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Accurate OH maser positions from SPLASH: Understanding the origins of OH masers with an unbiased survey

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Abstract

The hydroxyl radical (OH) was the first molecule discovered in the interstellar medium (ISM) and can produce strong stimulated spectral line emission (OH masers). The Southern Parkes Large-Area Survey in Hydroxyl (SPLASH) observed four ground-state OH transitions simultaneously in an unbiased way, covering a large area of the southern Galactic plane (176 square degrees). Limited to the Parkes' spatial resolution, accurate positions for these OH masers need further interferometric observations, which is the motivation for our work.

This thesis summary focuses on the results of the SPLASH pilot region ($334^\circ < l < 344^\circ$, $|b| < 2^\circ$) using the Australia Telescope Compact Array (ATCA). To date, except for the SPLASH pilot region, preliminary ATCA results in the Galactic centre region ($355^\circ < l < 5^\circ$, $|b| < 2^\circ$) have been finished and ATCA observations for all SPLASH region have been completed. In the SPLASH pilot region, 215 OH maser sites were detected and 111 of them are new detections. A planetary nebula (PN) IRAS 16333-4807 in the SPLASH pilot region was detected with OH masers, including the rare 1720 MHz OH maser. Major science results from this thesis summary include:

The seventh OHPN (OH-maser-emitting planetary nebula), the second OHPN with 1720 MHz OH maser emission and the only evolved object in whose circumstellar envelope the 1720 MHz maser is the strongest OH transition. The magnetic fields inferred from the Zeeman splitting of the 1720 MHz OH masers.

215 OH maser sites in the SPLASH pilot region. The classifications for these OH maser sites: 122 OH maser sites are associated with evolved stars, 64 sites are associated with star formation, two sites are associated with supernova remnants (SNRs) and 27 sites are of unknown origins. Evolved star sites with symmetric maser profiles tend to have redder infrared (IR) colours than those of evolved star sites with asymmetric maser profiles.

Preliminary results in the Galactic centre region. The distribution of evolved star OH maser sites is widely spread in Galactic latitude, whereas star formation OH maser sites are constrained to the Galactic plane.

1 Introduction

Masers are important astrophysical objects which can be used to understand the chemical and physical environment of the interstellar medium (ISM). OH maser emission has been detected in many transitions, including ground-state and excited-state transitions. The ground-state OH masers at 18 cm are usually the strongest and most widespread OH masers. In our Galaxy, ground-state OH masers are usually detected towards several different environments, e.g. circumstellar envelopes of evolved stars, high-mass star formation (HMSF) regions and supernova remnants (SNRs). Many surveys have been carried out towards ground-state OH masers, but most of them were targeted surveys or observed towards one or two ground-state transitions (e.g. 1612 MHz only; 1665 and 1667 MHz). These previous surveys suffer from biases (e.g. towards HMSF regions or evolved star sites), thus unbiased surveys in large areas are helpful to understand the origins of ground-state OH masers by investigating the proportion of masers associated with each kind of astrophysical object.

We used the Australia Telescope Compact Array (ATCA) to measure accurate positions of OH masers based on the results from the Southern Parkes Large-Area Survey in Hydroxyl (SPLASH). SPLASH observed OH in four ground-state transitions across the inner Galactic plane ($332° < l < 10°$, $|b| < 2°$ and $358° < l < 4°$, $2° < b < 6°$; in total 176 square degrees) in an *unbiased* way. After we obtained the accurate positions, we compared these positions with the Methanol Multibeam (MMB) survey, H_2O Southern Galactic Plane Survey (HOPS), Red *MSX* Source (RMS), SIMBAD and the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE) maps to identify which kind of astrophysical object they are associated with. Throughout this work an emphasis has been placed on the associations of OH masers with different astrophysical objects. Moreover, for each kind of astrophysical object, we investigate the statistical properties, such as the mid-infrared (mid-IR) colours of evolved star OH masers, association studies of star formation OH masers, 6.7 GHz methanol masers and/or 22 GHz water masers etc.

1.1 Thesis summary overview

Ground-state OH masers are widely distributed in various astrophysical environments. To date, SPLASH is the largest unbiased survey, which observed four ground-state OH transitions simultaneously with high sensitivities. Therefore, our ATCA observations will provide a census of ground-state OH masers in a large area of the southern Galactic plane, including the Galactic centre region. This thesis summary includes:

Section 2 briefly introduces a planetary nebula (PN) IRAS 16333-4807, which was found in the SPLASH pilot region and associated with 1612, 1667 and 1720 MHz OH masers. The work on this source has been published in Qiao et al. (2016a).

Section 3 summarizes accurate OH maser positions in the SPLASH pilot region (40 square degrees). The paper about the SPLASH pilot region has been published in Qiao et al. (2016b).

Section 4 contains the preliminary results from the Galactic centre region (40 square degrees). This study has been published in a conference paper, i.e. Qiao et al. (2017).

Section 5 concludes the projects I did at Curtin and presents long- and short-term projects associated with my PhD work.

2 OH masers associated with a PN

This section briefly introduces our work on a PN IRAS 16333-4807, which is from a co-authored publication “Unusual shock-excited OH maser emission in a young planetary nebula”. The bibliography of the paper is: Qiao, H.-H., Walsh, A. J., Gómez, J. F., Imai, H., Green, J. A., Dawson, J. R., Shen, Z.-Q., Ellingsen, S. P., Breen, S. L., Jones, P. A., Gibson, S. J. & Cunningham, M. R., 2016, ApJ, 817, 37. The published paper is referenced by this thesis summary as Qiao et al. (2016a).

2.1 Introduction

We have detected 1612, 1667 and 1720 MHz OH masers towards a PN IRAS 16333-4807 at two epochs using the ATCA, hereby confirming it as the seventh known case of an OH-maser-emitting PN (OHPN). This

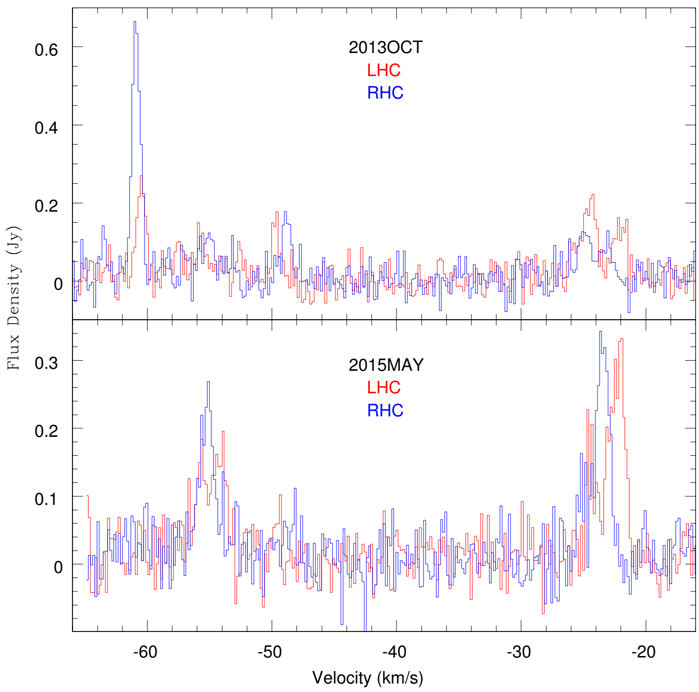

Figure 1: The RHC and LHC polarization spectra of the 1720 MHz transition at two epochs. The velocity resolution is 0.18 $km\,s^{-1}$.

is only the second known PN showing 1720 MHz OH masers after K 3−35 and the only evolved stellar object with 1720 MHz OH masers as the strongest transition. This PN is one of a group of very young PNe. The 1612 MHz and 1667 MHz masers are at a similar velocity to the 22 GHz water masers, whereas the 1720 MHz masers show a variable spectrum, with several components spread over a higher velocity range (up to 36 $km\,s^{-1}$). We also detect Zeeman splitting in the 1720 MHz transition at two epochs (with field strengths of $\sim$ 2 to $\sim$ 10 mG), which suggests the OH emission at 1720 MHz is formed in a magnetized environment. These 1720 MHz OH masers may trace short-lived equatorial ejections during the formation of the PN.

2.2 Magnetic field properties

One of the most important results in this work is the magnetic fields derived from the 1720 MHz OH masers at two epochs. Figure 1 shows the right- and left-hand circular (RHC, LHC) polarization spectra of the 1720 MHz transition, where we adopt the IEEE convention for polarization handedness. There is a clear frequency shift between the RHC and LHC polarizations in all components, indicating Zeeman splitting due to a significant magnetic field. The derived magnetic field along the line of sight is given in Table 2 (in the paper).

3 Results from the SPLASH pilot region

This section briefly presents a co-authored publication "Accurate OH maser positions from the SPLASH pilot region". The bibliography of the paper is: Qiao, H.-H., Walsh, A. J., Green, J. A., Breen, S. L., Dawson, J. R., Ellingsen, S. P., Gómez, J. F., Jordan, C. H., Shen, Z.-Q., Lowe, V., & Jones, P. A., 2016, ApJS, 227, 2. The published paper is referenced by this thesis summary as Qiao et al. (2016b).

3.1 Introduction

This paper is about high spatial resolution observations, using the ATCA, of ground-state OH masers. These observations were carried out toward 196 pointing centres previously identified in the SPLASH pilot region, between Galactic longitudes of 334° and 344° and Galactic latitudes of −2° and +2°. Supplementing our data with data from the MAGMO (Mapping the Galactic Magnetic field through OH masers) survey, we find maser emission towards 175 of the 196 target fields. We conclude that about half of the 21 non-detections were due to intrinsic variability. Due to the superior sensitivity of the follow-up ATCA observations, and the ability to resolve nearby sources into separate sites, we have identified 215 OH maser sites towards the 175 fields with detections. Among these 215 OH maser sites, 111 are new detections. After comparing the positions of these 215 maser sites with the literature, we identify 122 (57 per cent) sites associated with evolved stars (one of which is a PN), 64 (30 per cent) with star formation, two sites with SNRs and 27 (13 per cent) of unknown origin. The IR colours of evolved star sites with symmetric maser profiles tend to be redder than those of evolved star sites with asymmetric maser profiles, which may indicate that symmetric sources are generally at an earlier evolutionary stage.

3.2 The maser site images

Maser spots have been grouped into maser sites based on their separations. For each maser site, we present the spectrum or spectra, maser spots overlaid on the IR maps and their relative positional error ellipses for each maser spot (e.g. Figure 2). These images are one of the most important results from this paper.

In Figure 2, the bottom panel is a $6' \times 3'$ GLIMPSE three-colour image, which plots band 1 for blue, 2 for green and 4 for red, with band wavelengths of 3.6, 4.5 and 8.0 μm, respectively. Note that for masers in the Galactic latitude range of $|b| > 1°$, the three-colour image is made from the Wide-field Infrared Survey Explorer (*WISE*) data, based on band 1 for blue, 2 for green and 3 for red, with band wavelengths of 3.4, 4.6 and 12.2 μm, respectively. The image is centred on the maser site. All maser spots that were detected within this field of view are shown. 1612 MHz maser spots are presented with 3-pointed stars, 1665 MHz maser spots with plus symbols, 1667 MHz maser spots with cross symbols and 1720 MHz maser spots with triangles.

The middle-left panel presents the zoomed-in region around the maser site. This region is a square $21.6''$ on each side. The background is the same three-colour image as the bottom panel. In the centre of this panel, there is a white box, which shows the region of the zoomed area presented in the middle-right panel. The size of the middle-right panel is chosen such that all masers, together with the full extent of their error ellipses, will fit within the panel. Thus, different maser sites have different white box sizes in the middle-left panel.

The middle-right panel is a zoomed-in region showing the positions and relative error ellipses of all maser spots for this maser site. Each maser spot is represented both with a coloured ellipse and a coloured symbol, with different symbols for different transitions as described above. The position of the ellipse is the fitted position of that maser spot. The major axis, the minor axis and the position angle of the ellipse represents the relative positional uncertainty of the maser spot. At the bottom of this panel, there is a velocity colour bar. The colour of the ellipses and symbols shows the peak velocity of the maser spot. Note that there is no absolute coordinate presented in this panel because the

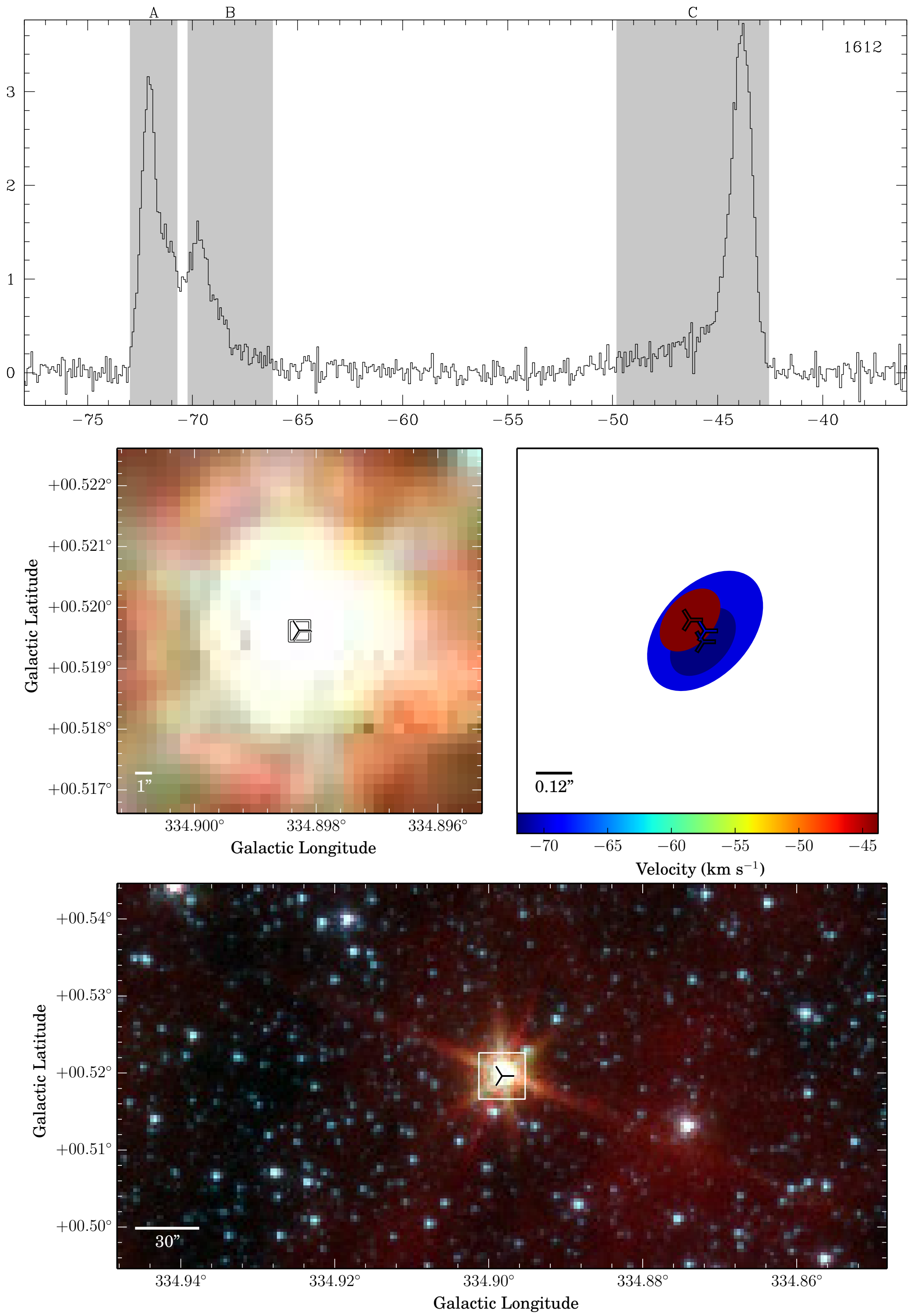

Figure 2: G334.898+0.520. The upper panel shows the unbinned spectrum, with the radial velocity with respect to the local standard of rest (LSR) on the x-axis in units $\mathrm{km\,s^{-1}}$ and flux density on the y-axis in units of Jy. The flux density is constructed from Stokes I. In the bottom, middle-left and middle-right panels, 1612 MHz maser spots are presented with 3-pointed stars, 1665 MHz maser spots with plus symbols, 1667 MHz maser spots with cross symbols and 1720 MHz maser spots with triangles.

absolute position uncertainty is only about 1″.

4 Preliminary result in the Galactic Centre region

This section includes a co-authored conference publication "Ground-state OH maser distributions in the Galactic Centre region". The bibliography of the paper is: Qiao, H.-H., Walsh, A. J., Shen, Z.-Q., & Dawson, J. R. 2017, IAU Symposium, 322, 141. The published paper is referenced by this thesis summary as Qiao et al. (2017). Further plans derived from this work will be presented in Section 5.2.1.

4.1 Introduction

Ground-state OH masers identified in SPLASH were observed with the ATCA to obtain positions with high accuracy ($\sim$1″). We classified these OH masers into evolved star OH maser sites, star formation OH maser sites, SNR OH maser sites and unknown maser sites using their accurate positions. Evolved star and star formation OH maser sites in the Galactic Centre region (between Galactic longitudes of -5° to $+5^\circ$ and Galactic latitudes of -2° and $+2^\circ$) were studied in detail to understand their distributions.

4.2 Results and implications

There are about 256 evolved star OH maser sites and about 31 star formation OH maser sites in the Galactic Centre region. Figure 3 shows their distributions.

Evolved star OH masers. Evolved star OH masers are widely distributed in Galactic latitude because they are either close to us, or they originate in the Galactic Bulge. We can see the density enhancement in the Galactic Bulge.

Star formation OH masers. Star formation OH masers are tightly constrained to the Galactic Plane. There are more star formation OH masers in the negative Galactic latitude (21 out of 31). It is interesting to note that the distribution of star formation OH masers is evenly distributed with respect to Galactic longitude. These OH masers do not

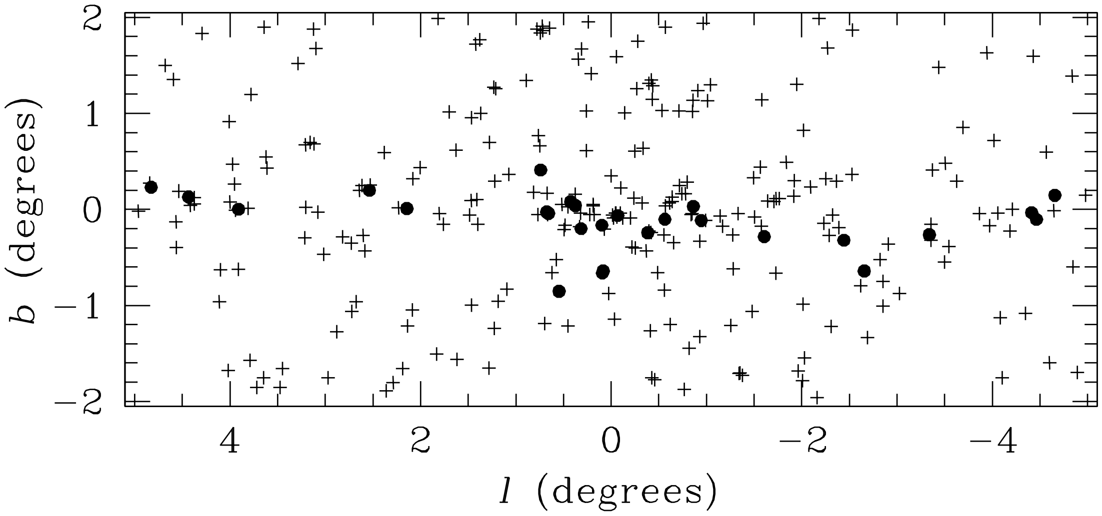

Figure 3: OH maser distributions in the Galactic Centre region. Pluses are evolved star OH masers and filled circles are star formation OH masers.

follow the dense gas concentrations that dominate at positive Galactic longitudes. Compared with the SPLASH pilot region (Qiao et al. 2016b; 64 star formation OH maser sites), there are less star formation OH maser sites in the Galactic Centre region, which contains more dense gas.

5 Conclusions and future work

5.1 Conclusions

This thesis summary has briefly summarized ground-state OH maser distributions in a large area of the southern Galactic plane, primarily by obtaining accurate positions for the OH masers derived from an unbiased survey, SPLASH. The following paragraphs present the major results of the previous sections as well as future work related to these results.

An unusual shock-excited OH maser at 1720 MHz (Section 2, Qiao et al. 2016a) in the SPLASH pilot region was investigated at two epochs. The Zeeman pair study for this source proved that our ATCA data could be used to infer in situ magnetic fields by investigating the Zeeman splitting of OH masers.

Accurate OH maser positions for the SPLASH pilot region (Section

3, Qiao et al. 2016b) were obtained for 215 OH maser sites with their identifications. Some statistical work has been conducted to further study the properties of each maser category, i.e. evolved star category and star formation category. More than half (122 out of 215) of OH maser sites are associated with evolved stars, showing double-horned profiles at 1612 MHz spectra. 111 of 215 OH maser sites are new detections. These results suggested that sensitive ATCA observations might double the number of known OH masers in the survey region.

Preliminary results from the Galactic centre region (Section 4, Qiao et al. 2017) were introduced. Compared with the SPLASH pilot region, there are about twice the number of evolved star OH maser sites (256 versus 122) and half the number of star formation OH maser sites (31 versus 64) in the Galactic centre region.

5.2 Future work

5.2.1 Galactic center region

For the Galactic center region, further investigations, such as statistical work on each maser category, need to be carried out in order to qualify the properties of OH maser sites. Several evolved star sites close to the Galactic center show very high velocities, which are about $\pm 300\ \mathrm{km\,s^{-1}}$. We will check whether these masers have other properties. Many interesting individual sources will be compared with the literature.

5.2.2 Remaining SPLASH region

After we finish the Galactic centre region work, we still have ATCA data in about 96 square degrees' region. We will compile a paper for this remaining region to give accurate OH maser positions. Similar statistical work including all SPLASH OH masers will be conducted to investigate IR and other properties for a large unbiased OH maser sample.

5.2.3 Maser time line in star formation regions

For all SPLASH region, we will select the star formation OH maser sites. There are many unbiased surveys for other maser species, such as 6.7 GHz methanol masers from the MMB survey and 22 GHz water masers from HOPS. Referring to the methods in Breen et al. (2010), we will construct a maser time line for star formation regions.

5.2.4 Magnetic field studies

As introduced in Section 2, ATCA data have the ability to study the Zeeman splitting of OH masers. Thus we can use these data to study the magnetic fields in both evolved star and star formation categories. Similar to "MAGMO" project, our aim is also to check whether Galactic magnetic fields can be traced with the Zeeman splitting of OH masers associated with star formation regions, especially for the OH masers unassociated with 6.7 GHz methanol masers. Moreover, we can also investigate the in situ magnetic fields of SNR 1720 MHz OH masers. Zeeman splitting studies on evolved star OH masers will also be carried out.

References

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