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A golden age for maser surveys

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Abstract. Masers are becoming increasingly important probes of high-mass star formation, revealing details about the kinematics and physical conditions at the elusive, early stages of formation. Over the last decade significant investment has been made in a number of large-scale, sensitive maser surveys targeting transitions found in the vicinity of young, high-mass stars. Individually, these searches have led to valuable insights into maser populations, their associated star formation regions, and often revealed further details such as Galactic structure. In combination, they become even more powerful, especially when considered together with complementary multi-wavelength data. Another consequence of large maser surveys has been the identification of a number of especially interesting sources that have been the subject of subsequent detailed studies. I summarize the recent plethora of maser surveys, their results, and how they are contributing to our understanding of star formation. Ongoing searches will ensure a bright future of maser surveys in the decade to come.

Keywords. masers, stars: formation, ISM: molecules

1. Introduction

In recent years, maser surveys have been able to capitalise on increased sensitivity of radio telescopes, allowing for large-scale, sensitive searches for a number of maser transitions that are commonly associated with star formation regions. We are now able to routinely cover large sections of the Galaxy and achieve high sensitivities and spatial resolutions, either in the initial survey or in follow up observations. Such surveys have allowed for meaningful population statistics and revealed new 'special' sources that have become the subjects of intensive targeted observations. Large-scale systematic searches are essential to our understanding of star formation and the masers themselves.

Here I summarise five significant surveys at various stages of completion, conducted in the southern hemisphere. They target a number of different maser transitions, including the ground-state OH masers, 6035 MHz excited-state OH masers, 6.7 GHz methanol masers, 22 GHz water masers and 44 GHz methanol masers. Particularly in the case of the Methanol Multibeam (MMB) survey, a plethora of targeted observations have also been conducted towards the large sample of 6.7-GHz methanol masers and these are mentioned in Section 2.1.3.

2. The surveys

2.1. *The Methanol Multibeam (MMB) survey and follow-up observations*

The Methanol Multibeam (MMB) survey was an unbiased, systematic search for both 6.7 GHz methanol masers and 6035 MHz excited-state OH masers within the Southern Galactic plane. The initial survey observations were made with the Parkes 64 m radio telescope, allowing 65% of the Galactic plane to be searched, covering a longitude range of 186°, through the Galactic Centre (GC), to 60° and latitudes of ±2°, as well as both

the Small and Large Magellanic Clouds. The survey was completed in scanning mode with a purpose-built 7-beam receiver which dramatically reduced the time required to complete the observations. In the end it took 120 days of observing time to conduct the initial survey which was chiefly allocated between 2006 and 2009. All detections without previously derived precise positions, of both the methanol and excited-state OH maser transitions, were subsequently followed up with high-resolution observations using either the Australia Telescope Compact Array or the Multi-Element Radio Linked Interferometer Network (MERLIN) resulting in positions accurate to 0.4 arcsec. The MMB survey is the largest, sensitive, systematic search for 6.7 GHz methanol and 6035 MHz excited-state OH masers ever conducted in the Galactic plane. A full description of the survey parameters can be found in Green *et al.* (2009).

2.1.1. *6.7-GHz methanol masers*

Methanol masers at 6.7 GHz are exclusively associated with sites of high-mass star formation (e.g. Minier *et al.* 2003, Xu *et al.* 2008, Breen *et al.* 2013) making them especially useful probes of these elusive regions. A total of 972 methanol masers were detected across the southern portion of the Galaxy (see Fig. 1) to a 3-σ detection limit of $\sim$0.51 Jy and are presented in a series of five catalogue papers (Caswell *et al.* 2010, Green *et al.* 2010, Caswell *et al.* 2011, Green *et al.* 2012a, Breen *et al.* 2015). Approximately 40% of the detections were discovered in the survey, and, combined with the known sources, have proved to be important targets for other types of masers, parallax observations and detailed multi-wavelength studies.

Recently, Green *et al.* (2017) presented the overall statistics of the MMB maser population, focusing on the 6.7 GHz methanol detections. They found that:

- The 972 detections implied a total Galactic 6.7 GHz methanol maser population of $\sim$1290 sources above the 3-σ detection limit of $\sim$0.51 Jy;
- 51 sources surpassed 100 Jy, 330 surpassed 10 Jy and the strongest detection was G 9.621+0.196 at 5200 Jy. 118 sources had peak flux densities less than 1 Jy;
- Velocity extents of the detected emission ranged from 0.3 km s^{-1} for G 37.767−0.214 and 28.5 km s^{-1} for G 305.475−0.096 and had a median value of 6.0 km s^{-1};
- 7% of the MMB sample shows variability of a factor of two, and weaker sources show the greatest levels of variability;
- Lower luminosity sources have smaller velocity ranges compared to higher-luminosity sources;
- There was evidence that brighter sources were seen towards arm origins.

2.1.2. *Excited-state OH masers*

The MMB survey also included the 6035 MHz excited-state OH maser transition, detecting a total of 127 sources, 47 of which were new to the survey (see Avison *et al.* 2016 for full details). All detections without previously derived precise positions were observed with the ATCA, and, combined with the 6.7 GHz methanol maser observations, allowed Avison *et al.* (2016) to determine that 52% of their 6035 MHz excited-state OH maser detections fell within 2 arcsec of a 6.7 GHz methanol maser detected in the MMB survey. Follow up spectra taken with the Parkes telescope also allowed for sensitive observations of both the 6035 and 6030 MHz transitions, resulting in the detection of 32 6030 MHz OH masers.

Since a number of the 6035 MHz excited-state OH masers had been presented previously in the literature, Avison *et al.* (2016) was able to assess the temporal variability of these sources. Through comparisons with observations made by Caswell & Vaile (1995) and Caswell (2003), Avison *et al.* (2016) were able to determine that 20% of the detected

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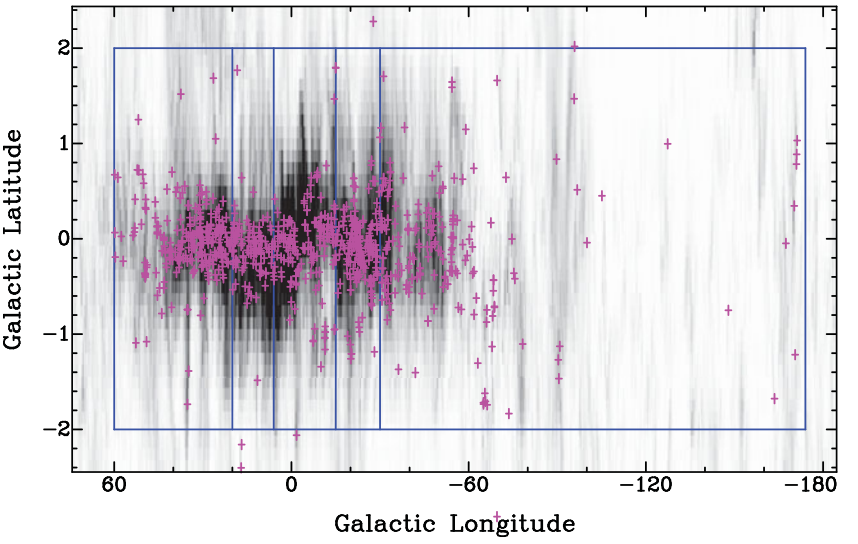

Figure 1. All 972 6.7 GHz methanol masers (crosses) detected in the MMB survey overlaid on CO emission from Dame, Hartmann, & Thaddeus (2001). The large rectangle indicates the full extent of the survey and the internal vertical lines indicate the boundaries of each of the survey catalogues.

6035 MHz OH masers had varied by more than a factor of two on timescales of seven or more years. A total of 12 sources that were previously presented in the literature where unable to be confidently detected in the MMB survey.

Full polarisation data of the 6035 MHz sources detected in the MMB survey, allowing the consideration of Zeeman pairs and the inferred magnetic field strengths and directions of sources across the Galaxy, will be presented in a forthcoming paper (Avison *et al.* in prep).

2.1.3. *Follow-up observations at 12.2-GHz methanol, 22-GHz water and ground-state OH*

Each of the 6.7 GHz methanol masers detected in the MMB survey were subsequently targeted for accompanying 12.2 GHz methanol maser emission using the Parkes radio telescope over four seperate observing sessions. A total of 431 12.2 GHz methanol masers were detected (and presented in four seperate catalogue papers; Breen *et al.* 2012a,b, 2014, 2016), equating to a detection rate of 45.3 %. The flux density distribution of the 12.2 GHz sources ranged from 0.3 to 976 Jy and only 11 sources surpassed peak flux densities of 100 Jy. From this work it was proposed that 12.2 GHz methanol masers were present in the second half of the 6.7 GHz methanol maser lifetime and hence trace slightly more evolved star formation regions.

In other follow-up work, Titmarsh *et al.* (2014, 2016) used the ATCA to target all of the 6.7 GHz MMB sources in the Galactic longitude range 341° (through the GC) to 20°. With a 5-σ detection limit of $\sim$250 mJy or better, 156 of the 323 6.7 GHz methanol masers in this longitude range were found to have associated water maser emission, equating to a detection rate of 47%. They further found that the water maser detection rate was slightly higher towards MMB sources that had accompanying 12.2 GHz methanol maser emission. A simple interpretation of this might suggest that water masers are therefore also seen at a slightly later stage of high-mass star formation than 6.7-GHz methanol masers, but both Breen *et al.* (2016) and Titmarsh *et al.* (2016) argue that water masers

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do not follow a simple evolutionary scheme, and the fact that they are collisionally pumped means that their presence is more often dependant on the interaction of the star formation region with the surrounding environment.

Follow up ground-state OH maser observations have also been conducted towards the MMB sources as part of the MAGMO project (the project to study the Magnetic fields of the Milky Way through OH masers), using the ATCA. This project simultaneously observes 1612, 1665, 1667 and 1720 MHz OH masers and the results of pilot observations are presented in Green *et al.* (2012b).

2.2. *H_2O Southern Galactic Plane Survey (HOPS)*

HOPS surveyed a large section of the southern Galactic Plane (290° < longitude < 30° and latitudes ±0.5°) for a number of spectral lines near 20 GHz, including the 22 GHz water maser line (Walsh *et al.* 2011). The initial survey was conducted with Mopra and identified 540 maser sites but had a slightly variable RMS across the survey region, resulting in a detection limit that was around 2 Jy, but up to 10 Jy in some areas. All water maser detections were followed up with high-resolution, high-sensitivity ATCA observations and resulted in the identification of 631 maser sites (Walsh *et al.* 2014). Comparison between the water maser positions with complementary data revealed that 433 of the 631 maser sites were associated with star formation (69% of sites). Data products from the HOPS survey are available at https://research.science.mq.edu.au/hops/public/index.php.

Walsh *et al.* (2014) found, as was the case in the MMB survey, that the highly variable water masers tended to be weaker. They also found that the water maser sites that were associated with star formation had fewer spots than those associated with evolved stars, but that the spots within a site were distributed further in the case of the star formation masers. They also found that a small number of sources showed linear spot distributions, arranged both parallel and perpendicular to the orientation of associated outflows.

Forthcoming high-sensitivity water maser surveys such as SWAG (Survey of Water and Ammonia in the Galactic Center; see Ott *et al.* in these proceedings) and RAMPS (Radio Ammonia Mid-Plane Survey; Hogge *et al.* in prep) will reveal the weaker water maser population that fell below the detection limit of HOPS.

2.3. *Southern Parkes Large-Area Survey in Hydroxyl (SPLASH)*

SPLASH is an unbiased, fully-sampled, large-scale OH and 1.6 - 1.7 GHz radio continuum survey of the Milky Way (Dawson *et al.* 2014). While the primary science driver is the diffuse OH emission, the sensitivity and the Galactic coverage of this survey make it one of the most extensive, sensitive maser surveys for all four ground state transitions of OH (1612, 1665, 1667, 1720 MHz). The survey covers 156 square degrees, extending from Galactic longitude 332°, through the GC to 8° with a latitude coverage of ±2°.

The initial Parkes survey has low spatial resolution (HPBW of 15 arcmin) but high sensitivity (rms of 65 mJy in a 0.18 $\mathrm{km\,s^{-1}}$ channel). All detections were re-observed with the ATCA in order to derive precise positions and achieve full polarisation observations. The high-resolution maser results from the SPLASH pilot region (334° < l < 344°, latitudes ±2°) detected a total of 215 OH maser sites, 111 of which were new detections and 64 sites (or 30%) were associated with star formation (Qiao *et al.* 2016). Future publications will detail the detections in the remaining longitude regions and present the full polarisation data, including the analysis of Zeeman splitting.

2.4. *MALT45*

Using an innovative survey strategy, MALT45 (Millimetre Astronomers Legacy Team 45 GHz) systematically surveyed five square degrees of the Galactic plane for a number

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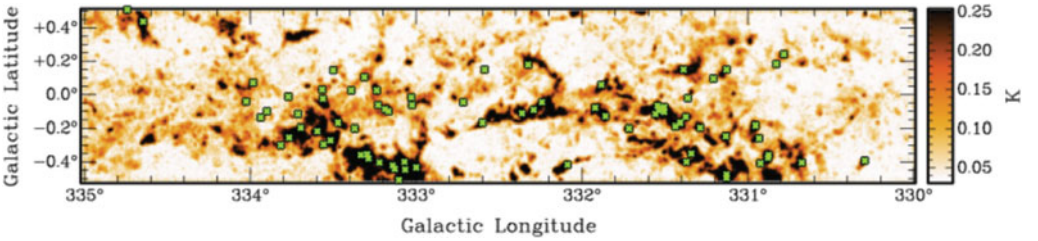

Figure 2. CS (1−0) map overlaid with the positions of 77 44 GHz class I methanol masers (crosses) from Jordan *et al.* (2015)

of 7 mm spectral lines, including the 44 GHz class I methanol maser, as well as SiO masers (Jordan *et al.* 2015). This initial survey observations were conducted with the ATCA, but in autocorrelation mode which resulted in a HPBW of ∼1 arcmin. From these observations, Jordan *et al.* (2015) identified 77 44 GHz class I methanol masers which are overlaid on a CS map (made in the same survey) in Fig. 2. Of the 77 class I methanol masers detected, 58 were new detections and 42 were located at sites devoid of other maser species. This survey achieved an rms noise of 0.9 Jy in a 0.2 km s^{-1} channel, and covered Galactic longitudes of 330° to 335° and latitudes ±0.5°.

Jordan *et al.* (2017) conducted further observations, made with the ATCA in a standard interferometric mode, towards all of the detected masers. In these observations they were able to identify 238 maser spots across 77 maser sites, and by comparing their cross-correlation data to auto-correlation data they were able to investigate the spatial scales of the emission regions and identify quasi-thermal contributions in the 44 GHz class I methanol maser line. They present comparisons between their masers with other star formation tracer such as CS (1−0), SiO v = 0 and the H53α radio-recombination line, along with dust continuum emission from the ATLASGAL survey (Contreras *et al.* 2013) and other maser species. Among other things, they find that the 44 GHz methanol masers without accompanying OH masers or recombination lines have lower luminosities.

2.5. *Dense Gas Across the Milky Way - The Full-Strength MALT45*

Building on the success of the MALT45 survey, we have begun a 2700h ATCA legacy survey to map 90 square degrees of the southern Galactic Plane at 7 mm. Like the initial MALT45 survey, this expanded survey will target a host of dense gas, shock tracers, recombination lines, 44 GHz class I methanol masers and SiO masers. The observations are conducted in auto-correlation mode and use on-the-fly mapping to allow us to cover a large portion of the Southern Galactic plane. Combined with existing MALT45 data, we will provide full coverage of the longitude range 270°, through the GC to 5° and latitudes of ±0.5°. Observations began in May 2017 and have already revealed many new sites of class I methanol maser emission which we hope to publish by mid-2018.

3. Summary

In the last five to 10 years there has been a wealth of large-scale, sensitive maser surveys conducted within the Galactic plane, specifically targeting masers that are associated with star formation regions. Together with surveys that are ongoing, they represent a huge resource for studies of maser emission and the star formation regions that they are associated with. While the surveys I have described are those which I have been involved with (and so are biased towards those conducted from the southern hemisphere) there are a number of other exciting maser surveys. In particular I note the water maser

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surveys SWAG and RAMPS, while limited to smaller regions of the Galaxy compared to HOPS, are much more sensitive and will provide very complementary information, particularly revealing the weaker population of water masers within our Galaxy. Other, large surveys such as THOR (The HI/OH/Recombination line survey of the Milky Way), GLOSTAR (Global view of star formation in the Milky Way) and KuGARS (Ku-band GAlactic Reconnaissance Survey) will nicely complement the southern surveys that I have described and will ensure that the golden age for maser surveys extends well into the future.

The success of the maser surveys I have described is largely due to the wisdom of Jim Caswell, who will continue to inspire large-scale maser surveys, and those conducting them, for many years to come.

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