(C_{ul}\) and \(C_{lu}\) are the equivalent collision coefficients for absorption and stimulated emission excited by collisions. Noting the results from equations \[1.32\] and \[1.33\] for the Einstein coefficients caused by radiation and assume a Boltzmann distribution for the collision coefficients.

Finally, using the Rayleigh-Jeans formula for \(I_\nu\) we obtain the following set of preliminary equations:

\[
A_{ul} = \frac{8\pi h \nu^3}{c^3} B_{ul}
\]

(1.101)

\[
g_l B_{lu} = g_u B_{ul}
\]

(1.102)

\[
\frac{C_{lu}}{C_{ul}} = \frac{g_u}{g_l} \exp \left( -\frac{\nu}{kT_{Ki}} \right)
\]

(1.103)

\[
I_\nu = \frac{2k\nu^3}{c^2} T_B
\]

(1.104)

Here \(T_B\) is the equivalent radiation Black Body radiation temperature at LTE of the cloud. Substituting all the above equations into equation \[1.98\] the following is obtained
after substitution and some simplification:

\[
\frac{N_u}{N_l} = \frac{g_u}{g_l} \left[ \frac{kT_B A_{ul} + C_{ul} \exp \left( -\frac{h\nu}{kT_{Ki}} \right)}{A_{ul} \left( 1 + \frac{kT_B}{kT_{Ki}} \right) + C_{ul}} \right] \tag{1.105}
\]

\[
= \frac{g_u}{g_l} \left[ \frac{1 + \frac{T_0}{T_B} \exp \left( -\frac{h\nu}{kT_{Ki}} \right)}{1 + \frac{T_0}{T_B} + \frac{h\nu}{kT_B}} \right] \tag{1.106}
\]

\[T_0 = h\nu C_{ul}/kA_{ul}\] has also been substituted. Using,

\[
\frac{N_u}{N_l} = \frac{g_u}{g_l} \exp \left( -\frac{h\nu}{kT_{Ro}} \right) \tag{1.107}
\]

it can be substituted for \(N_u/N_l\) into equation 1.106 to obtain

\[
\exp \left( -\frac{h\nu}{kT_{Ro}} \right) = \left[ \frac{1 + \frac{T_0}{T_B} \exp \left( -\frac{h\nu}{kT_{Ki}} \right)}{1 + \frac{T_0}{T_B} + \frac{h\nu}{kT_B}} \right] \tag{1.108}
\]

Expanding the exponentials to first order and rearranging the equation then yields,

\[
T_{Ro} = \left[ \frac{T_B + T_0 + \frac{h\nu}{T_B}}{T_{Ki} + T_0} \right] T_{Ki} \tag{1.109}
\]

Since \(h\nu/k = 4.8 \times 10^{-11} \nu\) it follows that this term is small even at GHz frequencies and we can simplify equation 1.109 to,

\[
T_{Ro} = \left[ \frac{T_B + T_0}{T_{Ki} + T_0} \right] T_{Ki} \tag{1.110}
\]

\[
T_{Ki} = \frac{T_{Ro}T_0}{T_B - T_{Ro} + T_0} \tag{1.111}
\]

Equation 1.111 allows an estimate the Kinetic Temperature \(T_{Ki}\) from a previous estimate of \(T_{Ro}\) provided \(T_0\) is known which is a constant equal to \(h\nu C_{ul}/kA_{ul}\).

If \(T_0\) is large it follows from equation 1.110 that the rotation temperature \(T_{Ro}\) is approximately equal to the kinetic temperature \(T_{Ki}\). On the other hand if \(T_0\) is small then the rotation temperature is approximately equal to the radiation temperature \(T_B\) of the cloud. An interesting but not obvious fact which emerges from equation 1.110, once re-arranged, is that:

\[
T_{Ro} = \frac{1 + \frac{T_0}{T_B}}{1 + \left( \frac{T_0}{T_B} \right) \frac{1}{T_{Ki}}} \tag{1.112}
\]

Equation 1.112 shows that the rotation temperature is in fact the Harmonic Mean of the radiation temperature and the kinetic temperature, since by definition the Harmonic Mean \(H\) for a set \(\{a_0x_0, a_1x_1, a_2x_2, ..., a_nx_n\}\) is given by,

\[
H = \frac{\sum_{i=0}^{n} a_i}{\sum_{i=0}^{n} \frac{a_i}{x_i}} \tag{1.113}
\]
1.7 Hydrogen Radio Recombination Line

The Hydrogen Radio Recombination Line (RRL) is a spectral line which observes the transition between highly excited atomic levels. The transition is caused by ultraviolet photons ionizing Hydrogen atoms which then recombine with the electrons. The electron, orbits initially with a high principal quantum number $n$ then cascades down to a lower orbital energy level, radiating away the energy in the form of the spectral line (Burke and Graham-Smith 2014). RRLs can be observed over a wide wavelength range, from millimetre to centimetre wavelengths; these provides important information on highly excited states of hydrogen, which allows the physical properties to be probed, and this provide details of the structure of the Interstellar Medium (ISM) e.g. line emitting plasma and HII regions.

Kardashev (1959) first discussed the possibly that HII regions with sufficient intensity above the thermal continuum background can produce RRLs of Hydrogen and Helium. Observations by Dravskikh and Dravskikh (1964) using the Pulkovo Observatory in the USSR and Hoglund and Mezger (1965) using the National Radio Astronomy Observatory (NRAO) in the United States of America, were the first to detect RRLs. Details of observations and the theory of various sources emitting RRLs is described by Gordon and Sorochenko (2009).

![Figure 1.4: Peak brightness temperature of Hydrogen RRL as a function of frequency; each line represents a different electron density (Sorochenko 1965).](image)

Peters et al. (2012) reviewed the physics of Hydrogen RRL emission: the populations depart significantly from Local Thermodynamic Equilibrium (LTE) over frequency ranges that depend on the electron density. Peters et al. considered Atacama Large Millimetre Array (ALMA) and EVLA observations of compact high-density HII

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27
regions, but they also show that for the larger, less dense H\textsc{ii} regions that might be mapped with a single-dish telescope, non-LTE effects are important in the centimetre-wavelength range. This is supported by Gordon and Sorochenko (2009), who use non-LTE analysis to show how the line brightness varies with frequency and electron density. Figure 1.4, reproduced here from Sorochenko (1965), illustrates the variability of the peak brightness temperature and electron density. The peak of each electron density curve in figure 1.4 is shifting towards the higher frequencies with larger densities. This is generated by the electrons’ large orbits around atoms: the larger the size of the atom the higher the chance for the atom to collide or interact with charged particles of ambient H\textsc{ii} gas. Through the collision of atoms, the outer electrons are stripped away which removes the atom’s ability to radiate, this then reduces the intensity emitted by the H\textsc{ii} region. The decrease of the slope in the curve is due to the probability of atoms colliding, which decrease as the gas density increases. From figure 1.4, Sorochenko suggests that the best wavelength to observe the effects of Stark broadening (also known as pressure broadening) is $\lambda = 2–5 \text{ cm}$ or approximately $5–15 \text{ GHz}$.

Therefore we can estimate the electron density from the frequency dependence of line brightness. The line brightness depends on electron temperature and density, so RRL maps can be used to infer the structure of ionised gas (e.g. Jaffe and Pankonin 1978). This thesis used the H92$\alpha$ RRL (8.3 GHz) to observe two well known sources (Orion A and Sagittarius A), as test regions for on-the-fly (OTF) mapping with the Deep Space Station (DSS)43 (70m-Tid) antenna.
1.8 Low-mass Star Formation

Low-mass stars like the Sun (with masses between \(\sim 0.3 M_\odot\) and \(\sim 2 M_\odot\)) are known to be formed in the dense cores of large molecular gas clouds. Shu et al. (1987) describe the different stages of star formation: initially the effects of rotation, thermal pressure and weak magnetic fields or turbulence, resist the gravitational force acting towards the centre of the cloud. However, over time, the resistance weakens through the slow leakage of magnetic (and turbulent) support by ambipolar diffusion and the central region increases in density.

This is followed by an accretion phase in which gravity causes material surrounding the dense gas to fall towards the central region. A circumstellar disk is formed due to residual angular momentum, and jets and outflows from the protostar can be detected at this stage (class 0).

After a period of \(\sim 10^7\) years the material in the immediate vicinity is exhausted and the accretion phase ceases. By this time, the pressure and temperature has increased enough to ignite hydrogen fusion in the core and the protostar begins the main sequence.

Observationally, low-mass Young Stellar Objects (YSO) have been split into four main evolutionary classes based on their spectral energy distribution. The shape of the spectral energy distribution describe the conditions at each stage of evolution. A representation of the evolutionary sequence and the associated spectral energy distribution for the classes 0 to III are shown in fig 1.5.

**Class 0**: Molecular gas has started to collapse onto itself with the core temperature rising. At this phase, the molecular cloud is optically thick, accretion luminosity is absorbed, and infalling material comes to a halt at the protostar’s surface. The spectral energy distribution resembles a single black body with a temperature between 20 and 30 K, peaking in the far-IR band at \(\lambda \sim 150\) \(\mu m\).

**Class I**: Rotation of the protostellar object begins to build up an accretion disk. The core becomes magnetized, and the magnetic field is compressed and amplified by dynamo processes during the contraction. While magnetically driven outflows are developed to bleed off momentum and energy along the rotational axis of the system (Pudritz et al., 2007). At this point the protostellar object can be detected in the near-IR wavelength (\(\sim 100\) \(\mu m\)). The profile of the spectral energy distribution corresponds to a 50–100 K black body, originating in the accreting envelope, plus additional 200–400 K components in the disk.

**Class II**: After \(\sim 10^7\) years, the accretion phase ceases and the material in the vicinity is exhausted; the protostar starts the main sequence. At this stage planets begin to form. The pre-main-sequence core is visible at optical and near-infrared wavelengths, and is identified as a Classical T Tauri Star (CTTS).

**Class III**: Object is now identified as a Weak-line T Tauri Star (WTTS) and is visible in the near-IR and optical wavelengths. Some circumstellar material may be present in the form of a thin disk, however, the spectral energy distribution is generally well fit by a reddened blackbody with little or no intra-red excess emission.
Figure 1.5: Schematic representation of the evolutionary sequence for low-mass stars. Created by Purcell (2006) adapted from Lada and Wilking (1984) and van Dishoeck and Blake (1998).
1.9 Radio window and mapping the ISM

At high frequencies, the telescopes used within this thesis detect the molecular rotation transitions (see figure 1.6) that are ideal for studying the initial conditions of star formation. The information in spectral line profiles allow studies of the kinematic properties of molecular clouds, as extinction by dust grains declines with decreasing frequency. A limitation of observing at these frequencies with ground based telescopes, is the Earth’s atmosphere with its absorption lines, because water (H₂O) and oxygen (O₂ and O₃) form absorption bands in this window. The Precipitable Water Vapor (PWV) in the atmosphere affects the transmission and noise, and decreases with increasing height above the sea level. Even at high altitudes, there is variability of PWV caused by diurnal cycles and seasonal changes (going from Summer to Winter). Alternatively, one can move above the atmosphere using Balloon, Aircraft, or Rocket observatories which is an expensive solution to PWV.

In this project various molecular clouds of the Milky Way Galaxy through single-dish telescopes like Mopra, NANTEN2, and DSS43 have been mapped at high radio frequencies (between ∼22 GHz and ∼492 GHz) where these telescopes have sub-arcminute resolution. Single-dish telescopes at the millimeter and submillimeter wavelengths are commonly used over long periods of time, for large scale Galactic surveys (Heyer and Dame 2015). The general design is a circularly symmetric paraboloid dish (or mirror), sometimes dipole antennas are used at the lowest frequencies. The radiation from the sky is reflected to a secondary mirror, that focuses the signal into the optics of the telescope and then into the receiver. Full details of the telescopes used are discussed in the relevant chapters.

From figure 1.6, it can be seen that Mopra operating between 95-115 GHz is able to receive radio signals. NANTEN2 operates at 460 GHz and 492 GHz which are not opportune for radio astronomy, however it is located 4865-m above sea level, compensating for much of the signal reception problems. DSS43 (70m-Tid) is at ground level so at the frequency of 23 GHz it is not heavily affected by atmospheric absorption. However, poor weather conditions (heavy clouds, and rain) can cause serious effects for all of these telescopes.
Figure 1.6: A plot from [Wilson et al., 2009, figure 1.1], illustrating the transmission of the Earth’s atmosphere for electromagnetic radiation. The fraction of the atmosphere affecting transmission is shown on the left vertical axis, and the corresponding altitude on the right axis. These axis indicate the needed hight to reach a transmission of 0.5. The fine line variations are a result of molecular transitions [Townes and Schawlow, 1975]. Labels on the top of the diagram show the different types of instruments needed to measure at the given frequencies and wavelengths. Arrows at the bottom of the figure indicate the type of atomic or nuclear process that give rise to radiation at those frequencies and wavelengths. As an example, if we take the line at $\lambda=100 \mu$m, half of the astronomical signal would reach an altitude of $\sim 45$ km. Comparing that to $\lambda=10$ m the astronomical signal is able to reach the Earth’s surface.
1.10 Aims and outline of thesis

The broad aim of this work is to characterise the structure of molecular clouds. By probing molecular clouds containing possible stellar nurseries, we can gain a better understanding of the phases of the ISM, how this influences our Galaxy’s evolution and how it shapes the future form of the Galaxy.

In particular, this thesis investigates the poorly studied regions of Chamaeleon and Lupus, to understand the physical conditions of the region and known stellar objects. This gains us a better insight into the conditions of the stellar environment.

Carina has been extensively observed at high resolution in wavelengths of optical, X-ray, and Infra-Red (IR). However, in the radio and microwave wavelength regime, our understanding of the gas towards the region is limited, and so we aim to gain a better understanding through new observations.

Lastly, this work presents a technical aspect, implementing a new observing technique to the largest single dish telescope in the Southern Hemisphere (DSS43), which will increase its long term scientific capability.

The outline of this thesis is as follows: chapter 2, presents new sub-arcminute maps towards Chameleon II in the $^{12}$CO, $^{13}$CO, and C$^{18}$O emission lines. The high resolution allows us to dissect the region to gain a better understanding of the conditions towards some of the known stellar objects within the region; chapter 3, presents sub-arcminute resolution maps in $^{12}$CO (4–3) and [C$\text{I}$] towards Carina, providing a better view of the physical conditions of the region; chapter 4 presents observations towards the Lupus molecular cloud, a precursor project to the OTF mapping with DSS43. The project uses strip mapping to observe parts of Lupus in the ammonia transitions (1,1) and (2,2). The limitations of the telescope’s observing capability, as well as demonstrating the kind of science that can be achieved are discussed in this chapter; chapter 5, presents the implementation and data reduction details of OTF mapping using the DSS43, in response to the limitations discussed in chapter 4. The test on-the-fly (OTF) observations were conducted towards the well known regions of Orion A and Sagittarius A, in the H95α radio recombination line; this thesis concludes with Chapter 6 by summarising the main results and discussing potential future work.

Appendix A includes contributions to 12 papers by the author of this thesis.
Chapter 2

Chamaeleon Molecular Clouds

2.1 Introduction

Located in the Southern constellation of Chamaeleon within Galactic longitudes \(-68^\circ < l < -40^\circ\) and Galactic latitudes \(-30^\circ < b < -8^\circ\), the Chamaeleon dark clouds are among the nearest to the Sun \((d \sim 115–215\) pc; Luhman, 2008). Chamaeleon is an ideal target to study low-mass-star formation because of the high Galactic latitude, which avoids the contamination of other clouds along the line of sight (Hayakawa et al., 2001).

The Chamaeleon dark clouds have an angular size on the sky of a few square degrees, containing three main regions (Cha I, II, III), and they are isolated from other major star forming regions. Figure 2.1 is an integrated intensity map of \(^{12}\text{CO}\) towards the Chamaeleon region, with the different regions marked on the map (Boulanger et al., 1998). Cha I (to the West) is seen as an extended region with emission not as dense compared to the other regions within Chamaeleon. Cha II and Cha III are located on the Eastern side; Cha II is a large centrally concentrated cloud, while Cha III has more extended emission. The dark clouds within Cha I and Cha II contain evidence of recent low-mass-star formation (Luhman, 2008, and references therein). Of the three regions Cha I has been the target of various studies, while Cha II and Cha III are less well observed (Barrado y Navascués and Jayawardhana, 2004; Luhman, 2008).

Studies towards Chamaeleon have investigated the properties of the interstellar medium and magnetic field, using various wavelength: extinction (Dobashi et al., 2005), optical spectroscopy (Luhman and Muench, 2008), polarisation toward field stars (Gerakis and Whittet, 1995), and continuum in the far-infrared (Lehtinen et al., 2001; Evans et al., 2003; Ikeda et al., 2012), in millimetre wavelengths (Henning et al., 1993; Reipurth et al., 1996), and centimeter wavelengths (Lehtinen et al., 2003). A summary of the different surveys and observations that have been carried out towards Chamaeleon can be found in Luhman (2008).
This chapter focuses on the Cha II dark cloud in the Carbon Monoxide (CO) molecular lines (J=1–0 transitions of $^{12}$CO, $^{13}$CO, C$^{17}$O, and C$^{18}$O), marked in the purple box in figure 2.1. Cha II has modest star formation activity (Porras et al., 2007), and a mass of 1500-2000 M$_\odot$ (Boulanger et al., 1998; Mizuno et al., 2001). Previous CO maps towards Cha II have suffered from poor resolution, limited coverage, or both. Through high resolution, large coverage maps of the CO isotopologues towards Cha II, we are able to characterise the region, and resolve the structure within dense clumps.

### 2.1.1 Stellar Population

Young stars were first discovered in the Chamaeleon dark clouds through their variability and H$\alpha$ emission (Hoffmeister, 1962; Henize, 1963; Mendoza, 1972). The masses of the clouds and the densities of young stars within them are low compared to many other star-forming regions. The close proximity of Chamaeleon and its isolation from other young stellar populations makes it an excellent target for studies of low-mass star formation.

According to the evolutionary models of Baraffe et al. (1998) and Chabrier et al. (2000), star’s within Cha I have a median age of $\sim$2 Myr, and star formation has continued to the present time (Luhman, 2007). The combination of the census of known members and molecular observations of the cloud imply a star formation efficiency of $\sim$10% for Cha I, which is an upper limit since some of the clouds have probably dissipated, particularly in the northern half (Luhman, 2007).

Primarily because of the high resolution surveys by the Spitzer legacy program,
Cha II has recently been a region of interest to study for its young stellar population (Evans et al., 2003). In particular, Porras et al. (2007), as part of the Spitzer Legacy Program “From molecular Cores to Planet-forming disks” (c2d), observed Cha II along with four other regions (Lupus, Perseus, Serpens and Ophiuchus). Cha II contains a number of pre-main-sequence stars, low-mass T Tauri stars, brown dwarfs, and one intermediate-mass Herbig Ae/Be star known as DK Cha or IRAS 12496-7650. Pre-main-sequence stars with detections of Hα have been identified by Schwartz (1977) and Hartigan (1993). Follow up observations by Whittet et al. (1991); Prusti et al. (1992) and Larson et al. (1998) using near-infrared and infrared astronomical satellite (IRAS) data suggest these sources contain circumstellar material. Brown dwarfs with disks have been identified through deep near-infrared data and the cores to disk (c2d) catalogue. Alcalá et al. (2006) and Allers et al. (2007) describe the population of brown dwarfs, some of which possess disks or are identified as Young Stellar Objects (YSO).

Figure 2.2 illustrates the spatial distributions of the known objects towards the Chamaeleon II region, using catalogues of Schwartz (1977); Allers et al. (2007); Spezzi et al. (2007, 2008).

Several Herbig-Haro (HH) objects, bright knots of emission colliding with nearby clouds at high velocity, were identified in Cha I (HH 48-50) and Cha II (HH 52-54) by Schwartz (1977). The HH 52, 53, and 54 sources are located in the North-West region of Cha II (represented as green and yellow triangles in figure 2.2). Optical images, spectra and velocity measurements towards HH 52-54 have been obtained by Graham and Hartigan (1988) who noted that HH 54 has extended outflows which could be as large as 400 pc. Bjerkeli et al. (2014) examined HH 54 in greater detail (optical image shown in figure 2.3) with Herschel-HIFI, Atacama Pathfinder Experiment (APEX) and the Spitzer telescopes to construct a 3D radiative transfer models of an associated bow-shock. Peak positions of high-J CO transitions were blue shifted from the lower J, which indicate association with a dissociative shock as the jet impacts slower moving gas. Detail studies in the CO, H$_2$O, H$_2$, [OI], [C II], [Ne II], [Fe II], [S I], and [Si II] emission lines have been conducted towards the region (summarised by Luhman, 2008).
Figure 2.2: Digital sky survey blue image\textsuperscript{1} of Chamaeleon II overlaid with contours of $^{13}$CO (1–0) integrated intensity (1, 2...5 K) from this work. Known young objects towards Chamaeleon II are marked: points taken from Schwartz (1977) in green, those from Allers et al. (2007) in blue, and those in Spezzi et al. (2007, 2008) in red and yellow respectively. Symbols represent objects types: HH sources are indicated as a triangle, pre-main-sequence stars are shown using a star symbol, diamonds represent candidate YSOs and other objects are shown as a circle.

\textsuperscript{1}Map taken from \url{https://archive.stsci.edu/cgi-bin/dss_form}
2.1.2 Molecular gas

Its high Galactic latitude and close proximity to our Sun, make Chamaeleon an ideal target to examine the molecular gas, free from background contamination of CO emission within the Galactic plane (Mizuno et al., 1998). Mizuno et al. (2001) has described the observations searching for molecular gas in the mm-wavelength as limited, despite extensive studies being carried out in other wavelengths. Chamaeleon has been mostly mapped in the CO isotopologues, $^{12}$CO (Boulanger et al., 1998; Mizuno et al., 2001), $^{13}$CO (Mizuno et al., 1998; Hayakawa et al., 2001; Gahm et al., 2002), and C$^{18}$O (Torsseva et al., 1990; Mizuno et al., 1999; Hayakawa et al., 2001; Gahm et al., 2002; Haikala et al., 2005). Based on CO observations, the total mass of Cha I is $\sim$1000 M$_\odot$ and Cha II and Cha III each have masses of 1500–2000 M$_\odot$ (Mizuno et al., 2001).

The first large scale $^{12}$CO (1–0) observations towards the region were carried out by Boulanger et al. (1998), comparing the molecular gas with data from IRAS, extinction and HI, to study the distribution of interstellar matter in the complex. Boulanger et al. (1998) used the Columbia University 1.2-m Sky Survey telescope at Cerro Tololo in Chile, towards the Chamaeleon region, as part of the Galactic CO survey by Dame et al. (2001).

A higher resolution (beam size of 2.6′) $\sim$491 deg$^{-2}$ $^{12}$CO (1–0) map towards the Chamaeleon and the its neighbour Musca, presented by Mizuno et al. (2001) using NANTEN, describing the total mass towards Cha II of $\sim$8300 $\odot$. Figure 2.4 is taken from figure 1 of Mizuno et al. (2001), and shows the integrated intensity distribution of $^{12}$CO (1–0).
A survey in the $^{13}$CO (1−0) emission line towards the Chamaeleon and Musca (shown in figure 2.5) was carried out by Mizuno et al. (1998), identifying 25 small dense clouds widely distributed over $\sim 11^\circ \times 13^\circ$. Mizuno et al. (1998) found spatial correlation between the small clouds and with 33 isolated X-ray emitting T Tauri stars (TTS).

Large scale observations towards the Cha II and III cloud complexes were carried out by Hayakawa et al. (2001), in the $^{12}$CO, $^{13}$CO, and C$^{18}$O emission lines, with similar coverage to Mizuno et al. (2001). Hayakawa et al. (2001) created column densities of $^{12}$CO, and C$^{18}$O and made comparisons to visual extinction ($A_V$), finding variations between the three different regions in Chamaeleon. Mizuno et al. (1999) also carried out a large scale survey towards the region in the C$^{18}$O emission line survey identifying 11 dense cores within Cha II.

Observations towards smaller regions within Cha II have been carried out by Knee (1992), and Olmi et al. (1997). Knee (1992) observed the outflows coming from the HH 52-54 area, and Olmi et al. (1997) studied the C$^{18}$O outflow from IRAS 12553-7651.

Figure 2.4: NANTEN integrated intensity of $^{12}$CO (1−0) towards the Chamaeleon–Musca region, taken from figure 1 of Mizuno et al. (2001). The boundaries of the observation are indicated as solid back line.
Note: The text is not fully transcribed due to the complexity of the image and the need for manual interpretation of the diagrams.

Figure 2.5: NANTEN integrated intensity of $^{13}$CO (1–0) towards the Chamaeleon–Musca region, taken from figure 1 of Mizuno et al. (1998). The contour is at 0.9 K·km·s$^{-1}$ (3σ), the crosses are positions of X-ray TTs identified by Covino et al. (1997), and the boundary of the observation is shown as the solid black line.

Other molecular line observations towards Chamaeleon, have targeted the interstellar medium near individual dense cores and young stellar objects, using the CS (Olmi et al. 1997, Belloche et al. 2006, Löhr et al. 2007), HCN and HNC (Tennekes et al. 2006), and NH$_3$ (Bourke et al. 1995) emission lines. NH$_3$ observations towards this region are limited with Bourke et al. (1995) observing a small set of southern molecular clouds one of which was Chamaeleon. Observed at the coordinates of R.A. (J2000) 13$^h$03$^m$41$^s$, Dec. (J2000) $-76°44'03''$, Bourke et al. (1995) detected NH$_3$ (1,1) and (2,2) transitions using the Parkes radio telescope and K-band maser receiver, but there has not been a detailed study of Chamaeleon conducted with the NH$_3$ emission line.

Most of the studies of molecular gas have been focused towards Cha I, for its high stellar population compared to Cha II and III. However, towards the Cha II region most of the CO observations have been carried out by the NANTEN observatory.
2.2 New Observations and Data Processing

Previous observations of Chamaeleon in CO line have suffered from either poor resolution, poor sensitivity or both. Four CO J=1–0 isotopologues (\(^{12}\)CO, \(^{13}\)CO, C\(^{18}\)O, and C\(^{17}\)O) were observed towards Chameleon II using Mopra for its sub-arcminute resolution and high sensitivity.

2.2.1 The Mopra Radio Telescope

The Mopra Telescope is a 22-m radio telescope located at the edge of the Warrumbungle Mountains near Coonabarabran at an elevation of 866-m (see figure 2.6). Mopra is owned by the Australia Telescope National Facility (ATNF) which is a part of the Commonwealth Science and Industrial Research Organisation (CSIRO) Astronomy and Space Science division and runs in partnership with a collaboration of research institutes. The telescope is primarily used for 3-mm spectroscopy and Very-Long-Baseline Interferometry (VLBI) experiments, making this telescope the largest single dish millimetre-wave telescope in the Southern hemisphere. With a sub-arcminute resolution and the ability to cover large areas of sky in a short amount of time, Mopra is an ideal telescope for this project. Mopra is equipped with the University of New South Wales (UNSW) Digital Filter bank (MOPS) in its ‘zoom’ mode, with 4 × 137.5 MHz dual-polarization bands. The dataset generated has a spectral resolution of \(~0.1 \text{ km s}^{-1}\) over at least 4096 channels for each of the isotopologues.
Table 2.1 describes the receivers available on the Mopra telescope. For this thesis the 3-mm band is used as the CO isotopologues fall within this range.

<table>
<thead>
<tr>
<th>Band (mm)</th>
<th>Frequency Range (GHz)</th>
<th>Central Observing Frequency</th>
<th>Antenna Beam FWHM (arcsec)</th>
<th>Average $T_{sys}$*</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>76–117</td>
<td>@ 90 GHz</td>
<td>~0.5</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td></td>
<td>@ 115 GHz</td>
<td>~0.4</td>
<td>30</td>
</tr>
<tr>
<td>7</td>
<td>30–50</td>
<td>@ 42 GHz</td>
<td>~0.6</td>
<td>82</td>
</tr>
<tr>
<td>12</td>
<td>16–27</td>
<td>@ 24 GHz</td>
<td>~0.6</td>
<td>119</td>
</tr>
</tbody>
</table>

* Under good weather conditions.

Table 2.1: Receivers available on Mopra.

2.2.2 CO observations

Observations of the CO isotopologues towards Cha II were conducted under project code M2000 over three periods: 03-14 July 2014, 20-22-27 August in 2014; and 14-16 September 2015. Two sets of observations were performed: reference checks and fast-on-the-fly (FOTF) mapping towards the Cha II region. The reference checks were carried out through position-switched observations towards the reference positions used as part of the FOTF mapping. This checked for detections of line emissions towards the reference positions. For reference positions which detected line emission, the spectrum would later be added to the scans affected by these contaminated reference positions. Cha II was mapped in a series of $24' \times 24'$ regions, with an overlap of $4'$. Each $24' \times 24'$ region was observed as two $24' \times 12'$ maps scanning along the $\alpha$ axis, and another two maps scanning along the $\delta$ axis. In addition, each $24' \times 24'$ region used a reference scan with a different position (see table 2.2). Position-switching observations towards the FOTF mapping reference positions, revealed detections in $^{12}$CO and $^{13}$CO, affecting three regions as shown in table 2.2.

The system temperature ($T_{sys}$) is a measurement of the level of received power from the source, sky, telescope and instrument and hence the thermal noise in the spectrum. Calibration of $T_{sys}$ occurred every 30 min with reference to an ambient temperature paddle that is moved in front of the receiver. Figure 2.7 shows the $T_{sys}$ maps for the CO isotopologues: $^{12}$CO, $^{13}$CO, and C$^{18}$O. The $T_{sys}$ of $^{12}$CO is two times higher than the $T_{sys}$ of $^{13}$CO and C$^{18}$O maps. The $^{13}$CO and C$^{18}$O maps have the $T_{sys}$, because these lines share the same 2-GHz band of the correlator. The strips seen in parts of figure 2.7 are caused by scanning along the $\alpha$ and $\delta$ axis where poor or deteriorating weather conditions have occurred. The small ‘dots’ or ‘dashes’ of lower apparent noise occur where ‘bad’ pixels, rows or columns were identified and interpolated over (the low noise is a result of interpolating over several nearby pixels; see Burton et al., 2013).
Figure 2.7: $T_{\text{sys}}$ maps for (from left): $^{12}$CO, $^{13}$CO, and C$^{18}$O, in units of $T_A^*$ (K). The dark striping is inherent to the data set, resulting from scanning in the $\alpha$ and $\delta$ directions in variable observing conditions.
2.2.3 Data processing

The ATNF software packages LIVEDATA, GRIDZILLA\(^2\) and MIRIAM (Sault et al., 1995), along with scripts in Interactive Data Language (IDL) and PYTHON were used for data reduction. The Mopra system exports the raw data files in a Radio Physics Flexible Image Transport System (RPFITS) file format which needs LIVEDATA or similar to read it. The data of each observation is initially processed through LIVEDATA, which applies a bandpass calibration and a linear baseline subtraction. The calibrated data then undergoes a flagging process, initially developed by Rebecca Blackwell (private communication), where spectra with high noise or non-linear baselines are removed. The data is then imaged with GRIDZILLA, which sets the reference frequency and gridding parameters to create the data cube. The images are gridded finely (pixel scale of 0.2\(\text{'}\)) within GRIDZILLA to allow further processing, removing effects caused by the contaminated reference spectra and removing spectra with high root mean square (RMS) noise. Data cubes are manually inspected to identify poor quality, typically possibly caused during observing. Most of the poor data quality issues, spectra with high noise and/or contaminated reference spectrum, could be resolved through processing. If the majority of the data contains high noise, then the field would be observed again.

IDL scripts remove pixels, voxels, rows, and columns with high RMS noise, by interpolating over the surrounding pixels in the data cube. The cleaned data cube is then binned down to the appropriate Mopra resolution, further smoothing pixels, columns, and rows. A higher order baseline fit to a 4th and 7th degree polynomial is then applied to the spectra. The separate files containing a single 24\(\text{'}\)\(\times\)24\(\text{'}\) map is then merged together through a combination of MIRIAM tasks FITS, REGRID, and IMCOMB. The FITS task, would import and export the files into and out of the MIRIAM environment. The REGRID task is used to align the separate files and lastly, the IMCOMB task combines the separate files into one, the images are weighted in the region of overlap to minimise the RMS noise.

2.2.3.1 Contaminated reference positions

Three of the observed regions were affected by the reference position containing emission, in particular the \(^{12}\text{CO} \ (1–0)\) and \(^{13}\text{CO} \ (1–0)\) emission lines were the most affected. The \(^{17}\text{C}O\) and \(^{18}\text{C}O\) datasets were not affected, as the contaminating emission was not strong enough to be visible. Table 2.2 shows the image centre of a 24\(\text{'}\)\(\times\)24\(\text{'}\) map and the corresponding reference position. Figures 2.8 and 2.9 show spectra (\(^{12}\text{CO}\) and \(^{13}\text{CO}\), respectively) taken towards the different reference positions that were used to map Chamaeleon II. Line parameters of the contaminated \(^{12}\text{CO}\) and \(^{13}\text{CO}\) reference spectra are given in tables 2.3 and 2.4.

Data cubes which show an ‘absorption’ feature, are checked for contamination by emission in the reference scan. This contamination can be confirmed by observing the reference position of the FOTF mapping in more depth and identifying the detected

\(^2\)http://www.atnf.csiro.au/computing/software/livedata/
emission in the spectrum. Section 2.2.3.1 describe the detection of line emission towards the reference positions of the FOTF maps. To mitigate the effect of reference contamination, the COADDING.PY PYTHON script (see section B.1) allows the reference spectrum to be added into the data cube. The noise of the data cube would increase a slight fraction because of the addition of the reference spectrum, which itself contains noise.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12:55:00.4, −76:48:00</td>
<td>13:35:44.3, −76:48:00⁴²</td>
</tr>
<tr>
<td>3</td>
<td>13:02:26.6, −77:12:00</td>
<td>13:29:31.5, −77:12:00</td>
</tr>
<tr>
<td>5</td>
<td>13:02:19.9, −77:36:00</td>
<td>13:30:50.6, −77:36:00</td>
</tr>
</tbody>
</table>

⁴² Reference contained line emission

Table 2.2: Chameleon observing fields and reference positions.

Figure 2.8: $^{12}$CO spectra towards the reference positions of the Chamaeleon II FOTF maps.
2.3 Results

The analysis presented in this section uses the $^{12}$CO, $^{13}$CO, and C$^{18}$O emission lines; the C$^{17}$O line did not contain emission and was therefore excluded from analysis. Figure 2.10 presents the average spectrum over the entire image for each of the lines observed. Line parameters of the average spectra are given in Table 2.5.

The average $^{12}$CO emission lies within a velocity range between $\sim 0$ km s$^{-1}$ and $\sim 6$ km s$^{-1}$, the $^{13}$CO is also similar with a range $\sim 0$ km s$^{-1}$ and $\sim 5$ km s$^{-1}$, while the C$^{18}$O is not as extended with range $\sim 1$ km s$^{-1}$ between $\sim 4$ km s$^{-1}$. This is quite narrow for a whole cloud, suggesting that internal motions are limited, and there is thus little dynamical activity. Because of the differing abundances of $^{12}$CO, $^{13}$CO, and C$^{18}$O, the different levels of peak temperature are expected, with $^{12}$CO having the highest temperature of 3.93±0.03 K, compared with $^{13}$CO with 1.37±0.02 K and C$^{18}$O with 0.13±0.01 K.

The average line profile of $^{12}$CO, suggest the emission is optically thick as the peak shows a top-hat feature. The average line profiles of $^{12}$CO and $^{13}$CO (shown in figure 2.10) are asymmetrical, where the blue line wing (0–2 km s$^{-1}$) has enhanced emission compared to the red wing (4–6 km s$^{-1}$). The different centroid velocity for the isotopologues is because of the blue wing is present within $^{12}$CO and $^{13}$CO velocity.
Table 2.3: $^{12}$CO line parameters of the used reference positions.

<table>
<thead>
<tr>
<th>No.</th>
<th>Reference position</th>
<th>Peak (K)</th>
<th>Velocity Centroid (km s$^{-1}$)</th>
<th>FWHM (K·km s$^{-1}$)</th>
<th>Area (K·km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13:35:44.3, $-$76:48:00$^a$</td>
<td>0.40±0.06</td>
<td>3.72±0.06</td>
<td>0.77±0.14</td>
<td>0.33</td>
</tr>
<tr>
<td>2</td>
<td>13:35:21.7, $-$77:12:00$^a$</td>
<td>0.60±0.06</td>
<td>2.92±0.04</td>
<td>0.83±0.04</td>
<td>0.53</td>
</tr>
<tr>
<td>3</td>
<td>13:29:31.5, $-$77:12:00</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>4</td>
<td>13:34:57.7, $-$77:36:00$^a$</td>
<td>0.86±0.06</td>
<td>3.12±0.04</td>
<td>1.14±0.09</td>
<td>1.05</td>
</tr>
<tr>
<td>5</td>
<td>13:30:50.6, $-$77:36:00</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

$^a$ Reference contained line emission

Table 2.4: $^{13}$CO line parameters of the used reference positions.

<table>
<thead>
<tr>
<th>No.</th>
<th>Reference position</th>
<th>Peak (K)</th>
<th>Velocity Centroid (km s$^{-1}$)</th>
<th>FWHM (K·km s$^{-1}$)</th>
<th>Area (K·km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13:35:44.3, $-$76:48:00$^a$</td>
<td>2.40±0.07</td>
<td>3.65±0.03</td>
<td>1.89±0.07</td>
<td>4.83</td>
</tr>
<tr>
<td>2</td>
<td>13:35:21.7, $-$77:12:00$^a$</td>
<td>2.71±0.06</td>
<td>3.31±0.03</td>
<td>2.71±0.07</td>
<td>7.81</td>
</tr>
<tr>
<td>3</td>
<td>13:29:31.5, $-$77:12:00</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>4</td>
<td>13:34:57.7, $-$77:36:00$^a$</td>
<td>4.41±0.07</td>
<td>3.18±0.02</td>
<td>2.16±0.04</td>
<td>10.14</td>
</tr>
<tr>
<td>5</td>
<td>13:30:50.6, $-$77:36:00</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

$^a$ Reference contained line emission
profile, where the blue wing in $^{12}$CO is larger than $^{13}$CO.

![Figure 2.10: Average CO line profiles of $^{12}$CO, $^{13}$CO, C$^{18}$O, and C$^{17}$O emission towards Chamaeleon II.](image)

<table>
<thead>
<tr>
<th>Line</th>
<th>Peak (K)</th>
<th>Centroid velocity (km s$^{-1}$)</th>
<th>FWHM (K·km s$^{-1}$)</th>
<th>Area (K·km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}$CO (1–0)</td>
<td>3.93±0.03</td>
<td>2.77±0.01</td>
<td>2.69±0.02</td>
<td>11.06</td>
</tr>
<tr>
<td>$^{13}$CO (1–0)</td>
<td>1.37±0.02</td>
<td>2.98±0.01</td>
<td>1.60±0.02</td>
<td>2.34</td>
</tr>
<tr>
<td>C$^{18}$O (1–0)</td>
<td>0.13±0.01</td>
<td>3.04±0.03</td>
<td>1.16±0.07</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Table 2.5: Fitted line parameters of the averaged spectra shown in figure 2.10.

Figure 2.11 presents 1σ noise maps of $^{12}$CO, $^{13}$CO, and C$^{18}$O, determined from the standard deviation of the continuum channels between the velocity ranges of $v = (-30 - 0)$ km s$^{-1}$ and $v = (10 - 30)$ km s$^{-1}$ in each pixel. The striping within figure 2.11 for all three isotopologues, is the effect of a variety of system temperatures and observing conditions of the scans taken along the $\alpha$ and $\delta$ direction. There are a few pixels which have especially high noise, a result of a high $T_{\text{sys}}$ that has been substituted with a spectrum interpolated from surrounding pixels. Evidence of merging the different tiles during the data processing is obvious in the $^{12}$CO and $^{13}$CO RMS maps, where the overlap of each tile is seen.

Although the $^{13}$CO, and C$^{18}$O lines are within the same 2-GHz band of the corre-
lator the RMS noise distribution between both lines is different. The major difference between these maps is primarily due to the different processing approach taken for these lines. Processing $^{13}$CO requires the sections of the map to be imaged individually, which includes a step correcting for contaminated reference positions (see section 2.2.3 and 2.2.3.1). This resulted in artefacts within the completed map, where the edges of the observed sections can be seen. This is different to processing the C$^{18}$O dataset, where the reference spectra were not contaminated and the entire dataset could be imaged as a whole. This minimises the artefacts caused by low sensitivity when imaging individual sections. However, $^{13}$CO and C$^{18}$O do show some similarities of high RMS noise.

Figure 2.12 is a key image created to assist with the discussion of areas of interest. The areas of interest were selected by visually identifying dense regions in the C$^{18}$O integrated intensity map, and an area around the HH sources 52 to 54. The positions of known stellar objects towards Cha II is shown in figure 2.2 using the catalogues of Schwartz (1977); Allers et al. (2007); Spezzi et al. (2007, 2008). These areas are associated with positions which have been identified as dense cores by Mizuno et al. (1999).

Examining the areas of interest, some of the selected areas contain known stellar objects. The yellow box (which is denoted as region A) contains Infra-Red (IR) sources (ISO-ChaII 30, 31, 42, and 45), 2MASS sources J12590656-7707401 and J13002412-7710225, and the most noted of these objects is IRAS source 12553-7651, a low mass Pre-Main-Sequence (PMS) source with a C$^{18}$O outflow (Olmi et al., 1997), implying a region with high C$^{18}$O column density. This region contains strong C$^{18}$O emission with spatially concentrated clumps. The green box, (region B) contains Two Micron All-Sky Survey (2MASS) J12544527-7642197 towards the small clump of dense C$^{18}$O emission, however there are some more stellar objects surrounding the area. The aqua box (region C), contains the HH sources 52 to 54, these sources have been identified has having molecular outflows in $^{12}$CO and $^{13}$CO emission line (Knee, 1992). Region D, is shown as a blue box, which contains the intermediate star DK Cha and 2MASS J12533665-7706394 towards the dense C$^{18}$O emission, and some stellar objects identified in the surrounding area. Lastly, the red and orange boxes (regions E and F, respectively) contain little or no known stellar objects, with region E containing the 2MASS source J12592350-7726589. However, towards the bottom left (SE) of region F, there is a small stellar population.
Figure 2.11: RMS noise maps for (from left): $^{12}\text{CO}$, $^{13}\text{CO}$, and $^{18}\text{O}$, in units of $T_A^*$. The striping seen for all three isotopologues is the effect of a variety of system temperatures and observing conditions, of the scans taken along the $\alpha$ and $\delta$ direction.
Figure 2.12: C$^{18}$O integrated intensity image of Chamaeleon II, indicating areas of interest shown as coloured boxes: Region A (yellow), region B (green), region C (aqua), region D (blue), region E (red), and region F (orange). The symbols indicate the known stellar objects towards the region: HH sources shown as triangles, PMS stars as a star symbol, pentagons indicating brown dwarf stars, diamonds representing candidate YSOs and unconfirmed candidate YSOs shown as circles. The orange crosses are C$^{18}$O cores identified by Mizuno et al. (1999).

2.3.1 Peak intensity

Peak intensity emission maps of $^{12}$CO, $^{13}$CO, and C$^{18}$O, are shown in figures 2.13, 2.14, and 2.15. Within these figures some of the imaging artefacts can be identified, such as, in all three emission lines, the dark strip at the bottom right is the result of high noise. Because of the image processing techniques used, the small maps were processed individually before merging which causes high noise at the edge of the small maps, there is higher noise where the smaller maps overlap with each other. The $^{12}$CO and C$^{18}$O maps are heavily affected, while some evidence of high noise is shown in $^{13}$CO. The
peak intensity is very susceptible to noise, because the process of taking the maximum value in the spectrum is highly biased by noise.

Examining figures 2.13 to 2.15, we see the visible emission becoming less widespread from $^{12}\text{CO}$ to $^{18}\text{CO}$ because of the abundances of the $[^{12}\text{CO}]$ isotopologues. The $^{12}\text{CO}$ emission is widely distributed with uniform emission above $\sim 6\text{K}$. The uniformity of the peak temperature in the optically thick $^{12}\text{CO}$ line, suggests that the gas excitation temperature is almost uniform (isothermal condition). Some sub-structure can be seen in figure 2.13 near region A (yellow). In region E (red) there appears to be elevated peak temperature at the N and E of the region, but this might be due to the increased noise at the individual map boundaries. The most obvious feature of the $^{12}\text{CO}$ peak temperature map is the clear boundary of the emission NE of regions A and F (yellow and orange). The high temperature found within $^{12}\text{CO}$ is not well correlated with the peak temperatures in $^{13}\text{CO}$ (figure 2.14). Sub-structure can be identified in figure 2.14 region D. The NE cloud boundary is still evident, and there is clearly a sharp dropoff to the NE, whereas the S and W boundaries are less clear. There is increased peak temperature in region E (red), but it is not well-correlated with the increased peak temperature in the $^{12}\text{CO}$ map. There are widespread high peak temperatures ($> 4\text{K}$) in region D (blue), not obviously correlated with increased noise. Identifying peak emission is particularly difficult in figure 2.15 because of the low signal to noise ratio. However, dense emission can be clearly seen around region A. $^{12}\text{CO}$ is widely seen throughout the map because a part of Cha II was observed as part of this work, so it would be difficult to determine how widespread the $^{12}\text{CO}$ emission is in Chamaeleon from these maps.
Figure 2.13: $^{12}$CO peak intensity towards Chamaeleon II between velocity $-2\text{ km s}^{-1}$ and $6\text{ km s}^{-1}$; contours at 6 and 8 K (black and white respectively).
Figure 2.14: $^{13}$CO peak intensity towards Chamaeleon II between velocity $-2$ km s$^{-1}$ and 6 km s$^{-1}$; contours at 3 (black), 4, and 5 K (white).

The average spectrum for C$^{18}$O had a peak temperature of 0.13±0.01 K, the low temperature is because of the emission of C$^{18}$O is not widespread and emission detected is not as bright compared to $^{12}$CO or $^{13}$CO. Figure 2.15 shows a dense area within region A with contours of 2 K, significantly higher than the peak temperature from the average spectrum in figure 2.5.
2.3.2 Integrated intensity

Figures 2.16, 2.17, and 2.18 present the integrated intensities of $^{12}$CO, $^{13}$CO, and C$^{18}$O emission lines, respectively. Comparison between the integrated intensity maps of $^{12}$CO and $^{13}$CO shows a similar structure of widespread emission. However, around region E (red) we see a discrepancy where the $^{12}$CO appears to have temperatures around 17 K·km s$^{-1}$ and the $^{13}$CO does not trace the same structure. This is because the $^{12}$CO line is broad compared to the $^{13}$CO emission. Region A (yellow), is clearly seen in $^{12}$CO, $^{13}$CO, and C$^{18}$O emission line maps.

The RMS noises of the integrated intensity for $^{12}$CO, and $^{13}$CO are respectively 4.7 K·km$^{-1}$, and 1.2 K·km$^{-1}$.

Overall, the North East cloud boundary is less clear than in the peak temperature.
map, but still has a steeper drop-off than the cloud boundaries to the S and W. In
region A (yellow), the integrated intensity peaks up more than the peak temperature
does, and does so South of the C^{18}O peak temperature. Region B (green) does not show
much structure. Region C (aqua) has widespread high integrated intensity emission.
Region D (blue) does not show up in $^{12}$CO integrated emission but has widespread
strong emission in $^{13}$CO integrated intensity, and is one of the dominant regions in
integrated C^{18}O emission. Region E (red) shows linear features in $^{12}$CO and $^{13}$CO that
may be scan artefacts in the map, along with strong C^{18}O emission. Region F (orange)
has a gradient of $^{12}$CO integrated emission increasing West, but $^{13}$CO and C^{18}O show
more East–West structure.

Figure 2.16: $^{12}$CO integrated intensity towards Chamaeleon II between ve-
locity –2 km s$^{-1}$ and 6 km s$^{-1}$; contours at 8, 11, 14 (black), and 17 K·km s$^{-1}$
(white).
Figure 2.17: $^{13}$CO integrated intensity towards Chamaeleon II between velocity $-2 \text{ km s}^{-1}$ and $6 \text{ km s}^{-1}$; contours at 3 (black), 5, and $7 \text{ K km s}^{-1}$ (white).
Figure 2.18: C\textsuperscript{18}O integrated intensity, integrated from 2 to 4 km s\textsuperscript{-1}, of Chamaeleon II: contours at 0.7 (black), and 1.1 K·km s\textsuperscript{-1} (white).

2.3.3 Centroid Velocity

Figures 2.19 to 2.21 shows the velocity centroid (V\textsubscript{LSR}) of the CO emission lines. To highlight the emission, a mask has been applied to remove the RMS noise from each figure.
Figure 2.19: $^{12}$CO velocity centroid towards Chamaeleon II between velocity – $2\text{ km s}^{-1}$ and $6\text{ km s}^{-1}$; contours at 2, 2.5 (black), and $3\text{ km s}^{-1}$ (white).
Figure 2.20: $^{13}$CO velocity centroid towards Chamaeleon II between velocity $-2$ km s$^{-1}$ and 6 km s$^{-1}$; contours at 2, 2.5 (black), and 3 km s$^{-1}$ (white).
Figure 2.21: Chamaeleon II C^{18}O velocity centroid map, integrated from –2 to 6 km s\(^{-1}\); contours at contours at 2, 2.5 (black), and 3 km s\(^{-1}\) (white).

Region C (aqua) shows a bipolar pattern in centroid velocity with blueshifted emission to the West and red to the East. Between regions A, C, & D (yellow, aqua, blue), the \(^{12}\)CO velocity centroid is blueshifted to around 1 km s\(^{-1}\), while the \(^{13}\)CO velocity is blueshifted by a lesser amount, to about 2 km s\(^{-1}\). This is consistent with a large area of low density, possibly warm, gas moving systematically towards the observer. Region F (orange) seems to be somewhat redshifted compared to the bulk of the cloud; this is most clearly seen in \(^{13}\)CO, but can also be seen in the C^{18}O centroid velocity. Region A (yellow) appears redshifted in C^{18}O velocity centroid, with some redshifted emission in the southern part of the region visible in \(^{13}\)CO. The \(^{12}\)CO velocity centroid shows a similar pattern.
2.3.4 Velocity dispersion

Figures 2.22 to 2.24 show the velocity dispersion ($\sigma_V$) of the $^{12}$CO and C$^{18}$O emission line. Similar to section 2.3.3, a mask has been applied to remove the RMS noise from each figure to highlight the emission. Both figures 2.22 and 2.23 show a similar velocity dispersion of 1–1.5 km s$^{-1}$, with $^{13}$CO showing pockets of higher velocity dispersion. $^{13}$CO systematically narrower, as might be expected from the lesser optical thickness of the rarer isotopologue. In figure 2.24, the C$^{18}$O velocity dispersion mostly constrained between 0.1 and 0.5 km s$^{-1}$.

Regions C, E, F (aqua, red, orange) seem to have somewhat higher dispersions in the $^{13}$CO emission line. The highest velocity dispersion seen in the C$^{18}$O emission line is seen towards region E, with velocity dispersion around 0.5 km s$^{-1}$. In the case of region C, this reflects the presence of known outflows (HH 52–54).

![Diagram of velocity dispersion](image_url)

Figure 2.22: $^{12}$CO velocity dispersion towards Chamaeleon II between velocity ranges $-2$ km s$^{-1}$ and $6$ km s$^{-1}$; contours at 1 km s$^{-1}$ (white), and 1.5 km s$^{-1}$ (black).
Figure 2.23: $^{13}$CO velocity dispersion towards Chamaeleon II between velocity ranges $-2 \text{ km s}^{-1}$ and $6 \text{ km s}^{-1}$; contours at $1 \text{ km s}^{-1}$ (white), and $1.5 \text{ km s}^{-1}$ (black).
Figure 2.24: $^{18}$O velocity dispersion towards Chamaeleon II between velocity ranges $-2$ km s$^{-1}$ and $6$ km s$^{-1}$; contours at $0.1$ km s$^{-1}$ (white), and $0.5$ km s$^{-1}$ (black).
2.3.5 Channel maps

Integrated intensity channel maps of $^{12}$CO, $^{13}$CO, and $^{18}$O, between the ranges of -2 km s$^{-1}$ and 6 km s$^{-1}$, are shown in Figures 2.25, 2.26, and 2.27 respectively. Emission of $^{12}$CO (1–0) and $^{13}$CO (1–0) is spread over a velocity range of -2 km s$^{-1}$ and 5 km s$^{-1}$. The $^{18}$O emission is located within the bulk of the $^{12}$CO and $^{13}$CO emission, with the velocity range of 2 km s$^{-1}$ to 4 km s$^{-1}$.

Comparisons between $^{12}$CO, $^{13}$CO and $^{18}$O channel maps show similar features. Highly blue shifted $^{12}$CO emission is present within an area around region C (aqua), is not seen so clearly within the $^{13}$CO map. This is within close proximity to the source HH4. The emission in region D (blue) just south of region C is somewhat blue shifted in the –1 to 0 km s$^{-1}$ range.

The 1–2 km s$^{-1}$ range shows blue shift emission corresponding to much of the area between A, C, and D. The strong $^{12}$CO emission here and rather weaker $^{13}$CO area the likely cause of the change in $V_{\text{LSR}}$ in this area. It is also in the velocity range that the sharp cloud edge to the N & E becomes visible in region A (yellow).

The 2–3 km s$^{-1}$ panels start to show the bulk of the emission in velocity for both lines, and the $^{18}$O emission begins to be detected at this velocity the region E (red). In both $^{12}$CO and $^{13}$CO, emission is concentrated to the West of the map, towards the rest of the Cha II cloud. The East edge of the cloud is steep, separated from the main Cha II cloud. It is in this velocity range that the sharpest cloud boundary to the East in both $^{12}$CO and $^{13}$CO maps is present.

In the 3–4 km s$^{-1}$ panels we start to see a clump towards $\alpha=13:06$, $\delta=-77:00$ (an area above region F). The bulk of the $^{18}$O emission is found within region A (yellow). $^{13}$CO (1–0) emission is mostly seen around this velocity range, while $^{12}$CO (1–0) is particularly strong towards the Western region.

In the 4-5 km s$^{-1}$ panel, $^{12}$CO (1–0) emission is still present, compared to $^{13}$CO (1–0) where only two clumps are visible and no $^{18}$O (1–0) emission is seen. $^{12}$CO is mainly seen on the West side of region A (yellow), and $^{12}$CO is also concentrated to the West.
Figure 2.25: Channel map of $^{12}$CO emission towards Chamaeleon II: contours at 3, and 5 K km s$^{-1}$.
Figure 2.26: Channel map of $^{13}$CO emission towards Chamaeleon II: contours at 0.8, 1.8, and 2.8 K·km s$^{-1}$. 
Figure 2.27: Channel map of $C^{18}O$ emission, between the range of 2 km s$^{-1}$ and 4 km s$^{-1}$ towards Chamaeleon I. Contours at 0.5, 0.7 and 0.9 K km s$^{-1}$. [271x44]
2.4 Discussion

2.4.1 Comparison of CO transitions

The line parameters $^{12}$CO, $^{13}$CO, and C$^{18}$O can be compared by plotting the integrated and peak intensities against each other. This comparison provides an overview of the bulk of the gas and can be used to compare different regions to the bulk of the gas.

A series of correlation plots of peak intensity between $^{12}$CO and $^{13}$CO is shown in figure 2.28 and $^{13}$CO vs C$^{18}$O is seen in figure 2.29. Figures 2.30 and 2.31 are integrated intensity correlations of $^{12}$CO vs $^{13}$CO, and $^{13}$CO vs C$^{18}$O, respectively. Figures 2.28 to 2.31 show the data for the whole cloud (sub-figure a), correlation of the areas of interest (A–F) only (sub-figure b), and individual areas of interest are plotted with respect to the whole cloud (sub-figures c to h).

The comparisons of the peak and integrated intensities of the selected regions, will break down and show the variations amongst the different environments. This will assist in characterising the Cha II cloud and the sub-structure seen within this region.

2.4.1.1 Whole cloud

The distribution of $^{12}$CO and $^{13}$CO peak temperatures lie between the line ratios of 2 to 4 (figure 2.28a). The majority of points are within $\sim$1.5 K to $\sim$5.5 K for $^{13}$CO peak temperature, and $\sim$4.5 K to $\sim$9 K for $^{12}$CO peak temperature. The data points clustered around the intersection of the RMS lines (red and blue) reflect a region of no emission located near region A and region F. Figure 2.28a shows $^{12}$CO emission is saturated, while the upper limit of peak temperatures for $^{12}$CO is $\sim$9 K, and the corresponding $^{13}$CO peak temperatures takes on a wide range of values. This suggest that regions of low column density contain enough dense gas to emit optically thick $^{12}$CO emission.

The distribution of the peak temperatures of $^{13}$CO vs C$^{18}$O (figure 2.29a) is concentrated around the range of 1–4 K for $^{13}$CO and 0.5–2 K for C$^{18}$O. There is a significant amount of $^{13}$CO with corresponding C$^{18}$O which is below the RMS level of C$^{18}$O, which suggest majority of the $^{13}$CO emission is extended throughout the Cha II region.

Figures 2.30 and 2.31 show the integrated intensity correlation between $^{12}$CO vs $^{13}$CO and $^{13}$CO vs C$^{18}$O, respectively. The correlation between $^{12}$CO vs $^{13}$CO has an average line ratio of 4, and $^{13}$CO vs C$^{18}$O is widespread, but clusters along the line ration of 8. Figure 2.30 shows a cluster of $^{12}$CO and $^{13}$CO near the lines indicating the RMS limits for which the data points come from the region where emission is not seen, located near regions A and F. The lack of emission suggest the selected areas are towards the edge of the dense gas.
Figure 2.28: Peak intensity scatter plot of $^{12}$CO vs $^{13}$CO, comparison of the entire region is shown in figure 2.28a, and a composite of only the selected areas (regions A to F) is shown in figure 2.28b, the different colours correspond the selected regions as indicated in figure 2.12. Figures 2.28c and 2.28d contains peak intensity of $^{12}$CO vs $^{13}$CO towards regions A and B, respectively, in comparison of the whole cloud (figure 2.28a). Each panel contains red and blue lines showing the RMS limits of the $^{13}$CO (4.1 K) and $^{12}$CO (1.2 K), respectively. The black lines represent ratios between $^{12}$CO and $^{13}$CO, the solid line is unity, and the dashed lines are ratios of 2, 3, and 4.
Figure 2.28: Peak intensity scatter plot of $^{12}\text{CO}$ vs $^{13}\text{CO}$, figures 2.28e to 2.28h contain peak intensity of $^{12}\text{CO}$ vs $^{13}\text{CO}$ towards regions C to F, respectively, in comparison of the whole cloud (figure 2.28a). Each panel contains red and blue lines showing the RMS limits of the $^{13}\text{CO}$ (4.1 K) and $^{12}\text{CO}$ (1.2 K), respectively. The black lines represent ratios between $^{12}\text{CO}$ and $^{13}\text{CO}$, the solid line is unity, and the dashed lines are ratios of 2, 3, and 4.
Figure 2.29: The same as figure 2.28, but between $^{18}$O and $^{13}$CO, comparison of the entire region is shown in figure 2.29a and a composite of only the selected areas (regions A to F) is shown in figure 2.29b. The different colours correspond the selected regions as indicated in figure 2.12. Figures 2.29c and 2.29d contains peak intensity of $^{12}$CO vs $^{13}$CO towards regions A and B, respectively, in comparison of the whole cloud (figure 2.28a). Red and blue lines indicate the RMS limits of the $^{18}$O (1.1 K) and $^{13}$CO (1.2 K) peak intensity maps, and the black lines represent line ratio, unity (solid line), and 1.5, 2, and 4 (dashed line).
Figure 2.29: The same as figure 2.28 but between $^{18}$O and $^{13}$CO, figures 2.29e and 2.29f contains peak intensity of $^{12}$CO vs $^{13}$CO towards selected regions C to F, respectively, in comparison of the whole cloud (figure 2.28a). Red and blue lines indicate the RMS limits of the $^{18}$O (1.1 K) and $^{13}$CO (1.2 K) peak intensity maps, and the black lines represent line ratio, unity (solid line), and 1.5, 2, and 4 (dashed line).
Figure 2.30: Integrated intensity scatter plot of $^{12}$CO vs $^{13}$CO, comparison of the entire region is shown in figure 2.30a, and a composite of only the selected areas (regions A to F) is shown in figure 2.30b, the different colours correspond the selected regions as indicated in figure 2.12. Figures 2.30c and 2.30d contains peak intensity of $^{12}$CO vs $^{13}$CO towards regions A and B, respectively, in comparison of the whole cloud (figure 2.28a). The red and blue lines indicate the RMS of $^{12}$CO and $^{13}$CO at 4.7 K and 1.1 K, respectively. The black line show the ratio, solid is unity, and the dashed lines are 3, 4, and 6.
Figure 2.30: Integrated intensity scatter plot of $^{12}$CO vs $^{13}$CO, figures 2.28e and 2.28h contains integrated intensity of $^{12}$CO vs $^{13}$CO towards regions C to F, respectively, in comparison of the whole cloud (figure 2.28a). The red and blue lines indicate the RMS of $^{12}$CO and $^{13}$CO at 4.7 K and 1.1 K, respectively. The black line show the ratio, solid is unity, and the dashed lines are 3, 4, and 6.
Figure 2.31: Integrated intensity scatter plot of $^{13}$CO vs $^{18}$O, comparison of the entire region is shown in figure 2.31a, and a composite of only the selected areas (regions A to F) is shown in figure 2.31b, the different colours correspond the selected regions as indicated in figure 2.12. Figures 2.31c and 2.31d contains peak intensity of $^{13}$CO vs $^{18}$O towards regions A and B, respectively, in comparison of the whole cloud (figure 2.28a). The RMS of $^{13}$CO and $^{18}$O, shown as red and blue lines (1.13 and 0.34 K respectively), and black line represents line ratios at unity (solid), 4, 6, and 8 (dashed).
Figure 2.31: Figures 2.31e and 2.31h is the integrated intensity scatter plot of $^{13}$CO vs C$^{18}$O for the selected regions C to F (see figure 2.12 for location). The RMS of $^{13}$CO and C$^{18}$O, shown as red and blue is 1.13 and 0.34 K respectively. The line ratios are unity (solid), 4, 6, and 8 (dashed).
2.4.1.2 Areas of interest

Comparisons between the regions of interest can be made to understand Chamaeleon II as a whole. The data points within these regions are mostly clustered together in figures 2.28 and 2.31, with the exception of region A and region F, where these areas cover an area with no emission.

Region A sees peak intensity scatter plot of $^{12}$CO vs $^{13}$CO and $^{13}$CO vs C$^{18}$O sampled quite evenly at the high end. Samples throughout the high integrated intensity between $^{12}$CO vs $^{13}$CO possess line ratios of 3–4. Region A, indicates higher peak-temperature gas in the cloud, probably the warmer gas, but also has some high-density material. The high C$^{18}$O integrated intensity seen in figure 2.31c is most likely due to the C$^{18}$O outflow from the low mass PMS star IRAS 12553-7651.

Region B has data points concentrated to moderate $^{13}$CO peak and $^{12}$CO peak temperatures, with a fairly high $^{12}$CO/$^{13}$CO ratio. Similar to region A, the $^{12}$CO and $^{13}$CO integrated intensity scatter plot shows concentrated data points between ratios of 3 & 4, but with a tight cluster of values, with which suggests that the linewidths are very similar over the region. No very high C$^{18}$O peak temperature seen, suggesting that the gas is dense and cool, without very high-density material.

Region C concentrated in a similar way to region B, but with additional points with high $^{13}$CO peak temperatures, suggesting dense and cool gas with parts being very dense. Together with the high $^{13}$CO peak temperatures, this suggest high temperatures but moderate density consistent with heating a young star driving HH2–24. The region has extreme $^{13}$CO integrated intensities, but avoids high C$^{18}$O integrated intensities, which is consistent with warm outflow gas with lower density. Comparisons between $^{12}$CO/$^{13}$CO integrated intensity show a broad distribution between line ratios of three to six. Which suggest a distribution of extreme high-linewidth and high velocity dispersion, caused by the outflow material.

Region D samples high peak temperature gas with some very dense gas with high $^{12}$CO/$^{13}$CO peak intensity ratio connected with region C, which suggest high peak temperature gas but without the very high density-material seen in region A. Integrated intensity comparisons between $^{13}$CO and C$^{18}$O samples the whole range of C$^{18}$O integrated intensities, but is concentrated to high $^{13}$CO integrated intensity. This suggest that region D possess high density material to achieve high C$^{18}$O integrated intensity. Region D is concentrated to the line ratio of six in peak intensity and has high values of integrated intensity, this is consistent with high-temperature gas without much ratio in linewidth.

Region E looks similar to region C but less extreme. The samples of Region E possess a lower-density gas with $^{12}$CO/$^{13}$CO peak and integrated intensity line ratios, and high $^{13}$CO/C$^{18}$O peak and integrated intensity line ratios; suggesting some high-density gas, perhaps cool enough not to give high $^{13}$CO temperatures. This suggests that there may be higher linewidths in this region, though not as high as the outflow-dominated region C.

The peak intensity data points towards region F is the consistent with bulk of the
cloud, but the ratio of $^{13}$CO/$^{18}$O is low. Similar comparisons of integrated intensity is seen, which show a similar sampling of the cloud, but avoids high $^{13}$CO integrated intensities. This suggests region F is a quiescent region which has a lack of high density material.

2.4.2 Column density

Figure 2.32 shows the spatial distribution of the excitation temperature $T_{ex}$, derived from the peak temperature of $^{12}$CO using equation 1.61. The overall distribution of excitation temperatures are around $\sim 11$ K, with a range from $\sim 6$ K to $\sim 12$ K. This is within the reported values of Hayakawa et al. (2001), who detected excitation temperatures of $\sim 10$ K for Cha II, with a range of $\sim 5$ K to $\sim 15$ K.

The spatial distribution of the column densities of $^{13}$CO and $^{18}$O towards Cha II are shown in figures 2.33 and 2.34, respectively. The $^{13}$CO column density is between $1 \times 10^{15}$ cm$^{-2}$ and $8 \times 10^{15}$ cm$^{-2}$, and $^{18}$O is around $0.1 \times 10^{15}$ cm$^{-2}$ and $2.5 \times 10^{15}$ cm$^{-2}$.
Similar column density ranges can also be seen in figure 5 of Hayakawa et al. (2001).

Comparing the structures within figures 2.33 and 2.34, the densest regions of $^{13}$CO have a fair correlation with the $^{18}$O column density. The most prominent area is around region A, with a column density around $2 \times 10^{15}$ cm$^{-2}$.

Figure 2.33: $^{13}$CO Column density map towards Chamaeleon II; contours at 4, 6, and $8 \times 10^{15}$ cm$^{-2}$.
2.4.2.1 Comparison of column density

The correlation between column density of $^{13}$CO vs C$^{18}$O for the whole cloud and selected regions, are shown in figure 2.35. The orange line is a linear regression between the two column density, with a relationship of: $N_{C^{18}O} = (0.07 \times 10^{15})N_{^{13}CO}+1.2 \times 10^{15}$. Overall, there is a wide distribution of C$^{18}$O and $^{13}$CO column density, however bulk of the $^{13}$CO column density data points falls below the RMS noise limit of C$^{18}$O. Suggesting that most of the $^{13}$CO is not dense enough to form C$^{18}$O.

Examining the different regions we can start to characterise the density of the selected regions. Region D possesses the highest column density in $^{13}$CO and C$^{18}$O, with ranges between $0.5 \times 10^{16}$ cm$^{-2}$ and $0.95 \times 10^{16}$ cm$^{-2}$ in $^{13}$CO and $0.1 \times 10^{15}$ cm$^{-2}$ and $1.8 \times 10^{15}$ cm$^{-2}$ in C$^{18}$O. Bulk of the C$^{18}$O column density data points for region D is above the RMS limit, suggesting this is the densest region within Cha II.

The data points of Region A are widely distributed due to the size of the region.
sampled overlapping with areas of no emission. However the bulk of the $^{13}$CO column density data points are within a high range of $0.5 \times 10^{16}$ cm$^{-2}$ and $0.8 \times 10^{16}$ cm$^{-2}$. The corresponding C$^{18}$O column densities data points are also widely distributed, mostly between $0.4 \times 10^{15}$ cm$^{-2}$ and $2.1 \times 10^{15}$ cm$^{-2}$, where some of the highest C$^{18}$O column density data points is seen towards this region.

A high column density distribution in $^{13}$CO and C$^{18}$O is also seen in region E, with a $^{13}$CO column density range between $0.3 \times 10^{16}$ cm$^{-2}$ and $0.8 \times 10^{16}$ cm$^{-2}$ and wide C$^{18}$O column density range between $0.01 \times 10^{15}$ cm$^{-2}$ and $2.0 \times 10^{15}$ cm$^{-2}$. Bulk of the data points seen from region E overlaps with ranges seen from region A, however the number of data points within these ranges is widely spread out.

On the other hand, the distribution of the $^{13}$CO column density towards region B is clustered around $4 \times 10^{15}$ cm$^{-2}$, while the C$^{18}$O column density is widely distributed, around $0.01 \times 10^{15}$ cm$^{-2}$ and $1.4 \times 10^{15}$ cm$^{-2}$, with bulk of the whole cloud.

Region F has widely distributed $^{13}$CO column densities, with ranges between $0.1 \times 10^{16}$ cm$^{-2}$ and $0.6 \times 10^{16}$ cm$^{-2}$, but corresponding C$^{18}$O densities are mostly above the RMS noise limit.

Lastly region C, despite the a high $^{13}$CO column density range of $0.38 \times 10^{16}$ cm$^{-2}$ and $0.95 \times 10^{16}$ cm$^{-2}$, the C$^{18}$O column density is quite low, with most of the region below the RMS limit. This suggests that the area is dense with low column density, considering that the HH sources are located towards this area this is expected. From the selected regions, we see region F has the lowest upper limit of $^{13}$CO column density but its C$^{18}$O column density is similar to region B near the upper limits.
Figure 2.35: Column density scatter plot of $^{13}\text{CO}$ vs $^{18}\text{C}O$, of the whole cloud (figure 2.35a), composite of selected regions A to F (figure 2.35b), and figures 2.35c and 2.35d is selected regions in respect to the whole cloud. Each panel contains red and blue lines showing the RMS limits of the $^{18}\text{C}O$ ($0.4 \times 10^{15}$) and $^{13}\text{CO}$ ($1.4 \times 10^{15}$) respectively, the orange line is a linear regression fitting.
Figure 2.35: Column density scatter plot of $^{13}$CO vs C$^{18}$O, of the whole cloud (figure 2.35a), composite of selected regions A to F (figure 2.35b), and figures 2.35c and 2.35h is selected regions in respect to the whole cloud. Each panel contains red and blue lines showing the RMS limits of the C$^{18}$O ($0.4\times10^{15}$) and $^{13}$CO ($1.4\times10^{15}$) respectively, the orange line is a linear regression fitting.
2.4.3 Visual extinction

Figures 2.36 and 2.37 shows the column densities of $^{13}$CO and C$^{18}$O along the line of sight, respectively, overlaid with contours from the visual extinction map (Evans et al., 2009), which had a spatial resolution was 2'. Although the map coverage between the column densities maps and visual extinction are not complete, the dense regions seen within $^{13}$CO and C$^{18}$O correlate with the visual excitation contours of 3–11 mag.

Figure 2.36: $^{13}$CO Column density map towards Chamaeleon II overlaid with contours from Spizter visual extinction map (Evans et al. 2009); contours at 3, 5, 7, 9, and 11 mag.
Correlations between $^{13}$CO and C$^{18}$O column density with visual extinction ($A_V$) are shown in figures 2.38 and 2.39. The relationship between the column density to $A_V$, illustrates the concepts of the formation and destruction of CO (Frerking et al., 1982, and references therein). If there is little extinction, as in an area outside a cloud, photodestruction of molecules by the interstellar radiation field, especially the ultraviolet portion, will result in a low fractional abundance. If it is an area towards the dense regions of the cloud, high $A_V$, then the radiation is attenuated by grains and molecular line absorption, resulting in a corresponding increase in the CO fractional abundance. Self-shielding of the UV radiation that photodissociates the CO by line absorption results in an enhancement of all the more abundant CO isotopologues. UV region chemical fractionation occurs, further increasing the relative abundance of the $^{13}$CO isotope (Frerking et al., 1982).
Hayakawa et al. (2001) performed similar comparisons of column density to $A_V$ towards Chamaeleon II. The major difference between our comparisons with visual extinction and column density, is the range of the $A_V$ is between 0 to 25 mag, where Hayakawa et al. (2001) had a limited range of 0 to 12 mag. Hayakawa et al. (2001) obtained their extinction map by using adaptive-grid star-counts applied to the $J$ band though a Deep Near Infrared Survey of the Southern Sky (DENIS). As a result, the relationship between column density and $A_V$ presented in figures 2.38 and 2.39 is significantly different, although there are a large number of data points which follow the relationship. Figures 2.38 and 2.39 show the relationship of column density and visual extinction from Hayakawa et al. (2001) (red) and our dataset (orange).

Plotting only the areas of interest, we can clearly separate the regions within figures 2.38b and 2.39b. Comparisons between column density and $A_V$ is not complete for region A, because of the incomplete coverage of the visual extinction map towards region A. Despite this region A is similar to region D in the wide distribution at the high ends of column density and visual extinction, suggesting the regions which is optically thick is also shielded.

Region B, sees a compact clustering between column density and $A_V$, within the range $1 < A_V < 9$, suggesting the region has some dust shielding. Visual extinction in region C is quite low in both comparisons of column density, suggesting little to no shielding towards the region.

The data points in figure 2.38h and 2.39h show region f containing two distinct clusters. The first is the cluster $\sim 3 < A_V < 10$. Second cluster is the ‘tail’ within the $A_V$ range of 1 mag and 3 mag, which is the result of the area of no emission.

Region E has a visual extinction range between two and eight, higher than region C which has a similar column density ranges for $^{13}$CO and C$^{18}$O, this would suggest the region has some shielding.

Overall, we see regions with a stellar population have a high $A_V$ and column density range. While regions with stars within close proximity, such as regions B, E, and F, have some shielding and broad range of column densities. Lastly region C which has a high column density but low $A_V$, this is expected considering only the HH sources are seen towards this region.
Figure 2.38: $^{13}$CO vs $A_V$, of the whole cloud (figure 2.38a), composite of selected regions A to F (figure 2.38b), and figures 2.38c and 2.38h is selected regions in respect to the whole cloud. The red and orange lines are linear regression from Hayakawa et al. (2001) and this work, respectively.
Figure 2.38: $^{13}$CO vs $A_V$, of the whole cloud (figure 2.38a), composite of selected regions A to F (figure 2.38b), and figures 2.38c and 2.38h is selected regions in respect to the whole cloud. The red and orange lines are linear regression from Hayakawa et al. (2001) and this work, respectively.
Figure 2.39: NC$^{18}$O vs A$_V$, of the whole cloud (figure 2.38a), composite of selected regions A to F (figure 2.38b), and figures 2.38c and 2.38h is selected regions in respect to the whole cloud. The red and orange lines are linear regression from Hayakawa et al. (2001) and this work, respectively.
Figure 2.39: $^{18}\text{O}$ vs $A_V$, of the whole cloud (figure 2.38a), composite of selected regions A to F (figure 2.38b), and figures 2.38c and 2.38d is selected regions in respect to the whole cloud. The red and orange lines are linear regression from Hayakawa et al. (2001) and this work, respectively.
2.5 Comparison of Areas

As seen in Fig. 2.12, some of the regions of interest overlap with the C$^{18}$O cores identified by Mizuno et al. (1999), who presented a list of 11 C$^{18}$O cores, seven of the positions were covered as part of this work. Mizuno et al. (1999) suggested the molecular mass of the C$^{18}$O cores to be 110 M$\odot$, 11% of the total mass traced by $^{13}$CO.

Table 2.6 presents the line parameters of the seven C$^{18}$O cores (over a 2.7$'$ beamsize) towards the positions identified by Mizuno et al. (1999). The detections of the C$^{18}$O cores from this work, all contain a single gaussian, which supports Mizuno et al. (1999). However, one core which is not detected (No. 2 in table 2.6) because of the RMS noise level towards this area at $\sim$0.5 K, and Mizuno et al. (1999) have identified the peak emission at 0.7, so any possible detection could be lost within the noise. In addition, the position of No. 2 is towards the edge of the visual extinction map and confirmation of dust emission towards the region could not be identified and discussed. Dense C$^{18}$O emission is not seen towards the position of No. 7, which is towards the edge of the observed area, and is in the vicinity of a small population of PMS.

The new sub-arcminute maps presented as part of this work, have been able to resolve the C$^{18}$O cores identified by Mizuno et al. (1999) which were observed with a 2.7$'$ beam size. Therefore, we can characterise these regions of interest in better detail.

Region A contains a stellar population either towards and on the outskirts of the dense $^{13}$CO and C$^{18}$O emission. This region includes IRAS source 12553-7651, a low mass PMS star with a C$^{18}$O emission outflow (Olmi et al., 1997). Mizuno et al. (1999) has identified a C$^{18}$O core towards this region (shown as source No. 5). Substructure is seen within this region with the observed CO isotopologues which show this is the region with the highest C$^{18}$O peak temperature, contributed by the outflow from IRAS 12553-7651. From the velocity centroids of $^{12}$CO and $^{13}$CO there is a left to right gradient is seen within the region; high $^{13}$CO velocity dispersion is seen at the bottom of the region. The region is mostly seen within the velocity range of 3 km s$^{-1}$ to 5 km s$^{-1}$. Column density is high in both $^{13}$CO, and C$^{18}$O emission with available visual extinction data suggesting a wide range of 5 to 25 mag. Out of all of the areas of interest, region A, has the highest C$^{18}$O emission compared to the rest of the region. Comparisons of peak and integrated intensities suggest region A is a warm region with a high-density region.

Region B contains a dense C$^{18}$O core (source No. 3) and the stellar object 2MASS J12544527-7642197 towards the edge of the dense area, with a few known stellar objects just outside of the selected field. Comparing the region in respect to the cloud as a whole, region B has peak and integrated temperatures in the mid range for the $^{12}$CO and $^{13}$CO lines. This suggest a region that is dense and cool, but some high-density material as shown through the C$^{18}$O emission. Comparisons between column density and visual extinction, show the column density of the dust is relatively low compared to that in the other regions.
<table>
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<th>No.</th>
<th>No. 1999*</th>
<th>$l^*$</th>
<th>$b^*$</th>
<th>R.A. (J2000)</th>
<th>Dec. (J2000)</th>
<th>$T_A^*$ (K)</th>
<th>$V_{LSR}$ (km s$^{-1}$)</th>
<th>$\Delta V$ (km s$^{-1}$)</th>
<th>Area (K·km s$^{-1}$)</th>
<th>Peak Intensity* (K·km s$^{-1}$)</th>
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* taken from Mizuno et al. (1999).
§ from this work.

Table 2.6: Line parameters of $^{18}$O cores identified from Mizuno et al. (1999).
Region C was selected because it possesses extended emission in $^{12}\text{CO}$, seen as a blue wing in the average line profile in figure 2.10. This area also contains the sources [HH] 52 to 54, with molecular outflows in $^{12}\text{CO}$, and $^{13}\text{CO}$ (Olmi et al., 1997). Comparisons of our maps in $^{12}\text{CO}$ and $^{13}\text{CO}$ shows high $^{13}\text{CO}$ peak temperatures but relatively low $^{12}\text{CO}$, but little to no emission is identified in $^{18}\text{O}$ as indicated in correlation plots of peak and integrated intensity. As a result, column density is high in $^{13}\text{CO}$ but is not really seen in the $^{18}\text{O}$, suggesting that the region is not dense. Comparisons with column density and visual extinction reveal low visual excitation showing the region having less dust compared to gas. This region can be described as possessing high peak temperatures and low density, with parts of the region possessing high density material.

The intermediate mass stars DK Cha and 2MASS J12533665-7706394, as well as one of the identified dense $^{18}\text{O}$ cores (source No. 1) from Mizuno et al. (1999) are located within region D. Overall this area has the highest peak temperature range in $^{12}\text{CO}$ and $^{13}\text{CO}$ compared to the other regions, however $^{18}\text{O}$ has the second highest peak temperature range compared to region A. In the line comparisons the data points are clustered together, which is also seen in the scatter plots between N$^{13}\text{CO}$ and NC$^{18}\text{O}$. Comparisons of column density with visual extinction show the high column density is correlated with high visual extinction. This suggest that this region is shielded by dust, and contains high peak temperatures and densities.

Region E, containing only one known stellar object (2MASS J12592350-7726589) is located towards the edge of the dense $^{18}\text{O}$ emission marked as No. 4 in Table 2.6. This area has a high range of peak intensities in $^{12}\text{CO}$, $^{13}\text{CO}$, and $^{18}\text{O}$. The column density is widely distributed towards the high end of $^{13}\text{CO}$, and $^{18}\text{O}$, but comparisons with visual extinction suggest that this is a region with little dust.

Region F, is an area with extended emission in all of the isotopologues with no stellar objects within the area, but has an identified $^{18}\text{O}$ dense core (source No. 6). This is reflected in the peak and integrated intensity ratios where it is widely distributed and reflect the bulk of the Cha II gas. The widely distributed temperature range, is likely due to the low dust seen towards the area as indicated with comparisons of visual extinction, which suggest this is quiescent region.
2.6 Summary

New sub-arcminute resolution Mopra observations of $^{12}$CO (1–0), $^{13}$CO (1–0), and C$^{18}$O (1–0) emission lines, towards Cha II have been presented, allowing comparison between dense C$^{18}$O cores, and permit an understanding of the environment of the low-mass stellar population within the region.

From these new observations, the excitation temperature of $^{12}$CO, and the optical depths and column densities of $^{13}$CO and C$^{18}$O have been derived and are shown in figures 2.32 to 2.34. Excitation temperature and column density are consistent with those reported by Hayakawa et al. (2001). Comparisons between the column densities of $^{13}$CO and C$^{18}$O, against visual extinction finds different conditions surrounding some of the known stellar objects.

The areas selected to study, were based on visually identifying dense regions seen in the C$^{18}$O integrated intensity, and selecting an area around the HH sources 52 to 54 with a known $^{12}$CO outflow. The positions of seven of the 11 C$^{18}$O cores identified by Mizuno et al. (1999) (listed in table 2.6), were within the coverage of the C$^{18}$O integrated intensity map (figure 2.18). Overall, regions A and D, with stellar objects identified within the region, possess high temperatures and densities. In addition, high density material is seen towards these regions. Comparisons of column density corresponding to visual extinction, suggest that these areas are shielded by dust.

While on the other hand, regions B and E which have stellar objects located nearby are not shielded by dust. These regions have high column density, and have high temperatures. Lastly, regions C and F which is seen as areas of extended emission, have widely distributed temperatures. Region C, which covers HH sources has an environment of low density. Region F is an extended area, with very little dust.
Chapter 3

Carina Molecular Cloud

3.1 Introduction

The Carina Nebular Complex (CNC) also known as NGC 3372, is the Southern hemisphere’s largest and highest surface brightness nebular, located $d \sim 2.3\,\text{kpc}$ from our sun (Smith and Brooks, 2008). The CNC is part of the Carina spiral arm and located within the Galactic longitude $-71^\circ < l < -76^\circ$, and latitudes $-2^\circ < b < 1^\circ$ (Zhang et al., 2001). The close proximity to our sun is sufficient to resolve structures in detail, and the region is visually unobstructed by intervening dust, making this an ideal laboratory to understand the formation of stars compared to other regions where star formation has occurred (Smith and Brooks, 2008).

The molecular gas in the CNC is influenced by the close proximity to stellar populations (Smith and Brooks, 2008). Grabelsky et al. (1988) showed, as part of the Columbia Carbon Monoxide (CO) survey of the Galactic plane, that the Carina molecular cloud is a part of a Giant Molecular Cloud (GMC) complex. They identified that the molecular cloud is located on the near side of the Carina arm, and extends over 150 pc between Galactic longitudes of $-71^\circ < l < -75.3^\circ$, with an estimated total mass of $6.7 \times 10^5\,\text{M}_\odot$. The CNC contains star clusters within close proximity of η Carine (stellar clusters are shown in figure 3.3); the largest and most luminous known star within the Galaxy (Kumar et al., 2014).

Extensive observing campaigns have been conducted with space telescopes in the optical, X-ray, and infrared wavelengths (summarised by Smith and Brooks, 2008). The Hubble space telescope (HST) conducted large scale deep field optical observations towards Carina. Previous observations towards the CNC focused on smaller regions like η Carina, part of the Keyhole Nebula, and Trumpler 14. The new mosaic images of HST were obtained by the Advanced Camera for Surveys (ACS)/Wide field camera (WFC) with an Hα (F658N) filter, which revealed new details and discoveries of the complex region. Smith et al. (2010) reported new discoveries of Herbig-Haro jets. Large scale infra-red observations by Smith et al. (2000) (see Figure 3.3), revealed numerous embedded infra-red sources which were candidates for star-formation.

CNC was one of the first giant HII regions observed (using the Einstein Observatory) to produce diffuse X-ray emission; compared to other regions it is about 10-100 times
stronger (Seward et al., 1979; Seward and Chlebowski, 1982). This unusual property of CNC has made this the target region for other space based X-ray telescopes, like XMM-Newton, Chandra X-ray Observatory, and the Suzaku (Astro-E2) mission (Smith and Brooks, 2008). The origins of the high levels of diffuse X-ray emission towards the CNC are still unknown (Smith and Brooks, 2008).

The focus of this work is towards the northern region of the CNC (seen in figure 3.2). This is one of the three regions which Smith and Brooks (2008) have suggested as the main areas of interest for star formation. The northern cloud is a relatively pristine GMC with little star formation, which is irradiated by a massive cluster of stars (Smith and Brooks, 2008). By probing the molecular gas towards the northern CNC region in high spatial and spectral resolution, the physical properties of the Interstellar Medium (ISM) can be understood.

Figure 3.3: Figure 1 of Smith et al. (2000) containing: (a) a MSX band A data (6.8–10.8 μm) image of the CNC, and (b) a composite optical image of ionized gas towards the same region, ([O III] λ5007 emission is indicated as blue, Hα is shown as green, and red represents [S II] λλ6716, 6732 emission). The black cross in both panels indicates the position of η Carina.
Figure 3.1: Composite colour image of the Carina nebula, taken from figure 1 of Kumar et al. (2014). The image covers a $2.7^\circ \times 2.7^\circ$ area, centred at $\alpha$(J2000) 10:41:15.5 and $\delta$(J2000) $-59^\circ 40' 36.9''$. Kumar et al. (2014) created the figure using the WISE 4.6 $\mu$m (red), 2MASS $K_s$ (green), DSS $R$ band (blue) images. The white boxes note the approximate locations of different known star clusters within CNC (Trumpler 14, 15, 16; Bo 9, 10; Cr 228, 232, and NGC 3324). The location of $\eta$ Carinae, the South pillars, are also marked, as is the region targeted as part of Kumar et al. study (green box).
Figure 3.2: Herschel 500 $\mu$m map of the CNC-Gum 31 region, taken from figure 1 of Rebolledo et al. (2015). The dashed lines indicate the boundaries of the Mopra observations. The solid line shows the regions that enclose the gas associated with the CNC and Gum 31 regions. The light green areas identify the different areas towards CNC and Gum 31.
3.1.1 Stellar population

The CNC was originally viewed as an evolved H\textsuperscript{II} region devoid of star formation, with the energy input from massive stars shredding the few remnant gas clouds (Smith and Brooks, 2008). It was only from late-1980s that views of the CNC as an evolved star-forming region began to change (Grabelsky et al., 1988). In recent times, extensive wide-field and high resolution observing campaigns using space telescopes in the optical, infra-red and X-ray wavelengths have been carried out towards the Carina Nebular. As a result of these high resolution images, the view of CNC as an evolved region has changed dramatically, so that it is now viewed as an active star-formation region with a reservoir of quiescent molecular gas in which star-formation may occur (Smith and Brooks, 2008).

Star-forming regions within CNC have been identified within close proximity to some of the most massive stars known in our Galaxy (65 O type stars) and to star clusters which add to the complexity to the region (Smith and Brooks, 2008). Smith (2006) and Kumar et al. (2014) present the known star cluster locations and the number of O stars in each region. A list of studies towards the star clusters within the CNC have been presented by Smith and Brooks (2008). The northern CNC contains two star clusters, Trumpler 14 and Trumpler 15, dominating the central region, and three late-type hydrogen-rich Wolf-Rayet stars (Smith, 2006). Figure 3.1 (taken from Kumar et al., 2014), shows the star forming regions within the CNC together with \( \eta \) Carina, an unstable main-sequence star influencing the surrounding H\textsuperscript{II} region.

Smith and Brooks (2008) have noted the extensive studies into the high-mass star-formation within the CNC but work on the the low-mass pre-main-sequence stellar population has been relatively sparse. 70 H\textalpha emission line objects towards CNC were presented by Schwartz et al. (1990), as part of a H\textalpha Southern Survey. Ascenso et al. (2007) used deep and wide-field near-IR images from the New Technology Telescope and Very Large Telescope observations towards Trumpler 14. Povich et al. (2011) presented a catalogue of 1439 Young Stellar Objectss (YSOs) within a 1.42 deg\textsuperscript{2} field observed as part of the Chandra Carina Complex project. Kumar et al. (2014) generated a new catalogue of pre-main-sequence stars towards the Carina West Region (WR 22; green box in figure 3.1). Most recently Zeidler et al. (2016), used Visible and Infrared Survey Telescope for Astronomy (VISTA) to perform a deep, wide-field (6.76 deg\textsuperscript{2}) near-infrared survey covering the entire extent of the CNC.

3.1.2 Molecular Gas

Compared to other regions, the CNC does not have an extreme stellar environment like the Arches cluster near the Galactic Centre (Najarro et al., 2004), the Galactic clusters NGC 3603 (Moffat et al., 2002) and W49 (Welch et al., 1987), and the Large Magellanic Cloud (LMC) 30 Doradus (Massey and Hunter, 1998). However, some of these star-forming regions are located within the dense molecular gas surrounding the Galactic Centre, heavily obscured by intervening dust which makes these regions difficult to study (Smith and Brooks, 2008). Therefore, the location and close proximity of the
CNC makes an ideal target for examining high-mass star formation.

Zhang et al. (2001) described the distribution of various clouds and sub-complexes along the Galactic plane and their kinematics in sequential order. This is illustrated in figure 4a by Grabelsky et al. (1988) who shows the Carina spiral arm crossing the Sagittarius spiral arm near our sun. Figure 2 and Table 1 of Zhang et al. (2001), show that clumps near the CNC are coherently shocked compared to clouds near the North which are more fragmented. Zhang et al. (2001) suggest an age gradient in the various star clusters across the CNC. The star clusters of Trumpler 14 and Trumpler 16 are separated from IC 2581/NGC 3293 by a projected distance of ≈130 pc. Comparing the age of these regions, Trumpler 14 and Trumpler 16 are the youngest (age ~10^6 yr), and IC 2581/NGC 3293 is the oldest (age ~5×10^6 yr; Zhang et al., 2001).

The first CO observation towards the CNC was by Grabelsky et al. (1988), who mapped the region in 12CO (1–0) as part of the Colombia Galactic plane survey at 9′ angular resolution. The observations covered an area of ~2°×2°, centred towards η Carina. The first sub-arcminute resolution was obtained by Brooks et al. (1998), using the Mopra telescope, achieving 45″ resolution only in the 12CO (1–0) emission line towards the northern region.

More recently, Rebolledo et al. (2015) presented new large-scale maps in the 12CO (1–0) and 13CO (1–0) emission lines, over 8 deg^2 towards the CNC using the Mopra telescope with an upgraded spectrometer. Rebolledo et al. (2015) calculated a mean distribution of NH_2 (12CO) around 4.5×10^{21} cm^{-2}, with a maximum ~ 5.0×10^{21} cm^{-2}. Dust temperatures of the complex derived by fitting spectral energy distributions (SED), were also presented by Rebolledo et al. (2015), showing a mass of 10.6×10^4 M⊙. Figures 3.4a to 3.4d are a subset of the 12CO (1–0) and 13CO (1–0) line emission maps towards the CNC northern region, generated from the dataset of Rebolledo et al. (2015). The 12CO (1–0) and 13CO (1–0) data cubes from Rebolledo et al. (2015) were obtained for use within this work.
Figure 3.4: $^{12}$CO and $^{13}$CO maps from Rebolledo et al. (2015).
$^{12}$CO (4–3) emission line maps have been presented by Zhang et al. (2001) and Kramer et al. (2008), who probe the warm (T ≃ 50 K) and dense ($n > 10^{10}$ cm$^{-3}$) gas associated with Photo-dissociation regions (PDR). Zhang et al. (2001) observed with Antarctic Submillimeter Telescope and Remote Observatory (AST/RO), 1.7-m telescope located at the United States Amundsen-Scott South pole Station, to map an area roughly 150 × 100 pc. Zhang et al. (2001) was able to map an area of approximately 3 deg$^2$ towards CNC with a beam size of $\sim$3.5$''$.

Seven years later Kramer et al. (2008) observed two 4$'\times$4$'$ regions towards the northern and southern parts of the CNC in sub-arcminute (0.4$'$) resolution produced with NANTEN2. From these maps, they developed PDR models to reproduce the observed cooling lines of atomic carbon and CO.

Prior to this work, $[\text{C}_i]$ emission line observations towards the CNC have been observed by Kramer et al. (2008) and Zhang et al. (2001), who observed the same area as their respective CO (4–3) maps. Zhang et al. (2001) observed the $[\text{C}_i]$ $^3P_1$–$^3P_0$ transition using AST/RO and they were able to map a large area with a beam size of $\sim$3.5$''$. Using NANTEN2, Kramer et al. (2008) were able to observe two 4$\times$4$'$ regions within CNC. The maps have limited spatial coverage and spectral resolution, however they have sub-arcminute (0.4$'$) resolution in both $[\text{C}_i]$ $^3P_1$–$^3P_0$ and $[\text{C}_i]$ $^3P_2$–$^3P_1$ transitions.

### 3.2 Observations and processing

#### 3.2.1 NANTEN2

Observations were conducted with the NANTEN2 observatory (see Figure 3.5), a 4-m telescope on Pampa la Bola in the Chilean Atacama desert at an altitude of 4865-m. The telescope was originally at Las Campanas Observatory under the name NANTEN, operated solely by Nagoya University, before being moved to its current site. NANTEN2 is owned by Nagoya University in collaboration with other research institutes in Japan, South Korea, Germany, Chile and Australia.

NANTEN2’s high altitude and dry conditions allow observations at relatively high frequencies with minimal impact from Precipitable Water Vapor (PWV). Unfortunately, these extreme conditions also affect the electronics within the telescope proving data acquisition challenging. Due to the telescope’s location and dry conditions, it is able to observe atomic and molecular spectral lines in the 110 GHz to 880 GHz range with a unique large scale mapping capability. For the higher frequencies, NANTEN2 uses the Sub-Millimeter Array Receiver for Two frequencies (SMART) from Köln University which was used for this thesis (Graf et al., 2002). SMART is an 8-element dual-frequency array receivers, operating at frequencies of 460-492 GHz and 806-809 GHz. 2×4 pixel heterodyne array is capable of operating at low frequency and high frequency simultaneously. The tunable range of the two frequencies spans from 435 GHz to 495 GHz for the 460 GHz channel, and from 795 GHz to 880 GHz for the 810 GHz channel, with intermediate frequencies ($\nu_{IF}$) of 4 GHz and 1.5 GHz.
respectively. The telescope is housed in a dome, and during observations a movable GoreTex membrane is in front of the telescope (Kawamura 2008). This maintains surface accuracy during the daytime by minimising the impact from the Sun deforming the dish, and because at high frequencies the beam size is below a sub-arcminute, strong winds that would have affected the pointing accuracy is minimised. In September 2013, the old acousto-optical spectrometer (AOS) was replaced with the extended bandwidth Fast Fourier Transform Spectrometer (XFFTS) which has a 2.5 GHz bandwidth covered by 32768 channels (Klein et al. 2012). However, because the system is only able to process 1 GHz bandwidth, part of the data is automatically removed during data reduction. Table 3.1 gives a list of available receivers on the telescope. During the time of this project, the 810 GHz channel was unavailable.

Figure 3.5: The 4-m NANTEN2 radio telescope on the Atacama Plateau, Chile. Image: G. Wong

3.2.2 Observations

Observations with NANTEN2 were conducted between September 2013 and October 2015, with 16 days spent on $^{12}$CO (4–3) and 26 days for [C\textsc{i}]. The observations using SMART are conducted when the PWV is below 1-mm, because of the atmospheric opacity. When the PWV is above 1-mm, the telescope is configured to observe at lower

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frequencies between 115–345 GHz. The telescope is generally configured to observe 12CO (4–3) when PWV was between 0.7 and 1-mm and reconfigured to [C\text{I}] 3P_1–3P_0 observations when PWV was below 0.7-mm. The typical receiver noise temperatures at the band center for the 460 GHz channel is 250 K. Observations towards the CNC had an average T_{sys} of 567 K and 599 K for the [C\text{I}] and 12CO (4–3) frequencies, respectively.

As the SMART receiver is an array, a series of footprints were made to create the large scale map of the northern CNC region. The sampling spacing of a footprint, is determined by the beam width for a given frequency and the angular separation of the pixels on the sky. Because the telescope is capable of receiving sky signal at two frequencies, the sampling of a target region is determined by the higher frequency of the observations i.e. the beam width of 24.5′′ at 810 GHz. During these observations the higher frequency was not available, but the configuration was still left in this setting.

To achieve a Nyquist sampled map, sampling spacing was set to 8.5′′. This resulted in a footprint with a size of 340′′×170′′ or in other words, pixel separation (4×85′′) × (2×85′′) for a Nyquist sample at 810 GHz. The footprints generated from the 460 GHz receiver, are oversampled as a result of the 810 GHz sampling spacing, however the signal-to-noise ratio of the lower frequency is increased after spatial resampling to the angular resolution consistent with a ∼0.6′ beam width for 460 GHz.

The telescope would slew to an OFF position, after completing a single on source on-the-fly (OTF) scan every 30-sec. The 30-sec time duration is due to the Allan stability time estimate for the receiver (Allan, 1966). A calibration load measurement was conducted for every two OFF measurements, this would be done shortly after an OFF measurement was done.

A footprint can be configured to scan along different Galactic longitude and latitude, and α and δ. In addition, SMART can be orientated to observe a footprint at a given position angle on the sky. For this project the observations used a reference position of l = 287.5° and b = 1.5°. The general observing strategy for both the CO (J = 4–3) transition and [C\text{I}], is to observe the source conducted between elevations of 30° and 70°. Each field would be observed at least twice, and for each time the scanning direction would change (scanning along the Galactic longitude and latitude axes).

For the 12CO (4–3) observations, the SMART array rotates 180° and scanning axis is changed every time NANTEN2 observes the same region. This allows for max-
mum coverage, in exchange for poor sensitivity only when a electronic/technical issues affecting one of the receivers in the SMART array. In other words, if a beam was affected by electronic issues another ‘footprint’ would observe the same area in a different orientation.

![Diagram of NANTEN2 footprint overlaid with scanning pattern](http://astronomy.swin.edu.au/nanten2/meetings/2012/Nanten2012/SMTOTF-tiling.pdf)

Figure 3.6: Illustration of a NANTEN2 footprint overlaid with scanning pattern one of the beams. The grey rectangle is the area observed from a completed footprint, dimensions are $340'' \times 170''$. The arrows indicate the OTF scanning pattern for one of the beams (in this case beam 3). Latitude OTF scans are shown in (a), beams slew along the latitude axis for a distance of $85''$ (angular separation between beams). Once complete, the telescope is moved to the reference position, or to start the next OTF scan; the beam is offset by $8.5''$ along the longitude axis. The steps are repeated for another nine times (total offset is $85''$). Longitude OTF scans are shown in (b), similar to the description for latitude scans, where slewing is along the longitude axis and the offsets are along latitude axis. The circles show the beam width and beam configuration of NANTEN2 ($\sim 0.5''$).

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2Adapted from [SMART-OTF-tiling.pdf](http://astronomy.swin.edu.au/nanten2/meetings/2012/Nanten2012/SMTOTF-tiling.pdf)
3.2.2.1 Local oscillator frequency offset

A problem which became apparent during data processing was a frequency offset in the data, discovered after comparing the velocity of the line peak for various position to the observations of Kramer et al. (2008) and Rebolledo et al. (2015). The cause of the frequency offset was identified to be the Local Oscillator (LO), which had an incorrect frequency pre-set. The LO was monitored over a few days to inspect the frequency of the peak and to note any variability. A spectrum analyser was used to monitor the LO every 5-minutes over a few days. The frequency of the LO is supposed to be set at 6100.0 MHz, however the recorded peak frequency was \( \sim 6097.4 \) MHz, resulting an offset of \( \sim 2.6 \) MHz. This offset of \( \sim 2.6 \) MHz resulted in a velocity shift of around \( \sim 1.6 \) km s\(^{-1}\). Allowing for this correction meant our results agreed with Kramer et al. (2008) and Rebolledo et al. (2015). Figure 3.8 shows all the spectra taken when monitoring the LO, a plot of the peak frequency over time, taken over three days, using the spectrum analyser to write a text file containing spectra every five minutes. Figure 3.9 shows an oscillating function, reflecting the day/night cycle during this period. The range of the peak frequency varies from 6098.0 MHz to 6097.8 MHz, a velocity shift \( \sim 0.12 \) km s\(^{-1}\), which at these frequencies is not a concern.

3.2.3 Data processing

The raw data generated by the Kölner Observatorium für SubMillimeter Astronomie (KOSMA) system within NANTEN2, is automatically calibrated and exported into a
Continuum and Line Analysis Single-dish Software (CLASS) file format [Pety, 2005]. The calibrated data undergoes further processing through the CLASS package within GILDAS, written in FORTRAN, which includes baseline subtraction, removal of birdies as well as the removal of standing waves from the spectra.

A script used within GILDAS was developed as part of processing the CNC dataset. The script would start by importing the calibrated data into the CLASS environment. The dataset would be checked for consistency, verifying that header information containing, source velocity and line frequency had been correctly set. At this stage the observed frequency is modified to factor in the LO frequency offset and the spectra is resampled to include this new change. A linear baseline subtraction is then applied to the entire dataset, removing continuum emission. Birdies which are visually identified are then removed from the spectra. Evaluation of the data quality is conducted visually through generating an average line profile (see figure 3.10) and 2D plot showing velocity and scan over the entire dataset (see figure 3.11) produced.

Figure 3.10: Sample average line profile of $^{12}$CO (4–3) generated from CLASS, the image has been modified to show the axis labels.

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4CLASS is a spectral line analysis package within the Grenoble Image and Line Data Analysis Software (GILDAS) suite of radio-astronomy processing software, which is available at: http://www.iram.fr/IRAMFR/GILDAS/
Depending on the data quality, high order baseline subtraction may need to be applied, and standing waves removed. The data are then imaged; this image can be exported to a Flexible Image Transport System (FITS) format file (Wells et al., 1981). Appendix B.2 describes the technical steps to manually process NANTEN2 data (previously presented as part of a workshop⁵), along with code to automatically process the data.

A major problem that became apparent during data reduction is processing errors caused by invalid data: scans which contain either no spectra, or only part of the spectra. The cause of the invalid data was the extremely dry conditions at the telescope affecting the electronics. Tables 3.2 and 3.3 indicate the days that data acquisition was heavily affected, and information describing the particular problems related to each day. The problem caused by the invalid data, is negated by removing the affected spectra from further processing.

Figure 3.11: Sample scan index plot of $^{12}\text{CO} (4–3)$ generated from CLASS the image has been modified to show the axis labels. This plot, scans vs velocity, is used to efficiently display a large set of spectra. Colour scale is the amplitude of the spectra. The repeating pattern seen, in red, is CO (4–3) line emission from the NANTEN2 footprints.

Table 3.2: Processing information of problematic CNC [C\textsc{i}] data.

<table>
<thead>
<tr>
<th>Date</th>
<th>Processing note</th>
</tr>
</thead>
<tbody>
<tr>
<td>21-05-2014</td>
<td>A ‘footprint’ was partially observed, which left blank space in the map, fortunately this position was reobserved.</td>
</tr>
<tr>
<td>02-06-2014</td>
<td>Part of the spectra taken from one of the receivers (N03), contained invalid data and was removed during processing.</td>
</tr>
<tr>
<td>06-07-2014</td>
<td>Data taken from one of the receivers (N05) did not contain valid data as a result the final image is missing these pixels.</td>
</tr>
</tbody>
</table>

Table 3.3: Processing information for the CNC $^{12}$CO (4–3) data

<table>
<thead>
<tr>
<th>Date</th>
<th>Processing note</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-11-2014</td>
<td>These observations proved to be the most difficult to process, large parts of the spectra were not present for a few beams and was excluded during processing. In the case of beam N06, spectra was missing between velocity range of –80 km s$^{-1}$ and –20 km s$^{-1}$. N05 contained no data. N04 data was missing between velocity range of –70 km s$^{-1}$ and –60 km s$^{-1}$, as the imaging was done within a velocity range of –50 km s$^{-1}$ and 5 km s$^{-1}$ this data was included. A similar case was for N02 with data missing from –100 km s$^{-1}$ and –80 km s$^{-1}$.</td>
</tr>
<tr>
<td>03-12-2014</td>
<td>One of the beams (N05) was missing spectra.</td>
</tr>
<tr>
<td>12-12-2014</td>
<td>Mid-way through observing, one of the beams (N06) stopped recording data.</td>
</tr>
<tr>
<td>25-06-2015</td>
<td>beams (N04) contained missing spectra and were removed from the processing.</td>
</tr>
<tr>
<td>27-06-2015</td>
<td>spectra were missing from one of the beams (N04); as a result the final image is missing these pixels.</td>
</tr>
</tbody>
</table>

3.3 Results

Figure 3.12 shows the average line profiles of the $^{12}$CO (4–3) and [C\textsc{i}] datasets towards the northern region in the CNC. Through the average line profile the CO (4–3) line emission lies within the velocity range –34 km s$^{-1}$ to –4 km s$^{-1}$. The [C\textsc{i}] on the other hand is fairly weak compared to the $^{12}$CO (4–3) emission. On the other hand the emission is clearly seen in the range of –23 km s$^{-1}$ to –4 km s$^{-1}$. The average line profile shown in figure 3.12 is similar to the average line profile of region 3 in Zhang et al. (2001).
Figure 3.12: Average line profile of $^{12}$CO (4–3) and [C\textsc{i}] towards the northern region in the CNC.

Figure 3.13 shows the root mean square (RMS) noise throughout the maps generated from the $^{12}$CO (4–3) and [C\textsc{i}] $^{3}$P$_{1}$$^{3}$P$_{0}$ data cubes. The darker colour tones within the images indicate a higher RMS temperature. The average RMS of $^{12}$CO (4–3) is at 0.6 K, while [C\textsc{i}] is at 0.9 K. The [C\textsc{i}] $^{3}$P$_{1}$$^{3}$P$_{0}$ noise map has a higher RMS compared to the $^{12}$CO (4–3) map, because of the poorer weather conditions and high atmospheric transmission for the [C\textsc{i}] observations compared to the CO (4–3) observations. Spectra with bad baselines or extremely high RMS noise were removed before the imaging process. Data from beams with missing spectra were also removed. The white ‘rectangles’ in the $^{12}$CO (4–3) image result from removing data taken from two beams (adjacent to each other), this is also the case for the missing pixels in the [C\textsc{i}] image. Fortunately, because the sampling of the lower frequencies in SMART is oversampled, the missing spatial area is overlapped by other beams, or tiles. Dark square patches in both images are caused by similar reasons to these above. However, because each position has been observed at least twice, data are available for the missing spectra.

A dark square at the bottom in the $^{12}$CO (4–3) image is the result of a single bad baseline, which could not be removed during the data processing stage. Images were integrated over the velocity range where line emission was detected. Sections 3.3.1 and 3.3.2 contain peak and integrated intensity maps of CO (4–3) and [C\textsc{i}]. Figure 3.14 shows the coverage of the [C\textsc{i}] map overlaid on the Deep Space Station (DSS) optical image, marked with the positions of stellar clusters, O-type stars $\eta$Carina and HD 93129A, and H\textsc{ii} regions Car I and II identified by Oberst et al. (2011).
Figure 3.13: RMS maps of $^{12}$CO (4–3) (left) and [C I] $^3P_1$–$^3P_0$ (right) towards northern region of [CNC]. Spots of light colour indicate where data was missing or corrupt, similarly the dark square was poor weather conditions.
Figure 3.14: Major components of the CNC overlaid on an optical DSS blue inverted-greyscale. The solid contours outline the H\textsc{ii} regions Car I and II at 1 Jy in 843 MHz (thermal; Bock et al., 1999) radio-continuum emission. The grey contours outline the integrated intensity of $^{12}$CO (1–0) (Rebolledo et al., 2015) at 10, 45, and 80 km s$^{-1}$. The centres of the stellar clusters are marked with crosses. η Carine and HD 93129A are marked as yellow stars. The dashed blue line outlines the observation coverage from the Nanten2 [C\textsc{i}] observations, the $^{12}$CO (4–3) observations has a similar coverage (see Fig. 3.13 for the details of the observation coverage).

### 3.3.1 Peak intensity

The peak intensity images of CO (4–3) and [C\textsc{i}] within the velocity range of $-36$ km s$^{-1}$ to $-4$ km s$^{-1}$, are presented in figures 3.15 and 3.16, respectively. The effects of the image processing are seen in figure 3.15 with missing pixels shown in white. Signal to noise ratio for the CO (4–3) peak emission is high enough to clearly identify extended structures within the region, as well as the dense areas. The upper limits of peak temperature are 20 K and 4 K for CO (4–3) and [C\textsc{i}], respectively, higher than the peak in the average line profile.

Because of the low signal to noise, figure 3.16 is in false colour to assist with identifying peak emission. The dark red blocks in figure 3.16 are at the same positions of high noise shown in the [C\textsc{i}] RMS figure 3.13. Despite this, the peak intensity emission of round 2.8 K to 3.8 K can be seen towards the centre of the figure.
Figure 3.15: Peak intensity of $^{12}\text{CO}$ (4–3) line emission towards Carina. Contours are set at 4, 7 (black), and 10 K (white).
<table>
<thead>
<tr>
<th>Galactic Longitude</th>
<th>Galactic Latitude</th>
</tr>
</thead>
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</tr>
<tr>
<td>287.20°</td>
<td>-00.80°</td>
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<td></td>
<td>-00.90°</td>
</tr>
</tbody>
</table>

Figure 3.16: Peak intensity of $[$C\textsc{i}$]$ line emission towards the northern CNC. Contours are set at 3 (black), and 4 K (white).
3.3.2 Integrated intensity

Integrated intensity of CO (4–3) and [C\textsc{i}] are presented in figures 3.17 and 3.18 respectively, integrated over the velocity range $-36\text{ km s}^{-1}$ to $-4\text{ km s}^{-1}$. Figure 3.17 clearly identifies the dense areas towards the region, this was also confirmed by Rebolledo et al. (2015) who sees similar structures.

Compared to the peak intensity of [C\textsc{i}] (figure 3.16), the integrated intensity has clearly identified [C\textsc{i}] emission with minimum impact from the high noise present in the dataset. There are a few areas around the edges which are a result of the high noise, however this does not impact on the analysis as these areas are neglected.

Figure 3.17: Integrated intensity of $^{12}$CO (4–3) line emission towards Carina. Contours are set at 10, 25 (black), 40, and 55 K·km s$^{-1}$ (white).
Figure 3.18: Integrated intensity of [C I] line emission towards Carina. Contours are set at 4, (black) 7, 10 K·km s\(^{-1}\) (white).
3.3.3 Channel maps

Integrated intensity channel maps for CO (4–3) and [C\textsc{i}] are presented in figures 3.19 to 3.22. In the case of the [C\textsc{i}] maps, the impact of the noise has nearly been eliminated, with pixels around the edge of the maps being the only evidence of high noise towards parts of the map.

It is clearly seen that the CO (4–3) and [C\textsc{i}] trace each other quite well, with the exception of two regions. The first area is around $b = -0.54^\circ$ and $l = 287.45^\circ$, which sees strong CO (4–3) emission around the velocity range of $-22\, \text{km\,s}^{-1}$ and $-16\, \text{km\,s}^{-1}$, with a peak of 4.6 K and centroid of $-20\, \text{km\,s}^{-1}$. [C\textsc{i}] is not seen towards this region, most likely due to the location of the CO (4–3) detection, close to the edge which contains high noise. As the [C\textsc{i}] dataset has poor signal to noise, possible [C\textsc{i}] emission will not be seen within these maps.

The second region is around $b = -0.86^\circ$ and $l = 287.22^\circ$, where in the $-12\, \text{km\,s}^{-1}$ panel which sees the CO (4–3) is extended around $1\, \text{K\,km\,s}^{-1}$. [C\textsc{i}] emission is not seen in this region, which suggest that at this velocity range the region is not photodissociated.

Examining the channel maps of CO (4–3) and [C\textsc{i}], not much widespread emission is seen between the velocity range of $-36\, \text{km\,s}^{-1}$ and $-32\, \text{km\,s}^{-1}$. Between $-32\, \text{km\,s}^{-1}$ and $-26\, \text{km\,s}^{-1}$ small areas of emission start to be seen in both lines, for the [C\textsc{i}] dataset this is at odds with the average line profile. This is because the amount of [C\textsc{i}] seen is quite small, and with the rest of the pixels for that given velocity containing only noise, the signal is averaged out for that velocity range. From the velocity range of $-26\, \text{km\,s}^{-1}$ and $-12\, \text{km\,s}^{-1}$, the bulk of the gas is seen in both lines, after which only the dense gas around $b = -0.6^\circ$ and $l = 287.3^\circ$ is seen will about $-4\, \text{km\,s}^{-1}$.

As the noise for various parts of [C\textsc{i}] is quite high (see figure 3.13), the channel maps are difficult to interpret for areas where CO (4–3) emission is low.
Figure 3.19: Channel map of CO (4–3) line emission towards Carina. Contours are set at 4, 7 (black), and 10 K km s$^{-1}$ (white).
Figure 3.20: Channel map of CO (4–3) line emission towards Carina. Contours are set at 4, 7 (black), and 10 K·km s$^{-1}$ (white).
Figure 3.21: Channel map of [C\text{I}] line emission towards Carina. Contours are set at 1, 2, 3, and 4 K \cdot \text{km s}^{-1} (white).
Figure 3.22: Channel map of [C\textsc{i}] line emission towards Carina. Contours are set at 1, 2 (black), 3, and 4 K km s\textsuperscript{-1} (white).
3.4 Discussion

3.4.1 Morphology

The spatial distribution of the CO (4–3) and [C\textsc{i}] emission are seen to trace each other reasonably well in the channel maps in figures 3.19 to 3.22. However, in areas around Trumpler 14 and 15, little [C\textsc{i}] emission is seen compared to CO (4–3). This is also seen in the integrated intensity maps (figures 3.17 and 3.18) which show the differences in the morphology of the two lines. The CO (4–3) is shown to be extended in figure 3.17 compared to figure 3.18 where the [C\textsc{i}] emission is seen towards the dense regions of the CO (4–3) emission. The exception is that the areas around the star clusters Trumpler 14 and 15, are is devoid of any [C\textsc{i}] emission.

Figure 3.23 compares the emission of CO (4–3) and [C\textsc{i}] with the 843 MHz radio-continuum from Bock et al. (1999). The spatial overlap is seen between the CO (4–3) emission and the dense 843 MHz radio-continuum, compared to the [C\textsc{i}] emission where it is seen to either surround or partially overlap with the radio-continuum.

Zhang et al. (2001) describes the location near Trumpler 14 containing an infrared peak that has been illuminated by the compact stellar cluster, and distribution of their emission maps (CO (4–3) and [C\textsc{i}]) as approximately coincident. The 205\,\mu m [N\textsc{ii}] map by Oberst et al. (2011), identifies two main peaks that is separated by 10.08\arcmin (6.74 pc), one the peaks is towards the dense area in Car I. Oberst et al. (2011) has described the areas around the star clusters largely devoid of gas and dust.

From figure 14 of Rebolledo et al. (2015), an average dust temperature of 27 K, and a range between 20 and 38 K is seen towards the northern region. The tail of the dust temperature distribution ($T_{\text{dust}} > 30$ K) is from the vicinity of massive star clusters Trumpler 16 and 14.

From the location of Car I with the GMC in the northern CNC region, we see a H\textsc{ii} region (Car I) South of Trumpler 14, containing high dust temperatures. The morphology of the gas suggest [C\textsc{i}], a tracer for PDR seen near the edge or partially overlapping with the brightest area within the 843 MHz radio-continuum.
3.4.1.1 Comparisons to optical

As CNC has been well observed in the optical wavelength, comparisons of CO (4–3) and [C\textsc{i}] can be made against these images, to identify any interaction or correlation of features. For this work, the comparison is made against an optical red image, a tracer for H\textalpha\ emission, taken from Skyview\footnote{http://skyview.gsfc.nasa.gov/current/cgi/query.pl}.

For easy reference, figure 3.24 is an optical red image overlaid with markers indicating the central positions of the stellar clusters Trumpler 14 and 15, the red contour is a 1 Jy contour of 843 MHz radio-continuum which is given the name Car I by Oberst et al.\cite{oberst2011}, and selected areas of further discussion are shown as coloured boxes in figure 3.24. The striking features seen within figure 3.24 can be compared to the CO (4–3), and [C\textsc{i}] emission channel maps.
Figure 3.24: Inverted greyscale optical DSS red image towards the northern CNC overlaid with 1 Jy contour from 843 MHz radio-continuum (Bock et al., 1999), the positions of the stellar clusters Trumpler 14 and 15 as shown as red crosses, and position of the O-type star HD 93219A is indicated as a yellow star. The boxes are selected areas of further discussion.

Figures 3.25 and 3.26 are contour channel maps with the optical (red) image in the background. Comparisons of the CO (4–3) and [C\textsc{i}] emissions to the optical features seen in figures 3.25 and 3.26 finds a comparison of optical features to emission seen in the channel maps.

The green box, shows a dark cloud surrounded by bright H\alpha emission in the optical image. Both CO (4–3) and [C\textsc{i}] is seen within this area between the velocity ranges of

\text{http://skyview.gsfc.nasa.gov/current/cgi/titlepage.pl}
–28 km s$^{-1}$ to –22 km s$^{-1}$, overlapping the bright area and bounded by the dark patches.

The light blue box, sees an optical feature resembling a bubble, the molecular emission shows corresponding emission at a velocity between $-22$ km s$^{-1}$ to $-10$ km s$^{-1}$. This area shows more [C$\text{i}$] compared to the CO (4–3); also this is an area with the largest velocity range of the data set.

The area marked by the purple box, shows the CO (4–3) and [C$\text{i}$] emissions within a velocity range of $-22$ km s$^{-1}$ and $-18$ km s$^{-1}$. The emission towards the area, shows emission around $-22$ km s$^{-1}$ as a small area, before spatially expanding in the following channels. The optical feature, correlate well with the emission in the $-22$ km s$^{-1}$.

The emission seen within the red box, contain a velocity range between $-22$ km s$^{-1}$ to $-14$ km s$^{-1}$. As distinct optical features towards this area are limited, it is difficult to determine if there is a relation between the optical features and molecular gas. This suggest that the CO (4–3) and [C$\text{i}$] emission is not interacting with the optical features, which could be a indication of gas behind or towards the end of CNC.

The orange and yellow boxes, are along the obscuring dust lane and overlap with the Car I region. Within the orange region, the molecular gas towards this region is within the velocity range of $-28$ km s$^{-1}$ to $-22$ km s$^{-1}$. Compared to the dark patch seen within the region, molecular surround the dark path around $-24$ km s$^{-1}$, and emission towards this area is mostly comprised of [C$\text{i}$] emission. In the yellow area, the molecular gas is mostly confined to the dust lane from $-30$ km s$^{-1}$ to $-22$ km s$^{-1}$.

Overall most of the CO (4–3) and [C$\text{i}$] emission seen within the velocity range $-28$ km s$^{-1}$ and $-22$ km s$^{-1}$, matches an optical feature. Beyond this velocity range limited comparisons between optical and CO (4–3) and [C$\text{i}$] emission can be made, which suggest the emission that is seen either within or behind the northern CNC as seen in the line of sight.
Figure 3.25: Contour channel map of CO (4–3) and [C\textsc{i}] emission towards Carina. [C\textsc{i}] contours are in yellow (1, 2, ... 3 K), and contours of CO (4–3) emission is shown as aqua (4, 7, 10 K). In the −34 km s\(^{-1}\) panel, red cross indicate the Trumpler 14 and 15 star clusters, the position of HD 932129A is shown as a yellow, and the red contour is 1 Jy of 843 MHz radio-continuum ([Bock et al., 1999]), which is also the position of the Car 1 as given by [Oberst et al., 2011].
Figure 3.26: Contour channel map of CO (4–3) and [C\textsc{i}] emission towards Carina. Same as previous, [C\textsc{i}] contours are in yellow (1, 2, ... 3 K), and contours of CO (4–3) emission is shown as aqua (4, 7, 10 K). The −4 km s$^{-1}$ panel, contains a red cross indicate the Trumpler 14 and 15 star clusters, the position of HD 932129A is shown as a yellow, and the red contour is 1 Jy of 843 MHz radio-continuum (Bock et al., 1999), which is also the position of the Car 1 as given by Oberst et al. (2011).
Examining the area towards Car I the CO (4–3) and [C i] emission appears to surround, with some overlap towards the edges, the 1 Jy contour of 843 MHz radio-continuum at Car I. A model of the structure of Car I is shown in figure 3.27. The H II region (Car I) is shown to expand into the molecular cloud, with some of the H II overlapping with the molecular cloud.

3.4.2 Comparison between lines

Point-to-point comparisons of the peak and integrated intensity of [C i] and CO (4–3), are presented in figures 3.28 and 3.29 respectively.

Figure 3.28 shows the peak intensities range of [C i] between 0.5 to 8 K, and CO (4–3) between 0.8 and 15 K. Although [C i] is seen to contain a broad range, the majority of the data points are within a range of 1 K to 4 K, suggesting not much variation despite having a wide range of temperatures seen in CO (4–3). The data points are somewhat clustered together in figure 3.28 compared to figure 3.29 where the data points are widely dispersed, making any discussions limited. This is caused by a combination of the low signal to noise ratio and high RMS in [C i] affecting the integrated intensity.
Figure 3.28: Scatter plot of the peak intensities of [C\(\text{i}\)] and \(^{12}\text{CO}\) (4–3). The solid line indicates a ratio of unity, and the dotted line is a line ratio of 2.
Figure 3.29: Scatter plot of the integrated intensities (over the velocity range −36 km s$^{-1}$ to −4 km s$^{-1}$) of [C I] and $^{12}$CO (4–3). As before, but the dotted line is the line ratio at 6.
3.4.3 Excitation Temperature

Using $^{12}$CO (1–0) data from Rebolledo et al. (2015) with the $^{12}$CO (4–3) data we can estimate the excitation temperature for the region using a ratio between the two transitions. The ratio of the two transitions of the same chemical species, provides an estimate of the physical conditions within the gas, independent of chemistry (Zhang et al., 2001).

The ratio of CO (4–3) and $^{12}$CO (1–0) is sensitive to a combination of density and temperature (Zhang et al., 2001). This is particularly sensitive to density when $T > 50$ K and sensitive to temperature when $n > 10^5$ cm$^{-3}$ and $T < 50$. Temperatures of $T > 50$ K are rare in molecular clouds, over large spatial scales, however Zhang et al. (2001) has described the high densities of $n \sim 10^5$ cm$^{-3}$ are necessary to thermalize the CO (4–3) transition are commonly found. Through radiative trapping in opaque cores, the density required to thermalize the CO (4–3) transition is lower of $n \sim 10^4$ cm$^{-3}$, which is the typical density seen in molecular clouds. As the ratio of CO (4–3) and $^{12}$CO can be impacted by temperature and density, Zhang et al. (2001) and this work assumes that the effects are caused by temperature variations.

Taking a similar approach to Zhang et al. (2001), we can obtain a quantitative estimate of the average excitation temperature, which assumes thermalized but optically thin emission. The CO data from Rebolledo et al. (2015) was spatially regridded to the spatial resolution of the CO (4–3) data. Using equation 1 of Zhang et al. (2001), we obtain an estimate of the gas temperature:

$$T \sim 55 K / \ln \left( \frac{16 T_{\text{peak}}^{1-0}}{T_{\text{peak}}^{4-3}} \right)$$

(3.1)

this equation assumes Local Thermodynamic Equilibrium (LTE) and optically thin conditions.

Figure 3.30 shows the excitation temperature derived from the Rebolledo et al. (2015) $^{12}$CO data (figure 3.30a), CO (4–3) data (figure 3.30b), and excitation temperature derived from the ratio between CO (4–3)/$^{12}$CO using equation 3.1 (figure 3.30c). Direct comparisons between Zhang et al. (2001) and figure 3.30c can not be made against Zhang et al. who uses a ratio of integrated intensity, instead of peak intensity, between data taken from AST/RO and the Columbia CO survey. In addition, Zhang et al. (2001) had degraded their CO (4–3) data to the spatial resolution of the $^{12}$CO maps from the Columbia CO survey.

However, we do see some regions with high excitation temperature spread out within figure 3.30c but it is not towards the extended areas as seen in the integrated intensity maps. Comparing figures 3.30a and 3.30b, which is assuming optically thick conditions, we find similar extended structure is traced, while figure 3.30a more dense areas with higher excitation temperatures. Comparisons of both figures 3.30a and 3.30b to figure 3.30c sees a different contrast. Taking similar assumptions to Zhang et al. (2001), the clouds are composed of many smaller optically thick cloudlets, we see that figure 3.30c has regions with high temperatures indicating self-absorption.
Figure 3.30: The various excitation temperature maps towards the northern region of CNC. Figure 3.30a is derived from the $^{12}$CO (1–0) map of Rebolledo et al. (2015), figure 3.30b derived from $^{12}$CO (4–3) using equation 3.1 from Zhang et al. (2001). The contours for figures 3.30a and 3.30b are 12, 16 (black), and 20 K (white). Figure 3.30c contains contours of 17, 19 and 21 K.
3.4.4 Column density

Spatial distribution of optical depth, using equation \[1.73\] is presented in figure [3.31]. Some of the dense regions in figure [3.31] have an optical depth \(\sim 0.2\). Towards the edges of the region, we see the optical depth increase to 0.8. The range seen in figure [3.31] is lower than what is seen in \cite{Rebolledo2015} who have a range between 0.2 and 1.1.

Figure 3.31: Optical depth spatial distribution of the \([\text{C}_1]\) line towards the northern \textit{CNC} region: contours at 0.3 (white) and 0.5 (black). To easily show the structure of optical depth, the colour scale has been reversed.
Column density was calculated through two methods, equation 4 from \cite{Zhang2001} who scales the integrated intensity and \cite{Lo2014, Ikeda2002} who factor in excitation temperature and optical depth. Figure 3.32 is the column density towards the northern CNC region, using the approach of \cite{Ikeda2002} and \cite{Lo2014}; see section 1.5.1). The region \( l = 287.08^\circ \) and \( 287.19^\circ \), \( b = -0.8^\circ \) and \( -0.9^\circ \) has a high column density with peak value of \( 3.8 \times 10^{17} \text{ cm}^{-2} \). This is generally higher than what is seen around the region of \( l = 287.29^\circ \) and \( 287.37^\circ \), \( b = -0.6^\circ \) and \( -0.7^\circ \), where the peak value is \( 3.2 \times 10^{17} \text{ cm}^{-2} \).

The peak column density is higher than what is reported by \cite{Ikeda2002}, who obtain a peak column density \( \sim 1.7 \times 10^{17} \text{ cm}^{-2} \). Although the peak column density may be significantly different, which may result from spatial resolution effects, figure 3.32 shows the dense regions within contour lines \( 1 \times 10^{17} \text{ cm}^{-2} \) and \( 2 \times 10^{17} \text{ cm}^{-2} \).

Comparisons between figures 3.32 and 3.33 shows a combination of noise effect and optical depth, being the only differences between the column density calculations. Figure 3.33 contains more noise compared to figure 3.32 because of the scaling of the integrated intensity which also scales the noise in the image. Not much noise is seen in figure 3.32 due to the application of a mask through the optical depth map (figure 3.31). While \cite{Lo2014, Ikeda2002} does constrain the column density through optical depth. Therefore, using either approach is a good approach to estimating column density.

Figure 3.34 is the \(^{13}\text{CO}\) column density map created using data from \cite{Rebolledo2015}, overlaid with contours seen in figure 3.32. While there does seem to be some agreement between the \(^{12}\text{CO}\) column density calculations, there appears to be a strong correlation between the peaks in the figure 3.33 and 3.34.
Figure 3.32: $[^{12}\text{C}]$ column density of the northern CNC region using the equations from Lo et al. (2014): contours at $1 \times 10^{17}\text{cm}^{-2}$ and $2 \times 10^{17}\text{cm}^{-2}$. 

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Figure 3.33: [C\textsc{i}] column density of the northern CNC region: contours at $1 \times 10^{17}\text{cm}^{-2}$ and $2 \times 10^{17}\text{cm}^{-2}$. 
Figure 3.34: $^{13}$CO column density of the northern CNC region using the CO data from Rebolledo et al. (2015): contours at taken from figure 3.32 $1 \times 10^{17}$ and $2 \times 10^{17}$. 
### 3.4.5 Northern CNC region

Using the coloured boxes in figure [3.24] as a reference, figures [3.30] to [3.34] can provide a qualitative idea of the physical conditions of the Northern CNC region. Comparisons between optical depth and column densities to the optical features show areas with similar properties.

Examining areas where CO (4–3) and [C\textsc{i}] emission coincide with the dust lane, areas highlighted by the orange, yellow, and green, these areas have emission between velocity range of \(-30\,\text{km\,s}^{-1}\) to \(-22\,\text{km\,s}^{-1}\). A high optical depth range between 0.5 – 1 with excitation temperature between 12 – 16 K is seen towards these areas. The area near the yellow box has temperature gradient from bottom left to top right. The [C\textsc{i}] column density towards this area is \(\sim1 \times 10^{17}\,\text{cm}^{-2}\) and \(^{13}\text{CO} \) column density \((0.1 – 0.5) \times 10^{23}\,\text{cm}^{-2}\).

Compared to areas where emission is extended in velocity space, \(-22\,\text{km\,s}^{-1}\) to \(-10\,\text{km\,s}^{-1}\), for the light blue, and \(-22\,\text{km\,s}^{-1}\) to \(-18\,\text{km\,s}^{-1}\), for the purple box, low optical depth of 0.2 – 0.5 is seen. Excitation temperatures towards these areas are higher, with ranges of 12 – 16 K and 16 – 22 K in the light blue and purple boxes, respectively. The variation is also seen in the [C\textsc{i}] column density with the light blue box possessing column densities of 0.2 – 1 \(\times 10^{17}\,\text{cm}^{-2}\) and the purple box with a range between 0.9 \(\times 10^{17}\,\text{cm}^{-2}\) and 1 \(\times 10^{17}\,\text{cm}^{-2}\). \(^{13}\text{CO} \) column densities are between a range of 0.1 – 0.3 \(\times 10^{23}\,\text{cm}^{-2}\) towards the light blue area, and the purple area possesses \(^{13}\text{CO} \) column densities between 0.2 \(\times 10^{23}\,\text{cm}^{-2}\) and 0.4 \(\times 10^{23}\,\text{cm}^{-2}\).

Lastly, emission within the red box is widely distributed, as a result of a wide range of excitation temperatures (16 – 20 K) seen within the area. The area possesses high optical depth 0.5–1, with high \(^{13}\text{CO}\) and [C\textsc{i}] column density of \((0.1 – 0.5) \times 10^{23}\,\text{cm}^{-2}\) and \((1 – 1.5) \times 10^{17}\,\text{cm}^{-2}\), respectively.

### 3.4.6 Car I

Examining the average line profile of CO (4–3) and [C\textsc{i}] towards the H\textsc{ii} region Car I area (see figure [3.35]), two peaks are identified at velocity centroid \(\sim-24\,\text{km\,s}^{-1}\) and \(\sim-12\,\text{km\,s}^{-1}\). The emission around \(\sim-24\,\text{km\,s}^{-1}\) is brighter than \(\sim-12\,\text{km\,s}^{-1}\), the difference is from the ionised gas impacting the red shifted emission. Comparing the peak position of \([\text{N}\textsc{ii}], l = 287.3843^\circ, b = -0.6301^\circ\) given by Oberst et al. (2011), (marked as a blue triangle in figure [3.23]) we see the spectral profile also containing two gaussians (see figure [3.35]).

Oberst et al. (2011) has described the Trumpler 14 as the external ionizing source for Car I, with the [C\textsc{i}] emission arising from the photodissociated surface of the nearby GMC. The \([\text{N}\textsc{ii}]\) ionized gas within Car I has the velocity centroid around \(-16\,\text{km\,s}^{-1}\) (Oberst et al. 2011) and contains a single gaussian. The ionised gas contains a single gaussian with a velocity centroid of \(\sim16\,\text{km\,s}^{-1}\), but the molecular and atomic gas shows a double gaussian profile with peaks either side of the ionised gas (velocity centroid \(\sim-24\,\text{km\,s}^{-1}\) and \(\sim-12\,\text{km\,s}^{-1}\)). This would suggest a part of Car I is blanked by the gas. This is supported by Oberst et al. (2011) who has suggested Car I as a H\textsc{ii}
Figure 3.35: Average line profiles of $^{12}$CO (4–3) (blue) and [C\textsc{i}] (red) towards selected areas within the northern CNC region.
region expanding into the GMC which wraps beneath and behind it.

The [C\textsc{i}] emission is surrounding or slightly overlapping with the densest part of Car I, the PDRs are forming between the edges of the GMC and Car I. Oberst et al. (2011) discusses the physical separation Trumpler 14 and the PDR seen around Car I, similar to that of R136 in 30 Dor. In both cases the molecular matter within the vicinity of the early-type stars has been destroyed or swept away (Oberst et al., 2011). Oberst et al. (2011) further goes on to compare the conditions between Car I and the molecular cloud in Orion (OMC-1), which shows that OMC-1 has PDRs forming closer to the exciting stars. The conditions within Car I have been described by Oberst et al. (2011), as being similar to nearby starburst galaxies NGC 253, NGC 3256, and M82. This is because of the high rates of star formation occurring over a large scale within Carina, which in turn results in in FUV fields and gas excitation conditions similar to those in starburst galaxies.

Zhang et al. (2001) discusses the [C\textsc{i}] emission occurring in the northern region, which they describe as region 3, likely originating from CO photodissociated by the intense UV radiation near the core of the nebula. Zhang et al. (2001) has suggested the formation and evolution of the molecular cloud complexes may be in part, a result of spiral density wave shock.

Kramer et al. (2008) used PDR models to interpret the observed line intensities, where they assume the observed emission stems from an ensemble of spherically symmetric PDR clumps and there is no emission from an interclump medium or a diffused halo surrounding the clouds. PDR clumps are modelled using the stationary KOSMA-\tau code (Röllig et al., 2006). Kramer et al. (2008) describes the cloud distribution follow the canonical mass and radius distributions found for molecular clouds. Kramer et al. (2008) analyzed two positions and found clumpy PDR models are consistent with the observed absolute intensities of their \textsuperscript{12}CO and [C\textsc{i}] lines to within 20%.

The current view of Carina is an evolved region, where much of the parent molecular cloud has been ionized or swept away (Oberst et al., 2011). Comparisons of peaks within the [O\textsc{i}] and [C\textsc{ii}] maps of Oberst et al. (2011) to Zhang et al. (2001) and Kramer et al. (2008), found consistent location of dense gas. Oberst et al. (2011) suggests that Trumpler 14 is the external ionizing source for Car I, with neutral lines emission arising from the photodissociated surface of the nearby GMC.

Figure 3.36 shows the \textsuperscript{13}CO and [C\textsc{i}] column density of the selected velocity ranges, based on the CO (4–3) and [C\textsc{i}] spectra seen in figure 3.35 and N\textsc{ii} peak position in Car I identified by Oberst et al. (2011). The blue shifted emission is seen in the right panels in figure 3.36 has the velocity range \(-28.07\, \text{km}\, \text{s}^{-1} < v < -19.78\, \text{km}\, \text{s}^{-1}\), the emission mid (middle panels) \(-19.78\, \text{km}\, \text{s}^{-1} < v < -15.78\, \text{km}\, \text{s}^{-1}\), and the red shifted emission (left panels) \(-15.88\, \text{km}\, \text{s}^{-1} < v < -10.04\, \text{km}\, \text{s}^{-1}\).

Overall the column density towards the Car I region, shows a higher column density in the blue shifted emission compared to the column density of the red shifted emission. Within the velocity range \(-19.78 < v < -15.78\), emission is only seen towards the edge of the Car I region, the column density that is seen towards the edge is higher than
what is seen in the column density for the velocity ranges of the blue and red shifted emission.

Figure 3.36: Column density of $^{13}$CO (top row) and [C\text{I}] (bottom row) of selected velocity ranges towards Carina. The velocity ranges were based on the average line profiles seen in figure 3.35. The range of the left panel is between $-28.1 \text{ km s}^{-1}$ to $-19.5 \text{ km s}^{-1}$, middle panel is between $-19.5 \text{ km s}^{-1}$ to $-15.8 \text{ km s}^{-1}$, and right panel is between $-18.7 \text{ km s}^{-1}$ and $-10.0 \text{ km s}^{-1}$. The red crosses are the stellar clusters Trumpler 14 and 15, the blue triangle is the peak position of [N\text{II}] identified by Oberst et al. (2011), and red contour is from the 843 MHz radio-continuum (Bock et al., 1999) at 1 Jy. Contours of $^{13}$CO column density (top panels), is at $0.5, 1.5...3.5 \times 10^{22} \text{ cm}^{-2}$, and the [C\text{I}] column density contours are at $0.3 \times 10^{17} \text{ cm}^{-2}$ and $1 \times 10^{17} \text{ cm}^{-2}$.
3.5 Summary

New maps of the $^{12}\text{CO}$ (4–3) and $[^{12}\text{C} \text{I}]$ $^3\text{P}_1-^3\text{P}_0$ emission lines, at sub-arcminute resolution with NANTEN2, have been presented towards the northern CNC region. These new observations provide a higher observing resolution compared to Zhang et al. (2001), and spatial coverage larger than Kramer et al. (2008), which has allowed us to gain better understanding of the wide scale CO (4–3) and $[^{12}\text{C} \text{I}]$ emission towards the northern cloud. Comparison of optical features to the CO (4–3) and $[^{12}\text{C} \text{I}]$ morphology, show most of the emission between the range $-28 \text{ km s}^{-1}$ and $-22 \text{ km s}^{-1}$ correspond to the structural features seen the optical. An exception is the area within the light blue box in figures 3.25 and 3.25, which shows CO (4–3) and $[^{12}\text{C} \text{I}]$ possess a broad velocity range $-22 \text{ km s}^{-1}$ to $-10 \text{ km s}^{-1}$.

Optical depth and column density have been derived from the new observations. The $[^{12}\text{C} \text{I}]$ optical depth has a range of 0.2 to 0.8, and the column density range is $(0.4 - 3) \times 10^{17} \text{ cm}^{-2}$. Comparisons of excitation temperatures between $^{12}\text{CO}$ (1–0) and $^{12}\text{CO}$ (4–3), found a range between 12 K and 22 K and areas with a broad velocity range possessing the highest excitation temperatures.

The distribution of the $^{12}\text{CO}$ (1–0) and $^{12}\text{CO}$ (4–3) emission has been compared to thermal ionised gas, supporting the suggestion that the molecular gas towards the GMC in the northern region is being pushed by the HII region, Car I (Oberst et al. 2011). Kinematics of Car I show two peaks at $\sim-24 \text{ km s}^{-1}$ and $\sim-12 \text{ km s}^{-1}$ both in CO (4–3) and $[^{12}\text{C} \text{I}]$, while towards the peak position of $[^{2}\text{N} \text{II}]$ from (Oberst et al. 2011) shows a similar characteristic with little emission seen between $-20 \text{ km s}^{-1}$ and $-16 \text{ km s}^{-1}$. The PDR models by Oberst et al. (2011), have suggested the intense Ultraviolet (UV) radiation fields from Trumpler 14, power both the HII and photo-dissociation regions.
Chapter 4

Lupus Molecular Clouds

4.1 Introduction

Located in the Southern constellation of Lupus between Galactic longitudes $334^\circ < l < 352^\circ$ and latitudes $+5^\circ < b < +25^\circ$ (see figure 1.1), these dark clouds are poorly studied and an area of interest for low-mass star formation processes. The dark clouds are a part of the Gould Belt and one of the richest associations of pre-main sequence (T Tauri) stars.

The Lupus and Ophiuchus clouds are on either side of the Upper-Scorpius subgroup of the Sco-Cen OB Association, and both clouds show thermal and dynamical effects from nearby massive stars (e.g. Tachihara et al. 2001; Tothill et al. 2009). In terms of star formation rate and stellar clustering, Lupus is an intermediate case between the heavily clustered sites such as Serpens and Ophiuchus and the more isolated and quiescent sites such as Taurus (Benedettini et al. 2012).

The Lupus clouds are made up of nine regions at an estimated distance of 140-200 pc (Comerón 2008) and was first described by Barnard (1927) as part of Catalogue of Dark Objects in the Sky. Thé (1962) was the first to split the Lupus stellar population into three spatially distinct groups (Lupus I, II, and III still used today), while Lupus IV was first described by Schwartz (1977). Lupus V was identified by Tachihara et al. (1996), while mapping the densest regions of an additional cloud near Lupus III. Since then Hara et al. (1999), has identified the remaining regions through observations with NANTEN. Figure 4.1 is an overall distribution of C$^{18}$O emission taken from Hara et al. (1999), which indicates the nine regions towards Lupus. This chapter will focus on the dense regions of the Lupus cloud (regions I, III and IV), which have evidence of ongoing star formation.
4.1.1 Young Stellar Population

The stellar population of the Lupus complex is mostly comprised of low-mass stars within the region, where a variety of the clustering is seen throughout the different regions. Lupus III has been described as containing the densest clustering of young stars compared to the other regions, while regions like Lupus I are isolated or sparse in star formation and regions like Lupus V is devoid of star formation (Comerón 2008).
The only stars which are not low-mass are intermediate-mass Herbig Ae/Be stars, HR 5999 and HR 6000, located towards Lupus III. One of the most active T Tauri stars known, RU Lup, was found in Lupus II (Merrill, 1941). Joy (1945) included RU Lup as one of the eleven initially proposed members defining the T Tauri class, also noting in the paper the frequent association of such stars with dark clouds. The Lupus clouds were recognised by Herbig (1952) and Walker (1956) as star forming sites and the, identified T Tauri stars as being pre-main sequence stars with a very young age.

Lupus has been investigated for magnetic fields (Vrba et al., 1992; Myers and Goodman, 1991), infrared sources and outflows, stellar population and X-ray emission. Based on optical polarisation of the light of stars observed towards and around them, magnetic field measurements have been taken towards Lupus regions I, II, III and IV.

At Infra-Red (IR) wavelengths Lupus has been observed by the Spitzer space telescope (Krautter et al., 1997; Merín et al., 2008; Wahhaj et al., 2010) and infrared astronomical satellite (IRAS) (Tachihara et al., 1996). The Spitzer cores to disk (c2d) survey looked into the photometry of the weak-line T Tauri stars (Wahhaj et al., 2010), while projects using IRAS identified luminous candidate proto-stellar objects (Tachihara et al., 1996). The weak T Tauri star population has also been observed in the X-ray wavelength. Lupus III was observed using the X-ray telescopes ROSAT in the 1990s and, more recently, XMM-Newton (Gondoin, 2006).

The large scale extinction maps by Cambrésy (1999), used star counts techniques to investigate the distribution of solid matter in molecular clouds. Comparisons between the extinction map of Lupus (see figure 4.2) and the $^{13}$CO map of Tachihara et al. (1996), found counterparts between the molecular and extinction maps. Cambrésy (1999) described $^{13}$CO as less sensitive than B star counts for low extinction.
4.1.2 Molecular gas

The molecular gas of the Lupus clouds spreads from the edge of the Galactic plane ($b \simeq +5^\circ$) to relatively high Galactic latitudes, $b < +25^\circ$ (Fig. I.I). This large-scale structure shows an extended mass of gas at low latitudes and, distributed along an arc towards higher latitudes, several smaller irregularly shaped clouds. Other smaller clouds are also scattered among the dominant structures.

The overall motion of the Lupus cloud seems to be a composition of rotation and expansion (Comerón, 1999) which is a distinctive feature of the Gould Belt. Gases associated with the Lupus clouds can be clearly distinguished from background gas even at the lowest latitudes, which in turn is identified by the gas with positive LSR radial velocities, between 2 and 10 km s$^{-1}$. This positive velocity, which is shared by the associated T Tauri stars (Dubath et al., 1996), is a distinctive feature of the Gould Belt, whose overall motion seems to be a combination of rotation and expansion (Comerón, 1999).

The overall distribution of molecular gas towards the Lupus cloud was, for the first time, revealed by a $^{12}$CO survey covering approximately 170 square degrees at an angular resolution of 30$'$ (Murphy et al., 1986), including previously known T Tauri star associations. It revealed a massive concentration of $^{12}$CO at lower Galactic latitudes on the outskirts of the Lupus III and IV clouds, and hinted at continuation of the complex...
towards higher latitudes which the surveyed area was not large enough to cover. The molecular mass estimated by Murphy et al. (1986), $3 \times 10^4 M_\odot$ has often been adopted in other works, however, it was noted by the authors that this is a highly uncertain value that may be incorrect by up to a factor of 2-3. The entire region has been observed in CO by Hara et al. (1999) and Tachihara et al. (2001), using the NANTEN telescope.

Identification of Lupus V by Tachihara et al. (1996) was first discovered by observing the densest regions of an additional cloud which corresponds to the densest region of the large concentration of molecular gas East (in Galactic coordinates) of Lupus III. Regions of Lupus I, II, III and V were mapped in $^{13}$CO at a resolution of 8’ by Tachihara et al. (1996). The survey was further extended in spatial coverage by Hara et al. (1999), who also carried out observations in the C$^{18}$O isotopologues, at a resolution of 2.7’. Hara et al. (1999) were able to identify some new concentrations of molecular gas and labeled these new regions Lupus 6 to 9. Other CO observations have been done, e.g. Vilas-Boas et al. (2000) who observed in $^{13}$CO and C$^{18}$O towards Lupus I, II, III and IV and listed 36 condensations in the four clouds. The $^{12}$CO maps by Cambrésy (1999); Hara et al. (1999); Tachihara et al. (2001) present the concentrations as peaks in a widespread distribution of molecular gas. Tothill et al. (2009) presented degree-scale maps of the $^{13}$CO (2–1) and $^{12}$CO (4–3) maps towards Lupus I, III, and IV regions. Comparisons of the Carbon Monoxide (CO) maps and the IR extinction maps from the c2d project, yields a better estimation of the physical conditions within Lupus. Observations done to date have been either done at poor resolution or mapped limited areas within the region.

However, in comparison to CO the number of observations done in the ammonia emission line towards Lupus is quite small. Bourke et al. (1995) first observed Lupus at three positions using the Parkes radio telescope and its K–band maser receiver. The three positions that Bourke et al. (1995) observed did not detect any transitions of NH$_3$.

Most recently Benedettini et al. (2012) conducted observations using the Mopra telescope using the on-the-fly (OTF) mapping mode, to identify high density NH$_3$ gas cores in the Lupus I, III and IV regions. Using a 2.5’ beam at 12mm, they mapped several regions in the NH$_3$ (1,1) and (2,2) transitions and found widespread emission. They were able to identify and characterise dense clumps within the cloud, and measured kinetic temperatures of 12–13 K towards dense molecular gas clumps.
4.2 New observations and data processing

4.2.1 Tid-70m

The Deep Space Station (DSS)43 (hereafter Tid-70m) is a 70-m radio telescope, a part of the CDSCC which is the largest and most sensitive steerable dish in the southern hemisphere. The CDSCC located in Tidbinbilla on the outskirts of Canberra, is part of the US National Aeronautics and Space Administration (NASA) Deep Space Network (DSN) and is operated by the Australian CSIRO Astronomy and Space Science (CASS) division. This facility contains three active telescopes DSS43, DSS34 and DSS45, with a further two under construction; the main role of these telescopes is deep space satellite tracking. However, in a host country agreement between Australia and NASA a fraction of observation time is available to the Australian astronomical
community. Due to the NASA operations at CDSCC, observations are conducted in a service mode where staff on-site set-up and conduct observations on behalf of the principal investigator. The typical time allocation of observations can be between 5 to 12 hours in length with limited Local Sidereal Time (LST) range. Given availability of the telescopes at CDSCC, projects that can be broken down into periods of 1-hour or less are more likely to be observed. These telescopes have also been utilised as part of Very-Long-Baseline Interferometry (VLBI), a collection of telescopes spread over a large area observing an object simultaneously.

The antenna structure are presented in figure 4.3, identifying different components of Tid-70m. Table 4.1 describes the current receivers installed at Tid-70m. At the time of this work, only the digital spectrometer with 64 MHz bandwidth at two intermediate frequencies was available.

<table>
<thead>
<tr>
<th>Receiver Name</th>
<th>Band (cm)</th>
<th>Frequency Range (GHz)</th>
<th>Illuminated Diameter (m)</th>
<th>Beam FWHM (arcmin)</th>
<th>Antenna Availability</th>
</tr>
</thead>
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<tr>
<td>L-band</td>
<td>18</td>
<td>1.4 – 1.9</td>
<td>70</td>
<td>8.0</td>
<td>DSS43</td>
</tr>
<tr>
<td>S-band</td>
<td>13</td>
<td>2.2 – 2.3</td>
<td>70</td>
<td>6.4</td>
<td>All antennas</td>
</tr>
<tr>
<td>X-band</td>
<td>3</td>
<td>8.2 – 8.6</td>
<td>70</td>
<td>1.8</td>
<td>All antennas</td>
</tr>
<tr>
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<td>17.0 – 27.0</td>
<td>70</td>
<td>0.8</td>
<td>DSS43</td>
</tr>
<tr>
<td>Ka-band</td>
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<td>31.9 – 32.2</td>
<td>34</td>
<td>1.0</td>
<td>DSS34, DSS35</td>
</tr>
</tbody>
</table>

Table 4.1: Receivers available for the antennas at the CDSCC

4.2.1.1 Hardware upgrades

During the period of this work, hardware upgrades were undertaken to provide new scientific capabilities for Tid-70m and potentially to other telescopes at the CDSCC facility. Although not used within this work, the following briefly describes the hardware upgrades for completeness of the scientific capabilities at CDSCC. The implications of the new hardware upgrades are discussed in section 6.3.2.

The receiver for the K-band (23 GHz) system on Tid-70m was replaced by the new ‘K2’ system, the major difference between the two systems is the introduction of a second beam to the telescope. Both beams in the ‘K2’ systems are able to use two intermediate frequency (IF) amplifiers simultaneously during observations.

The primary use of this new system was for observations towards extra-Galactic sources, which required to be on source for long periods of time. With the introduction of the ‘K2’ dual-beam system, it allows the telescope to use the beam-switching techniques for extra-Galactic sources. The beam-switching technique reduces the time taken to slew between OFF and ON positions compared to position-switching technique. Beam-switching observations involves pointing one of the beams towards the source and the second beam is at an offset and taking an OFF spectrum. After a set period, the telescope is tilted so the second beam is now observing the source, and
after a specified period, the telescope is tilted back so the first beam is taking an ON spectrum.

In addition to the installation of the ‘K2’ system, the extended bandwidth Fast Fourier Transform Spectrometer (XFFTS) was installed to support this system. This new wide band spectrometer is intended to replace the current spectrometer. The baseline stability and wide band allows multiple transitions of NH$_3$ to be observed without being affected by the limited sensitivity at the edge of the band with the old spectrometer. In addition, the new spectrometer is compatible with the new ‘K2’ system allowing the inputs of two IFs from each beam to be recorded. In other words, both circular polarisations from each beam is recorded and can be processed.

4.2.2 Observations

The observation were conducted over period from 2011 to 2012, in the 17.0 – 27.0 GHz range to detect the NH$_3$ (1,1) and (2,2) inversion transitions. At the frequency of the NH$_3$, the beam of Tid-70m at 0.8’ is three time smaller than the beam of Mopra at 2.5’, which would be ideal to map large areas of Lupus in high detail. However at the time of these observations, the only observation mode available was position-switching, resulting in higher overheads which would only limit the spacial coverage of the observations. Therefore, the approach used to observe parts of Lupus was to strip map, with full beam spacing, across selected parts of Lupus I, III and IV regions under project number T199. The positions selected for observing was written by N. F. H. Tothill, as an initial start for further observations towards the Lupus region.

Both NH$_3$ (1,1) and (2,2) inversion transitions were covered by a single 64 GHz bandwidth. Each positions was observed for a minimum of a minute, and the reference for a minute, to achieve a root mean square (RMS) noise of $\sim$0.1 K or lower. An exception was the position $\alpha$ (J2000) = 15:43:01.3, $\delta$ (J2000) = –34:09:15.0, a known position containing NH$_3$, which over the observing period had a total observing time of 6-minutes on-source to confirm the signal to noise of the spectra at various stages of observing.

The selected areas were chosen towards dense regions identified from Tothill et al. (2009). Figures 4.4 to 4.7 contain the beam positions of the T199 observations overlaid on $^{13}$CO (2–1) maps from Tothill et al. (2009).
Figure 4.4: Grayscale is $^{13}$CO (2–1) observations from Tothill et al. (2009); contours at 3, 5, 7, and 9 K. Beam positions (blue, and yellow) of T199 observations towards the Lupus I region. For a clear view, the areas within the red and oranges boxes are shown in figure 4.5.
Figure 4.5: Cut out regions from figure 4.4, figure 4.5a is extracted from the red box, and the orange box is shown in figure 4.5b. Beam positions (blue, and yellow) of T199 observations towards the Lupus I region. Grayscale is $^{13}$CO (2–1) observations from Tothill et al. (2009); contours at 3, 5, 7, and 9K. Circles filled in yellow indicate a detection in NH$_3$ (1,1).
Figure 4.6: Selected regions within Lupus III with T199 observations. Grayscale is $^{13}\text{CO}$ (2–1) observations from [Tothill et al. (2009)], contours at 3, 5, 7, and 9 K. Beam positions (blue, and yellow) of T199 observations towards the Lupus III (figure 4.5a) and Northern (figure 4.5b) region. Circles filled in yellow indicate a detection in $\text{NH}_3$ (1,1).
4.2.3 Data reduction

The software used to reduce position-switching data is ATNF Spectral Analysis Package (ASAP), designed for spectral line processing of single dish and single-pointing spectral-line observations. It is also possible to use Common Astronomy Software Applications (CASA), as it contains the ASAP software as a package, to use the ASAP commands include ‘sd.’ in front of any ASAP command. This is designed to process all Australia Telescope National Facility (ATNF) antennas and is based on the Astronomical Image Processing System (AIPS)++ package; the setting defaults of ASAP can be found in the users .asaprc file. A schematic representation of reduction pathway showing for the data reduction procedure is shown in Fig. 4.8.
Data reduction in [ASAP] starts by loading the data (referred to as a ‘scantable’), which can be done in two ways; using the reader object or through the scantable constructor. The input file formats that are recognised by [ASAP] are RPFITS, SD-FITS (single dish fits) and [ASAP]’s scantable format and AIPS++ MEASUREMENTSET2 format. This is done through the command `scantable`.

While it is useful to have many independent sources within one scantable, it is often inconvenient for data processing. The `get_scan` function can be used to create a new scantable with a selection of scans from an existing scantable. The selection can either be on the source name, with simple wildcard matching or set of scan IDs. Internally this uses the selector object, so for more complicated selection the selector should be
used directly instead.

Once the data has been loaded, the first step is to correct for the bandpass, which removes the effect of the bandpass and noise from the atmosphere and background. Millimeter-wave observations usually observe on source, then off source to observe the noise from background and atmosphere. Observing off source allows a measurement to be taken of the sky, free from source emission (equation 4.2), which can be used to remove the sky from the observation done on the source. Equation 4.1 describes the source of the emission when observing the source, made up of sky emission and source emission, as a function of frequency:

\[
T_\nu = T_{\text{sky}}(\nu) + T_{\text{source}}(\nu) \quad (4.1)
\]

\[
T_\nu = T_{\text{sky}}(\nu) \quad (4.2)
\]

During the observations what the telescope ‘sees’ is the ON and OFF spectrum. The ON spectrum contains the temperature of the sky and source that has been multiplied by the bandpass \(B(\nu)\), shown in equation 4.3. The OFF spectrum only has temperature of the sky which is also multiplied by the bandpass, described in equation 4.4.

\[
T_{\text{tel}} = (T_{\text{sky}}(\nu) + T_{\text{source}}(\nu)) \times B(\nu) \quad (4.3)
\]

\[
T_{\text{tel}} = T_{\text{sky}}(\nu) \times B(\nu) \quad (4.4)
\]

ASAP divides the ON spectrum by the OFF spectrum:

\[
T_{\text{Quotient}} = \frac{(T_{\text{sky}}(\nu) + T_{\text{source}}(\nu)) \times B(\nu)}{T_{\text{sky}}(\nu) \times B(\nu)} \quad (4.5)
\]

When you remove the effects of the bandpass.

\[
T_{\text{Quotient}} = 1 + \frac{T_{\text{source}}(\nu)}{T_{\text{sky}}(\nu)} \quad (4.6)
\]

Because the sky temperature is a constant over a small range of frequency, you remove the \(T_{\text{sky}}\).

\[
T_{\text{Quotient}} \times T_{\text{sky}} = T_{\text{sky}}(\nu) + T_{\text{source}}(\nu) \quad (4.7)
\]

\(T_{\text{sky}}(\nu)\) can be subtracted by the baseline subtraction.

When the spectrum contains channels that have bad data, that is either caused by radio frequency interference (RFI) or lack of sensitivity towards the edges of the baselines. The flagging task can be used to either ignore or remove selected data before being processed any further. Flagging in ASAP is done in two stages, selecting the data that is done through the CREATE_MASK task and flagging the data using the command flag.

Convert frequency scale to velocity scale (LSRK) and re-sample onto a common
channelisation. Any Doppler corrections due to the Earth’s rotation are applied in this step.

Information describing the frequency setup for each integration is stored fundamentally in frequency in the reference frame of observation. By default \texttt{ASAP} converts the spectrum to the reference frame (e.g. LSRK). For units, the user has the choice of frequency, velocity or channel. The set unit function is used to set the current unit for a scantable. All functions will (where relevant) work with the selected unit until this changes. This is mainly important for fitting (the fits can be computed in any of these units), plotting and mask creation. The velocity definition can be changed with the set doppler function, and the frequency reference frame can be changed with the set freqframe function.

A linecatalog can be used as an argument for set restfreqs. If a personal line catalog has been used (which has the same size as the number of number of IFs) or linecatalog selection has been used to reduce the number of entries, the line catalog can be used directly as an argument to set restfreqs.

For scans that has been observed at separate times with a significant time difference in between, alignment is necessary due to the Doppler effect.

Observing sources at frequencies higher than 20 GHz presents the problem of atmospheric opacity and gain-elevation which can affect the signal. Opacity or optical depth describes the transparency of the atmosphere above the telescope, which is largely due to the amount of water vapor that is in the atmosphere. The gain measures the degree of directivity of the antenna’s radiation pattern. This can be affected by changes in temperature, the position of the sun, cloudiness and shadows. Due to the design of the telescope and weather conditions, telescopes are not absolutely rigid. As a result, the effective collecting area and net surface accuracy vary with elevation as gravity deforms the surface. Deformations, at higher frequencies, represent a greater fraction of the observing wavelength. Correcting for gain-elevation involves compensating for the effects of elevation on the amplitude of the received signals.

Currently elevation is not written correctly into Tidbinbilla \texttt{rpfits} files. Therefore gain-elevation and opacity corrections will not work unless they are recalculated. \texttt{ASAP} currently contains gain-elevation curves for some telescopes and frequencies, for Tidbinbilla it is at 20 GHz. However for gain-elevation curves of telescopes that \texttt{ASAP} does not have, a manual process can be done. \texttt{ASAP} will need either a gain polynomial or text file tabulating gain factors at a range of elevations.

Scans with multiple source/reference cycles can be averaged with the \texttt{AVERAGE\_TIME} or \texttt{AVERAGE\_POL} tasks. The \texttt{AVERAGE\_TIME} task will combine spectra that were taken at the same position. For the highest signal to noise for total intensity, then averaging the polarisations together will achieve this.

When the nominal $T_{sys}$ measurement at the telescope is wrong due to an incorrect noise diode calibration, the scaling task can be used to correct the scale function. As a default it will only scale scans of the spectra and not the corresponding $T_{sys}$.

Ideally data from observations will give a flat baseline with some signal. However,
as a result of hardware issues, baselines fluctuate with frequency. By subtracting a polynomial from the spectrum, it will only leave line emission on a flat baseline.

Two tasks that can be done for baseline subtraction are POLY_BASELINE or AUTO_POLY_BASELINE. The **ASAP** task, AUTO_POLY_BASELINE will fit a first order polynomial to the selected channels and subtract this polynomial from the full spectra. The AUTO_PLOY_BASELINE allows a range of order for the polynomial fits to be applied. The threshold is the signal to noise threshold to use to delineate line emission from signal.

Throughout the whole data reduction process, the PLOTTER task can be used to view the spectra. **ASAP** uses an ASAPPLOTTER object for plotting, allowing multiple plot windows to be active at the same time. This task can optionally run in a multi-panel mode allowing multiple plots per panel. Presentation of the data is done through the SET_MODE function.

Fitting is a process of overlaying a matching Gaussian function to the signal. This process creates a model of the spectrum free of noise. **ASAP** is able to fit a multi-component Gaussian function such as the multiple transitions of NH$_3$. This is done through the FIT or AUTO_FIT task, and can be applied over a single or entire scantable selection.

**ASAP** is able to export and save the spectra and scantables in a variety of formats, which are suitable for reading into other packages. The following are the formats **ASAP** is able to export to:

- **ASAP** - The internal format used by **ASAP**. This is the only format that allows the user to restore the data, fits, etc, without any loss of information. As mentioned before, the **ASAP** scantable is an AIPS++ Table (a memory-based table). This function just converts it to a disk-based Table, which can be read by any AIPS++ tool.

- **FITS** - The most common format used by other astronomy software.

- **sdfits** - This is the Single Dish version of the FITS format. It was designed for interchange between packages, however a very few packages actually can read it.

- **ASCII** - Text based format suitable for the user to processing using PERL or PYTHON, GNUPLOT etc.

- **ms2** - MeasurementSet V2 data format used by AIPS++.

The plots can be saved either through the GUI window or command line of **ASAP**. File formats that the plotter can save are PNG, PS, EPS, and PDF.
4.3 Results

From the positions observed, 16 contained a detection of NH$_3$ (1,1), of which hyperfine transitions were only found at six positions. Examining the NH$_3$ (2,2) spectra for positions with NH$_3$ (1,1) emission, only three positions were seen to have a detection.

Figures 4.9 to 4.13 present the spectra for positions where NH$_3$ (1,1) has been detected and corresponding spectra in the NH$_3$ (2,2) transition. From the observations, the Lupus I strip map contained seven positions with a detection, eight in Lupus III, and Lupus IV only contained two positions with detections.

Line parameters of the NH$_3$ (1,1) detections is presented over tables 4.2 and 4.3. Table 4.4 presents the NH$_3$ (2,2) line parameters, towards the positions where NH$_3$ (1,1) was detected. Using the line parameters, optical depth, excitation temperature, column density, rotation, and kinetic temperature were derived through the equations described in section 1.6.1. For cases where estimation of the physical condition requires peak temperature of the NH$_3$ (2,2), but is not detected, the RMS for that spectrum is quoted at the standard 3$\sigma$ level.
Figure 4.9: NH$_3$ (1,1) and (2,2) spectra (figures 4.9a and 4.9b respectively) towards positions with detected NH$_3$ (1,1) emission, towards Lupus I ridge. The beam position of these detections are marked as yellow in figure 4.5a. Spectra for two positions have been scaled up by 2 (α J2000 = 15:43:01.3, δ J2000 = −34:09:15.0), and 4.5 (α J2000 = 15:42:58.6, δ J2000 = −34:09:49.0).
Figure 4.10: NH$_3$ (1,1) and (2,2) spectra (figures 4.10a and 4.10b, respectively) towards positions with detected NH$_3$ (1,1) emission. Lupus I NW region. The beam position of these detections are marked as yellow in figure 4.5b. Spectra is offset at increments of 1 K.
Figure 4.11: NH$_3$ (1,1) and (2,2) spectra (figures 4.11a and 4.11b respectively) towards positions with detected NH$_3$ (1,1) emission, towards Lupus III region. The beam position of these detections are marked as yellow in figure 4.6a. The offsets of a spectrum are 1.1, 3, 5.1, and 7 K.
Figure 4.12: \( \text{NH}_3 \) (1,1) and (2,2) spectra (figures 4.12a and 4.12b, respectively) towards positions with detected \( \text{NH}_3 \) (1,1) emission, towards Lupus III region. The beam position of these detections are marked as yellow in figure 4.6b. Offset of spectra is at 1 and 1.5 K.
Figure 4.13: NH$_3$ (1,1) and (2,2) spectra (figures 4.13a and 4.13b respectively) towards positions with detected NH$_3$ (1,1) emission, towards Lupus IV region. The beam position of these detections are marked as yellow in figure 4.7. Position $\alpha$ (J2000) 16:01:40.0, $\delta$ (J2000) $-41:52:12.0$, is offset by 2 K.
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Table 4.2: Line parameters (peak temperature and velocity of peak) of the NH\textsubscript{3} (1,1) detections. Parameters without errors were fixed in the line fitting.
Table 4.3: Line parameters (FWHM and area) of the NH\textsubscript{3} (1,1) detections. Parameters without errors were fixed in the line fitting.

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<td>0.46 ± 0.06</td>
<td>5.0</td>
<td>0.48 ± 0.08</td>
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<tr>
<td>Lupus III</td>
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Table 4.4: NH$_3$ (2,2) line parameters. Parameters without errors were fixed in the line fitting.
Table 4.5: NH$_3$ (1,1) line parameters towards positions.

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<th>No.</th>
<th>R.A. (J2000)</th>
<th>Dec. (J2000)</th>
<th>$\tau_{\text{main}}$</th>
<th>$T_{ex}$ (K)</th>
<th>N(NH$_3$) ($10^{13}$ cm$^{-2}$)</th>
<th>$T_{rot}$ (K)</th>
<th>$T_{kin}$ (K)</th>
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</table>

4.4 Discussion

4.4.1 Lupus I

As Lupus I is the largest of the three regions studied here, and hence most of the observing time was spent towards this region. From the seven strip maps observed towards the region, two strip maps contained a detection (see figure 4.4): one at the North West area; and the other towards the ridge. The three pointings (sources 5 to 7 in table 4.2) contained a detection of NH$_3$ (1,1), with two of the three also containing NH$_3$ (2,2). Source 6 from table 4.2 contained the brightest emission of the dataset. Benedettini et al. (2012) identified an NH$_3$ clump within this location, which was labelled as Lup1 C4. Comparing the kinetic temperature of Benedettini et al. (2012) to the results here, a higher kinetic temperature range between 13.2 to 13.7 K is appropriate, higher than the reported 12.6 K by Benedettini et al. (2012). An upper kinetic temperature of 19.8 K was seen where NH$_3$ (2,2) was not detected.

However, the column density for that source 6 is three times higher than what is reported by Benedettini et al. (2012). Compared to sources 5 and 7, located on the
either side of source 6, we see a significant drop in the column density and values close to what is reported by [Benedettini et al. (2012)].

The Lupus NW detections contains four pointings with detections (source 1 to 4) located towards the edge of the $^{13}$CO (2–1) dense emission, with a spatial separation between the positions of source 2 and 3. A single gaussian was only seen towards this region, and detections towards this area was not seen by [Benedettini et al. (2012)]. Considering that the RMS noise seen towards these positions was around 0.06 K and the highest temperature seen within this strip was 0.32±0.03 K, it is possible that the observations of [Benedettini et al. (2012)] was not sensitive enough to detect NH$_3$, as they were using Mopra’s OTF capabilities. The velocity seen towards this area is seen to be around 6.5 km s$^{-1}$, which is consistent with the maps of [Tothill et al. (2009)].

4.4.2 Lupus III

Similar to the observations towards Lupus I, two strip maps contained detections. One towards a Class 0 protostar Lupus 3 MMS ([Tachihara et al. 2007]), and the other was seen towards the Northern region in Lupus III. [Benedettini et al. (2012)] only mapped the area towards Lupus 3 MMS, which they labelled as Lup3 C3, therefore any comparisons can only be made towards this area. Five pointings towards the Lupus 3 MMS region, detected NH$_3$ (1,1) with three of the five pointings containing hyperfines, and one pointing containing NH$_3$ (2,2). We find that one of the NH$_3$ velocity peaks is within the velocity of [Benedettini et al. (2012)]. Towards the Northern region, the three detections are within close proximity of the $^{13}$CO (2–1) dense emission and contain a single gaussian detection.

4.4.3 Lupus IV

From the two strip maps towards Lupus IV, two pointings (sources 16 and 17 from table [12]) located next to each other contained detections of NH$_3$ (2,2). The two detections are towards the dense peak of the $^{13}$CO map from [Tothill et al. 2009] (see figure [17]). With a RMS noise of 0.14 – 0.15 K, both pointings contain a single gaussian, with a peak intensity at 0.57–0.66 K and velocity of 3.4 and 3.8. Compared to [Benedettini et al. 2012], the detections are located near the position labelled as Lup4 C2. [Benedettini et al. 2012] has a central velocity of 4.06±0.05 km s$^{-1}$ for the main line with the slight difference between the two measurements may be due to the difference in beam size. Although, there are only two pointings, it has shown a gradient in velocity with the blue shifted pointing containing a higher peak. [Moreira and Yun (2002)] has described the area that is shaped by the influences of Upper-Cen-Lup, and noted a velocity gradient along the vector towards Upper-Cen-Lup. Based on the upper limits placed on the calculations for kinetic and rotation temperature, it is significantly higher than [Benedettini et al. 2012], who has estimated a kinetic temperature of 12.3 K which is also a upper limit.
4.4.4 Limitations of this work

Position-switching observations was the only available observing mode of Tid-70m, factoring the limited amount of observing time available this restricted any possibility to map large areas of Lupus. As a result, strip mapping was the alternative approach taken to sample across large areas of Lupus within the limited amount of time. Historically, position-switching was the first technique to be implemented due to its simplicity, particularly appropriate to the design of software control systems. A position-switching observation, which is sometimes called “point-by-point”, “step-and-integrate” or “point-and-shoot”, acquires total power measurements by moving the telescope to a source position (ON spectrum) then a nearby reference position (OFF spectrum), and integrating on each position in succession. Since position-switching involves moving the telescope to each position, measurements are usually made over 30 to 60 second time scales. Under the condition that the received signal from the instrumentation or the atmosphere has not changed significantly during the time between source and its respective reference measurement, position-switching will produce reliable astronomical measurements. The final signal is created when the individual source and reference measurements are differenced (or divided).

However, using the position-switching technique to map large areas presents a couple of problems. Mapping with the position-switching technique increases the overhead time caused by slewing between reference and pointing positions, which in the case of Tid-70m, will affect the limited amount of time that is available. As a result, maps created through position-switching mapping will have limited coverage which affects the type of science the telescope is able to do. Limitation of this telescope is demonstrated by the limited results seen in this chapter.

To improve the scientific return on this telescope, which has limited amount of available time, an alternative efficient observing technique needs to be used. One technique that allows an alternative to position-switching is OTF. OTF works similarly to position-switching observations; first going to the reference position, then move across to the region of interest for the source spectrum. In OTF mapping, after the reference spectrum is taken, the telescope is driven smoothly and rapidly across the field of interest while data is sampled at short intervals.

The advantages of OTF mapping are minimised time overhead, coverage and systematic changes. Time taken for the telescope to drive from the reference spectrum position to source spectrum position, like position-switching, is significantly reduced with OTF. With the overhead significantly reduced, this allows more time to look at objects that can be degrees wide, which is valuable for a time limited telescope. Systematic changes in experimental conditions are minimised as the region of interest is covered rapidly and integration time is short.

Some of the issues of the OTF technique is smearing, pointing accuracy and signal to noise ratio. Smearing of the beam is the result of the telescope moving across the region of interest, with the data being sampled as the telescope is moving, the potential accuracy is also less than an equivalent position-switching observation. The signal to
noise ratio will be lower due to the smaller integration time (Wilson et al., 2009), however this problem can be overcome by repeating the observations and “stacking” as necessary to increase to the signal to noise ratio.

4.5 Summary

The observing capabilities of Tid-70m restricted the spatial coverage needed to map parts of Lupus. As a result, strip mapping was conducted towards the dense parts of Lupus. This chapter presents the data of NH$_3$ (1,1) and (2,2) transitions towards the Lupus I, III and IV regions. Column density, kinetic and rotation temperature have been calculated where detections of NH$_3$ (2,2) transition are present. The kinetic and rotation temperatures derived from NH$_3$ (1,1) and (2,2) detections indicate temperatures of 11.7 - 45.8 K. Upper limits have been placed for estimation of kinetic and rotation temperatures where there was a detection of NH$_3$ (1,1) and non-detection of NH$_3$ (2,2). Calculation of column density of NH$_3$ (1,1) has a range of 9.0 to 35.7 × 10$^{13}$ cm$^{-2}$ over the detections (upper limits used for detections with only a primary hyperfine). Lupus I NW and Lupus III N detections have high line width range of 1.1 - 1.5 km s$^{-1}$ and 1.3 - 1.6 km s$^{-1}$ respectively. Compared to the CO line width maps of Tothill et al. (2009), the line width of CO is high in the same positions of our NH$_3$ (1,1) detections, where the range of Lupus I NW is 2.4 - 3.6 km s$^{-1}$ and Lupus III N is 2.4 - 2.7 km s$^{-1}$. The column density for the Lupus I NW and Lupus III North detections have a range of 15.7 – 35.7 × 10$^{13}$ cm$^{-2}$ and 9.4 – 27.4 × 10$^{13}$ cm$^{-2}$ respectively (upper limits have been used for detections that only contain a primary hyperfine).
Chapter 5

New mapping technique for Tid-70m and Hydrogen Radio Recombination Line Studies

This chapter has been published as ‘Implementation of Tidbinbilla 70-m on-the-fly mapping and Hydrogen radio recombination line early results’ - G. F. Wong; S. Horiuchi; J. A. Green; N. F. H. Tothill; K. Sugimoto; M. D. Filipovic, MNRAS 2016 458: 151-157 Contributions made by co-authors will be indicated in the relevant sections within this chapter.

5.1 Introduction

The Deep Space Station 43 (DSS-43) is a 70-m single dish radio telescope that is part of the National Aeronautics and Space Administration [NASA] Canberra Deep Space Communication Complex [CDSCC] located in the Australian Capital Territory (hereafter referred to as 'Tid-70m'). A small fraction of its time is devoted to radio astronomy and it is important to maximise the scientific return on this time. As such developments have been under way to implement on-the-fly [OTF] mapping capabilities, to allow for an efficient survey option. Following the preliminary work of Young et al. (2013), we present full details of the implementation of OTF mapping at the telescope allowing for greater mapping efficiency. More efficient spatial mapping of the ammonia inversion transitions in the 17–27 GHz K-band is a strong driver of the implementation of OTF on the Tid-70m, but the technique may be used to map other radio lines, such as Radio Recombination Line [RRL]s that fall in the cm-wave bands. We used OTF mapping with Tid-70m to observe the H92α [RRL] at 8.3 GHz towards the prominent Galactic Hii region Orion A (Ori A) and the Galactic Centre feature Sagittarius A (Sgr A).

OTF mapping involves sampling the sky while the antenna is moving at a constant rate, rather than integrating at a discrete position on the sky, then moving to the next position. The technique is widely used by mm- and submm-wave telescopes to produce large-scale maps in molecular transitions and the greybody continuum, such
as CO 3–2 mapping towards M83 (Muraoka et al., 2009), maps of CO and 1.1 mm continuum emission towards Ori A (Shimajiri et al., 2011), and 90 GHz maps of star-forming clumps (Jackson et al., 2013). Detailed descriptions of the technique have been presented by Mangum et al. (2007) and Sawada et al. (2008). Implementation of OTF mapping at the Australia Telescope National Facility (ATNF) Mopra telescope has yielded several large mapping surveys (e.g. Mangum et al. 2007; Jones et al., 2013; Braiding et al., 2015).

Peters et al. (2012) reviewed the physics of hydrogen RRL emission: the populations depart significantly from local thermodynamic equilibrium (LTE) over frequency ranges that depend on the electron density. Peters et al. consider Atacama Large Millimetre Array (ALMA) and EVLA observations of compact high-density HII regions, but also show that for the larger, less dense HII regions that might be mapped with a single-dish telescope, non-LTE effects are important in the centimetre-wavelength range. Gordon and Sorochenko (2009) used a non-LTE analysis to show how the line brightness varies with frequency and electron density. We may therefore estimate the electron density from the frequency dependence of line brightness. The line brightness depends on electron temperature and density, so RRL maps can be used to infer the structure of ionised gas (e.g. Jaffe and Pankonin, 1978).

5.2 OTF observing process

While many OTF scan patterns exist, we have implemented the simplest, the raster scan (see figure, 5.1), which is optimised for mapping rectangular regions. Raster scanning moves the telescope on-source (‘ON’) in a straight line, then offsets by a fraction of a beam, perpendicular to the scan direction, before moving the telescope in the opposite direction. An emission-free reference position, ‘OFF’, is also observed between scans to correct for the bandpass. As the telescope moves across the source, the spectrometer samples data at regular intervals (typically smaller than the beam size).

Our implementation is a variation of the raster geometry, where the order of observing on-source or reference position is flexible: an OFF can be observed before or after an ON, or after multiple ON scans (see §5.2.2 and 5.2.3 for details). Maps can be made in either \((\alpha \cdot \cos \delta_0, \delta)\) or \((\alpha \cdot \cos e_0, e)\) coordinate systems, with the scan direction parallel to either coordinate axis.

\(^1\)\(\alpha, e\) are azimuth and elevation. \(\delta_0\) is the declination of the starting position of the observation. The longitudinal coordinates are referred to as cross-Dec and cross-El in the telescope control system.
5.2.1 Software Architecture

The observing mode was implemented on the Tid-70m control software AUTO_SPEC, a PERL based script that acts as an interface to both the telescope and spectrometer. This software sends commands via two PERL modules: the network monitor control (NMC.PM) and the correlator (CORR.PM); these commands are sent to the antenna pointing control (APC) and the user interface (TKCOR) respectively.

Figure 5.2 is a schematic illustration of the architecture of the software control system. The NMC module interacts with the NASA-controlled modules of the telescope. The commands the NMC module sends are: setting position; offset; slew rate; stop and stow. The module also retrieves information on the current a and e coordinates, offsets, slew rate and supplementary information (temperature, pressure, humidity, wind speed, wind direction, precipitation and time). The antenna logs that are generated by the NMC module contain telescope commands and records of the position.

The CORR module interacts with the user interface TKCOR, a PERL/Tk module that is the interface of the process DUMMSY. DUMMSY sends commands to the physical correlator. Logs from the spectrometer are generated by CORR.PM.
5.2.2 Antenna

The commands to move the telescope come from the schedule file, setting the parameters of the observation, containing positional information for the reference position and starting position on source, time on source and frequency. Scanning axis and direction for on-source scanning are programmed into the control software AUTO_SPEC before observations begin. In a typical OTF mapping observation, where a reference position is taken, first, then a single on source observation:

1. **OTF** mapping begins with integrating on an emission-free reference position;
2. the telescope slews to the start position of the target source;
3. the **OTF** scan starts with AUTO_SPEC commanding the telescope control to settle on the $\alpha$ and $\delta$ starting point before moving the telescope in a set direction at a constant rate with a timer starting;
4. the scan rate of the telescope is calculated based on the beam size, and sampling rate:

$$ R = \frac{\theta_{int}}{t_{int}} = \frac{d\alpha}{dt} \cos \delta_0 $$

(5.1)
(assuming scanning in $\alpha \cos \delta_0$), where $R$ is the scanning rate of the telescope in degrees s$^{-1}$, $\theta_{int}$ is defined as $\theta_{FWHM}/n$ ($n$ is the number of times to sample the beam, generally $\geq 3$) and $t_{int}$ is the number of seconds per integration;

5. as the telescope continues to slew across the source, the antenna log samples the telescope’s position in $a$ and $e$ every 15 seconds.

6. the telescope will be sent the command to stop when the timer matches the on source time in the schedule file;

7. once the telescope has stopped, the next line in the schedule file is read.

Numbers 1–5 are illustrated in figure 5.1.

### 5.2.3 Spectrometer

The Tid-70m is equipped with a Parkes Multibeam correlator block. OTF observations can use the full 64 MHz bandwidth with two polarisation products of up to 2048 channels for each polarisation. As the telescope is being driven, the spectrometer is integrating the spectra over a minimum time interval of three seconds. The data from the spectrometer are then written to an ATNF format file (rpfits) along with time stamps, positional information, frequencies and summary information of the observation. The summary information contains start and finish time, observation project number, source name, starting position in $\alpha$ and $\delta$ as well as $a$ and $e$, number of Intermediate Frequencies (IFs), observed frequency, reference frequency and system temperature ($T_{sys}$/K). The spectrometer will only record the starting position of each row of the map into the spectrometer log file through the correlator module, and this starting position is derived from the schedule file, not the telescope encoders. The average position of each sample was therefore derived by cross-checking the NMC log against the spectrometer log file through the correlator module, and this starting position is derived from the schedule file, not the telescope encoders. The average position of each sample was therefore derived by cross-checking the NMC log against the spectrometer log file, taking into account slew times and correlator delays. This was done by the python data processing scripts fillobservatories.py and fixDirection.py. These scripts also adjust the sample positions (see section 5.2.4).

### 5.2.4 Data processing

Data processing of 70m-Tid OTF data uses the Common Astronomy Software Applications (CASA version 4.1 and 4.2; McMullin et al., 2007). The raw file (rpfits) containing header information, tables and observation data is imported into CASA, with positions converted into radians. Correcting the position of each integration is based on converting the recorded velocity taken from the NMC log into radians and compensating for...
the initial delay caused by the correlator. The scan rate \((R)\), is then used to correct
the position of each integration along the \(\alpha \cos \delta_0\) axis:

\[
\alpha_i = \alpha_0 + \frac{R}{\cos \delta_0} \cdot (t_i - t_0)
\]

(5.2)

where \(\alpha_0\) and \(t_0\) are the starting R.A. and time, and \(\alpha_i\) and \(t_i\) are the R.A. and time of
the current integration (\(\delta_0\) is the corresponding declination for \(\alpha_0\)). The new positions
are written into the scan table, as well as the recalculated \(a\) and \(e\) for each new position.
The antenna temperature \(T_A\) is obtained by bandpass correcting the raw spectrum:

\[
T_A = T_{sys} \cdot \frac{ON - OFF}{OFF}
\]

(5.3)

\(T_{sys}\) is the system temperature, \(ON\) is the on-source spectrum and \(OFF\) is the reference
spectrum.

The schedule file contained a reference scan for each on-source scan; the sdcal task
in casa assumes this format. Polynomial baseline subtraction can occur at this stage,
or a continuum subtraction can be applied after the imaging stage is completed to
preserve the continuum emission. Smoothing functions such as the Hanning function
can also be applied if the target spectral line is narrow. Calibrated data are then
exported into a measurement set (MS) format for the imaging stage, which creates a
position-position-velocity cube using both circular polarisations. The gridding kernel
is the default 2-D top-hat function with a 1-pixel width. Continuum subtraction from
the image cube can be applied (if baseline subtraction was not applied to the spectra),
through the specification of a line-free channel range, resulting in a continuum cube
and emission line cube. The data cube can then be exported to fits. The detailed
casa data reduction procedure is described in Appendix B.3.2.

5.3 Test Observations

The HII region Ori A and Galactic Centre source Sgr A were the targets for our test
observation\(\textsuperscript{7}\) (Table 5.1). Observations were conducted under Tid-70m project number
T206, as part of the OTF development programme. Our test observations used the 8.2–
8.6 GHz X-band receiver, the central frequency was set to 8.31 GHz, and we recorded
both circular polarisations with 64 MHz bandwidth, sampling at a quarter FWHM with
the minimum three second intervals. The beam has FWHM of 1.8', and individual scans
(map rows) were spaced by 30'' in Dec, while the telescope scanned along the \(\alpha \cdot \cos \delta_0\)
axis. A schedule file parameter set the time taken for the telescope to complete each
scan: These observations used 120s-long scans with 30s integrations on the reference
position. The Hanning function was not applied for the maps presented, as RRLs are
broad spectral features, so Hanning is not required. Opacity correction was not applied

\(\textsuperscript{7}\)Observing at CDSCC is done as a service mode (i.e. observations are conducted by staff on-site, and
not by the primary investigator), because of the unknown time availability of the allocated astronomy
time. Therefore, the source selection, spectrometer configuration (e.g. frequency) and observations
were conducted by S. Horiuchi.
to our maps, but attenuation due to opacity would be within 5% at the lowest elevation during the 8 GHz observations. There was no comparison to a flux calibrator source, but our observations agree within 10% with those of Cesarsky (1973).

Ori A and Sgr A were mapped with the same telescope scan speed of $-2.48 \text{ mdeg s}^{-1}$ along $\alpha \cdot \cos \delta_0$; converting the scan speed to $\alpha$ and using the minimum integration time of 3s, Ori A and Sgr A have cell sizes of 0.45$'$ and 0.51$'$ respectively along the scan direction, and 0.5$'$ across the scan direction. Offsets caused by the delay of the spectrometer were between 0.30$'$ and 0.60$'$ for Ori A and 0.34$'$ and 0.68$'$ for Sgr A. The scan speed is taken from the NMC log which records telescope speed, and the integration time is taken from correlator logs (The negative scanning speed indicates that the telescope was moving in decreasing $\alpha \cdot \cos \delta_0$). The effect of these corrections is to shift each scan row by a slightly different amount along the scan direction. The resulting Sgr A image has a continuum peak shifted to the position of Sgr A* compared to the uncorrected image which had a 2.5$'$ offset from Sgr A*.

Both sources were observed with channels of width 1.13 km s$^{-1}$. The Ori A integrated H92$\alpha$ emission map is shown in Fig. 5.3. Continuum subtraction was applied to the Ori A cube after the imaging process, as this correctly produced a flat spectrum. Sgr A was observed on two separate days; data from each day were processed separately before merging the datasets during the imaging stage. H92$\alpha$ integrated and channel maps towards Sgr A are shown in Figs. 5.4 and 5.5 respectively. While the data cube has a channel width of 1.13 km s$^{-1}$, the channel map in Fig. 5.5 uses a channel width of 15 km s$^{-1}$. Due to the complex emission structure of the region, an attempt was made to select a line-free channel range to create a polynomial to remove continuum emission from the spectra. Examining the attempted continuum subtraction, we see the Northern region with continuum emission successfully removed, however around the Southern peak ($\delta < -28^\circ55^\prime$) broadband emission can still be seen.

5.4 Discussion

5.4.1 Orion A

Our data constitute the first fully-sampled single-dish RRL map of Ori A, though sparsely-sampled maps made up of selected beam positions have previously been published by Jaffe and Pankonin (1978) and by Peimbert et al. (1988); the RRL structure (Fig. 5.3) is similar to that seen in a 23 GHz continuum map (resolution 42$''$, Wilson and Pauls, 1984). Many hydrogen RRL transitions have been observed with single-dish telescopes towards Ori A, mostly towards similar positions, so that the beams overlap. Table 5.3 lists H($n$$\alpha$) RRL transitions observed towards positions close to the peak brightness that we observe in Ori A. The spectrum corresponding to the peak brightness in our H92$\alpha$ map (Fig. 5.6 and Table 5.2) may be compared to a previous observation of the same transition by Cesarsky (1973), which used the DSN Goldstone antenna, then 64 m in aperture, with beamwidth of 2.5$'$. No pointing coordinates are given, but the published line parameters ($T_A = 4.65$ K, $V_{LSR} = -2.7 \pm 2$ km s$^{-1}$, $\Delta \nu =$
Table 5.1: Table showing the different sources observed, the date observed, the amount of time taken to observe, map size in arcmin, central position of the map and reference position.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ori A</td>
<td>2013-09-24</td>
<td>2.4 h</td>
<td>18.9′ × 17.5′</td>
<td>42 × 36</td>
<td>05:35:19.2 -05:18:47.7</td>
<td>05:40:30.0 -05:16:16.0</td>
</tr>
<tr>
<td>Sgr A</td>
<td>2013-09-23</td>
<td>2.8 h</td>
<td>20.4′ × 16.0′</td>
<td>42 × 42</td>
<td>17:45:58.9 –28:58:22.1</td>
<td>17:55:00.0 –28:00:00.0</td>
</tr>
<tr>
<td></td>
<td>2013-09-24</td>
<td>1.3 h</td>
<td>20.4′ × 10.5′</td>
<td>42 × 21</td>
<td>17:45:58.9 –28:43:28.3</td>
<td>17:55:00.0 –28:00:00.0</td>
</tr>
</tbody>
</table>
Figure 5.3: Integrated H92\(\alpha\) emission map towards Ori A; contours at 20, 40, 60...140 K km s\(^{-1}\).

Table 5.2: Gaussian fits to sample H92\(\alpha\) spectra.

<table>
<thead>
<tr>
<th>Region</th>
<th>R.A. J2000</th>
<th>Dec J2000</th>
<th>(V_{LSR}) (km s(^{-1}))</th>
<th>(\Delta\nu) (km s(^{-1}))</th>
<th>(T_A) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ori A</td>
<td>05:35:17.8</td>
<td>-05:22:15.0</td>
<td>-2.7(\pm)0.3</td>
<td>25.0(\pm)0.7</td>
<td>5.07(\pm)0.12</td>
</tr>
<tr>
<td>Sgr A</td>
<td>17:45:41.4</td>
<td>-28:52:14.9</td>
<td>-40.5(\pm)0.8</td>
<td>56.2(\pm)2.0</td>
<td>0.88(\pm)0.03</td>
</tr>
</tbody>
</table>
Figure 5.4: Integrated H92α emission map with incomplete continuum subtraction towards Sgr A; contours at 20, 30, 40...70 K km s$^{-1}$. 
Figure 5.5: On-the-fly channel maps with incomplete continuum subtraction of H2O emission towards Sgr A; contours at 0.3, 0.45, 0.6, 0.75, 0.9 K.
$26 \pm 2 \text{ km s}^{-1}$), agree with our results (Table 5.2) within the error intervals, except for line amplitude; but even here, the discrepancy of 0.42 K is less than 10%.

Fig. 5.7 is replotted from Sorochenko (1965), with observational data points added by taking the line brightnesses from Table 5.3 divided by the emission measure of the HII region (EM of $4.0 \times 10^6 \text{ cm}^{-6} \text{ pc}$ taken from McGee and Newton 1981), and shows the variation of RRL brightness with electron density. All the lines denoted by pentagons are observed at similar positions, and the filled pentagon is the value taken from our map. Triangles denote observations with no position given. The model curves show that we should expect significant changes in the relative line brightnesses around 10 GHz as the electron density increases from 100 cm$^{-3}$ to 1000 cm$^{-3}$. Observations at these frequencies therefore present an opportunity to probe the electron density directly through RRLs, and large-scale mapping of RRLs at these frequencies may allow us to map electron density structure.

The data points in Fig. 5.7 generally lie near the model curves for electron densities of 100 and 200 cm$^{-3}$. Points lying significantly away from these tracks are at an uncertain position (7.8 GHz) or an upper limit (24.5 GHz). Estimates of the electron density towards Ori A generally lie at least an order of magnitude higher: Smirnov et al. (1984) calculated an electron density of $(1 \pm 0.3) \times 10^4 \text{ cm}^{-3}$, based on Stark broadening of RRLs, and García-Díaz and Henney (2007) suggest the electron density is generally around 2000 cm$^{-3}$ throughout Ori A, based on optical spectroscopy.

García-Díaz and Henney (2007) found a layer of low-electron-density emission towards Ori A, lying in front of the main ionised region, and is blueshifted. Fig. 5.7 shows that low-electron-density gas emits very strongly around 10 GHz, so it is possible that much of the H92α emission that we see arises in lower-density material. Wen and O’Dell (1995) modelled the dense layer of ionised material in Ori A as being 0.1–0.2 pc thick, so the denser gas might account for less than half of the $4 \times 10^6 \text{ cm}^{-6} \text{ pc}$ emission measure; hence there could be a large amount of low-density gas to generate the RRLs. To confirm this possibility, a full spatial analysis of RRLs across frequencies and comparison to continuum maps would be required. This falls outside the scope of this paper.

5.4.2 Sagittarius A

Sgr A has been mapped interferometrically in the H92α RRL using the VLA (Zhao et al., 1993; Roberts and Goss 1993; Lang et al., 2001, 1997), but the high resolution of these maps rules out simple comparisons to our data.

Pauls et al. (1976) and Pauls and Mezger (1980) used the 100-m Effelsberg telescope to map H85α and H109α RRL emission towards the Sgr A region. Continuum subtraction was applied on the Sgr A data set, although due to the strong Sgr A non-thermal emission affecting the entire band profile, there still remains some continuum emission seen in the maps as broadband emission in the southern peak ($\delta < -28^\circ 55'$). However, we see a ‘peanut’ shape in our H92α map (Fig 5.4) similar to that seen by Pauls et al. (1976) in H85α (10 GHz, 1.3’ beam); our channel map (Fig 5.5) and the spectrum to-
Figure 5.6: H$^{2}$O spectrum towards Ori A at the position of peak $T_{L}$ (coordinates top right).

Figure 5.7: Brightness temperature at the center of a line as a function of frequency (Sorochenko [1965]), overlaid with peak antenna temperatures (Table 5.3) of Hydrogen RRLs towards Ori A observed at different frequencies.
Table 5.3: Table containing Hydrogen RRL transition, rest frequency, peak brightness temperature ($T_A$), beam efficiency, line brightness temperature corrected for beam efficiency ($T_L$) and available publications with single dish observation towards Ori A in the H$\alpha$ RRL. The H109$\alpha$ $T_L$ appears to have already been corrected for beam efficiency ([Jaffe and Pankonin] 1978). The H64$\alpha$ $T_L$ had already been corrected for beam efficiency and with a smaller beam than our observations (42$''$), the data point in Fig 5.7 is an upper limit ([Wilson et al.] 1997). Our 92$\alpha$ spectrum (R.A. 05:35:14.8, Dec. –05:22:32.4) is towards the overlap of the other H(n)$\alpha$ transitions.

<table>
<thead>
<tr>
<th>Transition</th>
<th>Rest Frequency (GHz)</th>
<th>$T_A$ (K)</th>
<th>$\eta$</th>
<th>$T_L$ (K)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>51.07</td>
<td>0.67</td>
<td>0.65</td>
<td>1.03</td>
<td>Hollis and Ulich (1977)</td>
</tr>
<tr>
<td>53</td>
<td>42.95</td>
<td>0.98</td>
<td>0.65 $\pm$ 0.05</td>
<td>1.97</td>
<td>Peimbert et al. (1988)</td>
</tr>
<tr>
<td>64</td>
<td>24.51</td>
<td>—</td>
<td>—</td>
<td>5.05</td>
<td>Wilson et al. (1997)</td>
</tr>
<tr>
<td>65</td>
<td>25.40</td>
<td>1.54</td>
<td>0.47</td>
<td>3.28</td>
<td>Churchwell et al. (1970)</td>
</tr>
<tr>
<td>76</td>
<td>14.69</td>
<td>2.95</td>
<td>0.70</td>
<td>4.21</td>
<td>McGee and Newton (1981)</td>
</tr>
<tr>
<td>91</td>
<td>8.67</td>
<td>4.28</td>
<td>0.70</td>
<td>6.11</td>
<td>Quireza et al. (2006)</td>
</tr>
<tr>
<td>92</td>
<td>8.31</td>
<td>4.65</td>
<td>0.70 $\pm$ 0.2</td>
<td>6.64</td>
<td>Cesarsky (1973)</td>
</tr>
<tr>
<td>92</td>
<td>8.31</td>
<td>4.57</td>
<td>0.70</td>
<td>6.53</td>
<td>This work</td>
</tr>
<tr>
<td>94</td>
<td>7.79</td>
<td>2.04</td>
<td>0.53</td>
<td>3.85</td>
<td>Gordon and Meeks (1967)</td>
</tr>
<tr>
<td>109</td>
<td>5.01</td>
<td>—</td>
<td>0.65</td>
<td>6.45</td>
<td>Jaffe and Pankonin (1978)</td>
</tr>
<tr>
<td>110</td>
<td>4.87</td>
<td>5.40</td>
<td>0.75</td>
<td>7.20</td>
<td>Davies (1971)</td>
</tr>
<tr>
<td>126</td>
<td>3.24</td>
<td>2.70</td>
<td>0.70</td>
<td>3.86</td>
<td>McGee and Gardner (1968)</td>
</tr>
<tr>
<td>134</td>
<td>2.70</td>
<td>2.20</td>
<td>0.75</td>
<td>2.93</td>
<td>Zuckerman and Palmer (1970)</td>
</tr>
<tr>
<td>158</td>
<td>1.65</td>
<td>1.60</td>
<td>0.70</td>
<td>2.29</td>
<td>McGee et al. (1969)</td>
</tr>
<tr>
<td>166</td>
<td>1.42</td>
<td>0.56</td>
<td>0.67</td>
<td>0.84</td>
<td>Pedlar and Davies (1972)</td>
</tr>
<tr>
<td>192</td>
<td>0.92</td>
<td>0.17</td>
<td>0.67</td>
<td>0.25</td>
<td>Pedlar and Davies (1972)</td>
</tr>
<tr>
<td>198</td>
<td>0.84</td>
<td>0.10</td>
<td>0.55</td>
<td>0.18</td>
<td>Zuckerman and Ball (1974)</td>
</tr>
<tr>
<td>220</td>
<td>0.61</td>
<td>0.17</td>
<td>0.67</td>
<td>0.25</td>
<td>Pedlar and Davies (1972)</td>
</tr>
</tbody>
</table>
towards the emission peak (Fig. 5.8) are consistent with the finding of Pauls and Mezger that the dominant H109α (5 GHz, 2.6′ beam) emission occurs at $V_{LSR} \sim -40 \text{ km s}^{-1}$.

5.4.3 On-the-fly mapping on the 70-m

Our maps use a 30″ row spacing, more finely-sampled than the Nyquist row spacing criteria suggested by Mangum et al. (2007), resulting in oversampling of the rows. Our scan rate implies an oversampling factor ($n_{os}$ in Eq. 10, Mangum et al., 2007) close to 1.5 for Sgr A and 2 for Ori A.

Mapping a region the size of Ori A (18.9′×17.5′ map) by position switching would take about 25 hours, an order of magnitude more than the time taken to map it with OTF (Table 5.1). The major contributor to the time requirement for position switching is the telescope motion overhead, as the telescope moves back and forth between the map position and the reference. From OTF mapping logs, each such movement takes 12–32 s, 25 s on average. Most of this time is required to accelerate, decelerate and settle the telescope, so it is likely not to be strongly dependent on the distance to the reference position. Because mapping of the bright hydrogen RRLs only requires a few seconds’ integration (compared to the tens of seconds of movement overhead), RRL mapping gains the most efficiency from OTF.

The ammonia inversion transitions in the 17–27 GHz K-band are widely used to probe the temperature of cold dense gas; OTF may be used to map these lines. A 10′×10′ position-switching map with 60 s integration on-source per position, mapped at half-beam spacing will take $\sim 29 \text{ h}$ and reach rms noise of $\sim 0.07 \text{ K}$. This sensitivity is likely to be useful for ammonia analysis. To map a similar area with OTF spacing map rows by half a beam and sampling each row every third of a beam, using the
minimum 3 s integration time, takes 1.4 hours, achieving an estimated rms noise level of 0.3 K. Co-adding 12 repeated maps (taking into account that the OTF map is more densely sampled than the position-switched map), will yield an rms of $\sim 0.07$ K in $\sim 17$ hours, about 0.6 of the time required for the position-switching map. Each row of the OTF map takes 150 s, so the reference position is checked every 3.5 min; 4 min is the approximate maximum time between reference spectra at K-band. K-band observations will require opacity and gain-curve corrections for the corrected temperature scale ($T_A^*$) which is applied after importing into the Common Astronomy Software Applications (CASA) package. Smoothing using the Hanning function can be applied at a later stage.

For compact ammonia sources, observing efficiency can be increased by averaging the ends of the scan rows as an OFF spectrum in the data processing, removing the need for a reference scan. This approach will require reformatting the raw file to allow CASA to separate on-source spectra from OFF spectra for processing.

5.5 Conclusions

The 70-m Tidbinbilla radio telescope is now capable of OTF spectral line mapping. We have tested the new observing mode by mapping radio recombination line emission towards Orion A and Sagittarius A: Our data are consistent with published data towards these regions.

We have combined our measurement of the peak brightness towards Orion A with other measurements from the literature over a wide range of frequency, and plotted the line brightnesses over the theoretical curves of Soroenko (1965). The line brightness measurements are most consistent with electron densities of 100–200 cm$^{-3}$, much lower than the usual estimates of the electron density of the Orion nebula. This discrepancy may reflect the more efficient RRL emission from lower-density gas. Comparison of OTF brightness over a wide frequency range has the potential to constrain the electron density of large ionised regions, but this requires large-scale mapping to allow different beams to be compared as well as to analyse spatial structure. OTF mapping, which is highly efficient at mapping RRLs, can enable this analysis.

Due to the long times required for the Tid-70m to switch between source and reference, large maps of bright lines (such as RRLs) are very efficiently mapped by OTF while smaller maps of fainter lines (requiring longer integration times) do not gain as much. At K-band, the requirement to go to a reference position every $\sim 4$ min sets a limit to the mapping efficiency that can be achieved. Even so, maps of ammonia inversion transitions should be significantly more efficient using OTF. Ideally, to demonstrate the full capabilities of OTF mapping with Tid-70m, other frequencies would be used in this new mode. The work done as part of the Lupus molecular clouds and software upgrade with Tid-70m has been demonstrated to be promising. Unfortunately the computer controlling the spectrometer, broke down and a management decision was taken to concentrate on a new spectrometer.
Chapter 6

Summary and Future Work

This thesis presents an investigation into the structure of molecular cloud regions, Chamaeleon, Carina, and Lupus, some of which have been poorly studied in the radio wavelength. These regions have been observed with a selection of the following molecular lines: Carbon Monoxide \( \text{[CO]} \) used to trace extended emission, atomic Carbon \( \text{[C\text{\small{I}}]} \) used to trace photo-dissociation, or Ammonia \( \text{NH}_3 \) used to accurately measure cool temperatures.

Chamaeleon is a low mass star forming region and observations towards Chamaeleon II (focus of this thesis) have mostly been carried out by NANTEN the 4-m radio telescope which has a poor resolution, for the \( ^{12}\text{CO} \) emission line the beam size is 2.7\arcmin. Our observations with the larger Mopra radio telescope has produced maps with sub-arcminute resolution.

While on the other hand, the Carina Nebular Complex \( \text{[CNC]} \) contains high mass stars, which include \( \eta \text{Carina} \) an O-type star that is the brightest in the Galaxy. This region has been extensively surveyed at high resolution in wavelengths of optical, X-ray, and Infra-Red \( \text{[IR]} \). However, high resolution maps at radio wavelengths towards the Northern \( \text{[CNC]} \) region, have been limited with previous observations either possessing low resolution or limited coverage.

The Lupus molecular clouds are similar to Chamaeleon clouds, a low mass star forming region. The focus of this work is \( \text{NH}_3 \) observations towards Lupus regions I, III, and IV, which has only been observed by the Mopra radio telescope.

In the following sections the results of the Chamaeleon, Carina, Lupus, and the on-the-fly \( \text{[OTF]} \) implementation on Tid-70m are summarised and recommendations are given for future work.
6.1 Chamaeleon

6.1.1 Summary

The dark clouds towards the Southern constellation of Chamaeleon are among the nearest to the Sun \(d \sim 115–215\) pc \cite{Luhman2008}. Isolated from other major star forming regions, the Chamaeleon dark clouds contain three main regions (Cha I, II, and III), of which the poorly studied Cha II was the focus of this thesis. The stellar population within the region is comprised of low-mass stars, and an intermediate-mass Herbig Ae/Be star known as DK Cha.

Previous observations towards Cha II have been mostly large scale surveys using the NANTEN telescope, in the CO isotopologues \(^{12}\)CO, \(^{13}\)CO, and \(^{18}\)O. These observations are limited by the resolution of the beam of NANTEN which is \(\sim 2.7'\) at these frequencies.

For the first time this thesis presents new sub-arcminute maps, using the Mopra radio telescope, towards Cha II in the CO isotopologues \(^{12}\)CO, \(^{13}\)CO, \(^{17}\)O, and \(^{18}\)O (1–0) transitions. These new maps have resolved the structure of previously identified dense \(^{18}\)O emission. Two of the dense \(^{18}\)O clumps identified contained stellar objects, one of which contained a \(^{18}\)O outflow. Another two regions were within close proximity of known low-mass stars, whilst the rest of the identified dense clumps, which were diffused compared to other areas, were devoid of any known stellar objects.

The excitation temperature of \(^{12}\)CO, optical depth and column densities of \(^{13}\)CO and \(^{18}\)O have been derived using the new maps. The newly produced maps of excitation temperature and column densities, agree with the comparisons of Hayakawa et al. \cite{Hayakawa2001}. Column densities of \(^{13}\)CO and \(^{18}\)O made against visual extinction found different conditions surrounding the dense \(^{18}\)O emission, some which contain known stellar objects. The highest \(^{13}\)CO column density towards region D, around \(8 \times 10^{23}\) cm\(^{-2}\), was located near DK Cha. Region A which possess a \(^{18}\)O outflow, has highest temperatures and density towards the Cha II region.

Comparisons of the \(^{18}\)O dense clumps where made against each other, discussing the physical conditions, stellar activity and visual extinction. It was found that areas with a stellar object located in the dense clump possessed a higher \(^{13}\)CO and \(^{18}\)O column density compared to other identified regions where known stellar objects surrounded the dense clumps. These dense regions appear to be the most evolved within Cha II cloud.

6.1.2 Future Work

The observations presented only covered a part of Cha II, therefore to get a complete picture of the entire cloud, new observations are needed to extend the CO maps. This can also be taken further, and high-resolution observations towards the Cha I and III regions (which have not been conducted) will be able to characterise the gas and provide comparisons to Cha II.

Follow up observations in \(^{12}\)CO (4–3) could be used to compare the excitation
temperatures of $^{12}$CO. Observations towards dense regions, using other tracers like this will provide a better temperature estimate of these dense clumps.

An estimate of the physical conditions of the molecular gas can be achieved through observations of ammonia (NH$_3$), which can trace at a higher density compared to CO. NH$_3$ is an ideal probe to low temperatures as it will yield direct estimates of the temperature and column density throughout the map areas. Through the derived NH$_3$ excitation temperature, comparisons can be made to the CO excitation temperature, to look for any negative correlation between density and temperature. This will give insight into dense regions seen in CO and to suggest if these regions are starting to form cold dense cores.

These maps of temperature and density can be fed back into the CO maps in order to calibrate the temperature and column density, and improve the analysis of the large-scale CO maps. In the literature there have been limited observations done with NH$_3$ towards Cha II.

### 6.2 Carina

#### 6.2.1 Summary

A study of $^{12}$CO (4–3) and [C$\text{I}$] $^3P_1–^3P_0$ emission has been conducted towards the CNC and its environment. This thesis presents new sub-arcminute observations of $^{12}$CO (4–3) and [C$\text{I}$] $^3P_1–^3P_0$ emission lines towards the northern region of CNC. An area of $\sim 22.7' \times \sim 36.8'$ has been mapped with a resolution of 0.4', using the radio telescope NANTEN2. Previous observations of CO (4–3) and [C$\text{I}$] emission lines towards this region have been limited by either poor resolution or coverage: Zhang et al. (2001), used the Antarctic Submillimeter Telescope and Remote Observatory (AST/RO) to mapped $\sim 3$ deg$^2$ towards CNC with a resolution of $\sim 3'$; and Kramer et al. (2008) mapped two 4$'$ × 4$'$ areas with a resolution of 0.4' towards the northern and southern regions of CNC.

Comparisons have been made between the features seen in the optical image and morphology of CO (4–3) and [C$\text{I}$] emission lines. Emission between the velocity range of $-30 \text{ km s}^{-1}$ and $-20 \text{ km s}^{-1}$ found structural features in both emission lines matching optical features, implying interaction with H$\text{II}$ region.

Examining the 843 MHz radio continuum which mapped the H$\text{II}$ region Car I, CO (4–3) and [C$\text{I}$] emission lines were detected towards the H$\text{II}$ region. The average line profile of CO (4–3) and [C$\text{I}$] towards Car I showed two velocity components identified at velocity centroids $\sim 24 \text{ km s}^{-1}$ and $\sim 12 \text{ km s}^{-1}$. The line profile characteristic supports the assertion by Oberst et al. (2011), that the ionizing gas (H$\text{II}$ region, Car I) is pushing into the Giant Molecular Cloud (GMC). The Photo-dissociation region (PDR) models by Oberst et al. (2011), have suggested the intense Ultraviolet (UV) radiation fields from Trumpler 14, power both the H$\text{II}$ and photo-dissociation regions.

The excitation temperature ratio between $^{12}$CO (1–0) and $^{12}$CO (4–3), found high temperatures along the dust lane and around Car I. Optical depth and column density
have been derived from the [C\textsc{i}] map. Analysis of [C\textsc{i}] optical depth has a range of 0.2 to 0.8, and the column density range is \((0.4 - 3) \times 10^{17}\ \text{cm}^{-2}\). Equations used from Ikeda et al. (2002) and in section 1.5.1 found column density calculated through Ikeda et al. (2002) higher than what is calculated through section 1.5.1. This is because the equation in section 1.5.1 (Lo et al., 2014) uses the CO (4–3) excitation temperature as part of [C\textsc{i}] column density calculations, while Ikeda et al. (2002) scales the integrated intensity.

### 6.2.2 Future Work

The current maps have missing pixels/sections or bad baselines, which resulted in spectra being removed from the dataset before the imaging. Therefore, completing the mapping of the CNC and reobserving certain footprints to create a fully sampled map is ideal. Another possibility is to increase the signal-to-noise ratio of \(^{12}\text{CO}\) (4–3) and [C\textsc{i}] maps by observing the same region again, which would be particularly useful for the [C\textsc{i}] map as the signal to noise for parts of the map was low.

NANTEN2 is capable of observing [C\textsc{i}] \(^3\text{P}_2-^3\text{P}_1\), this will allow a better estimate of the amount of molecular gas that is transitioning to cooler gas. As Carina is a complex region, follow up large scale observations in the NH\textsubscript{3} emission line can better determine the temperature of the region.

### 6.3 Lupus

#### 6.3.1 Summary

The Lupus molecular clouds are a poorly studied area of interest for low-mass star formation processes. Although restricted by the limited observing capabilities of Tid-70m at the time, full beam spacing strip mapping was conducted towards dense clouds in Lupus (regions I, III, and IV). Detections of NH\textsubscript{3} (1,1) and (2,2) transitions towards the Lupus I, III and IV regions were found. In most cases, upper limits (where NH\textsubscript{3} 2,2 was not detected) were used to constrain optical depth, column density, kinetic and rotation temperature. The kinetic and rotation temperatures derived from NH\textsubscript{3} (1,1) and (2,2) detections indicate temperatures of 11.7 - 45.8 K. Calculation of column density of NH\textsubscript{3} (1,1) has a range of 9.0 to \(35.7\ 10^{13}\ \text{cm}^{-2}\) over the detections (upper limits used for detections with only a primary hyperfine).

Lupus I NW and Lupus III N detections have high NH\textsubscript{3} line widths in the ranges of 1.1 - 1.5 km s\(^{-1}\) to 1.3 - 1.6 km s\(^{-1}\) respectively. Compared to the CO line width maps of Tothill et al. (2009), the line width of CO is high in the same positions of our NH\textsubscript{3} (1,1) detections, where the range of Lupus I NW is 2.4 and 3.6 km s\(^{-1}\) and Lupus III N is 2.4 to 2.7 km s\(^{-1}\). The column density for the Lupus I NW and Lupus III North detections have a range of 15.7 - 35.7 \(10^{13}\ \text{cm}^{-2}\) and 9.4 - 27.4 \(10^{13}\ \text{cm}^{-2}\) respectively (upper limits have been used for detections that only contain a primary hyperfine). The temperatures were found to be higher than previously published because of the beam size (2.5\arcmin) of previous observations.
6.3.2 Future Work

Several regions of Lupus I, III and IV in the NH$_3$ (1,1) and (2,2) transitions were mapped by Benedettini et al. (2012) with the Mopra telescope, who found widespread emission. However, Benedettini et al. (2012) did not map the entire region, therefore observing areas not covered by Benedettini et al. (2012) with either a 2.5′ beamsize or better will allow a complete picture of NH$_3$ clumps within the region.

As this work is a precursor to Tid-70m OTF mapping, follow up observations using the OTF mapping will be able to resolve the dense structure identified by Benedettini et al. (2012). To fully characterise the ammonia, good signal-to-noise is required with a root mean square (RMS) noise of 0.01 K, as the optical depth is estimated from the ratio of the multiple components in the transition and the satellite components are often considerably fainter than the main component. Additionally the (2,2) inversion transition is fainter than the (1,1) by a significant factor. Therefore, any observations towards these regions require multiple scans towards the same position to gain a better signal-to-noise ratio of $\sim$5.

From the follow up observations, the parameters of $T_{ex}$ and $N$(NH$_3$) can be compared with the dense gas properties and the associations with or without Young Stellar Objects (YSOs). This will characterise the dense clumps within the different Lupus regions.

From this work, NH$_3$ detections towards Lupus I NW and the Northern region of Lupus III were identified either outside or near the edge of the dense $^{13}$CO (2–1) emission. Explanations as to why the NH$_3$ detection is located near the CO emission was not identified as a part of this work. This is particularly interesting because NH$_3$ emission is usually identified within the dense CO emission. A possible explanation for what is seen in this work is freeze-out of NH$_3$ emission onto the dust grains. To get a better understanding of these detections, follow up observations covering a larger area and higher resolution will be required. This will help identify the cause and possibly the mechanisms for the NH$_3$ emission to be identified towards the edge of the dense CO emission.

6.4 New mapping technique for Tid-70m and mapping Radio Recombination Line (RRL)

6.4.1 Summary

Addressing the limitations of Tid-70m presented in chapter 4, Tid-70m is now capable of OTF mapping capabilities, for the first time, because of new software developed for this thesis by the author. The ability to map areas in a relatively short amount of time, especially when a limited amount of time is allocated to the scientific community, increased the telescope’s scientific capabilities.

As part of the OTF software development, allowing the telescope to survey areas of interest, data reduction processes have been developed primarily by the author.
to reduce Tid-70m OTF data. The data reduction is conducted using the Common Astronomy Software Applications (CASA) software package, because of its ability to process existing position-switching Tid-70m data.

To test OTF mapping with Tid-70m, the well known sources of Orion A and Sagittarius A were observed in the H92α RRL at 8.3 GHz. Although these two regions had not previously been mapped in the H92α RRL, comparisons could be made to other RRL transitions to determine the spatial structure of each region. Comparing the new Orion A H92α map to other RRL observations, there is good agreement in the position of the source and temperature confirming H92α observations by Cesarsky (1973). Sagittarius A was also compared to other RRLs, and good agreement was found in velocity and spatial structure, even though the map had incomplete baseline subtraction.

6.4.2 Future Work

Although the technique of OTF mapping has been implemented, there are further improvements which can be undertaken to the Tid-70m control system, to improve Tid-70m’s scientific capability. Testing OTF was primarily conducted on the Tid-70m, however the Canberra Deep Space Communication Complex (CDSCC) contains two active 34-m radio antennas with another two under construction. The telescope system used for the 34-m radio telescopes is similar to Tid-70m, meaning that it is relatively straightforward to configure the software to observe with this telescope. It would be possible, as a result, to use the current OTF mapping software with the 34-m telescope instead of Tid-70m.

To improve the positional accuracy of each sample during OTF observing, synchronising the control systems of the telescope and spectrometer will allow real time information to be recorded onto the data file. This will account for the acceleration rate, removing the need to include a delay factor in the data processing. Furthermore, extracting the telescope position in real time and recording this into the data export file will eliminate the requirement to interpolate the position of each sample. To enhance the scientific capability of Tid-70m, the OTF method can be implemented with the newly installed spectrometer.

For compact ammonia sources, observing efficiency can be increased by averaging the ends of the scan rows as an OFF spectrum in the data processing, removing the need for a reference scan. This approach will require reformatting the raw file to allow CASA to separate on-source spectra from the OFF spectra for processing, something that should be investigated in the future.

To extend the OTF observations towards Orion A and Sagittarius A, total power measurements towards the same region can be made, which can provide the electron density for each of the regions. In addition by observing other Hydrogen RRL transitions within the Tid-70m frequency range we can start to build a picture of the amount of electron density within each region.
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Appendix A

Other Contributions

A.1 Primary author

The following presents publications not related to the work within the thesis, which the author was the lead. Copies of the publications have also been attached.

A.1.1 Publication 1


A new catalogue identifying 48 compact H\textsc{ii} regions have been presented and discussed. In addition, a new 1420 MHz ($\lambda=20$ cm) radio-continuum image of the N19 region located in the southwestern part of the Small Magellanic Cloud (SMC) was also presented. Majority of the work was conducted by the author, using archival data to create a new map of the N19 region, discussing identification of the compact H\textsc{ii} regions, and comparing to other wavelengths to create a spectral index of each detection.
NEW 20-cm RADIO-CONTINUUM STUDY OF THE SMALL MAGELLANIC CLOUD: PART III – COMPACT H II REGIONS

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SUMMARY: We present and discuss a new catalogue of 48 compact H II regions in the Small Magellanic Cloud (SMC) and a newly created deep 1420 MHz (λ=20 cm) radio-continuum image of the N 19 region located in the southwestern part of the SMC. The new images were created by merging 1420 MHz radio-continuum archival data from the Australian Telescope Compact Array. The majority of these detected radio compact H II regions have rather flat spectral indices which indicates, as expected, that the dominant emission mechanism is of thermal nature.

Key words. Magellanic Clouds – radio continuum: ISM – catalogs

1. INTRODUCTION

The Small Magellanic Cloud (SMC), with its well established distance (~60 kpc; Hilditch et al. 2005) and ideal position in the sky - towards the coldest areas near the South Celestial Pole, allows observation of radio sources to be conducted without significant interference from Galactic foreground radiation. The SMC is an ideal location to study celestial objects like compact H II regions (Mezger et al. 1967), which may be difficult to study in our own and other distant galaxies.

The SMC has been surveyed at multiple radio frequencies using archival data (Crawford et al. 2011, Wong et al. 2011a, hereafter Paper I). Deep observations of SMC young stellar objects, compact H II regions, Supernova Remnants (SNRs) and Planetary Nebulae (PNe) were presented in Oliveira et al. (2012), Indebetouw et al. (2004), Filipović et al. (2005), Filipović et al. (2008) and Filipović et al. (2009), respectively. A catalogue of radio-continuum point sources (Wong et al. 2012) towards the SMC was derived from images taken from Crawford et al. (2011).

This is the third paper in this series; Paper I presented newly developed high sensitivity and resolution images of the SMC. The second instalment (Wong et al. 2011b, hereafter Paper II) presented a point source catalogue created from the images in paper I. In this paper, we present newly constructed images of the N 19 region covering the southwestern part of the SMC, at ν=1.4 GHz (λ=20 cm). We also present a catalogue of compact H II regions sources towards the SMC. The catalogue is derived from images at 4800 MHz (λ=6 cm) and 8000 MHz (λ=3 cm) from Crawford et al. (2011), a 2370 MHz (λ = 13 cm) mosaic image from Filipović et al. (2002), one of our SMC 20 cm mosaic radio-continuum images (Fig. 2 in Paper I), the N 19 images presented in this paper and an 843 MHz (λ=36 cm) MOST image (Turtle et al. 1998).
2. DATA

2.1. SMC Mosaic Radio-continuum Images

The 3 and 6 cm images (Fig. 3 and Fig. 1 in Crawford et al. 2011) were created by combining data from various ATCA projects that covered the SMC (Table 1 in Crawford et al. 2011). The 3 and 6 cm maps have resolutions of \( \sim 20'' \) and \( \sim 30'' \) and r.m.s. noise of 0.8 and 0.7 mJy/beam, respectively. The 13 cm radio-continuum catalogue was produced from a SMC mosaic radio survey of 20 square degrees (Filipović et al. 2002). These observations have a beam size of \( \sim 40'' \) and r.m.s. noise of 0.4 mJy/beam. The 20 cm mosaic image (Fig. 2 in Paper I) was created by combining data from ATCA project C1288 (Mao et al. 2008) with data obtained for a Parkes radio-continuum study of the SMC (Filipović et al. 1997). This image has a beam size of \( 17.8 \times 12.7'' \) with r.m.s. noise of 0.7 mJy/beam.

The 36 cm image comes from the MOST radio survey of 36 square degrees containing the SMC field (Turtle et al. 1998). These observations have a beam size of \( \sim 45'' \) and r.m.s. noise of 0.7 mJy/beam — equal to that of the 20 cm image.

Table 1 gives the field size and central position of all images used to derive the compact H\(_{\text{II}}\) region catalogue contained in this paper.

<table>
<thead>
<tr>
<th>Image</th>
<th>RA</th>
<th>Dec</th>
<th>Field Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 cm</td>
<td>01:00:00</td>
<td>-73:00:00</td>
<td>( 5'' \times 5'' )</td>
</tr>
<tr>
<td>6 cm</td>
<td>01:00:00</td>
<td>-73:00:00</td>
<td>( 5'' \times 5'' )</td>
</tr>
<tr>
<td>13 cm</td>
<td>01:00:00</td>
<td>-72:30:00</td>
<td>( 5'' \times 4'' )</td>
</tr>
<tr>
<td>20 cm</td>
<td>01:00:00</td>
<td>-72:00:30</td>
<td>( 7'' \times 9'' )</td>
</tr>
<tr>
<td>36 cm</td>
<td>01:00:00</td>
<td>-72:30:30</td>
<td>( 6'' \times 6'' )</td>
</tr>
</tbody>
</table>

2.2. The SMC N 19 region

Observations were conducted with ATCA (project C281) over two 12 hour sessions on August 25, 1993 and February 10, 1994. Two array configurations at 20 and 13 cm (\( \nu = 1377/2377 \) MHz) were used — 1.5B and 6B. More details about these observations can be found in Ye et al. (1995) and Bojić et al. (2010).

2.3. The SMC N 19 region

2.3.1. Image Creation

In order to create high-fidelity and high-resolution radio-continuum images of the SMC N 19 region, we searched the Australia Telescope Online Archive\(^1\) (ATOA), identifying three complementary ATCA observations that covered N 19: projects C468, C882 and C1607. The source 1934-638 was used as the primary calibrator and 0252-712 as the secondary calibrator for all ATCA SMC observations. A brief summary of the three ATCA projects is shown in Table 2.

The software packages MIRIAD (Sault and Killeen 2010) and KARMA (Gooch 2006) were used for the data reduction and analysis. Initial high-resolution images were produced from the full dataset using the MIRIAD multi-frequency synthesis (Sault and Wieringa 1994) with natural weighting. The deconvolution process used MIRIAD tasks MOSSDI, an SDI variant of the clean algorithm designed for mosaics (Steer et al. 1984).

Figs. 1-3 show maps from individual ATCA projects (Table 2), Figs. 4 and 5 show maps derived from combining multiple observations.

<table>
<thead>
<tr>
<th>ATCA Date</th>
<th>Array</th>
</tr>
</thead>
<tbody>
<tr>
<td>C468 1997 Aug 06-07</td>
<td>375</td>
</tr>
<tr>
<td>1995 Oct 26-27</td>
<td>1.5D</td>
</tr>
<tr>
<td>1997 Nov 22</td>
<td>6C</td>
</tr>
<tr>
<td>C882 2000 Jun 20-17</td>
<td>6B</td>
</tr>
<tr>
<td>C1607 2006 Dec 02-12</td>
<td>6B</td>
</tr>
<tr>
<td>2006 Dec 12-18</td>
<td>750A</td>
</tr>
</tbody>
</table>

2.3.2. Images

Comparing individual maps of N 19 (Figs. 1-3), we can see the effects of different array configurations. Fig. 1 is created from project C468, containing a combination of extended and point source emission, as a result of three different array configurations. Fig. 2 (project C882) only contains a long-baseline observation (array configuration 6B), so the map is dominated by point sources. Fig. 3 has extended and point source emission, derived from short and long-baseline array configurations 750A and 6B respectively. Table 3 lists the details of the individual maps.

<table>
<thead>
<tr>
<th>ATCA Beam Size</th>
<th>Position</th>
<th>r.m.s. noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>C468 5.3\times5.1</td>
<td>2,\hbox{,h}17 ,\hbox{min}7 ,\hbox{sec}</td>
<td>0.1</td>
</tr>
<tr>
<td>C882 6.6\times6.2</td>
<td>-1,\hbox{h}13 ,\hbox{min}3 ,\hbox{sec}</td>
<td>0.1</td>
</tr>
<tr>
<td>C1607 6.9\times5.5</td>
<td>-2,\hbox{h}28 ,\hbox{min}3 ,\hbox{sec}</td>
<td>0.1</td>
</tr>
</tbody>
</table>

\(^1\)http://atoa.atnf.csiro.au
Figs. 4 and 5 show images created from a combination of observations (Table 2): Fig. 4 was created from ATCA projects C468 and C1607 while Fig. 5 contains observations C468, C882 and C1607. The images contain a combination of point sources and extended emission.

Fig. 1. ATCA project C468 radio-continuum total intensity image of N19. The synthesised beam is $5\'\!3\times 5\'\!1$ and the r.m.s. noise is $\sim 0.1$ mJy/beam.

Fig. 2. ATCA project C882 radio-continuum total intensity image of N19. The synthesised beam is $6\'\!6\times 6\'\!2$ and the r.m.s. noise is $\sim 0.1$ mJy/beam.
Fig. 3. ATCA project C1607 radio-continuum total intensity image of N19. The synthesised beam is $6\farcs9 \times 5\farcs5$ and the r.m.s. noise is $\sim0.1$ mJy/beam.

Fig. 4. Combined ATCA projects C468 and C1607 radio-continuum total intensity image of N19. The synthesised beam is $5\farcs3 \times 5\farcs0$ and the r.m.s. noise is $\sim0.1$ mJy/beam.
3. THE SMC COMPACT H II REGIONS: SOURCE FITTING AND DETECTION

Compact H II regions were identified by comparing our list of radio-continuum point sources (Paper II and Wong et al. 2012) to an Hα observation from the Magellanic Cloud Emission Line Survey (MCELS; Smith et al. 1999). Sources were examined visually to confirm that matched Hα sources were point or point-like in Hα and within ∼5′′ of the radio point source detection.

The list of candidate compact H II regions was narrowed down by cross-checking with catalogues of known objects like supernova remnants (Filipović et al. 2008) and planetary nebulae (Filipović et al. 2009, Crawford et al. 2012, Bojičić et al. 2010).

Table A1 gives the names, positions (J2000, derived from the 1420 MHz image of the whole SMC) and the integrated flux values at various frequencies for the compact H II regions. The integrated fluxes in columns 5–12 are: flux density values taken from the MOST image; 1420 MHz flux density measurements from SMC (high resolution Fig. 2, Paper I) and new N 19 (Fig. 5) mosaic images; flux measurements retrieved from the N 77 20 and 13 cm images (Ye et al. 1995); flux values from an SMC 2370 MHz mosaic image (Filipović et al. 2002); 4800 and 8640 MHz flux values from Crawford et al. (2011; Figs. 1 and 3).

4. RESULTS AND DISCUSSION

Figs. 1–3 show the individual intensity mosaic maps of the N19 region derived from projects C468, C882 and C1607, respectively, while Figs. 4 and 5 are images created by combining different observations. All these images can be downloaded from: space-science.uws.edu.au/mc/smc/N19/. A sample of 48 compact H II regions was selected; table A1 lists the compact H II regions with integrated flux values at various frequencies. These flux values are derived from gaussians fitted to the images described in Section 2.
30 of the 48 catalogue sources were detected at more than one wavelength. Spectral indices $\alpha$ ($S_{\nu} \propto \nu^\alpha$), with errors, were estimated for all of these sources, fitted to all available flux measurements. Integrated fluxes at 1 GHz were also derived from these fits. Integrating the fitted spectra from 10 MHz to 100 GHz yielded fluxes (in $10^{-26}$ W m$^{-2}$) which were then converted into radio luminosities using the known distance to the SMC. Table A2 lists all compact H$\text{II}$ regions: The estimated flux density at 1 GHz; spectral index with errors; and the radio luminosity (i.e. the luminosity of the compact H$\text{II}$ region over the radio spectrum) in units of $10^{26}$ W and in solar luminosities.

The radio luminosity distribution (Fig. 9) peaks around $\sim$0.3$L_\odot$: It falls off towards higher luminosities as there are fewer sufficiently bright stars to power compact H$\text{II}$ regions at such high luminosities; it falls off towards lower luminosities due to the lack of completeness of our catalogue. Our catalogue is likely to be quite complete down to a limiting radio luminosity of $\sim$0.3$L_\odot$.
4.1. Notes on individual sources

4.1.1. J005914-721103 (Source 33)

This compact H II region candidate is the extreme positive outlier in Figs. 7 and 8, with a spectral index of $+2.0 \pm 0.4$; it is only detected in the 13 cm and 20 cm N 77 images, so the spectral index is defined purely by these fluxes. It is possible that this is a compact H II region with a very high-frequency spectral break, so that it has a spectral index of 2 even in the higher-frequency maps. However, in the 13 cm image, the source is located at the edge of the primary beam, so that the 13 cm flux is rather unreliable, and so this spectral index may not be accurate. It is also possible that this source could be a variable background galaxy that flared during the N 77 observations, and is otherwise undetected. The very high estimated luminosity is largely due to the extreme spectral index, and is unlikely to be accurate — if the source is indeed a compact H II region with a very high cutoff frequency, the high luminosity is due to extrapolation of the low-frequency spectral index to the whole radio region.

4.1.2. J010132-715042 (Source 36)

This is the other source with a highly positive spectral index ($+1.0 \pm 0.4$), and could only be detected in the 20 cm and 36 cm images. It is likely that this is a compact H II region whose spectral break lies between 36 cm and 20 cm. Fitting a single power-law to these data then gives an average spectral index of about 1. This will also lead to a large overestimate in the luminosity.

4.1.3. J012408-730904 (Source 48)

This compact H II region candidate has a very high radio luminosity of $23.5 \, L_\odot$; this estimate comes from a combination of a positive estimated spectral index (which implies rising flux through the GHz spectrum, and hence a large luminosity) and very high fluxes in all images. The source is detected at 36 cm, and the higher-frequency data yield a spectral index of $\sim -0.2 \pm 0.1$. This is quite consistent with the source being a compact H II region with a cutoff
frequency between 843 MHz and 1.4 GHz. Although the luminosity may be overestimated, this is clearly a very luminous radio source. If it is a compact H II region, it is likely to be powered by a cluster of young high-mass stars, which can supply such a large luminosity.

5. CONCLUSION

In this paper, we present a new catalogue of 48 candidate compact H II regions within the SMC. This catalogue is derived from previously-presented datasets, and from a new set of high-sensitivity and high-resolution radio-continuum images of the N 19 region at 1420 MHz (λ ≈ 20 cm), created from archival ATCA data. We have collected flux measurements at as many wavelengths as possible for all sources, and used these fluxes to fit a power-law radio spectrum, which, in turn, yields estimates of the flux at 1 GHz and the spectral index. The distribution of spectral indices is consistent with a population of sources dominated by compact H II regions, i.e., peaked around α ≈ 0, with better data yielding sharper peaks, and a few sources with significantly positive spectral indices — consistent with compact H II regions whose cutoff frequencies lie within our frequency range. We have also estimated the radio luminosity of the sources: The distribution of radio luminosities is strongly peaked around a presumed threshold luminosity, but includes some very luminous regions, such as J012408-730904, whose very high radio luminosity suggests that it is powered by a cluster of young high-mass stars.

Acknowledgments — The Australia Telescope Compact Array is part of the Australia Telescope National Facility which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO. This paper includes archival data obtained through the Australia Telescope Online Archive (http://atoa.atnf.csiro.au). We used the KARMA and MIRIAD software packages developed by ATNF. We thank the anonymous referees and Richard Sturm for their valuable comments, which have led to an improved paper.

REFERENCES

### Table A1. Compact H\textsuperscript{ii} regions and their fluxes.

<table>
<thead>
<tr>
<th>No</th>
<th>Name</th>
<th>RA (J2000)</th>
<th>Dec (J2000)</th>
<th>S\textsubscript{1400} (mJy)</th>
<th>S\textsubscript{1400} (SMC) (mJy)</th>
<th>S\textsubscript{1400} (N19) (mJy)</th>
<th>S\textsubscript{1217} (NTT) (mJy)</th>
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* Values taken from Indebetouw et al. 2004
### Table A2. Compact H\textsc{ii} regions and their properties.

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<td>—</td>
</tr>
<tr>
<td>11</td>
<td>J004808-731454</td>
<td>00:48:08.6</td>
<td>-73:14:54</td>
<td>14.9</td>
<td>0.0 ± 0.1</td>
<td>7.1</td>
<td>1.9</td>
</tr>
<tr>
<td>12</td>
<td>J004848-730558</td>
<td>00:48:18.7</td>
<td>-73:05:58</td>
<td>—</td>
<td>—</td>
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<td>—</td>
</tr>
<tr>
<td>13</td>
<td>J004826-730606</td>
<td>00:48:27.0</td>
<td>-73:06:06</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>14</td>
<td>J004829-730626</td>
<td>00:48:29.9</td>
<td>-73:06:26</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
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<td>15</td>
<td>J004836-725759</td>
<td>00:48:36.4</td>
<td>-72:57:59</td>
<td>2.1</td>
<td>0.1 ± 0.4</td>
<td>1.1</td>
<td>0.3</td>
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<tr>
<td>16</td>
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<td>00:49:14.8</td>
<td>-73:10:57</td>
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<td>J004948-724840</td>
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<td>-72:48:40</td>
<td>4.8</td>
<td>-0.1 ± 0.2</td>
<td>1.4</td>
<td>0.4</td>
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<tr>
<td>18</td>
<td>J004946-731024</td>
<td>00:49:46.1</td>
<td>-73:10:24</td>
<td>—</td>
<td>—</td>
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<tr>
<td>19</td>
<td>J005043-724655</td>
<td>00:50:43.4</td>
<td>-72:46:55</td>
<td>—</td>
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<tr>
<td>20</td>
<td>J005141-731331</td>
<td>00:51:41.2</td>
<td>-73:13:31</td>
<td>6.7</td>
<td>0.1 ± 0.3</td>
<td>3.9</td>
<td>1.0</td>
</tr>
<tr>
<td>21</td>
<td>J005148-725041</td>
<td>00:51:48.3</td>
<td>-72:50:41</td>
<td>5.5</td>
<td>0.0 ± 0.3</td>
<td>2.6</td>
<td>0.7</td>
</tr>
<tr>
<td>22</td>
<td>J005158-732030</td>
<td>00:51:58.3</td>
<td>-73:20:30</td>
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<td>—</td>
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<td>23</td>
<td>J005212-733604</td>
<td>00:52:12.6</td>
<td>-73:36:04</td>
<td>0.4</td>
<td>0.7 ± 1.4</td>
<td>2.8</td>
<td>0.7</td>
</tr>
<tr>
<td>24</td>
<td>J005729-732223</td>
<td>00:57:29.9</td>
<td>-73:22:23</td>
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<td>-0.1 ± 0.3</td>
<td>1.1</td>
<td>0.3</td>
</tr>
<tr>
<td>25</td>
<td>J006518-732849</td>
<td>00:58:16.5</td>
<td>-73:28:49</td>
<td>7.7</td>
<td>0.1 ± 0.3</td>
<td>5.1</td>
<td>1.3</td>
</tr>
<tr>
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<td>J005911-721140</td>
<td>00:59:11.0</td>
<td>-72:11:40</td>
<td>17.3</td>
<td>-0.6 ± 0.3</td>
<td>1.2</td>
<td>0.3</td>
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<td>00:59:14.9</td>
<td>-72:11:03</td>
<td>1.1</td>
<td>2.0 ± 0.4</td>
<td>1365.6</td>
<td>355.2</td>
</tr>
<tr>
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<td>J010058-713527</td>
<td>01:00:58.5</td>
<td>-71:35:27</td>
<td>7.2</td>
<td>-0.0 ± 0.1</td>
<td>2.7</td>
<td>0.7</td>
</tr>
<tr>
<td>29</td>
<td>J010132-715042</td>
<td>01:01:32.2</td>
<td>-71:50:42</td>
<td>1.7</td>
<td>1.0 ± 0.4</td>
<td>35.4</td>
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<tr>
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<td>J010143-715331</td>
<td>01:02:43.6</td>
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<td>0.5</td>
<td>0.1</td>
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<tr>
<td>31</td>
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<td>01:02:48.7</td>
<td>-71:53:14</td>
<td>8.1</td>
<td>0.0 ± 0.2</td>
<td>4.1</td>
<td>1.1</td>
</tr>
<tr>
<td>32</td>
<td>J010503-715926</td>
<td>01:05:03.8</td>
<td>-71:59:26</td>
<td>8.4</td>
<td>0.5 ± 0.3</td>
<td>20.2</td>
<td>5.3</td>
</tr>
<tr>
<td>33</td>
<td>J010504-715900</td>
<td>01:05:05.0</td>
<td>-71:59:00</td>
<td>3.4</td>
<td>0.3 ± 0.4</td>
<td>4.7</td>
<td>1.2</td>
</tr>
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<td>-71:59:46</td>
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<td>0.2 ± 0.4</td>
<td>5.0</td>
<td>1.3</td>
</tr>
<tr>
<td>35</td>
<td>J010832-721119</td>
<td>01:08:32.4</td>
<td>-72:11:19</td>
<td>1.7</td>
<td>-0.5 ± 0.3</td>
<td>0.1</td>
<td>0.0</td>
</tr>
<tr>
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<td>J010912-731138</td>
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<td>-73:11:38</td>
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<td>-0.1 ± 0.1</td>
<td>14.2</td>
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<td>-73:15:46</td>
<td>5.9</td>
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<td>1.5</td>
<td>0.4</td>
</tr>
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<td>38</td>
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<td>-73:15:50</td>
<td>6.5</td>
<td>0.1 ± 0.2</td>
<td>3.3</td>
<td>0.9</td>
</tr>
<tr>
<td>39</td>
<td>J011447-731946</td>
<td>01:14:47.1</td>
<td>-73:19:46</td>
<td>9.3</td>
<td>-0.5 ± 0.3</td>
<td>0.9</td>
<td>0.2</td>
</tr>
<tr>
<td>40</td>
<td>J011724-730917</td>
<td>01:17:25.0</td>
<td>-73:09:17</td>
<td>15.5</td>
<td>-0.7 ± 0.1</td>
<td>0.9</td>
<td>0.2</td>
</tr>
<tr>
<td>41</td>
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<td>01:24:08.1</td>
<td>-73:09:04</td>
<td>51.2</td>
<td>0.4 ± 0.2</td>
<td>90.0</td>
<td>23.4</td>
</tr>
</tbody>
</table>
NOVO PROUČAVANJE MALOG MAGELANOVOG OBLAKA U RADIJO-KONTINUUMU NA 20 cm: DEO III - KOMPAKTNI H II REGIoni

G. F. Wong, M. D. Filipović, E. J. Crawford, N. F. H. Tothill, A. Y. De Horta and T. J. Galvin

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УДК 524.722.7-77 : 524.523
Стручни чланак

Представљамо нови каталог од 48 компактних H II региони у Малом Магелановом Олаку (MMO). Такође, представљамо и нове радио-континуум слике N19 региони који се налази у југозападном делу MMO. Нове слике су креиране спајањем свих расположивих 20 см посматрања са ATCA телескопа (Australian Telescope Compact Array). Већина детектованих компактних H II региони има типичан "раван" спектар што указује да је доминантни емисиони механизам термалне природе.
A.1.2 Publication 2


A second in a series of papers, this paper presents a new catalogue of radio-continuum sources towards the Small Magellanic Cloud in the 6 and 3-cm wavelengths. Majority of the work presented was made by the author, identifying radio continuum sources from new high-sensitivity and resolution radio-continuum images of the SMC.
NEW 6 AND 3-cm RADIO-CONTINUUM MAPS OF THE SMALL MAGELLANIC CLOUD: PART II – POINT SOURCE CATALOGUE

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(Received: March 8, 2012; Accepted: March 19, 2012)

SUMMARY: We present two new catalogues of radio-continuum sources in the field of the Small Magellanic Cloud (SMC). These catalogues contain sources found at 4800 MHz ($\lambda=6$ cm) and 8640 MHz ($\lambda=3$ cm). Some 457 sources have been detected at 3 cm with 601 sources at 6 cm created from new high-sensitivity and resolution radio-continuum images of the SMC from Crawford et al. (2011).

Key words. Magellanic Clouds – radio continuum : galaxies – catalogs

1. INTRODUCTION

The Small Magellanic Cloud (SMC), well known for its close proximity ($\sim 60$ kpc; Hilditch et al. 2005) and ideal location in one of the coldest areas of the radio sky (also towards the South Celestial Pole), allows observations of radio emission to be made without interference from the Galactic foreground radiation (Haynes et al. 1986). Therefore, the SMC is an ideal location to study radio sources like supernova remnants (SNRs; Filipović et al. 2005, 2008, Payne et al. 2007, Owen et al. 2011, Haberl et al. 2012), H ii regions (Reid et al. 2006) and Planetary Nebulae (PNe; Filipović et al. 2009a, Crawford et al. 2012) which may otherwise be difficult to study in our own and other more distant galaxies.

Extensive radio-continuum surveys of the SMC have been made over the last 40 years using various interferometric observations like the Molonglo Observatory Synthesis Telescope (MOST; Ye et al. 1995) and Australia Telescope Compact Array (ATCA; Filipović et al. 2002, Payne et al. 2004, Filipović et al. 2009b, Mao et al. 2008, Dickel et al. 2010), and single dish observations from the 64-m Parkes radio-telescope (Filipović et al. 1997, 1998).

Catalogues of radio-continuum point sources covering the region of the SMC have been created from these surveys, and from wider surveys of the southern sky (see the summary of these catalogues in Wong et al. 2011a,b).

We recently published a set of new high-resolution radio-continuum maps of the SMC at 6 and 3-cm, created by combining observations from ATCA (Crawford et al. 2011, hereafter Paper I). We now present a catalogue of radio-continuum sources in the region of the SMC derived from our 6 and 3 cm radio-continuum maps (Fig. 1 and Fig. 3 in Paper I).

In Section 2 we describe the data used to derive the radio-continuum point sources. In Section 3 we describe our source fitting and detection methods. Section 4 contains our conclusions and the appendix contains the radio-continuum source catalogue.
2. DATA

The 6 and 3 cm maps (Fig. 1 and Fig. 3 in Paper I) were created by combining data from various ATCA projects that covered the SMC (Table 1 in Paper I). The majority of the data used come from ATCA project C1207 (Dickel et al. 2010). The 3 and 6 cm maps have a resolution of 20′′ and 30′′, and sensitivity of 0.8 and 0.7 mJy/beam, respectively.

Table 1 contains the field size of all the images used to derive the radio-continuum sources contained in this paper (Tables A1 and A2).

Table 1. Field size (in J2000) of images used in this study.

<table>
<thead>
<tr>
<th>Image</th>
<th>RA1 (°)</th>
<th>RA2 (°)</th>
<th>Dec1 (′′)</th>
<th>Dec2 (′′)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 cm</td>
<td>00h 26m</td>
<td>01h 27m</td>
<td>−70 35′</td>
<td>−75 21′</td>
</tr>
<tr>
<td>6 cm</td>
<td>00h 26m</td>
<td>01h 28m</td>
<td>−70 29′</td>
<td>−75 29′</td>
</tr>
<tr>
<td>13 cm</td>
<td>00h 27m</td>
<td>01h 35m</td>
<td>−70 30′</td>
<td>−75 15′</td>
</tr>
<tr>
<td>20 cm</td>
<td>00h 10m</td>
<td>01h 43m</td>
<td>−69 16′</td>
<td>−75 40′</td>
</tr>
<tr>
<td>36 cm</td>
<td>00h 16m</td>
<td>01h 40m</td>
<td>−72 30′</td>
<td>−74 38′</td>
</tr>
</tbody>
</table>

3. SOURCE FITTING AND DETECTION

The MIRIAD task IMSAD (Sault et al. 1995) was used to detect sources in the 3 cm and 6 cm images, requiring a fitted Gaussian flux density >5σ (3.5 mJy). All sources were then visually examined to confirm that they are genuine point sources, excluding extended emission, bright side lobes, etc.

The catalogue of radio-continuum sources contains positions RA(J2000), Dec(J2000) and integrated flux densities at 3 cm (Table A1) and 6 cm (Table A2). Table 2 provides a summary of the images and resulting catalogues of radio-continuum sources used in this study. In addition, the 13, 20 and 36 cm information from Wong et al. (2011a,b) is repeated for comparison. Table 2 also contains the number of sources identified within the field of the 13 cm image (see Table 1), the smallest of all the survey regions compared.

Table 2. Information on the images and catalogue of radio-continuum sources.

<table>
<thead>
<tr>
<th>λ (cm)</th>
<th>RMS (mJy/beam)</th>
<th>Number Within the Beam Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA</td>
<td>Dec</td>
<td>Sources the 3 cm image</td>
</tr>
<tr>
<td>3</td>
<td>0.8</td>
<td>457</td>
</tr>
<tr>
<td>6</td>
<td>0.7</td>
<td>601</td>
</tr>
<tr>
<td>13</td>
<td>0.4</td>
<td>743*</td>
</tr>
<tr>
<td>20</td>
<td>0.7</td>
<td>1500</td>
</tr>
<tr>
<td>36</td>
<td>0.7</td>
<td>1089</td>
</tr>
</tbody>
</table>

* Values include the original catalogue retrieved from Filipović et al. (2002)

4. CONCLUSION

We present a new catalogue of radio-continuum sources towards the SMC, containing sources found at 3 cm and 6 cm.

The 3 cm and 6 cm catalogue, containing 457 and 601 sources respectively, has been created from new high-sensitivity and resolution radio-continuum maps of the SMC from Paper I.

Acknowledgements - The Australia Telescope Compact Array and Parkes radio telescope are parts of the Australia Telescope National Facility which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO. This paper includes archived data obtained through the Australia Telescope Online Archive (http://atoa.atnf.csiro.au). We used the KARMA and MIRIAD software packages developed by the ATNF.

REFERENCES


APPENDIX

Tables A1 and A2 in Appendix are available online at http://saj.matf.bg.ac.rs/184/pdf/Appendix.pdf.

НОВО ПРОУЧАВАЊЕ МАЛОГ МАГЕЛАНОВОГ ОБЛАКА У РАДИО-КОНТИНУУМУ НА 6 И 3 cm: ЂЕО II - КАТАЛОГ ТАЧКАСТИХ ИЗВОРА

G. F. Wong, E. J. Crawford, M. D. Filipović, A. Y. De Horta, N. F. H. Tothill, J. D. Collier, D. Drašković, T. J. Galvin and J. L. Payne

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УДК 52–13–77 : 524.722.7

Стручни чланак

У другом делу ове студије представљамо нове ATCA радио-континум каталоге тачкастих објеката у пољу Малог Магелановог Облака (MMO) на $\lambda=6$ cm ($\nu=4800$ MHz) и $\lambda=3$ cm ($\nu=8640$ MHz). Укупно, у овом новом каталогу представљено је 457 тачкастих објеката детектованих на 3 cm и 601 на 6 cm.
A.2 Co-author

The following is a list of publications which the author has made a significant contribution.

A.2.1 Co-author publication 1


Abstract: We report high resolution observations of the $^{12}$CO(1 → 0) and $^{13}$CO(1 → 0) molecular lines in the Carina Nebula and the Gum 31 region obtained with the 22-m Mopra telescope as part of the The Mopra Southern Galactic Plane CO Survey. We cover 8 deg$^2$ from $l =$ 285$^\circ$ to 290$^\circ$, and from $b =$ −1.5$^\circ$ to +0.5$^\circ$. The molecular gas column density distributions from both tracers have a similar range of values. By fitting a grey-body function to the observed infrared spectral energy distribution from Herschel maps, we derive gas column densities and dust temperatures. The gas column density has values in the range from $6.3 \times 10^{20}$ to $1.4 \times 10^{23}$ cm$^{-2}$, while the dust temperature has values in the range from 17 to 43 K. The gas column density derived from the dust emission is approximately described by a log-normal function for a limited range of column densities. A high-column density tail is clearly evident for the gas column density distribution, which appears to be a common feature in regions with active star formation. There are regional variations in the fraction of the mass recovered by the CO emission lines with respect to the total mass traced by the dust emission. These variations may be related to changes in the radiation field strength, variation of the atomic to molecular gas fraction across the observed region, differences in the CO molecule abundance with respect to H$_2$, and evolutionary stage differences of the molecular clouds that compose the Carina Nebula-Gum 31 complex.

Contribution: The author provided observing support with the Mopra radio telescope, observing ∼30 hours.

A.2.2 Co-author publication 2

Abstract: We present spatially resolved imaging obtained with the Australia Telescope Compact Array (ATCA) of three CO lines in two high-redshift gravitationally lensed dusty star-forming galaxies, discovered by the South Pole Telescope. Strong lensing allows us to probe the structure and dynamics of the molecular gas in these two objects, at \( z = 2.78 \) and \( z = 5.66 \), with effective source-plane resolution of less than 1 kpc. We model the lensed emission from multiple CO transitions and the dust continuum in a consistent manner, finding that the cold molecular gas as traced by low-J CO always has a larger half-light radius than the 870 \( \mu m \) dust continuum emission. This size difference leads to up to 50\% differences in the magnification factor for the cold gas compared to dust. In the \( z = 2.78 \) galaxy, these CO observations confirm that the background source is undergoing a major merger, while the velocity field of the other source is more complex. We use the ATCA CO observations and comparable resolution Atacama Large Millimeter/submillimeter Array dust continuum imaging of the same objects to constrain the CO-H\(_2\) conversion factor with three different procedures, finding good agreement between the methods and values consistent with those found for rapidly star-forming systems. We discuss these galaxies in the context of the star formation gas mass surface density relation, noting that the change in emitting area with observed CO transition must be accounted for when comparing high-redshift galaxies to their lower redshift counterparts.

Contribution: Observational support with the Australia Telescope Compact Array (ATCA) radio telescope observing \( \sim 20 \) hours.

A.2.3 Co-author publication 3


Abstract: We present observations of the first 10\(^\circ\) of longitude in the Mopra CO survey of the southern Galactic plane, covering Galactic longitude \( l = 320-330\(^\circ\) \) and latitude \( b = \pm 0.5\(^\circ\) \), and \( l = 327-330\(^\circ\), b = +0.5-1.0\(^\circ\). These data have been taken at 35-arcsec spatial resolution and 0.1 km s\(^{-1}\) spectral resolution, providing an unprecedented view of the molecular clouds and gas of the southern Galactic plane in the 109-115 GHz J = 1-0 transitions of \(^{12}\)CO, \(^{13}\)CO, C\(^{18}\)O, and C\(^{17}\)O. Together with information about the noise statistics from the Mopra telescope, these data can be retrieved from the Mopra CO website and the CSIRO-ATNF data archive.

Contribution: The author supported this project by providing observing support using the Mopra radio telescope, observing \( \sim 30 \) hours.
A.2.4 Co-author publication 4


Abstract: We examine three supernova remnants in the SMC, IKT 5 (supernova remnant (SNR) 0047-73.5), IKT 25 (SNR 0104-72.3), and DEM S 128 (SNR 0103-72.4), which are designated as Type Ia in the literature due to their spectra and morphology. This is troublesome because of their asymmetry, a trait not usually associated with young Type Ia remnants. We present Chandra X-ray Observatory data on these three remnants and perform a maximum likelihood analysis on their spectra. We find that the X-ray emission is dominated by interactions with the interstellar medium. In spite of this, we find a significant Fe overabundance in all three remnants. Through examination of radio, optical, and infrared data, we conclude that these three remnants are likely not Type Ia SNRs. We detect potential point sources that may be members of the progenitor systems of both DEM S 128 and IKT 5, which could suggest these could be Fe-rich core-collapse remnants.

Contribution: Assisted with radio continuum analysis towards the supernova remnants.

A.2.5 Co-author publication 5


Abstract: Using the new wideband capabilities of the ATCA, we obtain spectra for PKS 1718-649, a well-known gigahertz-peaked spectrum radio source. The observations, between approximately 1 and 10 GHz over 3 epochs spanning approximately 21 months, reveal variability both above the spectral peak at 3 GHz and below the peak. The combination of the low- and high-frequency variability cannot be easily explained using a single absorption mechanism, such as free-free absorption or synchrotron self-absorption. We find that the PKS 1718-649 spectrum and its variability...
are best explained by variations in the free-free optical depth on our line of sight to the radio source at low frequencies (below the spectral peak) and the adiabatic expansion of the radio source itself at high frequencies (above the spectral peak). The optical depth variations are found to be plausible when X-ray continuum absorption variability seen in samples of active galactic nuclei is considered. We find that the cause of the peaked spectrum in PKS 1718-649 is most likely due to free-free absorption. In agreement with previous studies, we find that the spectrum at each epoch of observation is best fit by a free-free absorption model characterized by a power-law distribution of free-free absorbing clouds. This agreement is extended to frequencies below the 1 GHz lower limit of the ATCA by considering new observations with Parkes at 725 MHz and 199 MHz observations with the newly operational Murchison Widefield Array. These lower frequency observations argue against families of absorption models (both free-free and synchrotron self-absorption) that are based on simple homogenous structures.

**Contribution:** Data processing and analysis of ATCA data.

**A.2.6 Co-author publication 6**


We present a detailed study of new Australia Telescope Compact Array and XMM-Newton observations of LHA 120-N 70 (hereafter N 70), a spherically shaped object in the Large Magellanic Cloud, classified as a superbubble. Both archival and new observations were used to produce high quality radio continuum, X-ray, and optical images. The radio spectral index of N 70 is estimated to be \( \alpha = -0.12 \pm 0.06 \), indicating that while a supernova (SN) or supernovae have occurred in the region at some time in the distant past, N 70 is not the remnant of a single specific SN. N 70 exhibits limited polarization with a maximum fractional polarization of 9% in a small area of the northwest limb. We estimate the size of N 70 to have a diameter of 104 pc (±1 pc). The morphology of N 70 in X-rays closely follows that in radio and optical, with most X-ray emission confined within the bright shell seen at longer wavelengths. Purely thermal models adequately fit the soft X-ray spectrum which lacks harder emission (above 1 keV). We also examine the pressure output of N 70 where the values for the hot (\( P_{\text{X}} \)) and warm (\( P_{\text{HII}} \)) phases are consistent with other studied H II regions. However, the dust-processed radiation pressure (\( P_{\text{IR}} \)) is significantly smaller than in any other object studied in Lopez et al. N 70 is a very complex region that is likely to have had multiple factors contributing to both the origin and evolution of the entire region. multi-frequency study was conducted towards the superbubble in the Large Magellanic Cloud (LMC).
Contribution: Author supported this project through data analysis of ATCA data.

A.2.7 Co-author publication 7


Abstract: Context. The XMM-Newton survey of the Small Magellanic Cloud (SMC) revealed 3053 X-ray sources with the majority expected to be active galactic nuclei (AGN) behind the SMC. However, the high stellar density in this field often does not allow assigning unique optical counterparts and hinders source classification. On the other hand, the association of X-ray point sources with radio emission can be used to select background AGN with high confidence, and to constrain other object classes like pulsar wind nebula. Aims: To classify X-ray and radio sources, we use clear correlations of X-ray sources found in the XMM-Newton survey with radio-continuum sources detected with ATCA and MOST. Methods: Deep radio-continuum images were searched for correlations with X-ray sources of the XMM-Newton SMC-survey point-source catalogue as well as galaxy clusters seen with extended X-ray emission. Results: Eighty eight discrete radio sources were found in common with the X-ray point-source catalogue in addition to six correlations with extended X-ray sources. One source is identified as a Galactic star and eight as galaxies. Eight radio sources likely originate in AGN that are associated with clusters of galaxies seen in X-rays. One source is a pulsar wind nebula candidate. We obtain 43 new candidates for background sources located behind the SMC. A total of 24 X-ray sources show jet-like radio structures.

Based on observations obtained with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and NASA.

Contribution: The author contributed with the analysis of the point sources, comparing the radio continuum point sources found within the 20-cm radio continuum maps.

A.2.8 Co-author publication 8

**Abstract:** It is thought that neutron stars in low-mass binary systems can accrete matter and angular momentum from the companion star and be spun-up to millisecond rotational periods. During the accretion stage, the system is called a low-mass X-ray binary, and bright X-ray emission is observed. When the rate of mass transfer decreases in the later evolutionary stages, these binaries host a radio millisecond pulsar whose emission is powered by the neutron star’s rotating magnetic field. This evolutionary model is supported by the detection of millisecond X-ray pulsations from several accreting neutron stars and also by the evidence for a past accretion disc in a rotation-powered millisecond pulsar. It has been proposed that a rotation-powered pulsar may temporarily switch on during periods of low mass inflow in some such systems. Only indirect evidence for this transition has hitherto been observed. Here we report observations of accretion-powered, millisecond X-ray pulsations from a neutron star previously seen as a rotation-powered radio pulsar. Within a few days after a month-long X-ray outburst, radio pulses were again detected. This not only shows the evolutionary link between accretion and rotation-powered millisecond pulsars, but also that some systems can swing between the two states on very short timescales.

**Contribution:** Conducted the observation, data reduction, preliminary data analysis of ATCA data towards the source IGR J18245-2452. See below for astronomer’s telegram that was released prior to this work being published.


**Abstract:** The new INTEGRAL transient source IGR J18245-2452 (ATel #4925 #4927 #4929 #4934 #4959 #4960 #4961 #4964) was observed with the radio Australia Telescope Compact Array on 2013-04-05 for a total of 6 hours. The array was in H214 configuration. The observation was performed at two different frequencies: 9 and 5.5 GHz.

**Contribution:** As described above, observation, data reduction, preliminary data analysis of ATCA data towards the source IGR J18245-2452 was conducted by the author.
A.2.9 Co-author publication 9


Abstract: A series of new radio-continuum ($\lambda=20, 13, 6$ and 3 cm) mosaic images focused on the NGC 55 galactic system were produced using archived observational data from the Australia Telescope Compact Array. These new images are both very sensitive (down to $\text{rms}=33 \mu\text{Jy}$) and feature high angular resolution (down to $<4''$). Using these newly created images, 66 previously unidentified discrete sources are identified. Of these sources, 46 were classified as background sources, 11 as H ii regions and 6 as supernova remnant candidates. This relatively low number of SNR candidates detected coupled with the low number of large H ii regions is consistent with the estimated low star formation rate of the galaxy at 0.06 $\text{M}_\odot\text{ year}^{-1}$. Our spectral index map shows that the core of galaxy appears to have a shallow spectral index between $-0.2$ and $-0.4$. This indicates that the core of the galaxy is a region of high thermal radiation output. Maps and analysis of NGC 55 was presented.

Contribution: The author provided assistance with data processing and analysis of the ATCA archived continuum data.

A.2.10 Co-author publication 10


Abstract: We present new observations of 34 young stellar object (YSO) candidates in the Small Magellanic Cloud (SMC). The photometric selection required sources to be bright at 24 and 70 $\mu\text{m}$ (to exclude evolved stars and galaxies). The anchor of the analysis is a set of Spitzer Infrared Spectrograph (IRS) spectra, supplemented by ground-based 3-5 $\mu\text{m}$ spectra, Spitzer Infrared Array Camera and Multiband Imaging Photometer for Spitzer photometry, near-infrared (IR) imaging and photometry, optical spectroscopy and radio data. The sources’ spectral energy distributions and spectral indices are consistent with embedded YSOs; prominent silicate absorption is observed in the spectra of at least 10 sources, silicate emission is observed towards four sources. Polycyclic aromatic hydrocarbon (PAH) emission is detected towards all but two sources. Based on band ratios (in particular the strength of the 11.3-$\mu\text{m}$ and
the weakness of the 8.6-µm bands) PAH emission towards SMC YSOs is dominated by predominantly small neutral grains. Ice absorption is observed towards 14 sources in the SMC. The comparison of H2O and CO2 ice column densities for SMC, Large Magellanic Cloud and Galactic samples suggests that there is a significant H2O column density threshold for the detection of CO2 ice. This supports the scenario proposed by Oliveira et al., where the reduced shielding in metal-poor environments depletes the H2O column density in the outer regions of the YSO envelopes. No CO ice is detected towards the SMC sources. Emission due to pure rotational 0-0 transitions of molecular hydrogen is detected towards the majority of SMC sources, allowing us to estimate rotational temperatures and H2 column densities. All but one source are spectroscopically confirmed as SMC YSOs. Based on the presence of ice absorption, silicate emission or absorption and PAH emission, the sources are classified and placed in an evolutionary sequence. Of the 33 YSOs identified in the SMC, 30 sources populate different stages of massive stellar evolution. The presence of ice- and/or silicate-absorption features indicates sources in the early embedded stages; as a source evolves, a compact H ii region starts to emerge, and at the later stages the source’s IR spectrum is completely dominated by PAH and fine-structure emission. The remaining three sources are classified as intermediate-mass YSOs with a thick dusty disc and a tenuous envelope still present. We propose one of the SMC sources is a D-type symbiotic system, based on the presence of Raman, H and He emission lines in the optical spectrum, and silicate emission in the IRS spectrum. This would be the first dust-rich symbiotic system identified in the SMC. Candidate Young Stellar Objects towards the SMC was presented and analysed.

**Contribution:** Using 20-cm catalogue, the author provided continuum analysis towards selected sources of towards the Small Magellanic Cloud.

### A.2.11 Co-author publication 11


**Abstract:** A series of new radio-continuum (λ=20 cm) mosaic images focused on the NGC 300 galactic system were produced using archived observational data from the VLA and/or ATCA. These new images are both very sensitive (rms =60 µJy) and feature high angular resolution (<10 ). The most prominent new feature is the galaxy’s extended radio-continuum emission, which does not match its optical appearance. Using these newly created images a number of previously unidentified discrete sources have been discovered. Furthermore, we demonstrate that a joint deconvolution approach to imaging this complete data-set is inferior when compared to an immerge approach.
Contribution: The author contributed with the data reduction of the achieved dataset.

A.2.12 Co-author publication 12


Abstract: We present a series of new high-sensitivity and high-resolution radio-continuum images of M31 at $\lambda=20$ cm ($\nu=1.4$ GHz). These new images were produced by merging archived 20 cm radio-continuum observations from the Very Large Array (VLA) telescope. Images presented here are sensitive to rms=60 $\mu$Jy and feature high angular resolution ($<10$ arcsec). A complete sample of discrete radio sources have been catalogued and analysed across 17 individual VLA projects. We identified a total of 864 unique discrete radio sources across the field of M31. One of the most prominent regions in M31 is the ring feature for which we estimated total integrated flux of 706 mJy at $\lambda=20$ cm. We compare here detected sources to those listed in Gelfand et al. (2004) at $\lambda=92$ cm and find 118 sources in common to both surveys. The majority (61%) of these sources exhibit a spectral index of $\alpha<-0.6$ indicating that their emission is predominantly non-thermal in nature, that is more typical for background objects.

Contribution: The author assisted with the data reduction and analysis of the radio continuum data.
Appendix B

Data Reduction

The following sections, present the data reduction code used as part of this work.

B.1 Coadding reference spectrum

For cases when the reference position of the on-the-fly (OTF) map has been observed has part of position-switching observations, COADD_REF.PY will add the reference spectra back into the data cube. This script will require a fits file data cube and reference scan in a text file format which has been exported from casa/asap. Spectrum within the data cube can be compared to the reference spectra and the newly processed coadded spectra. This was used as part of the Chamaeleon molecular cloud data processing, see section 2.2.3 for details.

```python
# Purpose: Co-add reference spectra in to map
# Author: G. Wong
# Date: 11.9.15
# Note: The reference scan would have already been processed, this script will
# align the spectra then co-add (add spectra in to the relavent channels)
import scipy
from astropy.io import fits
import matplotlib as mpl
import matplotlib.pyplot as plt
import astropy
import numpy as np
import math
mpl.rcParams['figure.figsize'] = 14, 7 # sort out the canvas size
import sys
import os.path
from matplotlib.ticker import AutoMinorLocator
# For monitoring purposes
def refresh_output():
```

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sys.stdout.write('')
sys.stdout.flush()

# Give an array and the value get the index
def find_nearest(array, value):
    idx = (np.abs(array - value)).argmin()
    return idx

# Import the reference scan (exported CASA text file)
def ref_data(filename = 'unknown.txt'):
    if filename == 'unknown.txt':
        print('Error: Check name of file name')
        return
    else:
        f = file(filename, 'r')
        x = []
        y = []
        lines = f.readlines()
        f.close()
        for l in lines:
            if not l.startswith('#'):
                vals = l.split()
                x.append(float(vals[0]))
                y.append(float(vals[1]))
        return x, y

# Plot spectra, reference spectra, and spectra that has been coadded for a single position
# Coadd the reference spectra (at a range) to the source spectra
# specify a x,y coordinates
def plotsrc(XsrcSpectra, YsrcSpectra, rIdx, hdu=[], rVelo=[], rAmp=[], scrVelo=[], show=True, saveFile='coadd_spectra.pdf'):
    amp_counter = rIdx  # start counter for reference channel
    new_spectra = []  # coadded spectra
    src_amp = hdu.data[:, YsrcSpectra, XsrcSpectra]
    for chan in src_amp:
        new_spectra.append(chan + rAmp[amp_counter])
        amp_counter = amp_counter + 1
    print('Coadding completed for single spectra')
    plt.clf()
    fig, (ax1, ax2, ax3, ax4) = plt.subplots(4, sharex=True, sharey=True)
    ax1.plot(scrVelo, hdu.data[:, YsrcSpectra, XsrcSpectra], drawstyle='steps-mid', color='red')  # original spectra
    ax2.plot(rVelo, rAmp, drawstyle='steps-mid', color='blue')  # reference spectra
    ax3.plot(scrVelo, new_spectra, drawstyle='steps-mid', color='green')  # modified spectra
# overlay all three
ax4.plot(scrVelo, hdu.data[:,YsrcSpectra,XsrcSpectra], drawstyle =
    'steps-mid', color='red', label='original') # original spectra
ax4.plot(rVelo, rAmp, drawstyle = 'steps-mid', color='blue',
    label='Reference') # overlay the reference spectra
ax4.plot(scrVelo, new_spectra, drawstyle = 'steps-mid', color='green',
    label='Coadded') # modified spectra
plt.legend(loc='upper center', ncol=3, bbox_to_anchor=[0.5, 4.3],
    borderaxespad=0.25)
plt.xlim(scrVelo[0],scrVelo[-1])
# Fine-tune figure; make subplots close to each other and hide x ticks for
# all but bottom plot.
fig.subplots_adjust(hspace=0)
plt.setp([a.get_xticklabels() for a in fig.axes[:-1]], visible=False)
minorLocator = AutoMinorLocator()
ax4.xaxis.set_minor_locator(minorLocator)
fig.text(0.5, 0.02, r"Velocity km$^{-1}$ (LSRK)", ha='center')
fig.text(0.07, 0.5, r"Brightness Temperature (K)", va='center',
    rotation='vertical')
if show == True:
    plt.show()
else:
    plt.savefig(saveFile)

########################################################
# loop through the data cube before processing
def coadd_spectra(rIdx, hdu = [], rAmp = []):
    print 'Array shape: X=%i Y=%i Z=%i' % (hdu.data.shape[2],
        hdu.data.shape[1], hdu.data.shape[0])
    y_count = 0
    for y in range(hdu.data.shape[1]):
        x_count = 0
        for x in range(hdu.data.shape[2]):
            x=float(hdu.data[12,y_count,x_count]) # select a slice in the spectra to
            check
            if math.isnan(x) == False: # is there any spectra in the position
                # Coadd the reference spectra (at a range) to the source spectra
                amp_counter = rIdx # start counter for reference channel
                new_spectra = [] # coadded spectra
                src_amp = hdu.data[:,y_count,x_count] # Save the spectra into variable
                for chan in src_amp:
                    new_spectra.append(chan + rAmp[amp_counter])
                    amp_counter = amp_counter + 1
                hdu.data[:,y_count,x_count] = new_spectra # modified spectra is written
                in to file
                status = 'Pixel X:%i, Y:%i' % (x_count, y_count)
                sys.stdout.write(status)
                sys.stdout.flush()
refresh_output()
x_count = x_count + 1
y_count = y_count + 1
print 'Coadding completed pixels X:%i Y:%i' % (x_count, y_count)
scr_data.writeto(output_data)  # Save to a new file
print 'File written: %s' % (output_data)

# Generate the list of velocities
def gen_srcVelo(hdu=[]):
    init_chan = -hdu.header['CRPIX3']
counter = 0
velo = []
for i in range(hdu.header['NAXIS3']):
    init_chan = init_chan + 1
    velo_chan = (init_chan * hdu.header['CDELT3'])/1000
    velo.append(velo_chan)
counter = counter + 1
return velo

# Check if the file exist
def file_checker(fName):
    flag = 0
    if os.path.isfile(fName) == True:
        print 'Valid filepath: %s' % (fName)
        flag = 0
    else:
        print 'Error: unknown file %s' % (fName)
        flag = 1
return flag

# Main section inputs
refFile = 'cham_ref5_12CO_1.txt'
sourceCube = '12CO_03_30_d1_v2_gridz_MEAN.fits'
output_data = '12CO_03_30_d1_v2_gridz_MEAN_test.fits'

# Check if the file exist
if (file_checker(refFile) == 0) and (file_checker(sourceCube) == 0):
    ref_velo, ref_amp = ref_data(filename = refFile)  # import the reference spectra
    scr_data = fits.open(sourceCube)
data = scr_data[0]
velo = gen_srcVelo(hdu = data)  # generate the velocity list
ref_array = np.asarray(ref_velo)
ref_index = find_nearest(ref_array, velo[0])  # index to start with in the ref scan

B.2 NANTEN2

The following document was presented as a tutorial for the NANTEN2 workshop at the then University of Western Sydney. This documentation provides an introduction to processing NANTEN2 data through the Continuum and Line Analysis Single-dish Software (CLASS) package within Grenoble Image and Line Data Analysis Software (GILDAS). The script used to process the data from NANTEN2, written by Dr. C. Buckbender and the author, is presented after the introduction tutorial. A description of the code is discussed in section 3.2.3.
1 Introduction

CLASS is part of the GILADS software package used for reducing spectroscopic data. GILDAS is mostly written in Fortran 90/95 with the other part being in C/C++ (used for keyboard interaction and plotting). Compared to other data reduction/processing software, CLASS is capable of selection criteria which is similar to a database management system. This allows easy manipulation of large datasets like those present from Nanten2 e.g. instead of manually creating a list of observations which you need to manipulate you just need to create a criteria and let the software find the observations.

This tutorial will describe the basic method of data processing for Nanten2 data. The data we will use in this tutorial is CI 1-0 observations towards Carina. We have problems with one of the beams, we will need to correct this problem. From the collection of data we will need to extract a few days.

- Load data
- Selecting the data
- View spectra
- Baseline and continuum subtraction
- Smoothing and Birdies
- Imaging
- Exporting to FITS
Once you have installed GILDAS you can start Class from the command line, you should normally only have to type ‘class’ and press Enter.

**TYPE** ! *get the history of the commands entered*

## 2 Load Data

The experiment we are interested in is within a single KOSMA file. We use the `CLASS` command `FILE IN` followed by `FIND` (see below).

```
FILE IN  CARINA-CNTR-CI_3P1–3P0_0002_missingSep13.kosma
FIND
LIST
```

This will select the file to open (`FILE IN`) and build a new index (`FIND`). The `LIST` command is used to display the observation information.

There are other options which will allow you to display the observation information in different formats. The following is just table demonstrates the different options for `LIST` and Fig. 1 shows an output from `LIST /TOC`.

## 3 Selecting the Data

The files from the telescope contain information of spectral lines observed, days observed, therefore selecting the information becomes important. Using the command `SET` and an additional keyword you can select data which you need. The following selects all scans according to the specified source name e.g. CARINA-CNTR (name used in the `IN_PAR` file). Once you have selected the data you want you will need to build a new index using the command `FIND`. Using the command `LOAD` conducts consistency checks, which then
Figure 1: Output from the CLASS command LIST /TOC, listing all of the observations contained in the file.

```
LA590> list /toc
Current index contains:
Number of sources...... 2
  TREC (SSB)     96 ( 2.3%)
  CARINA_CNTR 4800 ( 97.7%)
Number of lines........ 1
  CI_3P1-3P0    4806 (100.0%)
Number of backends..... 8
  NANTEN2-N00  512 ( 12.5%)
  NANTEN2-N01  512 ( 12.5%)
  NANTEN2-N02  512 ( 12.5%)
  NANTEN2-N03  512 ( 12.5%)
  NANTEN2-N04  512 ( 12.5%)
  NANTEN2-N05  512 ( 12.5%)
  NANTEN2-N06  512 ( 12.5%)
  NANTEN2-N07  512 ( 12.5%)
Number of setups....... 16
  TREC (SSB)   CI_3P1-3P0 NANTEN2-N00  12 ( 0.3%)
  TREC (SSB)   CI_3P1-3P0 NANTEN2-N01  12 ( 0.3%)
  TREC (SSB)   CI_3P1-3P0 NANTEN2-N02  12 ( 0.3%)
  TREC (SSB)   CI_3P1-3P0 NANTEN2-N03  12 ( 0.3%)
  TREC (SSB)   CI_3P1-3P0 NANTEN2-N04  12 ( 0.3%)
  TREC (SSB)   CI_3P1-3P0 NANTEN2-N05  12 ( 0.3%)
  TREC (SSB)   CI_3P1-3P0 NANTEN2-N06  12 ( 0.3%)
  TREC (SSB)   CI_3P1-3P0 NANTEN2-N07  12 ( 0.3%)
  CARINA_CNTR CI_3P1-3P0 NANTEN2-N00  500 (12.2%)
  CARINA_CNTR CI_3P1-3P0 NANTEN2-N01  500 (12.2%)
  CARINA_CNTR CI_3P1-3P0 NANTEN2-N02  500 (12.2%)
  CARINA_CNTR CI_3P1-3P0 NANTEN2-N03  500 (12.2%)
  CARINA_CNTR CI_3P1-3P0 NANTEN2-N04  500 (12.2%)
  CARINA_CNTR CI_3P1-3P0 NANTEN2-N05  500 (12.2%)
  CARINA_CNTR CI_3P1-3P0 NANTEN2-N06  500 (12.2%)
  CARINA_CNTR CI_3P1-3P0 NANTEN2-N07  500 (12.2%)
```

Figure 1: Output from the CLASS command LIST /TOC, listing all of the observations contained in the file.
allows you to use options like go where (shows where the pointings are located). An example of the output from go WHERE is seen in Fig. 2.

\begin{verbatim}
SET SOURCE CARINA_CNTR  ! Select source name
FIND                   ! build new index, based on criteria
LOAD
GO WHERE
\end{verbatim}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{output.png}
\caption{Output from the CLASS command \texttt{go where}, demonstrating the position of the pointings in respect to the centre offset.}
\end{figure}

4 View Spectra

After you have imported and selected the data which you need, you can then start to look at the data which is done as follows.

\begin{verbatim}
SET UNIT V F  ! velocity and frequency
SET MODE X -50 50
SET MODE Y -50 50
GET FIRST ! get the first spectra
PLOT ! plot spectra
\end{verbatim}

The \texttt{set unit} command sets the unit of the x axis on the bottom and top of the plot, other option is channel. \texttt{set mode} specifies the range of the
plot in either the x or y axis. GET FIRST retrieves the first spectra in the list. Finally PLOT images the spectra (see Fig. 3).

Alternatively, you can interactively select the range by typing SET MODE X or SET MODE Y then type PLOT.

If you need to iterate to the next spectra and so forth you type GET NEXT which retrieves the spectra in the list (see Fig. 4).

GET NEXT! get the first spectra
PLOT ! plot spectra

Figure 3: The plot from the GET FIRST and PLOT command.
If you would like to view the entire data set in one go is to use the following (it would be ideal to set the units and range first if you had not done so already).

```
PLOT /INDEX
```

This allows you to view a scan vs velocity with colour bar on the side to show the amplitude (see Fig. 5).
5 Baseline Subtraction

Although the data from Nanten2 is already calibrated the spectrum baseline is not perfect. One example is the baseline which will probably have the continuum contaminating the spectra. The following section of code demonstrates how to apply a low order polynomial to the spectrum.

| SET WINDOW -40 0 35 40 |
| DRAW WINDOW |
| ! baseline data |
| FILE OUT Carina_CI_2013_v1 single / overwrite |
| GET ZERO |
| FOR i 1 TO FOUND |
| GET NEXT |
| BASE 5 |
| WRITE |
SET WINDOW and DRAW WINDOW creates a mask to ignore the baseline subtraction to apply and display the mask on the plot. You would have identified the appropriate windows to mask when previewing the spectra in the previous step. By creating a new file you can directly write the new spectra to the file. Creating a loop, apply a 5th order polynomial to the spectra and save it to the newly created file.

You can see the changes by importing the file created into CLASS. I have used PLOT /INDEX to view the dataset.

FILE IN Carina_CI_2013_v1
FIND
LOAD
PLOT /INDEX

Figure 6: Scan vs velocity plot of the data after the data had baseline subtraction applied to it.
Figure 7: Zoomed in (set mode y -15 15) scan vs velocity plot of the data after the data had baseline subtraction applied to it.
6 Smoothing and Birdies

Sometimes your spectra will be contaminated by birdies or will need to smooth the spectra. This section demonstrates how to remove birdies by using the command `fill` and smooth the spectra. In this case we have used smooth three times which is similar to hanning 3.

```
FILE OUT Carina_CI_2013_v1_despike single /overwrite
FIND
FOR i 1 TO FOUND
  GET NEXT
  FILL 13 23 35 40 /NOISE
  SMOOTH
  SMOOTH
  SMOOTH
  WRITE
NEXT i
```

Figure 8: Scan vs velocity plot of the data after being despiked and smoothed. You can start to see emission around -10 to -30 km/s.
7 Imaging

Once the baseline subtraction and removal of birdies have been applied, imaging can begin. GILDAS does not have information on the Nanten2 telescope (i.e. diameter size, location, etc). Therefore you will need to specify the diameter of the telescope through the command LET MAP%diam 4. The following opens the previous file which had been despiked and creates an image. This section of code also includes the command HARD, used for saving the current plot as a colour page in eps file format.

```plaintext
FILE IN Carina_CI_2013_v1_despike
FIND
LOAD
PLOT /INDEX
HARD carina_CI_2013_rms_woSpike. eps /FITPAGE EPS COLOR

! Create image
LET map%diam 4
TABLE Carina_CI_2013_new /range 50 0 v
XYMAP Carina_CI_2013

LET NAME Carina_CI_2013
LET TYPE lmv
GO VIEW
```

There are other options which can view the data (see Fig. 10).
Figure 9: GO VIEW image.

Figure 10: Screen shot of the input options for viewing the spectra in different forms.

**INPUT & GO possibilities:**

**Commands for multichannel viewing:**
- **VIEW** interactive viewing of spectra data cube
- **3VIEW** interactive viewing of position/velocity diagrams
- **BIT** plot a color map of all or selected channels
- **MAP** plot a contour map of all or selected channels
- **XV** plot x-axis/velocity diagrams
- **YY** plot velocity/y-axis diagrams
- **SPECTRE** plot spectra from a data cube
- **VELOCITY** plot mean, velocity and width maps
- **OVER** Overlay bitmaps and contours of several images
- **COLOR, LUT** Fiddle Color Table

**Commands for analysis**
- **NOISE** Compute noise histogram of data cubes
- **MOMENT** Compute mean, velocity and width maps

**Commands for interaction with CLASS data:**
- **CLASS-CONVERT** conversion from old to new ODF data format
- **EXPLORE** interactive exploration of large data sets

Type: **INPUT command-name** for further information on a command
Type: **GO command-name** to execute a command
8 Exporting to FITS

Using the fits you can export your lmv image to a FITS file. This is done as the following:

\[ \text{VECTOR\ FITS EXPORT\_FILENAME. fits from FILENAME. lmv} \]

Where export\_FILENAME is the name of the export fits file and FILENAME is the name of lmv file created in the previous step. You should note there is another fits task in LAS module, this is will not export your image to a fits file.

9 Close session

Once you have finished you can just type exit to close the session. If you want to save some of the parameters defined by the set commands use save, which saves the commands to a file. You can import the parameters by typing @ FILENAME where filename is the name of your choosing, which will hopefully save you retyping these commands.

And with that data processing nanten2 data made simple ... kinda, good luck!
A Complete Code

The following is the code shown in previous chapters compiled together.

```
!# # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # #
! Purpose: Basic steps for processing Nanten2 data
! Developed on:
! − GILDAS Version: sep13a (01sep13 09:40 cest)
! Authors: G. Wong
! Date: 19.01.15
! Update: 6.2.15
!# # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # #
```

```
FILE IN   CARINA_CNTR–CI_3P1–3P0_0002_missingSep13.kosma
SET SOURCE CARINA_CNTR
FIND
LIST /TOC OBS SCAN
LOAD
SET PLOT HISTOGRAM
SET FORMAT LONG
SET UNIT V F
SET MODE X −50 50
SET MODE Y −50 50

GET FIRST
PLOT
PLOT /INDEX
SET WINDOW −40 0 35 40
DRAW WINDOW

! baseline data
FILE OUT Carina_CI_2013_v1 single /overwrite
GET ZERO
FOR i 1 TO FOUND
    GET NEXT
    BASE 5
    WRITE
NEXT i
```
! remove birdies

FILE IN Carina_CI_2013_v1
FIND
LIST /TOC OBS SCAN
LOAD
PLOT /INDEX

FILE OUT Carina_CI_2013_v1_despike single /overwrite
FIND
FOR i 1 TO FOUND
  GET NEXT
  FILL 13 23 35 40 /NOISE
  SMOOTH
  SMOOTH
  SMOOTH
  WRITE
NEXT i

! image data

FILE IN Carina_CI_2013_v1_despike
FIND
LOAD
PLOT /INDEX

LET map%diam 4
TABLE Carina_CI_2013 new /range -50 0 v
XY_MAP Carina_CI_2013

LET NAME Carina_CI_2013
LET TYPE lmv
GO VIEW
! export data
VECTOR\FITS Carina_CI.fits FROM Carina_CI_2013.lmv
!! Purpose: Main file for processing script for reducing and imaging NANTEN2 data.
!! Designed to be flexible for all projects
!!
!! Developed on: GILDAS Version: sep13a (01sep13 09:40 cest)
!!
!! Authors: C. Buckbender, G. Wong
!! Date: 15.09.14
!!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
! name checks and define global parameters
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
symbol silent "sic message class s-i"
symbol verbose "sic message class s+i"

! global file input
if .not.exist(global_in_fName) then
  def char global_in_fName*100 /global
endif

! global file output for rms eps file
if .not.exist(global_rms_plt_name) then
  def char global_rms_plt_name*100 /global
endif

! global file output
if .not.exist(global_out_fName) then
  def char global_out_fName*100 /global
endif

! source name
if .not.exist(global_src_name) then
  def char global_src_name*100 /global
endif

if .not.exist(global_src_velocity) then
  def real global_src_velocity /global
endif

if .not.exist(global_src_velocity) then
  def real global_src_velocity /global
endif

if .not.exist(global_frequency) then

def real global_frequency /global 
endif 
if .not.exist(global_frequency_resolution) then 
def real global_frequency_resolution /global 
endif 
if .not.exist(global_frequency_range) then 
def real global_frequency_range /global 
endif 
! start of the scan number 
if .not.exist(global_s_ScanNo) then 
def int global_s_ScanNo /global 
endif 
! global array for msk window 
if .not.exist(global_msk_win) then 
endif 
! global array for spectral window 
if .not.exist(global_frequency_range) then 
def real global_frequency_range /global 
endif 
if .not.exist(count) then 
def int count /global 
let count 0 
endif 
! functions (procedures) 
!############################################################################## 
! import the files into class 
begin procedure import 
message i import "##### Importing data" 
ON ERROR @recover 
set line CO_4-3 
set source 'global_src_name' 
set unit v 
sic mkdir "tmp/"'global_out_fName' ! sic cmd to create folder 
file in 'global_in_fName' ! input file 
file out "tmp/"'global_out_fName'/step1" single /overwrite ! create tmp 
foldar and attached /step1 
find /source 'global_src_name' /line CO_4-3 !/scan 'g_s_ScanNo' * 
list /toc obs scan ! temp log to keep track of things /dev 
set unit c
get f
extract 0 'channels' /index  ! only get channels with real data
set unit f
message i import "##### Importing data - completed"
end procedure import
!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
begin procedure modify
! Modify header parameters to useful values (position, velocity,
! frequency, beam efficiency) -> step'&1'.30m
! No input parameter
@ file_in_out '&1'
silent
for ient 1 to found
  get next
  modify freq 'global_frequency'
  modify velo 'global_src_velocity'
  write
next ient
verbose
end procedure modify
!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
begin procedure resample
! resample the spectra
message i resample "##### resample - start"
@file_in_out '&1'
find
def real new_bandwidth
def real new_central_channel
let new_bandwidth 'global_frequency_range/global_frequency_resolution'
let new_central_channel 'new_bandwidth/2'
exa new_bandwidth
exa new_central_channel
exa global_frequency
exa global_frequency_resolution
for i 1 to found
  get next
  resample 'new_bandwidth' 'new_central_channel' 'global_frequency'
    'global_frequency_resolution' f
  write
next i
message i resample "##### resample - completed"
end procedure resample
!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
begin procedure file_in_out
!
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say "file in out - start"
def int next_step this_step
let this_step '&1'
let next_step 'this_step+1'
file in "tmp/"'global_out_fName'"/step"'this_step'
file out "tmp/"'global_out_fName'"/step"'next_step' single /overwrite
find
say "file in out - Finished"
!
end procedure file_in_out
!
!##############################################################################
begin procedure file_in
!
if '&1'.eq.0 then
    file in 'global_in_fName' ! input file
else
    file in "tmp/"'global_out_fName'"/step"&1'
endif
find
!
end procedure file_in
!
!##############################################################################
begin procedure recover
!
let count 'count+1'
ignore number
next
!
end procedure recover
!
!##############################################################################
begin procedure despike
!
ON ERROR @recover
message i despike "##### despike - start"
@file_in_out '&1'
def real rms
for i 1 to found
    get n
    base 0
    let rms sigma
    swap
    set unit c
    fill 16382 16388 26185 26195 /noise 'rms' /inter ! select channel range
    set unit v
write
next
message i despike "##### despike - complete"
ON ERROR pause
end procedure despike
!
! baseline for the dataset requires 2 parameters, file name and baseline
poly
begin procedure base
ON ERROR @recover
message i base "##### base - start"
set unit v
@file_in_out '&1'
find
list /toc
@average '&1' ! the 1 is the parameter of the file step e.g. 1 for /step1
pen 1
draw window
pen 0
silent ! symbol: see below
get zero ! reset counter
for i 1 to found
get next
base '&2'
write
next i
verbose ! symbol: see below
set unit f
message i base "##### base - completed"
end procedure base
!
! average the entire image to create a single spectrum; requires a parameter
(no of file)
begin procedure average
!
@file_in_out '&1'
message i average "##### average task - start"
find
!average /2010 /nomatch !/noc pos !/resample
average /nocheck position
plot
message i average "##### average task - completed"
!
end procedure average

! Using the same method we can remove the birdies (internal RFI) by
  'despiking'

begin procedure fill

  ON ERROR @recover
  set unit v
  @file_in_out '&1'
  find
  for i 1 to found
    get next
    base 0
    fill -60 -52 5 8 /noise sigma ! File contaminated channels with Gaussian
      noise
    write
    next i
  verbose
  set unit f
end procedure fill

! plot the index of the scans

begin procedure plt_index

! create a plot of the entire dataset
  file in "tmp/"'global_out_fName'"/step'&1'
  find
  load
  plot /index
  set mode y -5 5
end procedure plt_index

begin procedure rms_plt

! modified from
  http://www.iram.es/IRAMES/events/summerschool2013/presentations
  message i rms-plt "##### rms-plt - start"
  @file_in_out '&1'
  find
  get zero
  silent
  for i 1 to found
    get next
base '&2'
let idx%sig[i] sigma
write next i verbose
clear g\limit /var idx%num idx%sig
g\box g\set marker 4 3 0.15 ! how do you want your marker to look like
g\point idx%num idx%sig
g\label "Observation scan number" /X
g\label "RMS [K]" /Y
hard 'global_rms_plt_name'"_rms_plt.eps" /fitpage eps color /overwrite
message i rms-plt "##### rms-plt - completed"
!
end procedure rms_plt
!
!##############################################################################
! create the image, requires three parameters for the name of the step and
! velocity range
!
begin procedure image
!
message i image "##### image - start"
set unit v
@file_in_out '&1'
! set the telescope and beam size of the observations,
! Gildas does not recognise NANTEN2 and its beams.
let map%diam 4
let map%beam 24 ! don't hardcode this, calculate from frequency
!
! Put the current data into a table data format, build the non-gridded table
def int next_step
let next_step '&1+1'
table "tmp/"'global_out_fName'"/step'"next_step' new
xy_map "tmp/"'global_out_fName'"/step'"next_step' ! Grid the data from
! the table
!
! view the cube
let name "tmp/"'global_out_fName'"/step'"next_step' ! name of file
let type lmv ! Same as above, this is asking for the file type
!go view ! view will display, shows integrated intensity map, cube
! and spectra at selected point
hard 'global_rms_plt_name'"_image.eps" /fitpage eps color /overwrite
set unit f
message i image "##### image - completed"
end procedure image
!
##############################################################################
!
begin procedure view_image
!
message i view_image "##### view_image - completed"
let name "tmp/"'global_out_fName'"/step"'&1" ! name of file
let type lmv ! Same as above, this is asking for the file type
go view ! view will display, shows integrated intensity map, cube

    ↦ and spectra at selected point
hard 'global_rms_plt_name"_image.eps" /fitpage eps color /overwrite
set unit f
message i view_image "##### view_image - completed"
!
end procedure view_image
!
##############################################################################
!
begin procedure spectra_extract
!
extract spectra from an image
@file_in_out '&1'
lmv "tmp/"'global_out_fName'"/step"'&1"'.lmv"
!
end procedure spectra_extract
!
begin procedure despike_new
@file_in_out '&1'
def int tolerance
def int maximum_joint_spikes
let tolerance '&2'
let maximum_joint_spikes '&3'
for i 1 to found
    get n
    @despike_standalone 'tolerance' 'maximum_joint_spikes'
write
next
end procedure despike_new
!
begin procedure make_noise
    define real ty /like ry
    if exist(noise_value) then
delete /var noise_value
endif
    define real noise_value /like ry /global

let ty ry
noise '&1' new
let noise_value ry
let ry ty
end procedure make_noise

! ##############################################################################
begin procedure despike_standalone
!
ON ERROR @recover
def real local_mean
def int tolerance count skip x idx
def int maximum_joint_spikes
def int kernel start end
let kernel 10
let tolerance '&1'
let maximum_joint_spikes '&2'
if .not.exist(spikes) then
def int three_sigma spikes spike_check /like ry
endif
if .not.exist(average) then
def real average /like ry
endif
let spikes 0
base 0
!
let three_sigma 1 /where (ry.gt.'3*sigma').or.(ry.lt.'-3*sigma')
!
Check which channels are above the given tolerance
let spikes 1 /where (ry.gt.'tolerance*sigma').or.(ry.lt.'-1*tolerance*sigma')
let spike_check spikes
!
This loop does the following:
!
First computing an array of ry length with the average values of the in a
!
2*kernel window around the individual channels. It calculates the number of
!
adjacent channels above the tolerance and writes a new array that replaces
!
the 1 by the number of adjacent channels above the tolerance. This allows to
!
exclude broad features that are not considered spikes
define real sum
compute sum SUM spikes
!
if sum.ne.0 then
let skip 0
for i 1 to channels
let count 0
!
Skipping is needed for the counting of adjacent channels
!
Adjacent channels are set at once
!
if skip.ne.0 then
let skip 'skip-1'
! Make sure the averaging does not run into out of bounds
! at the edge of the bandwidth
else if skip.eq.0 then
  if i.lt.'kernel+1' then
    let start 1
    let end 'i+kernel'
  else if i.gt.'channels-kernel-1' then
    let start 'i-kernel'
    let end channels
  else
    let end 'i+kernel'
    let start 'i-kernel'
  endif
  if spikes[i].eq.0 then
    if exist(avg) then
      del /var avg
    endif
    if exist(loc_spikes) then
      del /var loc_spikes
    endif
    define real avg loc_spikes /like ry[start:end]
    let loc_spikes spikes[start:end]
    let avg ry[start:end]
    let avg 0 /where (loc_spikes.ne.0)
    compute local_mean MEAN avg
    ! exa local_mean
    let average[i] local_mean
  else if spikes[i].eq.1 then
    let idx 'i+1'
    let x 1
    for /while spikes[idx].eq.1
      exa idx
      let x x+1
      let idx idx+1
    next
    for j 0 to 'x-1'
      if exist(avg) then
        del /var avg
      endif
      if exist(loc_spikes) then
        del /var loc_spikes
      endif
      define real avg loc_spikes /like ry[start:end]
      let loc_spikes spikes['start+j':'end+j']
      let avg ry['start+j':'end+j']
      let avg 0 /where (loc_spikes.ne.0).and.(x.le.maximum_joint_spikes)
compute local_mean MEAN avg
let idx 'i+j'
let spike_check[idx] x
let average[idx] local_mean
next
let skip x
endif
endif
next
@make_noise 'sigma'
def real average_exclude /like ry
def int second_spikes /like spikes
let average_exclude ry-average
let second_spikes 0
let second_spikes 1 /where (average_exclude.gt.'tolerance*sigma').or. &
(average_exclude.lt.'-1*tolerance*sigma')
let spike_check spike_check*spikes*second_spikes
let ry noise_value /where (spike_check.ne.0).and. &
(spike_check.le.maximum_joint_spikes).and.(spikes.eq.1)
endif
end procedure despike_standalone
!
!##############################################################################
begin procedure clip
! Clip pixels at the edges, using criterion on weight -> step3.lmv
! Input parameter #1 is the weight threshold
def real new_bandwidth
let new_bandwidth 'global_frequency_range/global_frequency_resolution'
def define image weight "tmp/"'global_out_fName'"/step"&1".wei" read
def define image im "tmp/"'global_out_fName'"/step"&1".lmv" write
for ichan 1 to 'im%dim[3]'
let im[,ichan] im%blank[1] /where weight.lt.&1
next ichan
delete /var weight
delete /var im
end procedure clip
!
!##############################################################################
begin procedure vel_wind
! select velocity window for removing Birdies
define int window_channels[2]
let window_channels int(reference-((velocity-global_msk_win)/velo_step))
define int plane_factor
def plane_factor 0
sic copy "tmp/"'global_out_fName'"/step"&1".lmv" &
"tmp/"'global_out_fName'"/"'global_out_fName'".msk"
! Load the variables with which we will work
define image cube "tmp/"'global_out_fName'"/step'&1'".lmv" read
define header head "tmp/"'global_out_fName'"/step'&1'".lmv" read
define image mask "tmp/"'global_out_fName'"/"'global_out_fName'".msk" write

! This polygon defines the region in which the noise is measured.
poly co_mask_noise_region.pol /pl

! First set all values in the mask to 0
let mask[,] 0

! Now only the relevant channels are treated
for plane 1 to 'cube%dim[3]'  
  rgdata cube[,]plane /var
  mean
  let mask[,]plane 0 /where
    (cube[,]plane.lt.'3*poly%rms').and.(cube[,]plane.ne.cube%blank[1])
  let mask[,]plane 1 /where
    (cube[,]plane.ge.'3*poly%rms').and.(cube[,]plane.ne.cube%blank[1])
  let mask[,]plane 0 /where (cube[,]plane.eq.cube%blank[1])
  next

for plane 1 to 'cube%dim[3]'  
  if plane.lt.4 then
    let mask[,]plane 0 /where (mask[,]plane+1].eq.0).or. &
    (mask[,]plane+2].eq.0).or.(mask[,]plane+3].eq.0).and.(mask[,]plane].eq.1)
  else if plane.gt.'cube%dim[3]-4' then
    let mask[,]plane 0 /where (mask[,]plane-3].eq.0).or. &
    (mask[,]plane-2].eq.0).or.(mask[,]plane-1].eq.0).and.(mask[,]plane].eq.1)
  else
    let mask[,]plane 0 /where ((mask[,]plane-3].eq.0).and. &
    (mask[,]plane+1].eq.0)).or.((mask[,]plane-1].eq.0).and. &
    (mask[,]plane+3].eq.0)).or.((mask[,]plane-2].eq.0).and. &
    (mask[,]plane+2].eq.0)).and.(mask[,]plane].eq.1)
  endif
  next

del /var cube
del /var mask

define image mask "tmp/"'global_out_fName'"/"'global_out_fName'".msk" read
define real vel_low['mask%dim[1]','mask%dim[2]']
define real vel_high['mask%dim[1]','mask%dim[2]']
let vel_low[,] 0
let vel_high[,] 0

for i 1 to 'mask%dim[3]'  
  for j '-2*plane_factor' to '2*plane_factor'

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let vel_low[,, i+j] where (mask[,, 'i'].eq.1).and.(vel_low[,,].eq.0)
let vel_high[,, i+j] where (mask[,, 'i'].eq.1)
next
next
exa head%convert[1,3]
exa head%convert[2,3]
exa head%convert[3,3]
def real center_channel vel_offset vel_resolution
let center_channel head%convert[1,3]
let vel_resolution head%convert[3,3]
let vel_offset head%convert[2,3]
exa center_channel
exa vel_resolution
exa vel_offset
exa vel_low[,,]
let vel_low[,,] ((center_channel-vel_low[,,])*vel_resolution*(-1))+vel_offset
let vel_high[,,] ((center_channel-vel_high[,,])*vel_resolution*(-1))+vel_offset
let vel_low[,,] mask%blank[1] where vel_low[,,].eq.0
let vel_high[,,] mask%blank[1] where vel_high[,,].eq.0
exa head%convert[3,3]
sic delete "tmp/"'global_out_fName'"/vel_low.lmv"
sic delete "tmp/"'global_out_fName'"/vel_high.lmv"
rgdata vel_low[,,] /var
greg\write image "tmp/"'global_out_fName'"/vel_low.lmv"
rgdata vel_high[,,] /var
greg\write image "tmp/"'global_out_fName'"/vel_high.lmv"
del /var vel_low
del /var vel_high
define image vel_low "tmp/"'global_out_fName'"/vel_low.lmv" write
let vel_low%convert head%convert
del /var vel_low
define image vel_high "tmp/"'global_out_fName'"/vel_high.lmv" write
let vel_high%convert head%convert
del /var vel_high
del /var mask
end procedure vel_wind
!
!##############################################################################
begin procedure rebase
!
! Gridding is a linear process which increases the SNR per pixel
! => Baseline of higher order + window depending on the position (defined
! from the CO cube)
! -> step5.30m
! Input parameter #1 is the baseline order
! input parameter #2 is the multiplication factor for the window size (1.4
\rightarrow for HCO+, 2 for HCN)

set unit v
@ file_in_out '1'
list /toc
silent
define image wind_low "tmp/"'global_out_fName'"/vel_low.lmv" read
define image wind_high "tmp/"'global_out_fName'"/vel_high.lmv" read
define integer ilamb ibeta
define double mylamb mybeta wleft[found] wright[found] wmin wmax width
\rightarrow factor

let wleft global_msk_win[1]
let wright global_msk_win[2]
let factor 0.5*(2-1)
for ient 1 to found
  get next
  let mylamb r%head%pos%lamof ! [rad]
  let mybeta r%head%pos%betof ! [rad]
  let ilamb nint((wind_low%convert[1,1]+ &
  (mylamb-wind_low%convert[2,1])/wind_low%convert[3,1]))
  let ibeta nint((wind_low%convert[1,2]+ &
  (mybeta-wind_low%convert[2,2])/wind_low%convert[3,2]))
  if ((wind_low[ilamb,ibeta].ne.wind_low%blank[1]).and. &
  (wind_high[ilamb,ibeta].ne.wind_high%blank[1])) then
    let wmin min(wind_high[ilamb,ibeta],wind_low[ilamb,ibeta])
    let wmax max(wind_high[ilamb,ibeta],wind_low[ilamb,ibeta])
    let width wmax-wmin
    let wleft[ient] wmin!-factor*width
    let wright[ient] wmax!+factor*width
  endif
  set window 'wleft[ient]' 'wright[ient]'
  base &2 /pl
  write
  next ient
delete /var wind_low
delete /var wind_high
!
file in "tmp/"'global_out_fName'"/step'&1'
find
load
plot /index
g\connect wleft idx%num
g\connect wright idx%num
verbose
set unit f
end procedure rebase
!
begin procedure plotRms
! Plot scan vs RMS
message i reduce "##### plotRms - start"
@file_in &1
set window /var global_msk_win
def real sig[found]
def real numbers[found]
for i 1 to found
get n
bas 1
exa sigma
let sig[i] sigma
let numbers[i] number
next
exa sig numbers
c1 pl
g\lim /var numbers sig
g\box
g\set marker 4 4 0.8
g\points numbers sig
g\label "Observation Number" /X
g\label "rms [K]" /Y
!
end procedure plotRms
!
begin procedure dropRms
! remove spectra above a given value
ON ERROR @recover
@file_in_out &1
def real upper
let upper &2
set window /var global_msk_win
for i 1 to found
get n
bas 1
if (sigma.lt.upper) then
write
endif
next
end procedure dropRms
!
begin procedure wavelets
! experimental task remove standing waves, not generally used but can be
→ applied if needed
@file_in_out &1
for i 1 to found
get n
EXPERIMENTAL\wavelet /base 3
pl
write
next
end procedure wavelets
!
begin procedure exportFits
! This is to export the cube to a fits file
message i reduce "##### Export to Fits file"
fits 'global_rms_plt_name"_cube".fits from
  "tmp/"'global_out_fName"/step"&1".lmv
message i reduce "File exported Name:"'global_rms_plt_name"_cube.fits"
end procedure exportFits
!
begin procedure reduce
message i reduce "##### Reduce - start"
!
Steps
! import the file into Gildas.
! resample the spectra within a range (allows for consistency checks).
! Apply a low order baseline (remove the continuum).
! Examine plot scan vs RMS, to identify any spectra which high RMS.
! Create a plot of showing all of the spectra to identify data quality issues.
! Remove spectra with a RMS above a given value using the plot showing scan
→ vs RMS.
! Substitute birdies (internal RFI) outside emission velocity range with a
→ RMS model (see Gildas documentation).
! Developed by Dr C. Buckbender, to remove birdies within the range of the
→ emission line.
! Another iteration to inspect RMS values across the dataset.
! If needed remove spectra at a given value.
! Inspect dataset again to see changes.
! Plot dataset to inspect data quality.
! if needed apply a higher order baseline subtraction.
! Create image.
! View image.
verbose
@ import
@ modify 1  
@ resample 2  
@ base 3 1  
@ plotRms 3  
@ plt_index 3  
@ dropRms 4 50  
@ fill 5  
@ despike_new 6 6 4  
@ plotRms 6  
@ dropRms 7 3  
@ plotRms 7  
@ plt_index 7  
@ base 8 3  
@ image 9  
@ view_image 10  

message i reduce "##### Reduce - completed"

end procedure reduce

!############################################################
! declare variables
!############################################################
say "########################################################"
say "Gildas (class) NANTEN2 data reduction"
say "########################################################"
say "CARINA CO 4-3"

global_in_fName = "Carina_2015_p1.30m" ! input file
global_out_fName = "CO_2015" ! directory of the output files
global_src_name = "CARINA_CNTR" ! Source name as seen within the system
global_rms_plt_name = "Carina_CO_4-3" ! Generic plot name

global_frequency = 461040.80 ! frequency of 12CO 4--3 in MHz
global_frequency = 461038.20 ! frequency of 12CO 4--3 (MHz) adjusted for the
    \rightarrow LO offset
global_src_velocity = -25

! Resampling parameters
global_frequency_range = 100 ! Frequency range of resampling in MHz
global_frequency_resolution = 0.16 ! Frequency resolution of each channel in
    \rightarrow MHz
global_msk_win = 1 -31 -5 ! A mask window of the source in km/s

@reduce ! Run data reduction
B.3 Tid-70m

B.3.1 Position-switching

ATNF Spectral Analysis Package (ASAP) is created using python, which allows easy development of streamline processing to automatically reduce the data through python scripting. Scripting the data reduction process uses the same task that would normally be done manually. The following code is an example to process position-switch data taken from Deep Space Station (DSS)43. Observations of NH$_3$ towards the Lupus regions I, III and IV were done on the 31/03/2012.

Python code used to reduce data observed towards Lupus IV. The code demonstrates the method to read in and select data from multiple scantables. This method retrieves each selected data then corrects for gain/el effects and does a frame conversion and alignment. After the scantables have been merged into one, the scantable is set to the rest frequency, and a mask is created and applied to the the baseline subtraction. Adjustments are made to the plotting window before the spectra are viewed for the last time.

```python
# This is a example of the ASAP data reduction process
# This set of observations was taken on 31/03/2012
# covering sections of the Lupus I, III and IV regions
from asap import *
# Load the rpfits file and inspect
d = scantable('2012_091_t199/2012-03-31_182325_T199.rpf')
print(d)
# Make the quotient spectra
q = d.auto_quotient()
print(q)
# Plot/select in velocity
q.set_freqframe('LSRK')
q.set_unit('km/s')
# Correct for gain/el effects
q.recalc_azel() # Tid does not write the elevation
q.gain_el()
q.opacity(0.05)
# Align data in velocity
q.freq_align()
q.set_restfreqs([23694.4955e6]) # set frequency for ammonia (1,1) detection
cropScan = q.average_pol()
plotter.set_layout(3,3)
plotter.set_histogram()
plotter.plot(cropScan)
cropScan.auto_poly_baseline()
plotter.plot()
```
B.3.2 OTF

The raw file from Tid-70m OTF is in rpfits format, importing the data uses the CASA task sdsave. The task sdlist creates a list summary of the observations. A plot of pointings before position correction can be generated through the command sdplot using the parameter POINTING in the argument PLOTTYPE. An experimental script created by us, corrects the OTF pointings using the velocity taken from the NMC log files. SDPLOT is used again to confirm adjustments made to the pointings. Calibration is completed through the task sdcal, with the parameter CALMODE set to QUOTIENT. Baseline subtraction can be applied through the command sdbaseline. To view the spectra, the task sdplot is used and setting the parameter PLOT TYPE to GRID. After calibration phase is completed, using the task sdsave exports the data into a measurement set (MS) file.

CASA task sdimaging generates the position-position-velocity cube. The cubes are generated by setting parameter DOCHANNEL to TRUE. The expandable parameters of DOCHANNEL is also required: START, STEP and NCHAN. START parameter indicates the beginning of the cube in the velocity axis. STEP parameter is the value for each channel. NCHAN is the number of channels along the velocity range. The values for START, STEP and NCHAN are in units of SPECUNIT. CELL is the spacing between each pixel, the values derived for the OTF maps are spacing between each scan along Dec and converting the scan rate (taken from the NMC log) from milli degree s$^{-1}$ to arc seconds s$^{-1}$ multiplied by the number of seconds per integration. Image size is set through the parameter IMSIZE, values are based on the number of samples the spectrometer has taken per scan and number of scans across source. SDIMAGING by default averages both polarisations during the imaging process.

If baseline subtraction has not been applied, continuum subtraction can be used through the task IMCONT. A line free channel range must be specified, before running the command. Integrated intensity images can be created by using the task IMMOMENTS. The image can be exported to the FITS file through the task EXPORTFITS.
# [Other]
# 8. Create moment maps (immoments)
# 9. Stat analysis (imstat)
#
#
# [Limitation]
# The script is based on CASA 4.2 (>= r26872) capabilities. It cannot
# be run on stand-alone ASAP.
# You’ll need an additional experimental script, fixDirection.py, to
# fix direction in scantable.
#
# Author: Kanako Sugimoto (NAOJ), Graeme Wong (UWS)
# History:
# 2013/Oct/09 The original Script Kanako Sugimoto
# 2014/Jan/14 Modifications by G. Wong to include orion data
########################################################################
# you will need to rename the standard summary file, change the NASA date to
# human date

# Predifined file names
outdir='processing_run/'
if not os.path.exists(outdir): os.mkdir(outdir)

rawdata = '2013-09-24_144424_O356_vac1.rpf'
dirfile = '2013_267_summary_mod.delay.txt'
rawtab = outdir+'orion_267_v1.raw.asap'
fixfile = outdir+'orion_267_v1.fixed.asap'
calfile = outdir+'orion_267_v1.cal.asap'
basefile = outdir+'orion_267_v1.base.asap'
msfile = outdir+'orion_267_v1.ms'
chanimage = outdir+'orion_267_v1.cal_RRpol.image'
line_img = outdir+'orion_267_v1.chan_RRpol.lineimage'
cont_img = outdir+'orion_267_v1.chan_RRpol.contimage'

# Data import
default(sdsave)
infile = rawdata
outfile = rawtab
sdsave()

#list scantable
default(sdlist)
infile = rawtab
outfile = outdir+'orion_267_v1.raw.list.txt'
sdlist()
default(sdplot)
infile = rawtab
plottype = 'pointing'
stack = 't'
    # change the color of plot symbol by source type
scanpattern = True
    # show time-line of scans
outfile = outdir+'orion_267_v1.raw.pointing1.png'
sdplot()
    # a little bit of tweaking of plot range (optional)
    # ax = sd.plotter.gca()
    # ax.set_xlim(xmin=92, xmax = 94)
    # ax.set_ylim(ymin=-5.15, ymax = -5.4)
    # ax.legend(loc=0)
    # pl.draw()
    # sd.plotter.save(filename = 'orion_267_v1.raw.pointing2.png')

    # Fix OTF pointings
shutil.copytree(infile, fixfile)
execfile('fixDirection_v1.py')
myfix = fixDirection(fixfile, dirfile) # if you get an error at this point
    # check the summary file
    myfix.set_scan_pattern(velocity='2.4771mdeg/s', scan_axis=0)
myfix.fill_direction(exclude='ORI*w', flag=True)
del myfix

    # Re-calculate Az-El with the new directions
scan = sd.scantable(fixfile, average=False)
scan.recalc_azel()
scan.save(name=fixfile, format='ASAP', overwrite=True)

    # Plot pointing (after fix)
default(sdplot)
infile = fixfile
plottype = 'pointing'
stack = 't'
    # change the color of plot symbol by source type
scanpattern = True
    # show time-line of scans
outfile = outdir+'orion_267_v1.fixed.pointing.png'
overwrite = True
sdplot()
    # a little bit of tweaking of plot range (optional)
ax = sd.plotter.gca()
ax.set_xlim(xmin=84, xmax = 83.4)
ax.set_ylim(ymin=-5.5, ymax = -5.15)
ax.legend(loc=0)
pl.draw()
sd.plotter.save(filename = outdir+'orion_267_v1.fixed.zoom.png')

    # calibration
default(sdcal)
infile = fixfile
outfile = calfile
calmode = 'quotient'
sdcal()

# Plot calibrated spectra
default(sdplot)
infile = calfile
plottype='grid'
cell = '1arcmin'
restfreq = '8309.3832MHz'
subplot = 66
flrange = [-1., 10.]
sprange = [-200, 200]
specunit = 'km/s'
histogram = True
frame = 'LSRK'
sdplot()
ax = sd.plotter.gca()
ax.set_xlim(xmin=-200, xmax = 200.)
ax.set_ylim(ymin=-1, ymax = 7.)
pl.draw()
sd.plotter.save(filename = outdir+'orion_267_v1.cal.png')

# baseline
default(sdbaseline)
infile = calfile
outfile = basefile
specunit = 'km/s'
restfreq = '8309.3832MHz'
outframe = 'LSRK' # CASA 4.2
maskmode = 'auto'
blfunc = 'poly'
order = 1
outform = 'asap'
overwrite = True
sdbaseline()

# Plot baselined spectra
default(sdplot)
infile = basefile
plottype='grid'
cell = '1arcmin'
restfreq = '8309.3832MHz'
subplot = 66
flrange = [-1., 10.]
sprange = [-200, 200]
specunit = 'km/s'
histogram = True
frame = 'LSRK'
sdplot()
ax = sd.plotter.gca()
ax.set_xlim(xmin=-200, xmax = 200.)
ax.set_ylim(ymin=-1, ymax = 10.)
pl.draw()
sd.plotter.save(filename = outdir+'orion_267_v1.base.png')

# convert to MS file
default(sdsave)
infile = basefile
outfile = msfile
outform = 'MS2'
sdsave()

# WORKAROUND to fix antenna diameter
rb.open(msfile+'/ANTENNA', nomodify=False)
rb.putcell('DISH_DIAMETER', 0, 70.)
rb.close()

# imaging
default(sdimaging)
infiles = msfile # CASA 4.2
outfile = chanimage
outframe = 'LSRK' # CASA 4.2
specunit = 'km/s'
restfreq = '8309.3832MHz'
nchan = 900
start = -450
step = 1.12743 # original
# step = 1.12754
dochannelmap = True
# stokes = 'RR'
phoecenter = '' # J2000 05h30m00.0 -05d22m00.0'
cell = ['0.45arcmin', '0.5001arcmin']
imsize = [42, 36]
overwrite = True
sdimaging()

# Continuum subtraction
default(imcontsub)
imagename = chanimage
linefile = line_img
contfile = cont_img
fitorder = 1
chans = '300~369,425~500'
overwrite = True
imcontsub()

# Moments maps
# different moment maps
moment_img = 'orion_267_v1_mom0.line.immonents'
default(immoments)
imagename = line_img
outfile = moment_img
moments = 0
axis = 'spectral'
chans="range=[369chan, 427chan], restfreq=8309.382MHz, frame=LSRK")
overwrite = True
immoments()

moment_img = 'orion_267_v1_mom1.line.immonents'
outfile = moment_img
moments = 1
immoments()

moment_img = 'orion_267_v1_mom2.line.immonents'
outfile = moment_img
moments = 2
immoments()

moment_img = 'orion_267_v1_mom8.line.immonents'
outfile = moment_img
moments = 8
immoments()

# export moment map to fits
exportfits(imagename='orion_267_v1_mom0.line.immonents',
           fitsimage='orionA.fits')

# image stats
outdir='processing_run/
if not os.path.exists(outdir): os.mkdir(outdir)
line_img = outdir+'orion_267_v1.chan.lineimage'
default(imstat)
imagename = 'orion_267_v1_regrid.fits#line_img'
axes = -1
box = '5,15,15,25'
listit = True
robust = False
verbose = True
chans = '300~369,425~500'
imstat()

imgstat = imstat()
rms = (imgstat['rms'][0])
rms_list.append(float(rms))
print '>> rms:'+ str(rms)
peak = (imgstat['max'][0])
B.3.2.1 Summary File Generator

The following code creates a new summary file used for the data processing of Tid-70m OTF observations. This python code uses two input files, original summary file generated from the correlator and the network monitor and control (NMC) log file. The script will write a new column which will include a delay time, from executing the telescope to start slewing and the correlator starting to record integrations. This script has also included the time delay for a beam as a result of offsets in the positions. The comment under notes, indicates the preparation to extract the slew commands to the telescope (using the GREP command).

```python
# Purpose: Extract the telescope timestamps from the telescope command log,
# the write it to the new summary file using an existing one
#
# Author: G. Wong
# Created: 27.11.14
#
# Notes: grep 'RO XDEC' 132671050.L01.4305000999.0 | grep 'BD'| grep -v 'CLR'
#        > telescope_cmds_output.txt
#
import datetime as dt  # the datetime naming convention is confusing beware
from datetime import *

def log_file(filename):
    f = open(filename, 'r')
    lines = f.readlines()
    # print lines
    f.close()
    return lines

# split the string and convert to seconds
def getSec(s):
    l = s.split(':')
    return int(l[0]) * 3600 + int(l[1]) * 60 + int(l[2])

# get the string output from comparing the difference in time and
eleminate any string that starts with -1 day return the output in seconds
def conv_2_sec(input_str):
    split_str = input_str.split()
    if not split_str[0].startswith('-1'):
        sec = getSec(split_str[0])
        return sec
    else:
        return 281
```

281
sec = getSec(split_str[2])
return sec

# Main section

# Input files & The logs from the telescope
log_output = log_file('telescope_cmds_output.txt')
summary_output = log_file('2013_267_summary_mod.txt')
new_summary_file = open('2013_267_summary_mod.delay.txt', 'w')

for l in summary_output:
    prt = l.split()
    if not (prt == []) and (len(prt) > 5):
        date_time = prt[1].split('.')  # check for the 2nd element is a date time
        if not (len(date_time) < 2) and (prt[3].endswith('w') != True):
            tele_startTime = prt[0].split('.')
            # start looking and cross matching the second file
            counter = 0
            sec_lst = list()
            for i in log_output:
                ele = i.split()
                time_diff_str = datetime.strptime(tele_startTime[2], '%H:%M:%S') - 
                               datetime.strptime(ele[1], '%H:%M:%S')
                t_diff_sec = conv_2_sec(str(time_diff_str))
                sec_lst.append(t_diff_sec)
                counter = counter + 1

            sec = min(sec_lst)
            sec_index = sec_lst.index(min(sec_lst))
            newline = l.rstrip("\n")
            new_summary_file.write(newline + str(sec+12) + "\n")

    elif (prt[3].endswith('w') == True):
        newline = l.rstrip("\n")
        new_summary_file.write(newline + "0 \n")
    else:
        newline = l.rstrip("\n")
        new_summary_file.write("#" + newline + "\n")

new_summary_file.close()  # close file
B.3.2.2 Position correction

```python
# fixDirection.py
#
# A workaround script to fix DIRECTION column in scantable of
# experimental OTF data taken by Tidbinbilla telescopes.
#
# [Limitation]
# The script is based on CASA capabilities. It cannot be run on
# stand-alone ASAP.
#
# Author: Kanako Sugimoto (NAOJ), Graeme Wong (UWS/CASS)
# History:
# 2013/Oct/09 The original Script Kanako Sugimoto
# 2015/Oct/25 The extrapolation is changed, one for slewing along RA and
# one for Dec
#
import os
import re
import numpy
from taskinit import gentools, qatool
from asap.scantable import is_scantable
import asap as sd
import math

class fixDirection:
    
    A experimental class to fix DIRECTION of scantable for OTF observation by
    Tidbinbilla telescopes.

    Usage:
    myfix = fixDirection(scantable='orion.fixed.asap',
                        dirinfo='2013_253_summary_orion.txt')
    myfix.set_scan_pattern(velocity='-2.4771mdeg/s', scan_axis=0)
    myfix.fill_direction(exclude='ORI*w', flag=True)

    def __init__(self, scantable='', dirinfo='', skipline=3):
        
        Set scantable name and a text file which stores direction information.

        Parameters:
        scantable: the name of scantable
        dirinfo : the name of a text file that stores directin info.
        skipline : the number of lines to skip in dirinfo before
                    reading data.
```
if not os.path.exists(scantable):
    raise Exception, "Input scantable '%%s' does not exist" % (scantable)
if not is_scantable(scantable):
    raise Exception, "Input data is not a scantable."
if not os.path.exists(dirinfo):
    raise Exception, "Direction information file '%%s' does not exist" % (dirinfo)
self.table = os.path.abspath(scantable)
self.dirfile = os.path.abspath(dirinfo)
self.verbose = False
self.dircolname = 'DIRECTION'
self.timecolname = 'TIME'
self.num_skip = skipline
# The default column order of direction information file
self.colorder = [
    "El", "IF",
    "Obs freq", "Ref freq", "Tsyst", "Corfac", "offset"]
# Mandatory columns in direction information file
self.mandatorycols = [
    "Start", "End", "Source", "RA", "Dec",
    "IF", "Obsfreq", "Tsyst", "Corfac", "offset"]
self.start = None
self.end = None
self.source = None
self.ra = None
self.dec = None
self.ifno = None
self.dirinfo_freqs = None
self.ifmap = None
self.velocity = 0.
self.scanaxis = -1
my_tb = gentools(['tb'])[0]
my_tb.open(self.table)
dirkw = my_tb.getcolkeywords('DIRECTION')
timkw = my_tb.getcolkeywords(self.timecolname)
my_tb.close()
# Get direction unit from the scantable
self.dir_unit = ['rad', 'rad']
if not dirkw.has_key('QuantumUnits'):
    print("Could not get units of %s. Using radian" % (self.dircolname))
else:
    self.dir_unit = self._format_direction_unit(dirkw['QuantumUnits'])
# Get time unit from the scantable
self.time_unit = 'd'
self.time_ref = 'UTC'
if timkw.has_key('QuantumUnits'):
    self.time_unit = timkw['QuantumUnits'][0]
else:
    print("Could not get units of %s. Using day" % (self.timecolname))
if timkw.has_key('MEASINFO'):
    self.time_ref = timkw['MEASINFO']['Ref']
else:
    print("Could not get reference of %s. Using UTC" % (self.timecolname))

# velocity unit
self.vel_unit = ['%s/%s' % (self.dir_unit[0], self.time_unit),
                 '%s/%s' % (self.dir_unit[1], self.time_unit)]

def _format_direction_unit(self, in_data):
    # ---------------------------------- #
    # format unit as a two elements array
    # ---------------------------------- #
    if type(in_data) == str:
        return [in_data, in_data]
    try:
        len(in_data)
    except:
        return [in_data, in_data]
    if len(in_data) > 1:
        return in_data[0:2]
    elif len(self.in_data) == 1:
        return [in_data[0], in_data[0]]

def fill_direction(self, ifs=[], pols=[], scans=[],
                   src='', exclude='', flag=True, verbose=False):
    """
    Extrapolate per dump pointing direction and fill DIRECTION column
    in scantable.
    """
    Parameters:
    ifs : a list of IFNOs to extrapolate DIRECTION
    pols : a list of POLNOs to extrapolate DIRECTION
    scans : a list of SCANNOS to extrapolate DIRECTION
    src : a SRCNAME string to extrapolate DIRECTION
         (e.g., 'ORI-*')
    WARNING: SRCNAMEs are not checked when finding
             corresponding time slot from dirinfo file
    exclude : a SRCNAME string to exclude from operation
              (e.g., 'ORI-*w')
flag : flag rows in scantable for rows extrapolation was not successful (default: True)
verbose : verbose output (default: False)

""
self.verbose = verbose
if self.scanaxis < 0:
    raise Exception, 'Set scan velocity and orientation before filling direction'

# Read direction info file
self._read_dir_info()
# Get scantable information
self._get_if_map(ifs)

print("Scan orientation = %s" % ('RA' if self.scanaxis==0 else 'dec'))
print("Scan velocity %f %s" % (self.velocity, self.vel_unit[self.scanaxis]))
# selection string by scan, pol, and source names
basestr = ""
if len(scans) > 0:
    basestr += "SCANNO IN %s" % (str(list(scans)))
if len(pols) > 0:
    if len(basestr) > 0: basestr += " AND ":
        selstr += " POLNO IN %s" % (str(list(pols)))
if len(src) > 0:
    if len(basestr) > 0: basestr += " AND ":
        basestr += "SRCNAME==pattern('%s')" % (src)
    if len(exclude) > 0:
        if len(basestr) > 0: basestr += " AND ":
            basestr += "SRCNAME!=pattern('%s')" % (exclude)

my_tb = gentools(['tb'])[0]
my_tb.open(self.table, nomodify=False)
try:
    for sif in self.ifmap.keys():
        print("Start interpolating scantable IF%d" % sif)
dif = self.ifmap[sif]
if dif is None:
    print("No corresponding directions. Skipping IF%d" % sif)
    selstr = ("IFNO==%d" % sif)
    if len(basestr) > 0:
        selstr += " AND "+basestr
        if self.verbose: print("Table selection string: %s" % selstr)
        seltb = my_tb.query(selstr, sortlist="TIME")
        if self.verbose: print("%d rows are selected" % seltb.nrows())
        times = seltb.getcol("TIME")
        srcnames = list(set(seltb.getcol("SRCNAME")))
        newdirs = self._get_interpolated_direction(times, dif, srcnames)
        for irow in range(seltb.nrows()):
try:
    dir = newdirs[irow]
seltb.putcell("DIRECTION", irow, dir)
except:
    if flag:
        seltb.putcell("FLAGROW", irow, 1)
seltb.flush()
seltb.close()
del seltb
finally:
    my_tb.flush()
    my_tb.close()

def _get_interpolated_direction(self, times, idx, srcnames=[]):
    # Extrapolate directions at times.
    # NOTE invoke set_scan_pattern() to set velocity before running
    # the method.
    # Parameters
    # times : a list of times to extrapolate direction from
    # idx : IF index in dirinfo file to select rows
    # srcnames : Source names to select rows in dirinfo file
    # Returns
    # a dictionary that stores combination of extrapolated
    # direction and index of input times,
    # dict[id of times] = [ra_new, dec_new]
    selidx = numpy.where(self.ifno==idx)[0]
    if len(srcnames) > 0:
        srcidx = []
        for src in srcnames:
            srcidx.extend(numpy.where(self.source==src)[0])
        commonidx = numpy.intersect1d(selidx, srcidx)
        del selidx
        selidx = numpy.array(commonidx)
    print("Interpolating IF%d in direction table" % idx)
    if self.verbose: print("Selected sources: %s" % str(srcnames))
    print("%d rows selected in direction file" % len(selidx))
    if self.verbose: print("Selected rows: %s" % str(selidx))
    stime = self.start[selidx]
etime = self.end[selidx]
    ra = self.ra[selidx]
dec = self.dec[selidx]
    if self.scanaxis == 0:
        x = ra
y = dec
else:
    x = dec
newdir = {}
timeorder = numpy.argsort(stime)
### WARNING HEREAFTER IGNORING SRCNAMES IN SCANTABLE
for irow in range(len(times)):
    tt = times[irow]
    tid = -1
    for idx in timeorder: # get the integrations in the scans
        # Loop over dirinfo rows and find corresponding row idx (tid)
        # where start <= times[irow] <= end
        if (tt-stime[idx])*(etime[idx]-tt) >=0:
            tid = idx
            break
    if tid < 0:
        print("Failed to find valid time range in direction file. irow \rightarrow = \%d, time=\%f" \% (irow, tt) )
        continue
    dir0 = x[tid]
    tt0 = stime[tid]
    # Do simple 1st order extrapolation, (dir0+self.velocity*(tt-tt0))
    # You can change interpolation algorithm by changing here.
    if self.scanaxis == 0:
        dir1 = y[tid]
        dirx = self._do_1d_extrapolate_RA(tt0, dir0, dir1, self.velocity, tt)
    # print ra[tid], dec[tid]
    # print 'dirx = \%f' \% (dirx)
    newdir[irow] = [dirx,dec[tid]]
else:
    # print tt0, dir0, self.velocity, tt-tt0 # start time, start
    # position, velocity,
    dirx = self._do_1d_extrapolate(tt0, dir0, self.velocity, tt)
    # possibility to add delays here
    # print ra[tid], dec[tid]
    # print 'dirx = \%f' \% (dirx)
    newdir[irow] = [ra[tid], dirx]
return newdir

def _do_1d_extrapolate(self, x0, y0, slope, x):
    # Do simple 1st order extrapolation.
    # Returns y = y0 + slope*(x-x0)
    return (y0 + slope*(x-x0))
```python
# tt0, dir0, self.velocity, tt
# x0, y0, slope, x

def _do_1d_extrapolate_RA(self, t0, x0, y0, velo, t):
    # ----------------------------------------------------------- #
    # t0 = start time, x0 = start RA, y0 = start Dec, velo = velocity in
    # radians, t = current time of pointing
    # ----------------------------------------------------------- #
    return (x0 + velo * math.cos(math.radians(y0)) * (t - t0))

def _get_if_map(self, ifs):
    # ----------------------------------------------------------- #
    # Compare frequencies of IFs in scantable with ones in
    # direction information file and find corresponding IF ID
    # pairs.
    #
    # Input: a list of IFNOS in scantable to look up.
    #
    # The method sets values to an attribute, ifmap. Ifmap is a
    # dictionary which stores an IF in dirinfo file (value) for
    # each of input IFNOS (key) in scantable, i.e.,
    # ifmap[scantable IFNO] = {dirinfo IF}
    # ----------------------------------------------------------- #
    scan = sd.scantable(self.table, average=False)
    if len(ifs) == 0:
        ifs = scan.getifnos()
    print("Getting IF map")
    scan.set_unit('MHz')
    self.ifmap = {}
    for idx in ifs:
        scan.set_selection(ifs=idx)
        freqs = scan._getabcissa()
        fmin = min(freqs)
        fmax = max(freqs)
        print("Scantable IF%d: [%f MHz, %f MHz]" % (idx, fmin, fmax))
        theif = []
        for fid, fobs in self.dirinfo_freqs.items():
            if (fobs-fmin)*(fmax-fobs) >= 0:
                theif.append(fid)
        if len(theif) == 0:
            print("Could not find corresponding IF in direction file.")
            self.ifmap[idx] = None
        elif len(theif) > 1:
            self.ifmap[idx] = theif[0]
            print("There are multiple corresponding IFs in direction
                   file:")
            for ii in theif:
                print("ID%d: %f MHz" % (ii, self.dirinfo_freqs[ii]))
    ```
print("Using the first one")
else:
    self.ifmap[idx] = theif[0]
    print("Found corresponding IF in direction file")
    print("ID%d: %f MHz" % (theif[0], self.dirinfo_freqs[theif[0]]))
    del scan

def set_scan_pattern(self, velocity=' ', scan_axis=0):
    """
    Set scan velocity and orientation of OTF observation.
    """
    Parameters:
    velocity : scan velocity string (e.g., '-20arcsec/s')
    scan_axis : scan orientation (0: 'RA', 1: 'Dec')
    """
    my_qa = qatool()
    if scan_axis > len(self.vel_unit):
        raise Exception, "Invalid scan axis"
    if not my_qa.compare(velocity, self.vel_unit[scan_axis]):
        raise Exception, "Invalid velocity unit"
    self.scanaxis = scan_axis
    self.velocity = my_qa.convert(velocity, self.vel_unit[scan_axis])['value']
    print("Scan velocity %f %s" % (self.velocity, self.vel_unit[self.scanaxis]))

def set_scan_pattern_cosDec(self, velocity=' ', scan_axis=0, Dec=' '):
    """
    Set scan velocity and orientation of OTF observation.
    """
    Parameters:
    velocity : scan velocity string (e.g., '-20arcsec/s')
    scan_axis : scan orientation (0: 'RA', 1: 'Dec')
    Dec : The Dec of the source
    """
    my_qa = qatool()
    if scan_axis > len(self.vel_unit):
        raise Exception, "Invalid scan axis"
    if not my_qa.compare(velocity, self.vel_unit[scan_axis]):
        raise Exception, "Invalid velocity unit"
    self.scanaxis = scan_axis
    cor_velo = my_qa.convert(velocity, self.vel_unit[scan_axis])['value']
                   # original conversion of the scan rate
    self.velocity = (cor_velo/math.cos(math.radians(Dec)))   # R.A.
                   # = X-dec/cos(Dec) the radians is to help get the conversion
    new_mdeg = ((self.velocity*180)/math.pi/24/60/60)*1000  # Do
                   # the conversion to from radians to mdeg/s
```python
# print("Scan velocity %s %f %f %f %s" % (velocity, new_mdeg,
→ cor_velo, self.velocity, self.vel_unit[self.scanaxis]))
print("Scan velocity %f mdeg/s, %f rad/day, %f %s" % (new_mdeg,
→ cor_velo, self.velocity, self.vel_unit[self.scanaxis]))

def set_column_order(self, order):
    """
    Set the order of columns in direction information file.
    """
    for name in self.mandatorycols:
        if name not in order:
            raise Exception, "A mandatory column '%s' does not exists" %
                    name
    self.colorder = order

def _read_dir_info(self):
    # ----------------------------------------------------------- #
    # Read a text file that stores direction information
    # and extract necessary information.
    # Note: Rows with valid elements smaller than the
    # registered column order (self.colorder) are ignored.
    # #
    # Attributes set in the method are:
    # - start, end, source, ra, and dec: per row values in dirinfo file
    # - dirinfo_freqs: a dictionary that maps IF and
    # correspondiong Obs freqs in dirinfo file
    # ----------------------------------------------------------- #
    f = open(self.dirfile, 'r')
    lines = f.readlines()
    f.close()
    # exclude successive white space from lines
    delimiter = re.compile('\s+')
    num_lines = len(lines)
    num_col = len(self.colorder)
    loc_tab = []
    for idx in range(self.num_skip, num_lines):
        thisline = lines[idx]
        if thisline.startswith('#'):
            continue
        thisline = thisline.rstrip('
')
        loc_list = delimiter.split(thisline)
        if len(loc_list) < num_col:
            if self.verbose:
                print("row %d does not have enough data." % idx)
                print("Skipping %d: %s" % (idx, str(loc_list)))
            else:
                loc_tab.append(loc_list[0:num_col])
```

if self.verbose:
    print("%d: %s" % (idx, str(loc_list[0:num_col])))
nrow = len(loc_tab)
dx = self.colorder.index("Start")
self.start = numpy.array([self._convert_to_time(loc_tab[irow][idx]) for irow in range(nrow)])
dx = self.colorder.index("Stop")
self.end = numpy.array([self._convert_to_time(loc_tab[irow][idx]) for irow in range(nrow)])
dx = self.colorder.index("Source")
self.source = numpy.array([loc_tab[irow][dx] for irow in range(nrow)])
dx = self.colorder.index("RA")
self.ra = numpy.array([self._convert_to_direction(loc_tab[irow][dx], 0) for irow in range(nrow)])
dx = self.colorder.index("Dec")
self.dec = numpy.array([self._convert_to_direction(loc_tab[irow][dx].replace(':', ',', '.'), 1) for irow in range(nrow)])
dx = self.colorder.index("IF")
self.ifno = numpy.array([int(loc_tab[irow][dx]) for irow in range(nrow)])
dx = self.colorder.index("Obs freq")
freqs = numpy.array([float(loc_tab[irow][dx]) for irow in range(nrow)])
unique_if = set(self.ifno)

idx = self.colorder.index("offset")
offset = [float(loc_tab[irow][idx]) for irow in range(nrow)]
# print offset
my_qa = qatool()
offset_val = numpy.array([my_qa.convert(my_qa.quantity(offset[irow], 's'), self.time_unit)['value'] for irow in range(nrow)])
self.start = self.start - offset_val

def _convert_to_time(self, value):
    # ---------------------------------- #
    # Convert a datetime string to a value
    # The unit of the value is the same as
    # that of TIME column in scantable.
    # Available formats of input:
    # - 'YYYY/MM/DD/hh:mm:ss.s'
# - 'YYYY.DDD.hh:mm:ss.s'
# ---------------------------------- #
my_me = gentools(['me'])[0]
my_qa = qatool()

if len(value.split('/')) > 3:
    # assuming conforming date time string.
    loc_val = my_me.epoch(self.time_ref, value)
else: # assuming 'YYYY.DDD.hh.mm.ss.ss'
    ydtime = value.split('.')
    if len(ydtime) < 3:
        raise Exception, 'Non-confirming date time string, %s' % value
    value = ydtime[0] + '/01/00/' + '.'.join(ydtime[2:])
    days = my_qa.convert(my_qa.quantity(int(ydtime[1]), 'd'),
                  self.time_unit)
    loc_val = my_me.epoch(self.time_ref, value)
    return my_qa.convert(loc_val['m0'], self.time_unit)['value'] \
          + days['value']

return my_qa.convert(loc_val['m0'], self.time_unit)['value']

def _convert_to_direction(self, value, axis=0):
    # ---------------------------------- #
    # Convert an string of angle to the
    # unit identical to that of DIRECTION
    # column.
    # Available formats of input angle:
    # - 'dd.mm.ss.s'
    # - 'hh:mm:ss.s'
    # ---------------------------------- #
    my_qa = qatool()
    return my_qa.convert(my_qa.toangle(value),
                  self.dir_unit[axis])['value']
Appendix C

OTF extract code

The following code is an extraction of code taken from the AUTO_SPEC.PL PERL script, which handles with the OTF procedure at Tid-70m.

```
#Test OTF version done without data recording (correlator) (gw)
sub otf_observe {
    my ($rd,$apply, $el_offs, $xel_offs) = @_;
    my $rstr;
    my $dstr;
    my $rstr_c;
    my $dstr_c;
    my ($i,$j,$time_left,$obsfreq1,$obsfreq2,$n_pairs);
    my $step_fracofbeam_oft = 0.25; # fraction of the beam
    my $scanrate_otf = 3; #seconds per step

    ############ schedule file check ############
    # Grab the the following from the schedule file
    my $freq1 = $bandfreqs{$rd->{band}}; #$rd->{band}
    my $beam1 = get_fwhm($freq1);
    logit("freq = $freq1
beam = $beam1
");

    my $step = $step_fracofbeam_oft*$beam1; #needed for OTF movements,
    → originally taken from auto_boresight
    # Construct a message about the observation to take place. Put it in the log
    observe_start_messages($rd);
    # update the text variables
    observe_update_text_variables($rd);
    # set no of cycles to average before writing
    logit("Setting correlator averaging to $rd->{no_avg} cycles\n");
    if ($corr->avg($rd->{no_avg})) { # number of averaging
        logit("Correlator averaging changed.\n");
    } else {
        logit_red("Problem changing correlator averaging!\n");
    }

    configure_correlator($rd->{cor_config}); # set up a correlator config
```
open_correlator_data_file($rd->{obs_code}); # open a data file if necessary

# we need to assemble the following arrays:
# @rapos, @decpos: The positions for the various offsets
# @names: Source names for each offset
my ($rref, $dref, $nref, $cfref, $tref) =
  determine_pos_offsets($rd->{source},$rd->{ratur},
  $rd->{dectur},$rd->{pos_switch},
  $rd->{pos_offset}, $rd->{pos_time}, $rd->{uneven_times});
my @rapos = @$rref;
my @decpos = @$dref;
my @names = @$nref;
my @change_freq = @$cfref;
my @integ_time = @$tref;

if ($debug) {print "names, rapos, decpos, change_freq = ".
  "@names , @rapos, @decpos, @change_freq\n";}

# zero a few variables
my $time_on_this_source = 0;
my $time_needed = 0;
my $time_spent = 0;
$tv_time_spent = sprintf "%.2f min", $time_on_this_source;

# go to first source
($rstr, $dstr, $rstr_c, $dstr_c) =
  get_inject_src_strings($rapos[0],$decpos[0]);

# send the position from the schedule file ()
if (!$nmc->source($names[0],$rapos[0],$decpos[0],"j2000") =~ /COMPLETED/) {
  logit_red("Problem sending source info to NMC!\n");
  logit_red("Try again...\n");
  if ($debug) { logit("Sending NMC request
    \nmc->source($names[0],$rapos[0],$decpos[0],"j2000")\n");}
  if (!$nmc->source($names[0],$rapos[0],$decpos[0],"j2000") =~ /COMPLETED/)
    { logit_red("Problem sending source info again to NMC!\n");
    } else {
      logit_green("Source info received by NMC on second attempt\n");
      }
  }

#used for writing the refval in the rpfits file
($obsfreq1, $obsfreq2) = get_obs_freq($rd);
if ($debug) {print "calculated obs freqs = $obsfreq1, $obsfreq2\n";}
$obsfreq1 += $rd->{freq_offset};
$obsfreq2 += $rd->{freq_offset};
if ($debug) {print "calculated obs freqs with offsets = $obsfreq1, $obsfreq2\n";
}
set_freq($obsfreq1, $obsfreq2,$rd);

update_canvas_possw (0, "slewing",$rd->{pos_switch});
my ($slewaz,$slewelevel) = getazelset($rapos[0],$decpos[0]);
exec_summary_change_text("SlewingToSource",$names[0],$slewaz*360.0,$slewelevel*360.0);
# update text variables
$tv_source = $names[0];
$tv_rastr = $rstr;
$tv_decstr = $dstr;

# wait for the antenna to get on source
$antstat = "Slewing to $names[0]";
logit("$antstat\n");
$ant_stat_widget->configure(-background => 'red');
$ant_stat_widget->update;
wait_on_source();
# once on source change the antenna status of GUI
$antstat = "On-the-fly mapping"; $antstat_changed = 1;
$ant_stat_widget->configure(-background => 'SpringGreen'); # originally green
$ant_stat_widget->update;

# calls boresight sub routine
if ($apply && !$abort) {
apply_boresight_offsets($el_offs, $xel_offs);
$global_bore_el_offs = $el_offs;
$global_bore_xel_offs = $xel_offs;
}

# Insert code here if Determine if a minical is needed

logit("############ OTF Code Parameters ############\n");
#TODO: direction should depend on rising/setting
# do a xEl and -xEl scan
logit("Getting all of the input parameters\n");
logit("Beam=$beam1, step_fracofbeam_oft = $step_fracofbeam\n");
logit("scanrate = $scanrate_oft, band (Schedule File)=$rd->{band}\n");
update_canvas_possw ($i, "slewing",$rd->{pos_switch});
if (!$abort) {
    #after the telescope has reached this point stop the telescope on the Xel
    if (!$nmc->clr_rat('XEL') =~ /COMPLETED/) {
        logit_red("Clear rate failed.
");
    } else {
        logit("clr_rat XEL\n");
        #End of IF clear rate
    }

    if (!$nmc->clr_rat('EL') =~ /COMPLETED/) {
        logit_red("Clear rate failed.
");
    } else {
        logit("EL axis cleared\n");
        #End of IF clear rate
    }

    logit("go and do the wait_on_source\n");
    wait_on_source();
    my $temp_arcsec = (($step/$scanrate_otf)*3600);
    logit("############ OTF Code telescope movement ############\n");
    logit("move the telescope set_rate:
        $temp_arcsec\n");
    #This will move the telescope in XDEC
    if (!$nmc->set_rate('XDEC', ($step/$scanrate_otf)*3600) =~ /COMPLETED/) {
        logit_red("Set rate (XDEC) failed.
");
    } #End IF !$abort

    #starting point for the for loop
    my ($az, $el, $time) = $nmc->get_offsets(); #Get the az el and time from
    get_offsets redeclaring to be on the safe side
    logit("get_offsets reports AZ=$az, EL=$el, Time=$time\n");
    logit("Source $names[$i] RA $tv_rastr Dec $tv_decstr Az $tv_az El $tv_el\n");

    # Sending the name to the correlator, contents send from the schedule file
    to the array to here
    if (!$corr->source($names[$i],$rapos[$i],$decpos[$i],"j2000")) {
        logit_red("Problem sending source info for $names[$i] to correlator!\n");
    }
    # Correlator integrate, passing the integrate time and record
    logit("integrate($integ_time[$i],$rd);
    calibrate($rd,1);
    integrate_otf($integ_time[$i],$rd);

    #stop the telescope clr_rat
    if (!$nmc->clr_rat('XDEC') =~ /COMPLETED/) {
        logit_red("Clear rate failed.\n");
    } else {

logit("XDEC axis cleared\n");
}  #End of IF clear rate

logit("################ END of the OTF section ############\n");

#$tv_source = $names[$i];
$tv_rastr = $rstr;
$tv_decstr = $dstr;

if ($abort) {return();}

# Finished with this source, change status to done.
$rd->{status} = "done";
return();
}  # END of otf_observe