ATCA survey of H$_2$O masers in the Large Magellanic Cloud

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ABSTRACT

We have analysed archival data taken with the Australia Telescope Compact Array (ATCA) during 2001–2003 and detected nine new interstellar and circumstellar H$_2$O masers in the Large Magellanic Cloud (LMC). This takes the total number of star formation H$_2$O masers in the LMC to 23, spread over 14 different star-forming regions and 3 evolved stars. Three H$_2$O maser sources (N105a/MC23, N113/MC24, N157a/MC74) have been detected in all the previous observations that targeted these sites, although all show significant variability on time-scales of decades. The total number of independent H$_2$O maser sources now known in the LMC means that through very long baseline interferometry astrometric measurements it will be possible to construct a more precise model of the galactic rotation of the LMC and its orbital motion around the Milky Way Galaxy.

Key words: masers – stars: formation – stars: mass-loss – Magellanic Clouds.

1 INTRODUCTION

There are more than a thousand H$_2$O maser sources currently known in the Milky Way (MW) galaxy (e.g. Valdettaro et al. 2001; Walsh et al. 2011). In contrast, the total number of maser sources detected in all species in the Large and Small Magellanic Clouds (LMC, SMC) is around 20 (see Ellingsen et al. 2010, hereafter EBCQF10, and references therein). The maser sources in the LMC and the SMC are important objects for addressing a range of astrophysical questions.

H$_2$O masers are typically associated with outflow activity from young stellar objects (YSOs) and the final copious stellar mass-loss phase of red giant and supergiant stars. All of the H$_2$O masers found in the Magellanic Clouds (MCs) to date are associated with either massive YSOs or red supergiants, both of which trace the present sites of star formation in these galaxies. Taking into account the relatively low metallicity of the MCs compared to the MW, some differences are expected in the dominant physical mechanisms and the time-scales that govern the process of star formation and stellar mass-loss.

Very long baseline interferometric (VLBI) observations can resolve each maser source into a cluster (or clusters) of compact maser features, whose three-dimensional motions (line-of-sight velocities and proper motions) can be measured. With current instruments with which astrometric accuracy of 10 μas is achievable, such studies are possible for star-forming regions in nearby galaxies at distances of

up to 1 Mpc (e.g. Brunthaler et al. 2005). Measuring the motions of the maser sources with respect to nearby (in terms of angular separation) quasars, it is possible to determine both a space motion and a trigonometric parallax distance (given sufficient astrometric accuracy) of the maser source. Within the MW on kiloparsec scales, H$_2$O maser sources are confined to the MW thin disc and have been used to derive fundamental Galactic structure parameters (Reid et al. 2009; Honma et al. 2012). The LMC and SMC are at distances of approximately 50 and 60 kpc, respectively (e.g. Cioni et al. 2000), so the amplitude of the trigonometric parallax is approximately 20 μas. This is too small to enable accurate parallax distance determinations with current instruments and techniques (e.g. Reid et al. 2009), but may be feasible through statistical approaches, or with future space-based VLBI missions.

With current, ground-based VLBI we are able to determine the space motion of maser sources within the MCs by measuring and correcting for the intrinsic internal motions of maser features in the source. The locations and past orbits of the MCs are important and controversial topics in studies of the star formation history and process of interactions of the galaxies in the MW–MC system (e.g. Diaz & Bekki 2012). Astrometric observations using data from ground-based optical telescopes and the *Hubble Space Telescope* have been used to measure the proper motions of the MCs (Piatek, Pryor & Olszewski 2008; Vieira et al. 2010; Kallivayalil et al. 2013). However, there exist non-negligible discrepancies among the results. The optical astrometry results are affected by the inclusion of stars from a variety of populations with different dynamical characteristics located along the same lines of sight. They are also affected by the galactic rotation model adopted (e.g. Haschke, Grebel &

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Table 1. Setup status of the analysed data of the ATCA observations towards the LMC.

Program code	Date (yyyy/mm/dd)	N_b [a]	Array[b]	Scan time[c]	Bandwidth (MHz)	N_{spect} [d]	Targets
C901	2001/01/07	3	750C	$18-19 \times 3-4$	8	1024	N105a, N113, N157a, N159, N160a and 0506$-$612
C973	2002/11/01–07	3	Wnnn[e]	$1-3 \times 2-3$	16	513	186 sources in H II regions and O-rich AGB stars
	2003/05/01–04	6	EW352	$5-7 \times 2-3$	16	513	28 sources in H II regions and O-AGB 815

[a]Number of scans $\times$ duration per scan in min.
[b]Array configuration.
[c]Number of available baselines.
[d]Number of spectral channels.
[e]The array configurations are named as combination of antenna positions labelled as W plus three digit numbers such as: W100, W110, W147, W168 and W196.

Duffau 2012), which is required to extract the centre-of-mass space motions of the galaxies from the observed proper motions.

In order to analyse the 3D kinematics of the individual H_2O maser sources in the MCs and to derive the dynamical parameters of these galaxies, efforts to increase the number of identified H_2O masers in these galaxies are important. Statistical analysis of the 3D kinematics of the maser sources will enable us to compare the kinematic properties of the MCs with those of the MW. In order to construct dynamical models of the MCs, each galactic model requires the present centre-of-mass space motion, the velocity field of the galactic rotation and the distance to the galaxy as free parameters in the model fitting. A large number of maser sources ($\gtrsim$20) are required to make such an analysis feasible. In this paper, we present H_2O masers in the LMC detected with the Australia Telescope Compact Array (ATCA), including nine newly discovered since the work of EBCQF10.

2 ANALYSIS OF ATCA ARCHIVAL DATA

We analysed archival observations of H_2O maser sources in the MCs taken in ATCA observations made on 2001 January 7 (programme C901), and in the period of 2002 February–2003 May (C973).[1] Table 1 summarizes the observing strategy and correlator setup used for the observations. In each of the observing sessions, all six 22-m antennas were used in the array, but for some observations only three baselines were useable. Data reduction was undertaken using the MIRIAD package, following the standard procedures for ATCA data. The visibility amplitude and phases were calibrated by referencing them to observations of flux density and phase calibrator sources. Phase calibration solutions were obtained from the scans on the phase calibrators, J045005.4$-$810102 and J050644.0$-$610941, one of which was observed every 10–20 min. Although there was a difference in the channel resolution for the correlator outputs in the different sessions, all data were smoothed to the achieve the same velocity resolution of $\sim$0.5 km s^{-1}. We then constructed synthesis images for each source to search for H_2O masers and to check the image fidelity.

For sources where a maser detection was confirmed and there was sufficient coverage of the uv-plane (mainly in the C973 2003-June session), we attempted to obtain the spectrum and the coordinates of the maser emission from the image cube. Even for the sources with

sufficient uv-coverage, there existed significant side lobes, making the astrometry difficult. The angular resolution of the ATCA observations was typically $\sim$0.5 arcsec (corresponding to a linear resolution of $\sim$0.1 pc at the distance of the LMC), within which most velocity components of a single maser source will be contained. Because we are mainly interested in the number of independent maser sources rather than the internal structures of the individual maser sources in this paper, we have only determined the coordinates of the brightest velocity components of the maser sources. The uncertainty in the measured maser positions is 1–2 arcsec in the cases where we could not uniquely determine the brightest point of the maser source due to the high side lobe levels. Columns 2 and 3 of Table 2 give the coordinates of the detected maser sources where we were able to determine them.

3 RESULTS

A total of twelve 22-GHz H_2O masers were detected towards the LMC in the C901 and C973 ATCA observations, eight and one of which are newly discovered interstellar and circumstellar sources, respectively. Table 2 lists the 16 interstellar H_2O masers in the LMC known to date [see also the latest review of maser source surveys towards the MCs in van Loon (2012)]. Table 3 gives the parameters of the newly detected circumstellar maser. Fig. 1 shows the ATCA cross-power spectra of the H_2O masers in the LMC.

The stellar source O-AGB 815 (2MASS J05351409$-$6743558) corresponds to an M4-type variable star (HV 1001) with a K magnitude of 8.14. Its H_2O maser is apparently weak ($\sim$0.2 Jy) and the maser luminosity is comparable to or lower than that seen in supergiants in the MW (e.g. VY CMa with an H_2O maser flux density of up to 1000 Jy at a distance of 1.1 kpc; Choi et al. 2008).

The eight newly detected interstellar H_2O masers (those for which Column 7 of Table 2 contains only the reference 4) are IRAS F04521$-$6928, HII 1107, HII 1186, N113a (in N113/MC24), IRAS 05202$-$6655, NGC 1984/OH 279.6$-$32.6, N214b and N180. In some regions, H_2O maser sources were spread over an area of the order of 1 arcmin. Taking into account the position uncertainty, we regarded maser emission located within a radius of 1–2 arcsec as a single source and they are shown in a single line in Table 2. There are 15 independent H_2O maser sources that are separated from each other by more than 1 arcmin (15 pc at the distance of the LMC).

Some bright H_2O maser sources were first detected more than 25 years ago (e.g. Scalise & Braz 1981). However, even for regions where there has been persistent maser emission over a long period, the sources have exhibited large flux density variability and sometimes drop below the detection threshold. For example, in the brightest maser source N113/MC24, the peak velocity of the brightest maser component has dramatically changed and the strongest

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[1] The C973 observations also targeted sources in the SMC, which we also reduced. However, the SMC data have been independently analysed and published by Breen et al. (in preparation) and in this paper we focus only on the sources in the LMC.

Table 2. Interstellar 22-GHz H_2O masers in the LMC. Some of the source names in the first column are those registered in the data archive. The source coordinates are cited from the latest result from this work, EBCQF10, Lazendic et al. (2002) or Oliveira et al. (2006). References for the coordinates are 1: Lazendic et al. (2002); 2: Oliveira et al. (2006); 3: EBCQF10; 4: this work. 1σ noise levels on the images (including side lobes) are given in the present results. References and catalogues for the corresponding objects are GC: Gruendl & Chu (2009); 2MASS: Two-micron All Sky Survey Point Source Catalog; 2MASX: 2MASS Extended Source Catalog.

Source name	RA (J2000) h	m	s	Dec. (J2000) °	′	″	Velocity Range (km s⁻¹)	Peak	Peak flux (Jy)	Ref.	1σ noise (Jy)	Counterpart stellar objects
IRAS F04521−6928	4	51	53.90	−69	23	27.8	205–245	233.4	2.5	4	0.08	GC J045153.29−692328.6
HII 1107	4	52	09.74	−66	55	21.8	250–275	273.5	0.9	4	0.07	2MASS J04520916−6655223
HII 1186	4	54	00.10	−69	11	54.5	245–255	245.5	5.0	4	0.08	2MASS J04540020−6911557
IRAS 05011−6815	5	01	01.83	−68	10	28.2	263–266	264.4	0.08	3	–	GC J050101.80−681028.5
N105a/MC23	5	09	52.00	−68	53	28.6	252–260	254.6	1.4	1, 3	–	GC J050952.26−685327.3
	5	09	52.74	−68	53	24.9	235–260	244.2	1.1	2, 4	0.09	GC J050952.26−685327.3
	5	09	52.55	−68	53	28.0	246–268	266.2	0.8	3	–	GC J050952.26−685327.3
N113/MC24	5	13	17.17	−69	22	21.6	249–286	257.1	2.0	3	–	GC J051317.69−692225.0
	5	13	17.69	−69	22	27.0	245–250	249.1	0.3	1, 3	–	GC J051317.69−692225.0
	5	13	25.31	−69	22	42.4	215–257	237.8	52.3	2, 4	0.11	2MASS J05132499−6922442
	5	13	25.15	−69	22	45.4	228–264	253.1	116	1, 2, 3	–	2MASS J05132499−6922442
N113a (in N113)	5	13	22.36	−69	22	38.6	235–265	238.1	3.1	4	2.56	GC J051321.43-692241.5
IRAS 05202−6655	5	20	16.90	−66	52	53.3	285–300	287.0	2.0	4	0.06	2MASX J05201653−6652544
NGC 1984	5	27	41.32	−69	08	05.9	255–265	258.3	3.3	4	0.07	2MASS J05274010−6908044
N157a/MC74	5	38	46.53	−69	04	45.3	253–271	269.0	6.5	1, 3	–	GC J053848.42−690441.6
	5	38	49.25	−69	04	42.1	263–268	267.3	0.5	3	–	GC J053848.42−690441.6
	5	38	46.80	−69	04	45.5	235–255	249.9	0.6	2, 4	0.09	GC J053848.42−690441.6
	5	38	52.67	−69	04	37.8	265–269	266.9	1.4	3	–	2MASS J05385273−6904374
N160a	5	39	43.83	−69	38	33.8	236–261	251.6	1.8	1, 2, 3	–	GC J053943.82−693834.0
	5	39	38.97	−69	39	10.8	252–260	253.1	2.5	3	–	GC J053939.02−693911.4
N159	5	39	29.23	−69	47	18.9	242–255	248.3	1.1	1, 3	–	GC J053929.21−694719.0
N214b	5	39	53.51	−71	09	51.6	225–230	228.7	7.8	4	0.09	2MASS J05395357−7109533
N180	5	48	26.44	−70	08	48.8	130–140	139.8	0.6	4	0.07	2MASS J05482622−7008502

Table 3. Same as Table 2 but for a circumstellar 22-GHz H_2O maser in the LMC, which was newly detected in this work.

Source name	RA (J2000) h	m	s	Dec. (J2000) °	′	″	Velocity Range (km s⁻¹)	Peak	Peak flux (Jy)	1σ noise (Jy)	Counterpart stellar object
O-AGB 815	5	35	14.57	−67	43	54.5	230–236	235.5	0.18	0.08	HV 1001, 2MASS J05351409−6743558

*Note.* The coordinates are cited from the Harvard Variable (HV) Star Catalogue.

spectral feature observed in this paper (observation in 2003 May) was not detected in the observations of EBCQF10 (2008 August). As a result, apparent position shifts (>1 arcsec or >0.25 pc) may occur due to the maser sources with such flux variability in the different locations (a Christmas tree effect). Clustering of H_2O maser sources on parsec scales is observed in some Galactic star formation regions (e.g. W51 North and Main; W3(OH) and W3 IRS5). Therefore, the observed position shifts may be due to variation in the relative flux density between maser sources within a cluster, although we cannot rule out the possibility that these shifts occur just due to the relative positional errors of the observations made at different epochs. N113/MC24 and N113a present one example of a cluster of H_2O maser sources (Lazendic et al. 2002; Oliveira et al. 2006; EBCQF10).

We looked for corresponding objects within 10 arcsec of the maser sources and these are listed in Column 9 of Table 2. Only the nearest sources from the maser position are listed. The corresponding 2MASS sources are located within 3 arcsec of the masers. Note that IRAS 05202−6655 seems to be associated with an extended infrared source (2MASX J05201653−6652544) and its population is unclear. Proximity to sources listed by Gruendl & Chu (2009) may be a good indication of association with a YSO.

4 DISCUSSION

Here we estimate possible detections of H_2O masers in the LMC using an H_2O maser luminosity function (H_2O-LF). Greenhill et al. (1990) derived the H_2O-LF for the MW, which will be improved by further unbiased H_2O maser surveys in the MW (e.g. Walsh et al. 2011). Similar to the approach used by Darling (2011) to estimate the expected number of H_2O masers in M31, we need to rescale the H_2O-LF using the relative star formation rates of the MW and the LMC ($\sim$4 and $\sim$0.4 $M_\odot yr^{-1}$, respectively; Diehl et al. 2006; Skibba et al. 2012).

The shortest on-source integration time for the present data was $\sim$3 min. With a velocity resolution of 0.5 km s⁻¹, the corresponding detection limit for the peak of any H_2O maser emission is estimated to be 1 Jy. Adopting a distance to the LMC of 51 kpc (corresponding to a distance modulus of 18.55; e.g. Cioni et al. 2000; Haschke et al. 2012) our detection limit corresponds to an isotropic H_2O maser luminosity of 2.4×10^{-5} $L_\odot$. We calculate the expected number of H_2O masers with the luminosities higher than this value in the LMC to be $\sim$15. This is in good agreement with the actual number of the identified sources over 1 Jy (16 sources in Table 2). This supports the argument that the number of H_2O maser
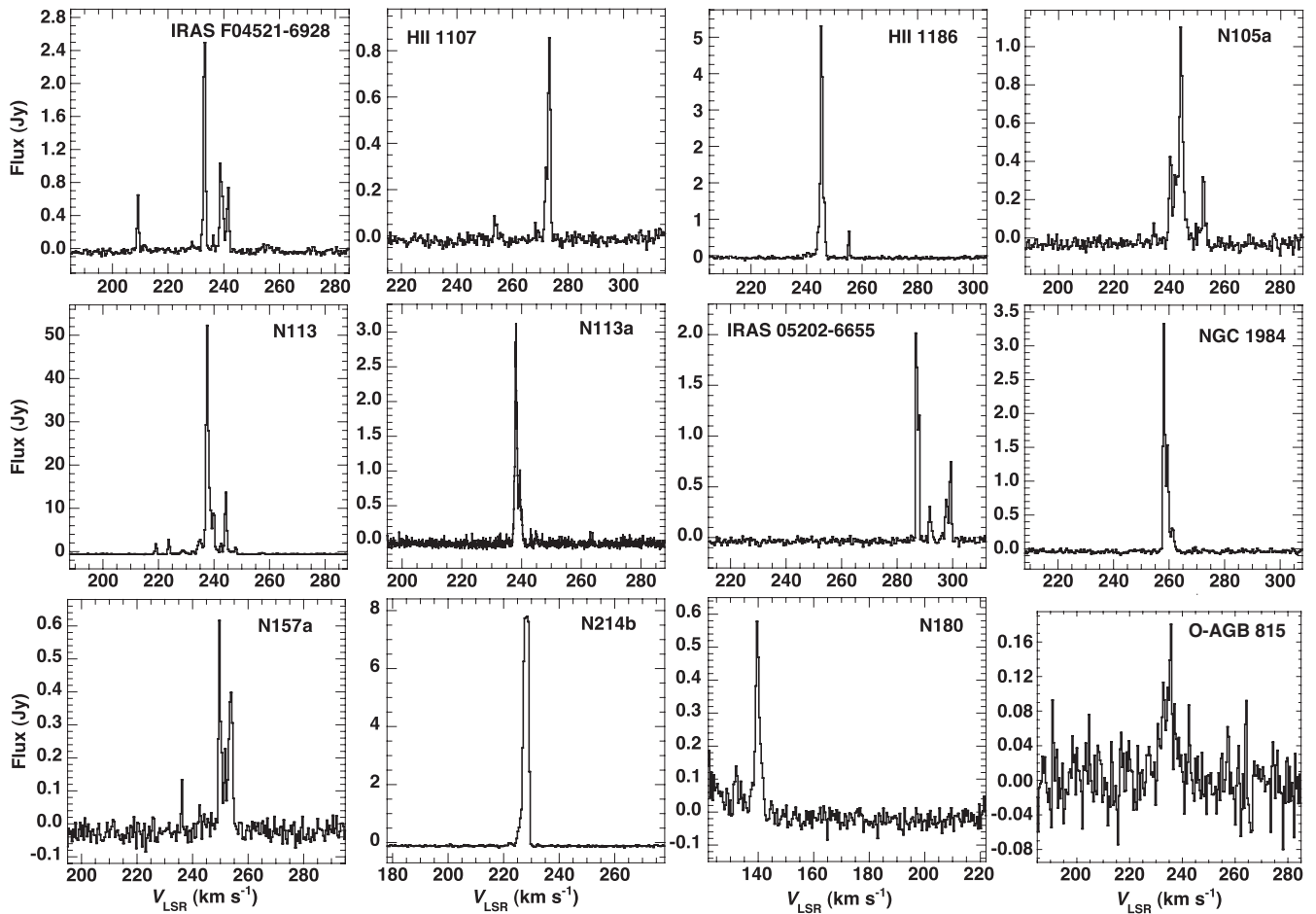
Figure 1. H$_2$O maser spectra taken with the ATCA in the 2003 May session, except for N113a taken in the 2002 November session.
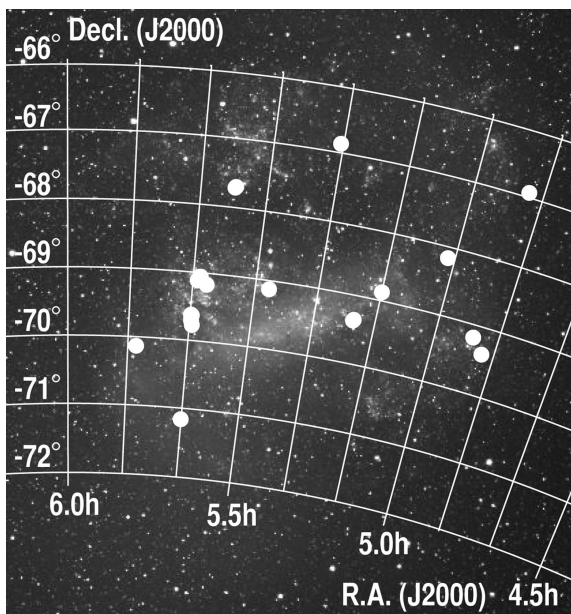
Figure 2. Distribution of all interstellar H$_2$O masers identified to date in the LMC on a gnomonic projection map. The background grey image is the optical image of the LMC taken from *SkyView*: http://skyview.gsfc.nasa.gov.

detections in the LMC is consistent with MW expectations when the difference in the star formation rates between the LMC and the MW is taken into account (Green et al. 2008; EBCQF10, and references therein). Although the same approach when applied to M31 results in an underestimation of the expected number of detections (prediction of ∼3 compared to the 5 detected; Darling 2011), the difference is less than a factor of 2 and within the estimated uncertainty of this approach.

EBCQF10 used the LMC YSO catalogue of Gruendl & Chu (2009) to investigate the infrared properties and spectral energy distribution (SED) of star formation regions with an associated H$_2$O maser and compared them to the entire sample. They showed that H$_2$O-associated YSOs have higher central mass, larger envelope radius, higher ambient density and higher total luminosity than the general YSO population. EBCQF10 classified YSO within 2 arcsec of the H$_2$O maser position as being associated. Applying the same criterion to the eight new LMC H$_2$O masers listed in Table 2, we find that three (HII 1186, N214b and N180) have a definite YSO each within 2 arcsec (table 9 of Gruendl & Chu 2009). In contrast, for the 16 LMC interstellar masers investigated by EBCQF10, 11 were within 2 arcsec of a definite YSO identified by Gruendl & Chu (2009). The cause of this discrepancy is not clear, it may indicate that the newly detected LMC H$_2$O maser sources are primarily associated with more evolved star formation regions than the sample of EBCQF10, which targeted all the CH$_3$OH, OH and H$_2$O masers known at that time. The three associations from the newly detected

masers have similar SED properties to the maser-associated sources of EBCQF10. However, none of them are sources identified by EBCQF10 as a high-probability maser candidate, so future searches towards these sources may provide additional H_2O masers in the LMC.

Including the three circumstellar H_2O masers associated with red supergiants (IRAS 04553−6825, 05280−6910, van Loon et al. 2001; HV 1001) as members of the young stellar population, there are 19 independent maser sources in the LMC. Even limited to 16 interstellar masers brighter than 0.5 Jy, through measurement of the proper motions of these masers (better than 100 μas yr^{-1} in a time baseline of 1 yr) it is possible to obtain 48 observables (the three-dimensional velocity vector components for each source). A basic dynamical model of the LMC requires nine free parameters in the fitting: a source distance, a three-dimensional centre-of-mass space motion vector, the galactic rotation axis inclination and position angle and a third (or higher order) polynomial galactic rotation curve. Fig. 2 shows that the H_2O masers are distributed throughout the LMC, mitigating the likelihood of bias in the model fitting which may occur if only a small number of independent locations were available. If the distance to the LMC and the axis of the galactic rotation are fixed in the model fitting (using previous accurate determinations), it will be possible to extract the velocity field of the LMC and more precisely determine the centre-of-mass space motion of the LMC from maser proper motion observations.

5 CONCLUSION

With the current sample of H_2O masers in LMC (19 in total) and the existence of position-reference quasars within a few degrees of arc of these masers (Imai et al., in preparation), VLBI astrometric observations to estimate the centre-of-mass space motion vector for the LMC are feasible. They may provide an opportunity for independently checking the results of optical astrometry measurements. Furthermore, measurement of the trigonometric parallax of the LMC ($\pi \approx 20$ μas) may be possible. With a position measurement accuracy achieved by the state-of-the-art VLBI astrometry mentioned previously, an individual measurement of the parallax will yield only a marginal detection. However, with independent measurements from ∼10 regions, each with potentially a few detections of the maser spot parallax, it will be possible to statistically improve the reliability and precision of the parallax detection. In the same observations it will also be possible to investigate the spatio-kinematical structure for each H_2O maser source and to study the physical properties of the star formation regions and the final stellar mass-loss in the MCs.

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