The Formation of Molecular Clouds in our Galaxy

OPAL Mopra Cover Sheet

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Proposal Details

Previous proposal number	M446
Previous publications	1
Proposal type	Large Project
Continuing	No
Scientific categories	star formation, interstellar medium in and around the Milky Way
Help required	Consultation
Used for PhD thesis	Yes

Instrument Information

Consulted archives	No
Time allocation	ATNF
Observations type	Spectral line + on-the-fly-mapping
Other information	Mapping

Abstracts

Scientific

We propose a major program to observe, for the first time, the formation of molecular clouds in our Galaxy. This program makes use of the Mopra, NANTEN2 and STO telescopes to measure the principal cooling lines from the molecular, atomic and ionized gas in the interstellar medium in the galactic plane. These lines (CO, CI, CII & NII), emitted in the mm, sub-mm and THz bands, provide diagnostics which can trace the state of the gas, including when and where molecular cloud formation is taking place. With Mopra we will map the distribution of the isotopologues of the CO molecule along a sector of Fourth Quadrant of the Galaxy. Having verified the technique of "fast mapping" with Mopra, we now wish to begin the program by mapping a 2x2 degree region of this sector, crossing from the edge of a spiral arm into the inter-arm gas.

Outreach

Mopra will be combined with telescopes in Chile and Antarctica in an investigation to study where and how giant clouds of molecular gas are formed in our Galaxy. This is a fundamental process occuring within the interstellar gas between the stars, one which dictates the rate at which stars can form in our Galaxy.

Scheduling

Special requirements	Fast mapping needed.
Preferred dates	**March. Night time needed.**

Total time for project	**800 hours (previous + this proposal + future requests)**
Allocated time so far	**50 hours (all previous semesters)**

OPAL Mopra Observations Table

Name	Position			LST range		Integration time (hours)	Repeats	Total time	Target type	Backend	Frequencies (GHz)	Rms required (mK)
	RA	Dec	Epoch	Start	End							
G326+0	15:44:00	-55:00:00	J2000	7:58	23:29	12.0	16	192.0	scanning/mapping	MOPS Fastmapping (4 x 137 MHz)	111	1000

Total time for semester: 192.0 hours

The Formation of Molecular Clouds in our Galaxy

An international collaborative program for the Mopra, NANTEN2 and STO telescopes

Overview

This is a continuation proposal for a project whose objective is to observe, for the first time, how molecular clouds form in our Galaxy. The rate at which molecular gas forms is the rate-determining step for star formation, and so is a central issue in understanding the star-gas cycle. This project brings together three telescopes: Mopra, NANTEN2 (a 4m sub-millimetre telescope in Chile run by the Universities of Cologne and Nagoya, with an Australian university consortium) and STO (the Stratospheric Terahertz Observatory, a 0.8m balloon-borne THz telescope in Antarctica led by the University of Arizona). It has the aim of mapping, at similar spatial and spectral resolutions, the principal cooling lines in the molecular, atomic and ionized gas across a spiral arm of our Galaxy. This will allow us to determine where the atomic gas is compressed and molecular clouds form. Mopra will be used to survey a sector of the fourth quadrant of the Galaxy to map the distribution of three isotopologues of CO (^{12}CO, ^{13}CO & C^{18}O), the principal tracer available for molecular gas. In a pilot study awarded time in April 2010 we tested the "fast-mapping" techniques required to map many square degrees of sky, and obtained strip scans across the galactic plane at 5 positions to verify that the CO isotopologues would be detectable with the required sensitivity. We now wish to begin the program, by obtaining data for the first section of the survey region.

Background

The Formation of Molecular Clouds

The evolution of much of our Galaxy can be understood through following its star-gas cycle. This is the cycle of materials that takes the elements produced by nucleosynthesis in the cores of the most massive stars, ejects them in stellar death and passes them through the phases of the interstellar medium, finally incorporating them into the next generation of stars. A critical part of the cycle that is not understood is how the molecular clouds form, the environment from which stars are then born (e.g. Bally, 2001). Our program will reveal where and by what means this occurs – whether by coalescence, self-gravity or shocks in turbulent flows – and so enable us to ascertain the rate of molecular cloud formation in our Galaxy. This sets the rate of star formation in the Galaxy, for stars then form inside the molecular clouds.

The manner in which atomic gas is gathered into molecular clouds has yet to be observed. It is clear, however, that from observations in some other galaxies, where the entire atomic and molecular structures can be overviewed, that molecular clouds are formed from large structures of atomic gas that envelope spiral arms (e.g. as in the galaxy M33; Engargiola et al., 2003). Such observations, however, lack the spatial resolution necessary to resolve the processes by which this occurs. These must be observed in our Galaxy, and requires us to map the requisite structures across a spiral arm.

Four principal mechanisms have been proposed for the process of assembling atomic gas into molecular clouds. These are (i) the self gravitational collapse of an ensemble of small atomic clouds, (ii) the random collisional agglomeration of small clouds, (iii) the accumulation of material within high pressure environments such as shells driven by the winds and supernovae from high mass stars, and (iv) the compression and coalescence of gas in the converging flows of a turbulent medium. They provide quite different pictures for the structure and evolution of molecular clouds. For instance, under mechanism (i) the gravitational collapse of a cluster of atomic clouds produces molecular clouds that are long-lived and stable, supported against gravity by internal turbulence and magnetic fields. This can be regarded as the classical view of a "giant molecular cloud" (e.g. Blitz & Williams, 1999). This contrasts strongly with the picture given by mechanism (iv), of compression in converging flows, where gravity plays little role. It produces molecular clouds that are transient features (e.g. Elmegreen, 2007).

Discerning the Processes at Work through Diagnostic Tracers

The reason we have not been able to observe molecular cloud formation to date is that we have lacked the capability to make the necessary measurements, for key processes cannot be studied with any diagnostic lines emitted from the principal components of the gas, the atomic and molecular hydrogen. For H_2, the energy levels are too widely spaced for the molecule to be excited in the typical environment where it is found, unless the gas has been heated to temperatures of order ~1,000K, e.g. by shock waves. For atomic gas, while there is a line at 21cm from the spin-flip transition of HI, its emission is not sensitive to the gas density and so cannot be used to discriminate between the cold, dense and the warm, diffuse phases of the gas.

It is necessary to follow the cycle using rarer species that trace the physical processes at work. In particular, these involve carbon, which can be found in ionized form (C^+) emitting in THz bands, in neutral form (C) emitting in sub-mm, and in molecular form (as CO) emitting in the millimetre. Ionized nitrogen (N^+), also emitting in the THz, is the other crucial diagnostic species, arising from the warm ionized gas. The C^+ and N^+ lines are major coolants of the ISM, as seen by the COBE satellite (Bennett et al., 1994). They provide probes of where molecular cloud formation is occurring (C^+) and of the rate of star formation (N^+) across the Galaxy. As an illustration of how these species can be used to follow the state of the gas, Fig. 1 shows a model prediction we have made for the emission from a UV-irradiated gas cloud, as the line of sight passes through the ionized, atomic and molecular components. Using the combination of these four species, their origins be ascertained and hence the state of the gas, including where the molecules are forming.

The Companion Facilities brought together to tackle the problem

Despite their importance the THz lines have been little studied as the atmosphere is virtually opaque to them. With the launching of the balloon-borne STO THz telescope this investigation now becomes possible. The program then requires tools able to make complementary observations at comparable spatial and spectral resolutions across the galactic plane in the diagnostic lines emitting in mm and sub-mm bands. These are now available through the Mopra and NANTEN2 telescopes. To these, we add the 21cm HI data gathered by Parkes and ATCA as part of the SGPS (McClure-Griffiths et al., 2005) to trace the atomic gas. The molecular line observations obtainable by Mopra are crucial here. This is because, as seen in Figure 1, C^+ emission can arise from all phases of the gas. *Without the CO that Mopra provides*, it will not be possible to distinguish between C^+ emission from the surfaces and the interiors of molecular clouds. *We would not be able to determine where the formation of molecular clouds is taking place*.

Aside from being the only telescope that is able to obtain the CO data needed with the requisite spatial resolution, Mopra also has the particular advantage that it can measure the three main CO isotopologues simultaneously (CO, ^{13}CO, $C^{18}O$). This allows the optical depth, and hence the column density of the gas, to be directly determined, in addition to measurement of the line intensity and profile. No previous CO survey conducted by any other facility has been able to make such a combination of measurements. This will result in a resource of enormous value to a wide range of other investigations on molecular clouds and star formation, in addition to the science we are proposing here.

Mopra "Fast-mapping" Test Data

Fast mapping for Mopra requires using a system cycle time of 2.048s instead of the standard 2.0s, and obtaining 8x0.256s bins in this period. The scanning speed of the telescope can be then increased without degrading the spatial resolution, though of course for a loss in sensitivity (which only makes this method useful for CO). Due to the increased data rate only 4 zoom modes can be used, instead of the normal maximum of 16. We investigated the performance of Mopra for fast mapping during the pilot study and have provided a report to ATUC on our findings. Fast mapping is not simply a scaled up version of normal mapping (i.e. by 8 times the speed) since the increased scan rates also result in partial coverage at the end of scans due to the rapid acceleration of the telescope. Scan lengths need to be adjusted to compensate. Also, to maximise efficiency, scans should be done as a series of long strips as opposed to square boxes. We have found, for instance, that scanning at 36″/s with 12″ spacing between rows (instead of 3″/s and 9″ for normal mapping) produces acceptable results, but that a 66′ scan length should be used to provide uniform spatial coverage over a 60′ long strip, before a reference sky measurement is taken. These strips are then repeated to cover a width of 5′ in ~75 minutes. Complete coverage of a 1°x1° field, scanning in both directions, would then take ~30 hours of telescope time, and with overheads for pointing and calibration a total of ~36 hours.

In Fig. 2-L we show a sample image obtained by fast mapping, of ^{12}CO emission in the Carina nebula. In Fig. 2-R we show a PV-diagram from a 4°x6′ *b*-strip scan conducted at $l=330°$ in ^{12}CO, illustrating that the sensitivity is sufficient for detecting CO line emission across the galactic plane.

Observations

The full region that STO will map in C^+ and N^+ will depend on the length of the balloon flight achieved, but this region will cover at least $l=323°–330°$ and $b=\pm1.5°$, since this is the region of the Galactic plane favoured from a circumpolar flight around Antarctica where the balloon itself restricts the viewing angle. It also passes from a spiral arm into an inter-arm region, through which molecular cloud formation must occur. This is the minimum region we need to survey with Mopra (i.e. 21 square degrees). If the maximum flight duration is achieved by STO the areal coverage could be twice this large.

We would map simultaneously the ^{12}CO, ^{13}CO, $C^{18}O$ & $C^{17}O$ lines (115.3, 110.2, 109.8, 112.3 GHz, respectively). For fast-mapping the achievable 1σ line detections should be ~0.6 & 0.4 K km/s at 115 & 110

GHz (this assumes a line width of 5 km/s and corrects for the dish efficiency). This compares with the "normal" mapping sensitivity of ~0.2 & 0.1 K km/s at the same frequencies. As discussed above, in 36 hours a 1°x1° region can be mapped to this level, scanning in two orthogonal directions.

CO observations can be obtained during nights in the summer months, as we have demonstrated during our pilot study, with a system temperature typically increased by ~30% and more periods with unacceptable baselines. Thus, in 16 x 12 hrs (with a 33% weather allowance) we anticipate being able to cover ~2°x2° of the survey region. We would cover the region shown in Figure 3 (*l*=325.25°–327.25°, *b*=±1°). We deem it prudent to begin the survey through this limited area map to ensure our mapping procedures are in order. We would then seek further extended time allocations for the winter periods with optimal weather conditions. To cover 21 square degrees will take ~2 months (at 12 hours / transit). However, by the time these observations are made we will know whether STO has been able to conduct a larger area survey and so need a larger Mopra survey. We suggest that this full time allocation might then be spread over 3 seasons, 2011–13.

Proposal Team and Analysis

The project team consists of scientists from UNSW (Burton, Storey, Tothill), together with the lead investigators for NANTEN2 from Germany (Stutzki, Simon) and for STO from the USA (Hollenbach, Walker, Kulesa, Martin). Burton has been involved in development at Mopra for over a decade, and with Storey wrote both the ARC proposal providing the UNSW–MOPS and the initial UNSW proposal funding the dish extension to 22m. Storey is also an acknowledged leader in instrumentation needs for Antarctic astronomy. Tothill is a post-doctoral fellow with extensive expertise in mm-wave astronomy, including a year wintering with the AST/RO telescope at the South Pole. Stutzki heads the Cologne group, and Simon has major responsibility for running NANTEN2; the group also has experience with large-scale molecular surveys using Herschel, SOFIA and the FCRAO. Hollenbach is project scientist for STO, a leading theorist on the excitation of the interstellar medium, who will lead the scientific interpretation of the data sets. Walker leads the University of Arizona radio astronomy laboratory (SORAL), and Kulesa is responsible for operations of STO. Martin has also wintered with the AST/RO telescope and leads a Herschel key project. His group at Oberlin are developing the analysis tools for STO, adapted from this Herschel project.

Data reduction is performed using the excellent Livedata and Gridzilla packages developed and recently updated by Mark Calabretta, with extensions added to handle the format of the MOPS data. The final images are large (the full survey will produce ~1 TB of reduced data), and require impressive amounts of memory to handle, but this is within the ability of high-range Linux PCs.

We are also seeking ARC DP funding to support the Mopra component of the project. STO and NANTEN2 are funded through significant grants from the NASA Long Duration Balloon program and the German & Japanese national & state funding agencies. Funding for the Australian involvement in NANTEN2 has been provided through ARC LIEF, with a renewal application also current.

Timeline and Data Release

STO is now scheduled for launch in January 2012 (it has been delayed for a year to accommodate a larger dewar which permits a longer flight). The SMART sub-mm multibeam receiver has been commissioned on NANTEN2, and a series of major survey projects with the telescope will begin in the 2010, including this program. It is anticipated that data collection will extend over 3-4 seasons (2010~13), similarly to Mopra. The Mopra data will be publicly released so that it can be used for other studies. We anticipate being able to do this within a year of completing the data collection, but depending on what funding support is received it may be possible to releases tranches of the data earlier. We plan to incorporate the data within the STO archive. This will use packages being developed by Martin for a Herschel key project, which can readily be extended to incorporate the data obtained in this project. This will provide both fits and class format files, and be accessible via a mySQL relational database, accessed via a wiki page.

Outreach

This data set will have tremendous value for a range of other studies on the ISM of our Galaxy, and so benefit the wider astronomical community. It will also contribute to providing a complete map of the molecular medium of the southern Milky Way, with an order of magnitude better spatial and spectral resolution than the currently available surveys. However, Mopra is currently not capable of undertaking a larger survey than we are proposing, including of the full southern Galactic Plane, without both an upgrade to a multibeam detector or the dedication of most of several winter observing seasons to such a project.

We will develop a public webpage portal for the project through a wiki. Here we will provide information on the project and release images and data where appropriate.

Response to Previous TAC Comments

"The TAC suggests that future proposals may be strengthened by the inclusion of additional detail on what this CO survey offers over any existing programs that overlap the survey area and further analysis of the need and detectability of the ^{13}CO *and* $C^{18}O$ *lines".*

This survey provides an order of magnitude better spectral *and* spatial resolution than the existing large scale CO maps of the southern galactic plane, those conducted by Dame et al. (2001) and by the first Nanten telescope (and still unpublished; see Onishi, 2008). The only other molecular survey that covers the region is the HOPS, but this has 5 times lower spatial and spectral resolution and is only sensitive to the gas in the dense cores, not that in the extended molecular clouds. There are limited area surveys, such as the Mopra DQS (Bains et al. 2006), which cover small fragments (~0.5°) of the survey area.

As discussed earlier, the CO isotopologues are used to derive the optical depth of the line emission, and so provide a measure of the column density of the gas. For the PV diagrams in our pilot study ^{13}CO line was detected over virtually the full extent of the ^{12}CO emission region, but the $C^{18}O$ line only at the brightest peaks. $C^{17}O$ is not expected to be seen. These isotopologues are also obtained for free; there is no additional observing time required and the only penalty is additional disk space and processing time for the analysis.

References

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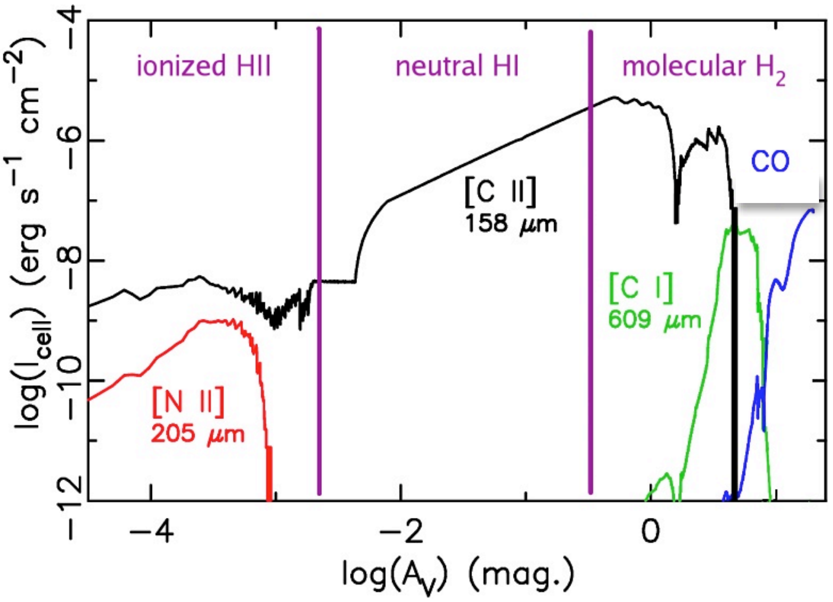

Figure 1. Model depiction of the intensity of diagnostic lines of carbon and nitrogen species as viewed through a UV-illuminated cloud from depths of A_V *=0 to 20 magnitudes, passing from the ionized exterior, through atomic gas, into the molecular cloud. Vertical lines show the HII-to-HI-to-*H_2 *boundaries found at the edges of dense interstellar clouds. This figure demonstrates that observations of the three carbon species (CO, [CI] & [CII]), combined with [NII], all made with similar spectral and spatial resolution, can be used to probe the structure of the gas. For instance, the presence of [CII] and [CI] but without CO will probe surface layers of molecular clouds where the* H_2 *must form but others molecules are still absent since they cannot self-shield*

from the UV. [NII] is used to disentangle the [CII] emission stemming from ionized gas. HI similarly can be used to disentangle [CII] emission from the neutral gas.

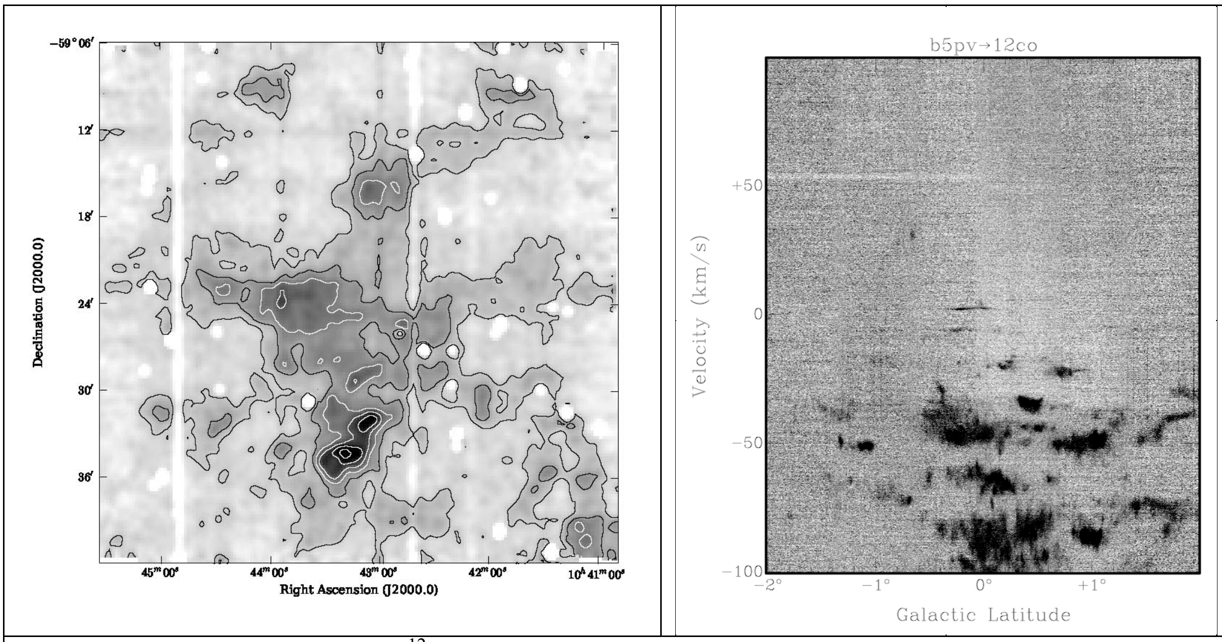

Figure 2 (left): Test map of the ^{12}CO J=1-0 emission in the Carina nebula obtained using the technique of "fast-mapping". The map covers 36′ x 36′ and represents ~6 hours of telescope time, obtained over several nights, including periods of thick cloud. It also has been incompletely scanned in RA and Dec, hence there are a number of scanning artefacts and missing data. Nevertheless the emission is clear. The map also provides a potent demonstration of how the capabilities of Mopra have improved since the telescope was commissioned. A similar map was obtained by Kate Brooks for her PhD thesis in 1996-97. It took several months to complete, while living at the telescope, and was obtained in only 1 polarization with a 45″ beam, 0.2 km/s & 64 MHz bandwidth and an under-sampled grid. The map above is dual-polarization, 30″ beam, 0.1 km/s & 137 MHz bandwidth, and is one of four measured simultaneously, observed from the PI's desk in short spells in-between teaching duties!

Figure 2 (right): Sample data from a 4° x 6′ *b*-strip scan across the galactic plane at *l*=330° obtained using "fast-mapping" during our pilot observations. Shown are position-velocity (PV) images of the ^{12}CO J=1-0 line emission covering *b*=±2° and V_{LSR}=±100 km/s. Data were also simultaneously obtained in the ^{13}CO, C^{18}O & C^{17}O lines; ^{13}CO was detected over most of the region of ^{12}CO, C^{18}O only in the brightest peaks and C^{17}O was not seen, but serves as a control for determining noise levels. Note also that the negative emission seen at +50 km/s is caused by emission from a reference position.

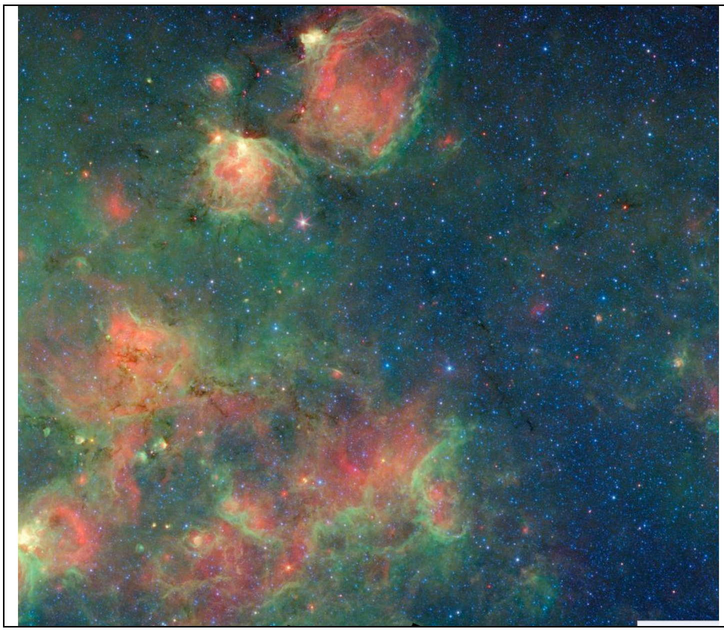

Figure 3: Infrared view of the area we would map for the first part of the survey, from *l*=325.25°-327.27° and *b*=±1°. Obtained with the Spitzer space telescope, the image shows 24μm (R), 8μm (G) and 3.6μm (B) continuum emission, covering 2°x2° at the edge of a spiral arm. To the left are a series of HII region, seen through their dust (R) and PAH (G) emission. To the right are seen mostly stars (B) in an inter-arm region. CO emission is, however, extended over field, as mapped by the Dame et al. (2001) Colombia survey at 8′ resolution, though is considerably brighter to the left side of the image than it is to the right. The range of processes that lead from molecular cloud formation to massive star formation must be take place across this region, making it a suitable place to begin this study.