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The Methanol Multibeam Survey: a unique window on high-mass star formation in our Galaxy

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Abstract. The Methanol Multibeam (MMB) survey has yielded over 1000 masers at the 6668-MHz methanol transition: a near-complete census throughout the Galactic disc, as evident from the discovery statistics, and corroborated by preliminary distance determinations. Each maser pinpoints a massive star in a brief early evolutionary phase. Follow-up comparisons reveal in most cases a matching IR source in the GLIMPSE survey. The methanol masers effectively distinguish the genuine high mass proto-stars from the many thousand IR mimics of similar color. Longer IR wavelength follow-ups by Herschel instruments, and in the radio mm-continuum, will refine the mass-range encompassed by the masers; and, complemented by radio measurements at short cm-wavelengths, will define the evolutionary stage of each site, distinguishing hyper-compact HII regions from an earlier phase. Follow-up studies of key molecular gas tracers, including closely associated masers (other methanol transitions, water and OH), reveal the extent of homogeneity in the population and environments of high mass stars.

Distance estimates based on the maser velocities have already allowed useful exploration of Galactic structure. Future astrometric parallax measurements extended to the full maser sample will precisely define the geometry of Galactic spiral arms of our Galaxy and independently define the velocity field, allowing a model-free study of Galactic rotation and dynamics. Associated OH masers (present at about half of the methanol sites) are being exploited to provide the first Galaxy-wide grid of 'in situ' magnetic field estimates.

Our detailed characterization of the Galactic methanol maser population provides a yardstick for extragalactic comparisons with M31 and the LMC. Notably, our survey of the LMC has shown its methanol maser population to be remarkably small relative to our Galaxy - a likely consequence of low LMC metallicity.

Keywords. masers — catalogs — Galaxy: structure — stars: formation — ISM: molecules

1. Introduction

The methods of observation and processing for the Methanol Multibeam (MMB) survey are presented fully in a 'techniques' paper (Green *et al.* 2009a), accompanied by a short account of the science objectives. In brief, strong maser emission from the 6668-MHz transition of methanol appears to be exclusively associated with high-mass stars at a short-lived very early phase in their evolution. The high sensitivity MMB survey of the Galactic plane has been designed to be a census of essentially all 6.6-GHz masers within the Galaxy. Following detection at Parkes, we then measured the maser positions with arcsecond accuracy. We have thus effectively compiled a comprehensive catalogue of high-mass star formation sites throughout the Galaxy in the unique early phase supporting maser emission. We now describe how the masers themselves, and follow-up of their counterparts at other wavelengths, are leading to far-reaching conclusions regarding the star formation process and Galactic structure.

2. The survey results

Catalogue numbers and spatial distribution.

From our survey, the final count of methanol 6.6-GHz methanol masers in our Galaxy will exceed 1000. We have already presented properties of 707 masers in the first four published portions of the catalogue (Caswell *et al.* 2010, 2011; Green *et al.* 2010, 2012a); a fifth portion is in preparation, to be followed by the results of our deeper study of a limited area, our 'piggyback' project (Green 2009a). The systemic velocities of the masers are readily estimated from their spectra, and yield a first order distance measurement. Significant conclusions regarding structure of the inner Galaxy, specifically the Galactic Centre zone, the bar, the 3-kpc ring and the origins of the spiral arms, have already been presented (Caswell *et al.* 2010, Green *et al.* 2009b; Green *et al.* 2011).

The maser population properties. A compilation of early heterogeneous maser catalogues (Pestalozzi *et al.* 2005) listed a total of 519 sites, which were then used by van der Walt (2005) to derive a likely total number of 6668-MHz methanol masers in the Galaxy of 1200, after applying estimated corrections for limited sensitivity. Using the same sample, Pestalozzi *et al.* (2007) derived a luminosity function for the masers. Our current survey with uniformly good sensitivity indicates that the luminosity function falls sufficiently rapidly at low luminosity as to be effectively a cut-off, and is at a level where we are sensitive to the lowest luminosity masers almost to the limits of the Galaxy (estimated to be a Galactocentric radius of about 13.5 kpc for the massive star population being traced). In addition to our main survey, some new weak sources are present in our deeper (piggyback) survey of a narrower latitude range confined to the inner Galaxy, which is currently being analysed (Ellingsen *et al.*, in preparation). The relatively few detections in this deeper survey corroborate the very high level of completeness of the main survey. We will explore expectations that distant low luminosity sources dominate our weakest detections, and are primarily responsible for residual incompleteness of the survey. Our observed population captures the majority of masers in the Galaxy, with minimal corrections needed to assess the full Galactic total - a total likely to somewhat exceed 1200, but generally in remarkable agreement with the preliminary estimate by van der Walt (2005). The total, when compared to the number of massive stars estimated to be present in our Galaxy, provides a measure of the fractional stellar lifetime traced by the maser phase and, from van der Walt's (2005) arguments, lies between 25000 and 45000 years.

Follow up in the IR. An exhaustive comparison with the GLIMPSE survey of the Spitzer space telescope has successfully identified counterparts for the majority of the masers (Gallaway *et al.* 2012), consistent with their identity as embryonic massive stars. The methanol masers effectively distinguish the genuine high mass stars and proto-stars from the many thousand IR mimics of similar color. Their characterization will be further enhanced when supplemented by longer wavelength data currently being obtained from the Herschel space observatory.

Follow up at short radio wavelengths. At radio frequencies, between 8 and 44 GHz, observations of the continuum emission are establishing the small fraction of masers in the later evolutionary stage extending to hypercompact (and to a few ultracompact) HII regions, a stage during which the methanol 6668-MHz masers appear to often reach a high luminosity, followed by abruptly 'turning off'. The recognition of an evolutionary age based on the maser properties is being pursued by follow-up observations of other maser transitions such as methanol masers at 12 GHz (Breen *et al.* 2010, 2011, 2012a,b) and at 37 GHz (Ellingsen *et al.* 2011). Class I methanol masers at 36 and 44 GHz (Voronkov *et al.* 2012) are further clues to the evolutionary state.

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The newly available ALMA facility offers the exciting prospect of very detailed characterization of each site in many other molecular tracers, indicating the features unique to the maser sites, which in turn will enhance our understanding of conditions that are necessary to trigger high-mass star formation.

3. Precise distances, Galactic structure, the Galactic velocity field, and the Galactic magnetic field

As noted in section 2, distance estimates based on the maser velocities have already allowed useful exploration of Galactic structure. This is possible because the maser velocity of a site is a good measure of systemic velocity of its environs. Future astrometric parallax measurements (see e.g. Reid *et al.* 2009; Rygl *et al.* 2010 for examples to date), when extended to the full maser sample, will remove the ambiguities currently present in some of the kinematic distances, will define the distances to higher accuracy, and, in conjunction with IR data, will establish the precise mass range of the massive star hosts. The ensemble of precise distances will eventually reveal the geometry of Galactic spiral arms of our Galaxy, and allow an independently determined velocity field, and a model-free study of Galactic rotation. Associated OH masers (present at about half of the methanol sites) are being exploited to provide the first Galaxy-wide grid of 'in situ' magnetic field estimates. First results from a portion of this systematic survey (Green *et al.* 2012) will shortly be followed by the full survey.

4. Extragalactic implications

Our detailed characterization of the Galactic methanol maser population provides a yardstick for extragalactic comparisons with M31 and the LMC. A similar comparison can be made for OH and water masers using existing data. For the LMC, the lower OH and water maser populations relative to our Galaxy appear to be in proportion to the relative star-forming rates of the two galaxies. In contrast, our methanol survey of the LMC shows a further factor of four underabundance relative to our Galaxy - which we have interpreted as a likely consequence of low LMC metallicity (Green *et al.* 2008).

5. Conclusions

The MMB survey is providing a near-complete census of 6668-MHz methanol masers throughout the Galactic disc. Supplemented by extensive follow-ups that are in progress, it will establish the mass and evolutionary stage of each maser site, which can then be correlated with the properties of the molecular clouds in which they dwell. The distribution in space and velocity will revolutionize our characterization of Galactic spiral structure.

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References

Breen, S. L., Ellingsen, S. E., Caswell, J. L., & Lewis, B. E. 2010, *MNRAS*, 401, 2219

Breen, S. L., Ellingsen, S. P., Caswell, J. L., *et al.* 2011, *ApJ*, 733, 80

Breen, S. L., Ellingsen, S. P., Caswell, J. L., Green, J. A., *et al.* 2012a, *MNRAS*, 421, 1703

Breen, S. L., Ellingsen, S. P., Caswell, J. L., Green, J. A., *et al.* 2012b, *MNRAS*, in press

Caswell, J. L., Fuller, G. A., Green, J. A. *et al.* 2010, *MNRAS*, 404, 1029

Caswell, J. L., Fuller, G. A., Green, J. A. *et al.* 2011, *MNRAS*, 417, 1964

Ellingsen, S. P., Breen, S. L., Sobolev, A. M., Voronkov M. A., Caswell, J. L., & Lo, N. 2011, *ApJ* 742, 109,

Gallaway, M., Thompson, M. A., Lucas, P. W., Fuller, G. A., Caswell, J. L., *et al.* 2012, *MNRAS*, in press

Green, J. A., Caswell, J. L., Fuller, G. A., *et al.* 2008, *MNRAS*, 385, 948

Green, J. A., Caswell, J. L., Fuller, G. A., *et al.* 2009a, *MNRAS*, 392, 783

Green, J. A., McClure-Griffiths, N. M., Caswell, J. L., *et al.* 2009b, *ApJ*, 696, L156

Green, J. A., Caswell, J. L., Fuller, G. A., *et al.* 2010, *MNRAS*, 409, 913

Green J. A., Caswell, J. L., McClure-Griffiths., N. M., *et al.* 2011, *ApJ*, 733, 27

Green, J. A., Caswell, J. L., Fuller, G. A., *et al.* 2012a, *MNRAS*, 420, 3108

Green, J. A., McClure-Griffiths, N. M., Caswell, J. L., Robishaw T., & Harvey-Smith L., 2012b, *MNRAS*, 425, 2530

Pestalozzi, M. R., Minier, V., & Booth, R. S. 2005, *A&A*, 432, 737

Pestalozzi, M. R., Chrysostomou, A., Collett, J. L., Minier, V., Conway, J., & Booth, R. S. 2007, *A&A*, 463, 1009

Reid, M. W., *et al.* 2009, *ApJ*, 700, 137

Rygl, K. L. J., Brunthaler, A., Reid, M. J., *et al.* 2010, *A&A*, 511, A2

van der Walt, J. 2005, *MNRAS*, 360, 153

Voronkov, M. A., Caswell, J. L., Ellingsen, S. P., Breen, S. L., Britton, T. R., Green, J. A., Sobolev, A. M., & Walsh, A. J. 2012, in: R. S. Booth, E. M. L. Humphreys & W. H. T. Vlemmings (eds), *Cosmic Masers from OH to* H_0, Proc. IAU Symposium No. 287 (Cambridge: CUP), p. 433

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