The Mopra–STO–Nanten2 Atomic and Molecular Gas Survey: The Formation of Giant Molecular Clouds

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	Yes
Time allocation	ATNF
Observations type	Spectral line + on-the-fly-mapping
Other information	Mapping

Abstracts

Scientific

We propose a Mopra CO survey across a spiral arm of our Galaxy in a region containing 5-10% of the gas and dust mass in the Galaxy. Mopra will provide the distribution and dynamics of the CO molecule in three isotopologues. As one application, we will determine how the formation of giant molecular clouds occurs. This fundamental process, which is the rate-determining step for star formation, has not yet been observed. We will make use of the high spectral and spatial resolution of the Mopra, Nanten2 and STO telescopes, combined with existing archival 21 cm wavelength radiation from atomic H, to measure the best cloud tracers arising from the molecular and atomic gas in the interstellar medium in the galactic plane. These lines (CO, [CI], [CII] and HI 21 cm) provide diagnostics that can trace the state and dynamics of the gas, including how and where molecular cloud formation is taking place.

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 occurring 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.
Total time for project	**1100 hours (previous + this proposal + future requests)**
Allocated time so far	**150 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)
	Glong	Glat	Start	End							
G324-330	327°.0	+0°.0	8:07	23:31	12.0	21	252.0	scanning/mapping	MOPS Fast-OTF (4 x 137 MHz)	111	2000

Total time for semester: 252.0 hours

The Mopra–STO–Nanten2 Atomic and Molecular Gas Survey: The Formation of Giant Molecular Clouds

Science Rationale

Overview. The basic activity of a spiral galaxy like our own is the continual collection of diffuse and fragmented gas and dust clouds into large Giant Molecular Clouds (GMCs) which contain 10^5 to $10^{6.5}$ solar masses of gas. The GMCs then produce most of the star formation in the galaxy. To some degree this process is a cycle, as stellar death not only partially replenishes the interstellar gas and dust (some gas is also added by infall of material onto the spiral disk), but the stars also destroy the GMCs and provide turbulence to the interstellar medium (ISM), thereby affecting the collection of the diffuse and fragmented ISM clouds back into GMCs. One of the largest unsolved mysteries in galactic studies is how GMCs are formed. This is a continuation proposal for a project whose objective is to provide an invaluable CO survey of a significant portion of the star-forming region of our Galaxy seen only from the Southern Hemisphere, and, as a primary application of this survey, to determine how molecular clouds form in our Galaxy. 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 (~1 arcminute) and spectral (< 1 km/s) resolutions, the principal cooling lines (and the best tracers) of molecular and atomic gas in this region. These lines will allow us to determine where and how the atomic gas and the "small" (see below) molecular clouds are collected to form GMCs. 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 previous approved time we have obtained strip scans across the galactic plane at 5 positions to verify that the CO isotopologues would be detectable with the required sensitivity, and will map ~1 square degree of our proposed survey area in time awarded for March 2011. We now wish to extend this a further 6 degrees of galactic longitude across a spiral arm, in the galactic plane (latitude b = –0.5 to +0.5 degrees where most of the gas lies) in order to survey a large enough area to include both spiral arm and interarm, and to encompass regions large enough to harbour the small clouds necessary to build GMCs. In future proposals for 2012-2013, we plan to map an additional 20 square degrees between longitudes 320 to 350 degrees, corresponding to the full STO survey area. This full Mopra CO survey will provide an archival legacy to the community that will enable the study of many problems (listed below) and will provide a template for the understanding of galaxy evolution in spiral galaxies too distant to study in detail with current spatial resolution and sensitivity.

The Formation of Molecular Clouds. Observations of external spiral galaxies show that massive stars and GMCs tend to form in the compressed regions of spiral arms, behind the spiral density wave shock. If the region of the galaxy is primarily atomic, then the atomic gas is somehow collected to form GMCs, as seen in M33 (Engargiola et al 2003). If the region is mainly molecular, such as in our own "molecular ring" which extends from about 3 kpc to 5 kpc in our Galaxy and which lies in our survey area, then the collection into GMCs may involve small molecular clouds ("fragments") bound by pressure rather than self-gravity. The manner in which gas is gathered into GMCs has yet to be observed, but four principal mechanisms have been proposed: (i) the self gravitational collapse of an ensemble of small clouds, possibly along magnetic field lines as in the Parker instability (Ostriker & Kim 2004), (ii) the random collisional agglomeration of small clouds (Kwan & Valdes 1987), (iii) the accumulation of material within high pressure environments such as shells driven by the winds and supernovae from high mass stars (McCray & Kafatos 1987), and (iv) the compression and coalescence of gas in the converging flows of a turbulent medium (Hennebelle & Perault 2000). They provide quite different pictures for the structure and evolution of GMCs. For instance, under mechanism (i) the gravitational collapse of a cluster of 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 GMC (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).

Distinguishing How GMCs Form. The assembly time for a GMC is approximately the radius (~100 pc) of a cluster of small clouds divided by the speed (~5 km/s, turbulent or gravitational) at which they come together, or ~20 Myr. Since this is comparable to, or greater than, the estimated ages of GMCs, we should observe as many or more clusters as we observe GMCs along each line of sight (i.e. ~1–10). Our survey area should include about 10-100 GMCs and a similar number of "forming" GMCs. We have discussed above the four theories of GMC formation. If clouds form by the gravitational collapse of a cluster of small clouds (i), our observations will show either a roughly spherical distribution of small clouds or possibly a filamentary distribution with the filaments following ballooned magnetic field lines out of the galactic plane (the Parker instability) with velocity characteristics of infall. In addition, our measurements determine the mass inside any cluster radius. We can compare gravitational (virial) velocities with the observed velocity dispersion of the clouds, and they should be comparable. If they form by random (no gravity) collisional coagulation of small clouds (ii), the velocity field of the cluster clouds will look more random and less systematic than infall and their velocities will exceed virial speeds. If they are formed in wind or supernova-driven shells (iii), the shell-like morphology will be apparent. If they formed by converging flows in a turbulent medium (iv), we should see overall a turbulent velocity field but local to the formation side the velocities will be coherent (converging) and not random, and the speeds will be super-virial.

Angular and Spectral Resolution. In order to contain sufficient mass to build a GMC an atomic cloud needs to have a hydrogen column of order 10^{21} cm^{-2}, which corresponds to a diameter of about 7 pc at interstellar pressures. Small molecular clouds need similar columns, but are cooler and denser and so may have sizes of order 1–2 pc. GMCs themselves have diameters of ~10–100 pc. Ensembles of small clouds that are moving at detectable (> 1 km/s) speeds to coalesce into GMCs will have ensemble diameters of 200–1000 pc. Our survey area goes through the molecular ring of our Galaxy at distances of typically 8 kpc, and therefore these sizes correspond to 1–3 arcminutes for the small clouds, 4–40 arcminutes for the GMCs, and 1.5–7 degrees for the ensembles of small clouds. Therefore, we require 1 arcminute spatial resolution to resolve individual clouds and a survey area that extends at least 7 degrees in the Galactic plane—preferably across a spiral arm.

The linewidths observed toward small individual clouds are of order 1 km/s and toward GMCs ~2–3 km/s. Velocity information is generally used to place the clouds along the line of sight (los), using the galactic rotation curve. In our direction, 1 km/s corresponds to about 30–40 pc[1]. However, if clusters of clouds are seen in the two dimensions on the sky, then we can also determine velocity dispersion in the cluster by eliminating any spatial elongation (called the "finger of God" by cosmologists) along the los. Figure 1 shows a los observed using Mopra by the GOT C+ Herschel team and one sees the various molecular clouds along the los (typically, we will see about 5-10 CO features per los). Therefore, we require < 1 km/s spectral resolution to determine the 3D distribution of clouds and the velocity distributions of clouds in ensembles.

Optimum Tracers and Facilities. CO is well known to be the best tracer of molecular gas: although hydrogen is the most abundant element in the ISM, molecular hydrogen needs to be warmer (>100 K) than much of the molecular cloud gas (T~10 K) to be detected. [CII] 158um and sub-mm [CI] lines are the best tracers of atomic gas (and gas which is H_2 but which has most carbon in C^+ and C), when used in conjunction with atomic HI 21 cm wavelength archival data. Mopra (CO), STO ([CII]) and Nanten2 ([CI]) all have the required spatial resolution (< 1 arcminute) and spectral resolution for this study[2]. Mopra is essential for this work because: (i) the science requires complementary [CII] data, which will only be taken by STO from Antarctica, and Mopra is the only telescope in the Southern Hemisphere capable of observing CO J=1–0 with sufficient spatial resolution; (ii) Mopra has uniquely broad bandwidth, allowing simultaneous CO, ^{13}CO, and C^{18}O observations and producing enhanced survey data; (iii) recent improvements in Mopra instrument and software now permit "on-the-fly" mapping, a greatly superior observing method that has not been used in previous surveys.

It should be noted that Nanten1 undertook a CO J=1-0 survey in this region, but it was sparsely sampled, lacked sufficient spatial resolution, and so is inadequate for this task. That data is also still unpublished (Onishi 2008). In addition, the GOT C+ Herschel project looked at numerous los in [CII] and combined that data with HI 21 cm and Mopra CO J=1–0 data (see Figure 1). They demonstrated the spectra we will obtain in our project, but their lack of mapping precluded them from answering the key problem of cloud formation. Two of the CoIs on this proposal include Pineda (the PI on the Mopra GOT C+ project) and Langer (the PI of the GOT C+ project), bringing their expertise and experience to our data analysis. In summary, the optimum observations to determine cloud formation include Mopra CO J=1–0 and STO [CII], complemented with existing HI 21 cm and planned Nanten2 [CI]. Both the latter two have similar spectral and spatial resolution to Mopra and STO.

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[1] There will be a "distance ambiguity" between the near and far side of the Galaxy, but we can use, for example, cloud sizes and virial velocity arguments to resolve this. Also, the region around the tangent point has no ambiguity.

[2] As a minor point, [NII] 205μm observations, also taken with STO, determine the amount of [CII] produced in HII regions, which is then subtracted from the total [CII] emission to estimate the amount of [CII] arising from atomic gas.

Archival Value of Mopra CO J=1–0 Survey. The full Mopra CO J=1–0 survey, when completed, will provide the community with a significant archive that can be mined to study numerous problems (sometimes with the addition of ancillary observations), such as: the distribution of GMC masses and sizes in this important region of the Galaxy (the full survey will encompass nearly 25% of the molecular mass of the Galaxy, and nearly 10% of the atomic mass); the distribution of the columns of molecular gas, or optical extinction A_V, through GMCs, which may be linked to the star formation rate in a GMC (see McKee 1989); the turbulent velocity field in the molecular ISM; the destruction of GMCs by supernovae and by the photoevaporation caused by hydrogen ionizing photons (EUV) as well as far ultraviolet (FUV) photons that heat neutral gas; the distribution of the FUV fluxes on molecular cloud surfaces; the structure (shape and clumpiness) of large and nearby GMCs, and the correlation of star formation rates within GMCs to their properties. It should be noted that, aside from being the only telescope that is able to obtain the CO data needed with the requisite spatial and spectral resolution, Mopra also has the particular advantage that it can measure the three main CO isotopologues simultaneously (^{12}CO, ^{13}CO, C^{18}O). This allows the optical depth, and hence the column density of the gas, to be directly determined (see Figure 2), 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.

Observations

The full region that STO will map (the launch from Antarctica will occur in December of 2011) 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=±0.5°, a region chosen to fulfill the requirements discussed above on cloud ensemble size and height of the molecular layer of the galactic plane, as well as including both arm and interarm regions. This is the minimum region we need to survey now with Mopra (i.e. 7 square degrees). If the maximum flight duration is achieved by STO, the areal coverage could be 4 times this large. This would be the "full" Mopra survey we envision.

We would map simultaneously the ^{12}CO, ^{13}CO & C^{18}O[3] lines (115.3, 110.2, 109.8 GHz, respectively) using fast-OTF, employing the method we have determined through our commissioning of this mode. Fast-OTF takes 8x256ms samples in each 2.048s cycle time and uses a series of 66′ long scans for each 60′ row to compensate for variable telescope speeds at the end of each scan row, scanning at ~30″/s (in contrast to ~3″/s and the square maps used with standard-OTF). With a typical T_{sys}~800/300K at 115/110 GHz respectively, the 1σ noise in a 0.1 km/s channel is T_A^*~2/0.8K after summing over the oversampled pixels and scanning in two orthogonal directions. For a typical ~5 km/s wide line, the 1σ survey line flux sensitivity will then be ~3/1 K km/s after correction for aperture efficiency. With ~30% overheads, in 43 hours a 1°x1° region can be surveyed. In March 2011 we plan to map 1°x1°. In this proposal we ask for time for the additional 1°x6°, or 21 x 12 hour shifts. We would cover the region shown in Figure 3 (l=323°–330°, b=±0.5°). To cover the maximal STO survey area of 30 square degrees will take an additional ~2 months (at 12 hours / transit). We suggest that this additional allocation might be spread over 2 seasons, 2012–13, but will defer this full request until the launch of STO.

Proposal Team and Analysis

The project team consists of scientists from Australia (Burton, Storey, Tothill, Rathborne, Rowell, Urquhart), together with lead investigators for Nanten2 from Germany (Stutzki, Simon) and for STO from the USA (Hollenbach, Walker, Kulesa, Stark, Martin, Pineda, and Langer). 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. 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. Rathborne, Rowell & Urquhart are experienced Mopra observers. 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 and will assist on the rapid data release of the proposed Mopra survey. Stark has considerable experience in CO and CI surveys, and has observing experience on Mopra. 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,

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[3] Note also that we will also obtain, for free, the C^{17}O line at 112.3 GHz, but it is not expected to be detectable.

adapted from this Herschel project. Langer and Pineda, besides being on the STO team, are the PI of the GOT C+ Herschel Key project and PI of the Mopra CO J=1–0 ancillary observations for GOT C+, respectively.

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.

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 for 2011 through ARC LIEF. We also note that a companion program to extend the work of STO, the High Elevation Antarctic Terahertz (HEAT) telescope, has also recently been funded with the combination of US NSF and Australian EIF (i.e. the PLATO program) support.

Timeline and Data Release

STO is now scheduled for launch in December 2011. The SMART multibeam receiver has been commissioned on Nanten2, and a series of major survey projects with the telescope will begin in 2011, including this program. It is anticipated that data collection will extend over 3 seasons (2011–13), similar to Mopra. **In order to maximize the broad scientific impact of this survey, we will immediately make the Mopra and Nanten2 data available over the web for all to use, without a proprietary period.** The initial data release will occur within *one month* of the data acquisition and consist of lightly processed and reformatted data that will be of particular benefit for other Mopra users. Subsequent data releases, expected to be made every ~6 months, will feature fully processed and calibrated FITS cubes for easy scientific visualization and interpretation. Ultimately, the Mopra data will be incorporated into the STO archive, making it easy to explore the entire cold interstellar medium seen through carbon ions, atoms, and molecules via a single unified dataset. An intuitive web page interface will allow the full archive to be queried via a relational database, so that small portions of the massive dataset can be easily downloaded (http://soral.as.arizona.edu/STO)[4].

Outreach

This data set will have tremendous value for a range of other studies on the ISM of our Galaxy, and so greatly 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 the full (30 square degrees) survey that we anticipate extending this program to cover, however, without an upgrade to a multibeam detector and the dedication of most of several 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. The STO project is described further at http://www.astro.uni-koeln.de/sto.

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[4] Note that the cubes from the bstrip scans we obtained in May 2010 are publicly available from this site.

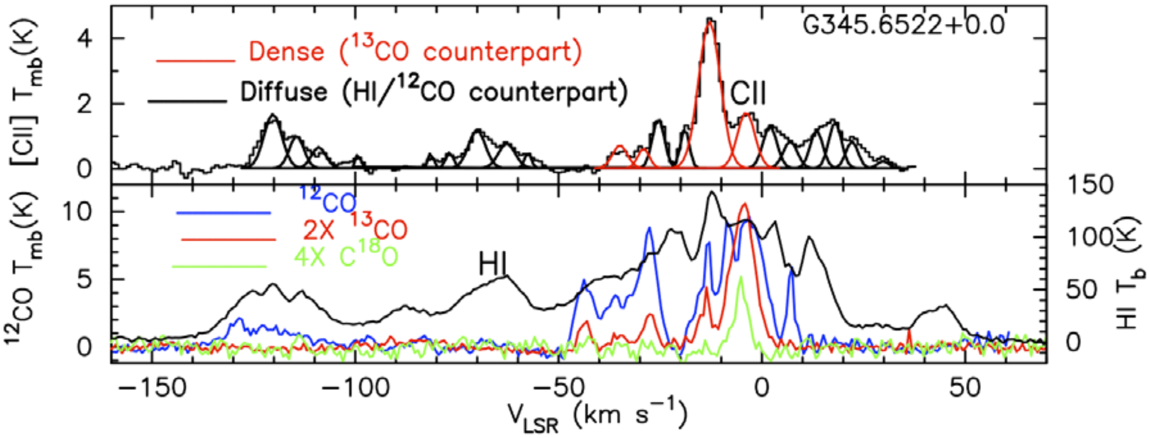

Figure 1. Spectra obtained on one line of sight by the GOT C+ Herschel Key Program (Langer, PI of GOT C+, and Pineda, PI of Mopra proposal for CO J=1–0 shown here, are CoIs on this proposal). Typically, the GOT C+ program found about 5 CO features per line of sight (los) in the longitude region we propose here. One sees how some [CII] components match with CO observations, indicating the surface of molecular clouds, but others match with HI components and not CO, indicating atomic clouds (however, mapping such as proposed here is needed to ensure these are not grazing los through the atomic surface of a GMC). In addition, we see that the various CO isotopologues indicate the columns through the molecular cloud (see Figure 2 as well), and therefore help determine the mass of the cloud. Some [CII] is neither associated with HI or CO and may indicate gas that is molecular H_2 but which has little CO because the FUV field photodissociates it and ionizes the carbon to C^+. Top panel is the [CII] observations along a line of sight at l=345 degrees and b=0 degrees. The black and red lines separate the [CII] into components seen in CO and HI respectively. The bottom panel shows the CO and HI observations. Note that in ^{12}CO, many velocity components (clouds) are seen, and that some have strong ^{13}CO or $C^{18}O$ components, indicative of high columns through the cloud (possibly indicating a GMC).

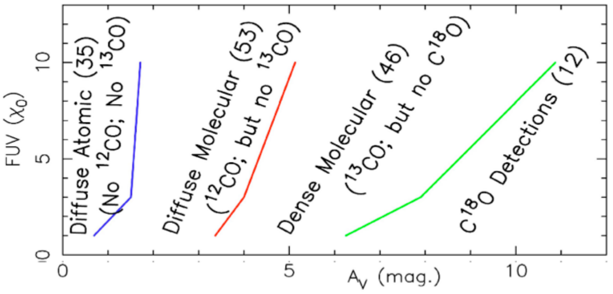

Figure 2. (courtesy GOT C+ team). Thresholds for CO detection. This theoretical figure shows how the CO isotopologues ^{12}CO, ^{13}CO and $C^{18}O$ constrain the column or optical extinction A_V through a molecular cloud. The sensitivity of our Mopra observations (see text) were combined with theoretical models of the chemistry of molecular clouds (including photodissociation, Visser et al 2009) to find the combination of incident FUV flux (χ_0) on the cloud and column (or A_V) through the cloud for detection of the various CO isotopologues. Our own previous tests of fast mapping in the proposed survey region show numerous detections of these three isotopologues, although of course ^{12}CO is the most extensive.

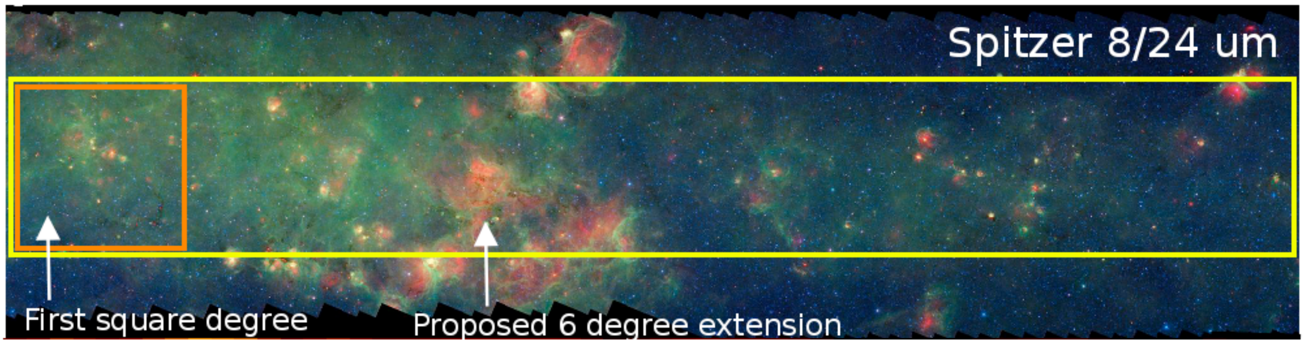

Figure 3: Infrared view of the area we would map, outlined by the yellow box extending from l=323°–330° and b=±0.5°, with the orange box being the scheduled March 2011 observations. Obtained with Spitzer, this image shows 24µm (R), 8µm (G) and 3.6µm (B) continuum emission across a spiral arm. It covers ~1 kpc in longitude, at a typical distance of 8 kpc, and will be seen in the third dimension using the velocity information we obtain. It contains about 30 already formed GMCs and a similar number of ensembles of clouds in the process of forming GMCs. To the left are a series of HII regions, seen through their dust and PAH emission. To the right are seen mostly stars 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 leads from ensembles of small clouds to giant molecular cloud formation to massive star formation must be taking place across this region, making it a suitable place to begin this study.