ATNF ATUC MEMORANDUM

To: ATUC

From: Michael Burton

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Subject **Draft of a major project for Mopra**

To assist in the discussion of possible key projects that Mopra could be used for, attached is a draft of a proposal to perform a large multi-line survey to help constrain star formation models.

The δ-Quadrant Survey

Turbulence-regulated Star Formation?

Michael Burton, Maria Hunt, Tony Wong, Ned Ladd[1]
University of New South Wales

Overview

The *δ-Quadrant Survey* is proposed as a major research program for the Mopra Telescope, addressing one of the major issues in the understanding of star formation – the role of turbulence in driving and self-regulating it. It will also provide Mopra with an important role in feeding science to the new generation of mm-wave interferometers in the southern hemisphere, firstly with the ATCA and then with ALMA. To conduct this project requires much of the available observing time in the winter season over the coming three years.

A comprehensive theory of star formation remains one of the major unsolved problems of astrophysics (e.g. Klein et al. 2003, Larson 2003). Although much has been learnt about how low-mass stars (i.e. solar mass and below) form in isolated mode, this accounts for only about 10% of all star formation. Recently a new "turbulent" model for star formation has emerged which holds the promise of providing a unified explanation for star formation from the smallest to the largest scales (MacLow & Klessen 2004). This model is so far only based on numerical simulations that are highly dependent on initial conditions and has yet to be constrained by observations. Through the *δ-Quadrant Survey* we aim to obtain the observations to provide these constraints. We will survey a 1.2° x 0.6° section of the southern galactic plane in a variety of molecular lines, each sensitive to different density conditions, in order to obtain the power spectrum of the turbulence distribution across a range of star formation complexes, from low mass to high. We will also survey an equivalent sized region in the Chameleon I & II clouds, two nearby clouds where low mass star formation occurs, but with quite different star formation efficiencies. We will do this using the new digital filterbank on the Mopra Telescope to simultaneously map the distribution of the 3mm-wavelength band lines with an on-the-fly (OTF) mapping technique.

Background – the problem faced by the standard model of star formation

Any successful model of star formation must be able to explain the low star formation efficiency of molecular clouds in the Galaxy – in other words the relatively long timescale on which gas is converted into stars. If star formation were dominated by gravitational instability then molecular clouds should be collapsing to form stars on a dynamical (i.e. free-fall) timescale, leading to a rate of star formation far in excess of the 1 $M_\odot$ per year rate that occurs today. It would have lead to the cessation of star formation within the Galaxy several giga-years ago. Some process must be working to slow down the rate of molecular cloud collapse.

Over the past two decades a 'standard' model of star formation has emerged that offers a physical understanding of how low mass stars form in an isolated mode (e.g. Shu, Adams & Lizano 1987). In it, molecular clouds are supported for most of their lifetimes against gravitational collapse by magnetic fields (e.g. Shu 1997). The field acts on the ions, with the neutral particles coupled to

[1] Sabbatical visitor from Bucknell University

the ions through collisions. Collapse occurs quasi-statically over long (~10^7 year) timescales, with dynamical collapse only occurring when high densities (> 10^5 cm^{-3}) are exceeded – when gravity is able to overwhelm magnetic support. Turbulence is not considered in this picture since it is considered unimportant on the scale of quasi-static cores.

However the formation of isolated, low-mass stars, for which this theory appears to work, is a special case, as most stars exist in binary or multiple systems. Efforts to extend the standard model to star formation in a cluster mode, or to massive star formation, have not been successful. The environment of giant molecular clouds, where this occurs, is far more complex than that of isolated, low mass cores. For instance, in the standard model, thermal pressure and stellar winds may disrupt the core before any massive stars mat form in it (e.g. McKee & Tan 2003). This has lead to the suggestion that massive stars may form by the coalescence of smaller stars (Bonnell, Bate & Zinnecker 1998). On the other hand, by adding turbulence to an accretion model, McKee & Tan (2003) have shown that massive stars can still form by accretion. More generally, the new "turbulent" models for star formation may explain the low star formation efficiency and turbulence observed across all scales in giant molecular clouds.

Turbulence Regulated Star Formation

In these turbulent models (see MacLow & Klessen 2004) supersonic turbulence is driven on large scales (tens of parsecs or more) and generates turbulence on smaller scales via an energy cascade. The supersonic gas motions quickly compress regions of gas, which may then undergo collapse in these denser clumps (leading to short lifetimes before collapse). Furthermore, the frequent disruption of clouds by turbulence (preventing collapse in many clumps) can account for the low observed star formation efficiency, which is ultimately set by the rate and characteristic scale of the energy injection.

The most serious objection to the idea of molecular cloud support via turbulence has been the rapid decay of turbulence in numerical simulations (e.g. Stone, Gammie & Ostriker 1998, MacLow et al. 1998). To overcome this problem it is necessary to argue that molecular clouds are dynamic, short-lived entities that do *not* require support for long periods against gravitational collapse (Ballesteros-Paredes et al. 1999). Furthermore, it is proposed that turbulent energy is continually replenished by energy sources whose origin remain unclear, but may include expanding supernova bubbles and large-scale galactic flows of gas.

A key goal of the *δ-Quadrant Survey* is to elucidate the nature of these energy sources and so determine whether that are indeed coupled to the star formation efficiency. This may be done by obtaining observational constraints on the driving scales of turbulence, and on the relationship between turbulence and star formation efficiency. This is possible by observing emission from a number of molecules of differing critical densities whose distributions, both spatially and in velocity, are able to provide the power spectrum of the turbulent gas. Using simply a bright tracer, like the CO molecule, is not sufficient for it primarily only provides a measure of the lower density molecular gas lying between the dense cores.

Using a 3D MHD code, Ballesteros-Paredes & MacLow (2002) have modelled the effect of different driving strengths on turbulence in molecular clouds. They find that strongly-driven turbulence leads to larger *density fluctuations* about the *mean density* than does weakly-driven turbulence. This effect may be sought observationally using emission tracers sensitive to different densities. In weakly-driven turbulence a low-density tracer, such as CO, will have a much wider distribution compared to a higher-density tracer, such as CS. In contrast, strongly-driven turbulence leads to a more similar spatial distribution between the high and low-density tracers, as there are both more regions at high density where both tracers can be excited and also more regions of lower density where *neither* is excited. Emission line ratios of molecules tracing different densities will therefore allow the variation in driving strength to be examined.

The Data Needs

The models described above also predict other criteria that can be used to determine the driving scale for turbulence. The larger the scale at which the turbulence is driven, the larger the dominant structures that will be seen in the maps. Thus measurements of molecules across molecular cloud complexes that trace widely different density regimes can be used to determine the dominant size scale of density structures in a particular region.

It is also of great interest to determine the scale at which variations in the star formation efficiency (SFE) occur. Models suggest that the SFE increases as the driving scale of the turbulence increases (Klessen, Heitsch & MacLow 2000), which suggests that these variations will occur on the scale of energy injection. To determine the energy injection scales requires wide-field, high-resolution images of both atomic and molecular gas. Determining the SFE requires an accurate inventory of the molecular gas as well as a census of the young stellar population. 21cm HI data can provide the relevant information on the atomic gas, and high spatial resolution mid-IR imaging the information on the young stellar population will be available for comparison with the molecular data obtained through the δ-Quadrant Survey. However the youngest sources will be too embedded to be seen in the mid-IR, and so sub-mm continuum data is needed to quantify their presence. This also allows the dust column density be determined, which can be compared to the stellar mass and the gas mass determined from line observations to provide constraints on the completeness of the surveys. The necessary molecular can be obtained using the Mopra Telescope through the *δ-Quadrant Survey*.

The δ-Quadrant Survey

We will begin this survey by mapping the distribution of ^{13}CO (J=1-0) line emission in a 1.2° x 0.6° region of the southern galactic plane centred on the molecular cloud complex G333.6-0.2. This is in the Fourth Quadrant of the Galaxy, and the field passes through the ring of molecular clouds that circle the Galaxy at 3-5 kpc from its centre. The southern part of the Galactic Ring remains poorly explored, and drawing inspiration from events in a well-known science fiction show, we have called this project the *δ-Quadrant Survey*. The region to be mapped is shown in Figure 1, which is from the MSX 21μm survey. To date, the only extensive molecular mapping of the region was through the Columbia survey using a 1.2m telescope, with a 9' beam, in the ^{12}CO (J=1-0) line (Bronfman et al, 1989).

The region selected for this survey is large enough to contain a varied sample of molecular regions within the Galactic plane. It contains a variety of high mass star forming clouds, surrounded by diffuse molecular and atomic gas. It is, however, a discrete region in the plane whose boundaries can be specified. It will in addition be contrasted to surveys conducted of the nearby, low-mass star forming clouds Chamaeleon I and II which lie away from the galactic plane. These two clouds exhibit quite different characteristics, in particular in their SFEs (13% in

Cha I but only 1% in Cha II), so providing a clear contrast to the Fourth Quadrant field in evaluating the role of turbulence in the regulation of the star formation occurring in each.

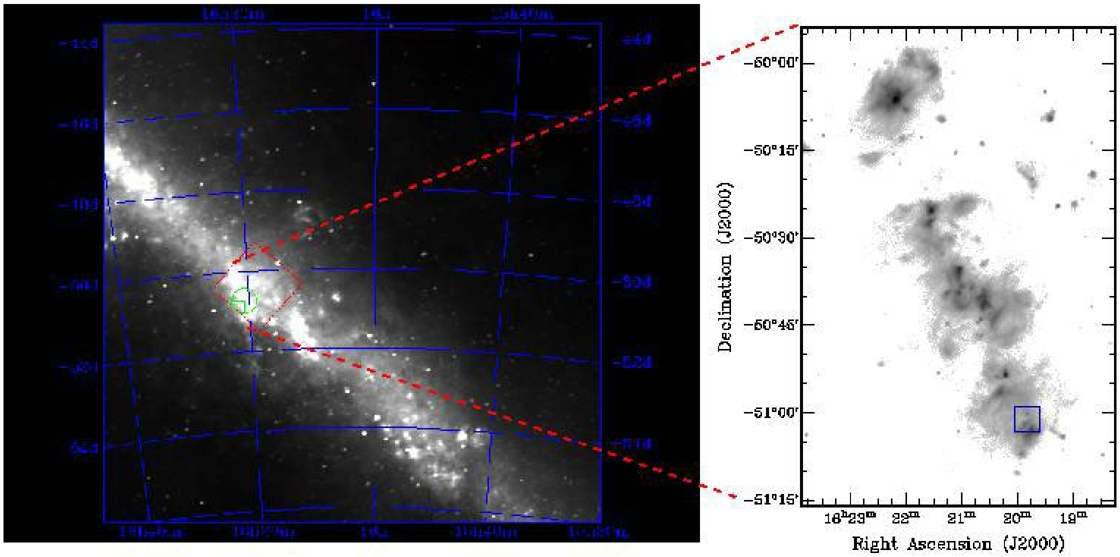

Figure 1. Map showing the region of the Fourth Quadrant selected for the δ-Quadrant Survey. The image shows the 21μm thermal emission from dust, as mapped by the MSX satellite. The circle shows the centre of our survey and the dashed lines indicate its extent. The 1.2°x0.6° region to be surveyed is expanded on the right, together with the size of each 5'x5' map that will be obtained with each OTF pass.

While the δ-Quadrant Survey cannot hope to compete in size with that being conducted in the First Quadrant by the FCRAO mm-antenna in Massachusetts (the Galactic Ring Survey), once the new digital filter bank is installed as the Mopra correlator, it will be possible to conduct the survey in several lines simultaneously. However, given the possible loss of ability to observe CO lines when the new MMIC receivers replace the current SIS receiver, it is prudent to begin the survey this year and map the distribution of the ^{13}CO line emission. ^{12}CO is invariably optically thick, so does not provide a good tracer of the extent of the lowest density molecular gas. Hence ^{13}CO will be observed, although even this isotope can be optically thick along high column density sight lines.

We will thus use Mopra to map two very different molecular cloud regimes in molecules that trace different densities within each. Once the ^{13}CO map is complete we then intend to map the same regions in CS, N_2H^+, HCO^+, HCN, SO, CH_3CN, CH_3OH and several of their optically thin isotopomers. These lines can all be observed simultaneously in a single 8 GHz bandpass of the new DFB (though whether we will be able to observe them in a single pass, or need two or more passes, depends on the programmability of the DFB for multiple lines, a facet of the instrument whose capability has not yet been fully determined). These lines have critical densities ranging from 10^3 to 10^6 cm^{-3}.

Data Analysis

The data will provide a series of position-position-velocity cubes (in each of the lines), which then will need to be analysed in a manner that allows them to be compared with numerical models. Two of the best ways to do this are wavelet analysis and principal component analysis (PCA). Wavelet analysis provides a technique to determine structure as a function of scale and position, unlike simple power spectra which only consider scale. It allows the data to be characterised in terms of a small number of parameters, which can then be compared to wavelet analyses of numerical models. Similarly, PCA describes data by a series of eigenimages of the 3D cube.

Complementary Data Sets

As discussed earlier, the scientific objectives of this program require data from a variety of atomic and molecular lines, as well as infrared and sub-mm wave continuum data. Fortunately these data sets will become available as this project progresses, allowing us to both feed off other research programs, as well as to be active participants in an international endeavour, greatly leveraging Mopra's effectiveness as we do. The following data sets are, or soon will be, available:

- Atomic data through the ATCA HI Galactic plane survey (McClure-Griffiths et al 2001).
- Mid-IR imaging through the public release of the Spitzer GLIMPSE survey along the Galactic plane (Benjamin et al 2004).
- Sub-mm continuum data from a survey that will be conducted by the APEX telescope (Kreysa et al 2003). We have initiated discussion with the MPIfR group at Bonn regarding sharing data sets and observing common field.
- A blind methanol maser survey has been conducted over this part of the Galactic plane (Ellingsen et al 1996), a tracer that provides an unambiguous signpost of the earliest stages of massive star formation.
- It would also be desirable to obtain continuum data at 22 GHz with the ATCA of the thermal radio emission of the δ-Quadrant field. In particular, the higher frequency and improved spatial resolution over previous surveys conducted with the ATCA provides sensitivity to UCHII and hyper-compact HII regions, associated with the early stages of massive star formation. Preliminary discussions with Chris Phillips have been held regarding this.

On The Fly Mapping

A new operations mode for Mopra has been developed in 2004, 'on-the-fly' (OTF) mapping, which is essential for the conducting of mapping surveys. It allows a map to be obtained by slewing the telescope while continuously collecting data. For a telescope like Mopra, which does not have a chopping secondary, this leads to a considerable increase in efficiency when observing extended regions.

Maps will be obtained by scanning 5'x5' regions, utilising a grid with a 10" spacing (31 rows) and will take ~70 minutes, with a further 10 minutes for set-up and pointing. With the new ACC the cycle time at Mopra can be reduced to 2 seconds. By scanning at 3.5 arcseconds per second a Nyquist-sampled cell (i.e. 14") will take 4 seconds to scan (i.e. 2 cycles) and a row 90 seconds to complete. A sky position will be obtained after each row, and a T_{Sys} measurement every 11 rows. We estimate that the sensitivity in a 35" diffraction resolution beam will be $\sigma_{map} \sim 0.3$K. Each map would be observed twice, once scanning in RA and the other time in Dec, reducing striping and providing some redundancy against weather and other interference. Full mapping parameters are listed in the table below.

Parameter	**Value**
Map Size	5 arcmin in RA and Dec
Cycle Time	2 seconds
Scan Rate	3.5 arcseconds per second
Row Spacing	10 arcseconds
Number of Rows	31 (row 16 through map centre)
Rows per Off	1
Rows per T_{Sys} Calibration	11
Time per Row	92 seconds (46 cycles, including lost cycle)
Time per Off Position	22 seconds (11 cycles, including lost cycle)
Assumed System Temperature	$T_{Sys}' \sim 400$K
Estimated Sensitivity per Map	$T_A^* \sim 0.3$ K (2 polarizations, 1 pass)
Bandwidth	64 MHz
Channel Spacing	0.2 km/s (60 kHz)
Estimated Time per Map	70 minutes + 10 minutes pointing & set-up

The total time required to undertake the survey is estimated as follows:

Parameter	**Value**
1.2° x 0.6° region	208 maps (i.e. 2 passes per position)
Total Mapping Time	280 hours (80 minutes per map)
Total Telescope Time	80 days (7 hours / day with 50% duty cycle)

This is effectively one observing season per line[2], making use of all time when the southern galactic plane is accessible. Similarly for Chamaeleon, whose RA allows it to be observed before the Galactic plane rises. Both data sets can thus be obtained together. In the first season the survey will be conducted in the ^{13}CO line, and in subsequent seasons in as many lines as

[2] However if only one pass per map is conducted the total time is reduced by half, to 40 days per season.

simultaneously attainable with the digital filterbank (at least 4). However, the area covered by subsequent surveys (probing higher densities) may be restricted to regions detected ^{13}CO to allow for increased integration times (and thus sensitivities) for the fainter lines.

Mopra's Niche

The Fourth Quadrant of the Galaxy remains little explored, especially its molecular content, since it is not reachable by mm-wave telescopes in the Northern Hemisphere. At the moment there is only one large mm-wave single-dish telescope in the Southern Hemisphere (Mopra!). Even as APEX (and eventually ALMA) are built, Mopra will still have the 3mm band largely to itself as these other facilities will be concentrating on the higher frequency bands. With the addition of the DFB, and the ability it brings to map several lines simultaneously, Mopra provides a unique and powerful facility.

The *δ-Quadrant Survey* provides it with an exciting piece of science to pursue, whose outcome is significant in furthering understanding of one of the major unsolved problems in astrophysics – the cause and control of star formation. While several data sets are necessary to pursue this science – the distribution of the ionized and neutral gas, the dust, as well as the stellar population of the star forming cores needs to be determined, as well as the molecular gas, it is the turbulence distribution in the molecular gas that is central to the problem. The other data sets are also in the process of being obtained, so this survey with Mopra is also timely. Furthermore, it will result in an extensive data base that will provide the basis of projects that will need ALMA to pursue.

Personnel

While this project has originated from the UNSW star formation group, we envisage this project as a community-wide endeavour, and will be soliciting for others to join in the survey in 2005. For 2004 we anticipate being able to obtain a single pass over the Fourth Quadrant and Chamaeleon fields, and have the following observing team available:

Academics	**Research Fellows**	**Students**	**"Friends"**
Michael Burton	Indra Bains	Paolo Calisse	Gary Deragopian
Maria Hunt	Andrew Walsh	Steven Longmore	Bruce Fulton
	Tony Wong	Cormac Purcell	John Shobrook
			Andre Phillips

We typically allocate duties in one-week periods, with two observers per period.

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