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Star-formation masers in the Magellanic Clouds: A multibeam survey with new detections and maser abundance estimates

J. A. Green[1,2]†, J. L. Caswell[2], G. A. Fuller[1], A. Avison[1], S. L. Breen[2,3], K. Brooks[2], M. G. Burton[4], A. Chrysostomou[5], J. Cox[6], P. J. Diamond[1], S. P. Ellingsen[3], M. D. Gray[1], M. G. Hoare[7], M. R. W. Masheder[8], N. M. McClure-Griffiths[2], M. Pestalozzi[5,11], C. Phillips[2], L. Quinn[1], M. A. Thompson[5], M. A. Voronkov[2], A. Walsh[9], D. Ward-Thompson[6], D. Wong-McSweeney[1], J. A. Yates[10] and R. J. Cohen[1]‡

[1]Jodrell Bank Centre for Astrophysics, Alan Turing Building, University of Manchester, Manchester, M13 9PL, UK

[2]Australia Telescope National Facility, CSIRO, PO Box 76, Epping, NSW 2121, Australia

[3]School of Mathematics and Physics, University of Tasmania, Private Bag 37, Hobart, TAS 7001, Australia

[4]School of Physics, University of New South Wales, Sydney, NSW 2052, Australia

[5]Centre for Astrophysics Research, Science and Technology Research Institute, University of Hertfordshire, College Lane, Hatfield, AL10 9AB, UK

[6]Department of Physics and Astronomy, Cardiff University, 5 The Parade, Cardiff, CF24 3YB, UK

[7]School of Physics and Astronomy, University of Leeds, Leeds, LS2 9JT, UK

[8]Astrophysics Group, Department of Physics, Bristol University, Tyndall Avenue, Bristol, BS8 1TL, UK

[9]School of Maths, Physics and IT, James Cook University, Townsville, QLD 4811, Australia

[10]University College London, Department of Physics and Astronomy, Gower Street, London, WC1E 6BT, UK

[11]Göteborgs Universitet Insitutionen för Fysik, Göteborg, Sweden

Abstract. The results of the first complete survey for 6668-MHz CH_3OH and 6035-MHz excited-state OH masers in the Small and Large Magellanic Clouds are presented. A new 6668-MHz CH_3OH maser in the Large Magellanic Cloud has been detected towards the star-forming region N 160a, together with a new 6035-MHz excited-state OH maser detected towards N 157a. We also re-observed the previously known 6668-MHz CH_3OH masers and the single known 6035-MHz OH maser. Neither maser transition was detected above $\sim$0.13 Jy in the Small Magellanic Cloud. All observations were initially made using the CH_3OH Multibeam (MMB) survey receiver on the 64-m *Parkes* radio telescope as part of the overall MMB project. Accurate positions were measured with the *Australia Telescope Compact Array* (*ATCA*). In a comparison of the star formation maser populations in the Magellanic Clouds and our Galaxy, the LMC maser populations are demonstrated to be smaller than their Milky Way counterparts. CH_3OH masers are under-abundant by a factor of $\sim$50, whilst OH and H_2O masers are a factor of $\sim$10 less abundant than our Galaxy.

Keywords. masers, surveys, stars: formation, Magellanic Clouds

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† E-mail:james.green@csiro.au
‡ Deceased 2006 November 1.

1. Introduction

The Magellanic Clouds exhibit maser emission across a number of molecular transitions from both regions where stars are forming (e.g., UCHIIs) and regions where they are dying (e.g., red supergiants and asymptotic giant branch stars). The latter, collectively known as circumstellar masers, and example transitions being 22-GHz water and 43, 86 and 123-GHz silicon oxide, are explored in detail elsewhere (van Loon *et al.* 1998; van Loon *et al.* 2001). Also dealt with elsewhere are the Magellanic Cloud masers associated with supernova remnants (Brogan *et al.* 2004; Roberts & Yusef-Zadeh 2005). The current work focuses purely on masers associated with star-formation, specifically water (H_2O), hydroxyl (OH) and methanol (CH_3OH).

Only three extragalactic 6668-MHz CH_3OH masers were known to exist before the current survey, and all were seen in the LMC. They were detected towards the nebulae N 105a/MC23 (Sinclair *et al.* 1992) and N 11/MC18 (Ellingsen *et al.* 1994), and towards the IRAS source 05011-6815 (Beasley *et al.* 1996). One 6035-MHz maser was known in the Magellanic clouds, detected towards the nebula N 160a/MC76 (Caswell 1995). The first systematic survey for 6668-MHz CH_3OH and 6035-MHz OH masers in the Magellanic clouds has been completed with the *Parkes* 64-m radio telescope. We report on the new detections of the survey together with maser abundance estimates.

2. Observations

Both the LMC and the SMC were surveyed by the Methanol Multibeam (MMB) project (Cohen *et al.* 2007) in the sidereal time ranges when the Galactic plane was not visible from the *Parkes* radio telescope. The observational setup was the same as for the main MMB survey, and as such is described in detail in Green *et al.* (2008). In addition to scanning the Magellanic Clouds in the same way as the Galactic plane survey, we also conducted targeted observations of known maser and star-formation regions. The scanning survey regions were chosen to fully sample the CO and H I distributions of Fukui (2001) and Staveley-Smith (2003). The LMC region surveyed is shown in Fig. 1, along with the CO clouds contained within the region. For the SMC the MMB team mapped $299° < l < 305°$, $-42° < b < -46°$, taking two passes and resulting in an rms noise of ~ 0.13 Jy. The LMC was scanned across 2° in longitude at a rate of 0.08° per min. These scans were separated by alternating latitude steps of 1.07 arcmin and 15 arcmin. This fully samples a $2° \times 7°$ block of the LMC in 56 scans. The SMC was scanned across 3° in longitude at a rate of 0.15° per min, fully sampling a $3° \times 4°$ block in 32 scans. Data processing for the scanning technique is the same as for the MMB Galactic survey Green *et al.* (2008). The scanning observations were made over the period 2006 January to 2007 November, concurrently with the Galactic survey, making use of the complementary LST range.

Targeted observations were performed toward 11 star-formation regions in the LMC and two known 22-GHz H_2O masers (Scalise & Braz 1982) in the SMC (see Table 1). These points in the sky were tracked with the pointing centre cycling through each of the seven receiver beams. This means each of the seven receiver beams was on source for 10 minutes (with the exception of N 157a where 20 minute integrations were taken). Data processing for the targeted pointings used the package ASAP. The bandpass reference for each beam was estimated using the median spectrum of the six “off-source” positions, and each median reference then combined with the corresponding total power spectrum “on-source” to determine a baseline- and gain-corrected quotient spectrum. The seven spectra were then combined to give a final best spectrum with an effective 70 min integration time (140 min for N 157a) and a typical rms of ~25 mJy in the total intensity spectrum. Flux densities were calibrated using observations of the continuum source PKS 1934−638. The

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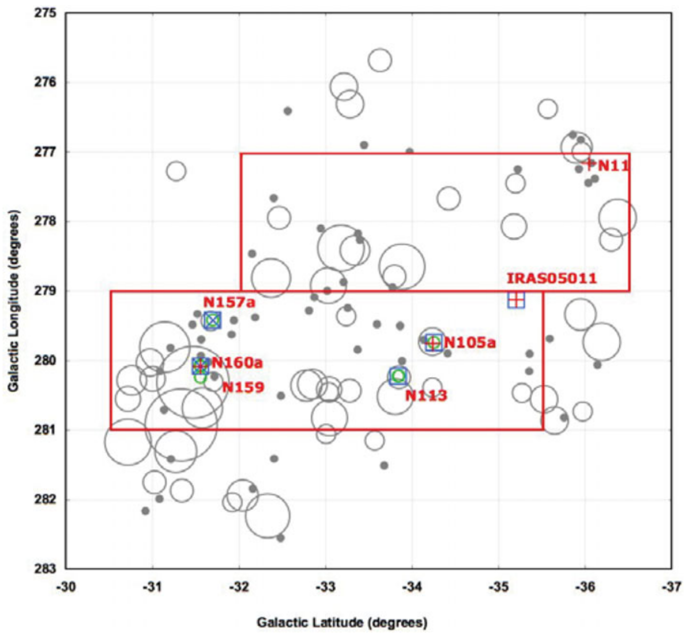

Figure 1. Map of the survey region of the LMC with small and large CO (J = 1−0) clouds from the data of Fukui *et al.* (2001) with overlaid maser positions. Small CO clouds are represented by dots and large clouds by circles scaled proportionally to the total cloud surface area. The labelled symbols represent the masers with squares the ground-state OH, circles 22-GHz H_2O, crosses 6035-MHz excited-state OH, and pluses 6668-MHz CH_3OH. One pass was conducted over the full region, $275° < l < 283°$, $-30° < b < -37°$ with an rms noise of $\sim$0.22 Jy. All regions with detected CO received a second pass and then as the known CH_3OH masers were all within the middle two blocks, the MMB team chose to concentrate on these and thus conducted a further two passes over $277° < l < 281°$, $-30° < b < -37°$, resulting in an rms noise of $\sim$0.09 Jy. We then further concentrated on the regions $279° < l < 281°$, $-30.5° < b < -35.5°$ and $277° < l < 279°$, $-32° < b < -36.5°$. These regions contain all the known masers, the largest CO clouds and over 70 % of the small CO clouds. A further four passes were conducted on these two regions (solid line outlined region), resulting in an rms noise of $\sim$0.06 Jy.

targeted *Parkes* observations were taken in 2006 June (N 11, N 105a, IRAS 05011−6815), 2006 September 3 (N 160a) and 2007 January 25 (N 157a) and are listed with their rms noise levels in Table 1.

In addition to the targeted *Parkes* observations, the *Australia Telescope Compact Array* (*ATCA*) was used 2007 July 21−22 to obtain precise positions for the new CH_3OH maser and for the two excited-state OH masers. A loop of the three targets and the phase calibrator 0530−727 was repeated 22 times over a 10-hour time span and five times on the following day. Within each loop, the three targets had integration times of 15, 2 and 4 minutes respectively. The array was in a 6 km configuration (6C), yielding a FWHM beamsize of 2.8 × 1.6 arcsec. The bandwidth was 4 MHz, spread across 2048 frequency channels, the same as for the *Parkes* spectra.

3. Results

In addition to detecting the three known CH_3OH masers at N 11, N 105a and IRAS 05011−6815 (Fig. 1), a new CH_3OH maser was detected ($> 5\sigma$ in the targeted observations) in association with the known excited-state OH maser in N 160a. The maser had

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Table 1. *Parkes* pointing positions for targeted regions in the Magellanic Clouds, together with rms noise levels for the total intensity spectra.

Position	Name	Pointing RA(J2000) $h\ m\ s$	Pointing Dec(J2000) $^\circ\ '\ ''$	rms noise (mJy)
1	N 11/MC18	04 56 47	−66 24 35	23
2	IRAS 05011	05 01 02	−68 10 28	26
3	N 105a/MC23	05 09 52	−68 53 29	26
4	"	05 09 59	−68 54 34	26
5	N 113/MC24	05 13 25	−69 22 46	26
6	"	05 13 18	−69 22 21	26
7	N 157a/MC74	05 38 47	−69 04 46	20
8	"	05 38 45	−69 05 07	20
9	N 159	05 39 29	−69 47 19	26
10	N 160a/MC76	05 39 44	−69 38 34	26
11	"	05 39 39	−69 39 11	26
12	S7	00 46 39	−72 40 49	22
13	S9	00 47 31	−73 08 20	21

a peak flux density of 0.20 Jy at a heliocentric velocity of 248 km s^{-1} and is spatially coincident with the previously known excited-state OH. A new excited-state OH maser was also detected ($> 5\sigma$ in the targeted observations), through a pointing at N 157a. The maser had a peak flux density of 0.22 Jy at a heliocentric velocity of 258 km s^{-1}. Nothing was detected towards the SMC pointings or towards an additional H_2O maser (recently discovered by J. Lovell, private communication).

4. The abundance of star-formation masers in the Magellanic Clouds

Through adopting a "luminosity" parameter of the peak flux density multiplied by the square of the distance, with a distance to the LMC of 50 kpc (Feast 1999), the maser populations of our Galaxy and the LMC can be compared to provide insight into how maser emission is affected by environmental parameters, such as metallicity and the ambient UV field, together with tracing different rates of star-formation. The lowest luminosity maser observed in the Magellanic Clouds for each species is taken as a "cut-off", and for sources above this cut-off an empirical ratio of the size of the maser population is estimated. The Galactic populations are taken as the estimated number of masers above the equivalent Galactic "cut-off". In cases where the Galactic population is well understood, but the Magellanic Cloud population is incomplete (even above the cut-off), then the ratio will be an upper limit. The results are discussed below by species and are summarised in Table 2.

1665-MHz OH. The Brooks & Whiteoak (1997) measurements list four sites of maser emission in the LMC, with strongest peaks ranging from 221 mJy to 580 mJy. Their measurements could have detected sources as weak as 50 mJy in favourable cases, but 200 mJy is treated as the cut-off, i.e. 500 Jy kpc^2. Adopting the ground-state OH luminosity function of Caswell & Haynes (1987), but scaling to a Sun−Galactic Centre distance of 8.5 kpc, the Galactic population is estimated to be 60 sources above the corrected cut-off and a ratio of $\leqslant 15$. The LMC results do not represent a complete survey, so the ratio is taken as a lower limit.

6035-MHz OH. The two LMC detections have "luminosities" of ~ 625 Jy kpc^2 and ~ 1000 Jy kpc^2 and so for this transition also, we adopt an approximate cut-off of 500 Jy kpc^2. From the discussion of Caswell & Vaile (1995), updated to include information from Caswell (2001) and Caswell (2003), only two sources in the Galaxy are found to

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Table 2. Comparison of maser populations. References: [a] Caswell & Haynes (1987); [b] Greenhill *et al.* (1990); [c] Sinclair *et al.* (1992); [d] Ellingsen *et al.* (1994); [e] Caswell & Vaile (1995); [f] Beasley *et al.* (1996); [g] Brooks & Whiteoak (1997); [h] Lazendic *et al.* (2002) and van Loon & Zijlstra (2001); [i] Current Work; † Although the Galactic ground-state OH population is unlikely to change significantly, both the CH_3OH and excited-state OH Galactic populations will be better defined once the MMB is completed and the excited-state OH Galactic population could conceivably increase. Therefore the 1:1 ratio for excited-state OH should be considered with this in mind. Luminosities for the LMC are based on a distance of 50 kpc and Galactic luminosities assume that the Galactic Centre is 8.5 kpc from the Sun. *See §5.4.1.

Molecule	Transition (MHz)	Luminosity Cut-off (Jy kpc^2)	LMC Pop.	Galactic Pop.	Pop. Ratio (Gal/LMC)
OH	1665	500	$\geqslant 4^g$	60^a	$\leqslant 15$
OH	6035	500	$\geqslant 2^{e,i}$	$2{,}20^e$	$\leqslant 1^\dagger$, $\leqslant 10^*$
CH_3OH	6668	500	$\geqslant 4^{c,d,f,i}$	214^i	$\leqslant 53^\dagger$
H_2O	22235	2500	$\geqslant 8^h$	88^b	$\leqslant 11$

be above this threshold. However, these are clearly very small number statistics, and this problem may be countered by using information on the whole Galactic population (exceeding 100). A general comparison with ground-state OH suggests that, to similar luminosity limits, the 6035-MHz masers are one-third as common (Caswell 2001). That would suggest a Galactic population of 20 above the cut-off, and a ratio of ∼ 10.

6668-MHz CH_3OH. The sources in N 11, N 105a and N 160a would have "luminosities" between ∼ 500 and ∼ 750 Jy kpc^2, giving a luminosity threshold of 500 Jy kpc^2. From the preliminary results of the MMB survey, resolving kinematic distances where possible and assuming the remaining are at the near distance gives a Galactic population of 214 (which is likely to be a lower limit as it is possible a larger proportion than assumed could be at the far distance). This results in a difference of populations by a factor of ∼ 50. As the CH_3OH results are based on a complete survey of the LMC, the population ratio for this maser species should be the most reliable. It therefore seems significant that, compared to our own Galaxy, the CH_3OH masers in the LMC are under-abundant relative to OH, which is perhaps suggestive that the LMC environment is less conducive for CH_3OH emission, than OH.

22-GHz H_2O. The small beams at this frequency make both the Galactic and Magellanic populations likely to be severely incomplete. However, using the known detections as described in Lazendic *et al.* (2002) coupled with the detection by van Loon & Zijlstra (2001), we have a minimum flux density of ∼ 1 Jy (when smoothing the 1.6 Jy weakest maser to a linewidth of 1 km s^{-1}). At the LMC distance this gives a "luminosity" threshold of 2500 Jy kpc^2 (a factor of ∼ 5 greater than the previous similar study of Brunthaler *et al.* 2006). Applying the derived Galactic luminosity function of Greenhill *et al.* (1990) this gives a Galactic population of 88 and a ratio of ∼ 11.

5. Conclusions

A complete survey of the Magellanic Clouds has been conducted as part of the MMB project and supplemented by a targeted search of known star-formation regions in the Large Magellanic Cloud. This has detected two new extragalactic masers: a fourth 6668-MHz CH_3OH maser towards the star-forming region N 160a in the LMC; and a second extragalactic 6035-MHz OH maser towards N 157a. The MMB team have also re-observed the three previously known 6668-MHz CH_3OH masers and the single 6035-MHz OH maser in the LMC. All these masers have had their positions determined with the *ATCA*

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and exhibit stability in spectral structure and intensity, even over the ~ 10 year separation between the current and previous observations. The current lower limits on the LMC maser populations are demonstrated to be up to a factor of ~ 50 smaller than the Milky Way, with the CH_3OH showing the largest discrepancy. With the LMC star formation rate believed to be about a tenth of our Galaxy (Israel 1980), H_2O and OH masers are broadly compatible, but the CH_3OH masers in the LMC are still under-abundant by a factor of ~ 5. This remaining disparity may be due to the lower oxygen and carbon abundances in the LMC, in agreement with the speculation of Beasley *et al.* (1996).

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