A Search for Water Masers Toward YSO Candidates in the LMC

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ABSTRACT

The proximity of the Large Magellanic Cloud (LMC) and its high star formation rate make it a prime candidate for the study of massive star formation outside of the Milky Way. A search for water masers associated with massive young stellar objects (YSOs) was conducted toward 25 star-forming regions in the LMC. A total of 11 masers toward two regions were detected. Two continuum sources were detected and one was matched with a YSO candidate based off of Spitzer infrared data. Detection of associated masers strengthen their candidacy as high-mass YSOs, significantly increase the number of known extra-galactic masers, and give insight into massive star formation outside of our galaxy.

Subject headings: masers — star forming regions

1. INTRODUCTION

The properties of any galaxy can generally be attributed to the activities of massive stars within them. Their winds and explosive deaths seed the interstellar medium with heavy elements which go into creating future generations of stars and planets. One of the most poorly understood areas of a massive star’s life is the earliest stages of formation as a young stellar object (YSO), before the onset of hydrogen fusion. The process by which low-mass stars form is fairly well understood in terms of a disk-YSO-outflow model, but the difficulty with high mass stars is how they can acquire so much matter in the accretion phase before the onset of fusion (see Zinnecker and Yorke 2007). Recently, some high-mass YSOs have been found to have accretion disks (Kraus et al. 2012).

1.1. Masers

One of the best ways to study star formation is through observations of molecular masers around massive YSOs. The bright, compact radio emission emanating from the masers can be observed at great distances, even through the obscuring dust clouds that hide the YSOs at visible wavelengths. With the use of radio interferometry, it is possible to associate masers with individual YSOs. The two strongest known masers, 22.2 GHz water and 6.7 GHz methanol, are often associated with the earliest stages of high-mass star formation (Beuther et al. 2002), especially methanol (Minier et al. 2003). Water masers often trace out high-velocity outflows in bipolar jets protruding from the central YSO (e.g. see Moscadelli et al. 2000). Methanol masers at 6.7 GHz primarily form around the accretion disks of massive YSOs (e.g. Moscadelli et al. 2010). Detection of these masers reveals information about the mass and evolutionary stage of the YSO.

1.2. Large Magellanic Cloud

The Large Magellanic Cloud (LMC) is a satellite dwarf galaxy of the Milky Way. The proximity of the LMC, its location outside the Galactic plane, and high star formation rate make it a favorable target for studies of extragalactic star formation. Star formation on a galactic scale in the Milky Way is triggered by density waves in the spiral arms (Roberts 1969). The LMC has no spiral arms however, so star formation in general there is probably induced by tidal interactions with the Milky Way. Another way to trigger star formation is through the shock waves of local supernovae (Elmegreen & Scalo 2004). Differences in physical properties between the Milky Way and the LMC (i.e. the LMC has no arms, less mass, lower metal-
licity and greater ambient UV flux, (see Meixner et al. (2006) and references therein) may cause variations in the star formation process. The accessibility of the LMC allows astronomers to study these differences, and hence a greater understanding of star formation in the universe as a whole.

2. DATA

Regions of massive star formation in the LMC were targeted for a 22.2 GHz water maser search. Observations were made with the Australia Telescope Compact Array (ATCA). The ATCA is the most sensitive, highest resolution radio interferometer with a view of the southern celestial sky, and thus the prime instrument to study the LMC. A total of 25 star forming regions were observed (see Fig. 1. Data were taken with the ATCA in March of 2008 and acquired from the Australia Telescope Online Archive. The ATCA was in its 1.5 km array mode, observing at a central frequency of 22.2 GHz with a bandpass of 16 MHz divided into 512 channels. Each channel had a spectral resolution of 31.25 kHz, corresponding to a velocity resolution of 0.422 km s\(^{-1}\). The integration time on each source was about 20 min over the course of seven hours.

Additional observations were taken with the ATCA in February of 2013 toward one of these sources, N206. N206 is a massive star-forming region south of the main bar (see Fig. 1). Several groups have looked at infrared data from the Spitzer Space Telescope Surveying the Agents of a Galaxy’s Evolution (SAGE) program to identify YSO candidates. Two papers in particular by Romita et al. (2010) and Beuhler (2011) have identified YSO candidates toward N206, based primarily on their IR colors and spectral energy distributions. A deeper and more detailed search of the region was undertaken in order to try to associate potential maser detections with YSO candidates determined by Romita et al. (2010) and Beuhler (2011). A total of four pointings toward 23 massive YSO candidates were taken with the ATCA in its 6 km array mode, with a total bandwidth of 3 GHz with a central frequency of 22.2 GHz. Since water masers often trace outflows from YSOs, it is not uncommon for them to be distributed ±100 km s\(^{-1}\) around the systemic velocity. For this reason, a special spectral zoom band of 16 MHz, with a high spectral resolution of 0.488 kHz, or a velocity resolution of 0.007 km s\(^{-1}\). A total velocity width of 228 km s\(^{-1}\) centered around the systemic velocity, sufficient to observe the high-velocity water masers. The integration time toward each pointing was 60 min over the course of six hours.

Each of the regions are larger than a single pointing, especially with the 6 km array. Only the brightest portion of the star-forming regions were observed. Instead of only looking at the brightest portion of N206 (which was done in 2008) additional pointings were selected in order to cover the area involving 23 massive YSO candidates.

3. ANALYSIS

3.1. Data Reduction

The data were reduced with MIRIAD, a radio data reduction package specifically designed for ATCA data. The data toward the massive star-forming regions were calibrated for amplitude, bandpass, and phase. A primary flux calibrator was observed at the beginning of the observing run, a source with a known flux that is sta-
ble over time. A bandpass calibrator was also observed at the beginning of the observing run. The bandpass calibrator is a bright source that measures the varying response of a radio receiver with frequency. A phase calibrator was observed intermittently between groups of target observations. The phase calibrator tracks the varying atmospheric conditions throughout the observing run. All three of these calibrators are then used to correct the program data so that it more accurately reflects the true signal received from the source.

3.2. Spectra

After the data were calibrated, spectra of signal intensity versus radial velocity were plotted. Radial velocities were computed from the doppler shift of the line based on motion between the source and the observatory. For non-relativistic velocities, the observed velocity is related to a frequency shift via the relation

\[ v_{\text{rad}} = c \left(1 - \frac{\nu}{\nu_0}\right) \]

where \(v_{\text{rad}}\) is the radial velocity, \(c\) the speed of light, \(\nu\) the observed frequency and \(\nu_0\) the rest frequency of the line. Since different masers will have different velocities with respect to the observer, shifts in frequency from the 22.235 GHz masing transition of water. The spectra were examined for strong, narrow peaks of emission, indicative of compact maser emission. Figure 2 shows a spectrum from a source with a strong maser peak.

3.3. Image Cubes

Upon inspection of the spectra toward the varying sources, radio images of the region of sky observed were made using MIRIAD’s INVERT task. This task takes the Fourier transform of the correlated signals obtained by the interferometer, and produces an image of the brightness distribution of the sky. A different image for each velocity increment was made, making a “cube” of image planes. These image cubes were then viewed using KVIS, part of the data visualization software associated with MIRIAD. Maser spots were searched for particularly in those image planes with velocities corresponding to peak emission in the spectra. Figure 3 shows a slice in velocity toward the star-forming region SF16.

4. RESULTS

A total of 10 maser spots toward two star-forming regions were detected. Their positions, peak fluxes, and radial velocities are listed in are listed in Table 1. There were five spots detected toward SF16, spread out over 15 km s\(^{-1}\). There were also six spots detected toward SF23, all of which peak at the same velocity.
Table 1: Detected H$_2$O Masers

<table>
<thead>
<tr>
<th>Source</th>
<th>RA</th>
<th>Dec</th>
<th>Peak Flux</th>
<th>Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>h:m:s</td>
<td>d:m:s</td>
<td>mJy</td>
<td>km s$^{-1}$</td>
</tr>
<tr>
<td>SF16a</td>
<td>04:52:09.119±0.020</td>
<td>-66:55:18.544±0.174</td>
<td>86±15</td>
<td>258.4</td>
</tr>
<tr>
<td>SF16b</td>
<td>04:52:09.166±0.007</td>
<td>-66:55:22.057±0.035</td>
<td>295±15</td>
<td>258.4</td>
</tr>
<tr>
<td>SF16c</td>
<td>04:52:09.134±0.008</td>
<td>-66:55:20.091±0.042</td>
<td>164±10</td>
<td>260.0</td>
</tr>
<tr>
<td>SF16d</td>
<td>04:52:05.286±0.010</td>
<td>-66:55:13.515±0.049</td>
<td>143±10</td>
<td>262.6</td>
</tr>
<tr>
<td>SF16e</td>
<td>04:52:09.271±0.007</td>
<td>-66:55:1.844±0.034</td>
<td>179±9</td>
<td>272.7</td>
</tr>
<tr>
<td>SF23a</td>
<td>05:04:24.555±0.017</td>
<td>-70:43:48.132±0.162</td>
<td>261±35</td>
<td>231.4</td>
</tr>
<tr>
<td>SF23b</td>
<td>05:04:24.564±0.041</td>
<td>-70:43:46.249±0.179</td>
<td>302±62</td>
<td>231.4</td>
</tr>
<tr>
<td>SF23c</td>
<td>05:04:24.789±0.039</td>
<td>-70:43:44.738±0.360</td>
<td>230±51</td>
<td>231.4</td>
</tr>
<tr>
<td>SF23d</td>
<td>05:04:24.959±0.048</td>
<td>-70:43:42.676±0.419</td>
<td>135±45</td>
<td>231.4</td>
</tr>
<tr>
<td>SF23e</td>
<td>05:04:25.152±0.041</td>
<td>-70:43:39.703±0.245</td>
<td>173±81</td>
<td>231.4</td>
</tr>
<tr>
<td>SF23f</td>
<td>05:04:25.428±0.017</td>
<td>-70:43:41.713±0.113</td>
<td>466±60</td>
<td>231.4</td>
</tr>
</tbody>
</table>

**SF16** Masers have been previously detected toward SF16, only recently published in March of this year (Imai et al. 2013). In this paper archival data was taken from the ATCA in 2001, 2002, and 2003 and eight new maser detections toward star-forming regions in the LMC were announced, including toward SF16. A relatively strong maser peak (900 mJy) at 273.5 km s$^{-1}$ was detected by Imai et al. (2013), probably associated with the infrared source 2MASS J04520916-6655223. This maser is probably associated with maser SF16e, however the other masers were not detected. This is not unexpected since water masers are notoriously variable on relatively short timescales (Felli et al. 2007). Fig. 4 shows the maser spectrum published by Imai et al. (2013) compared with this work toward the same area of the sky. Note that that maser SF16d is a completely new detection, possibly associated with a YSO distinct from the other masers.

Follow-up observations of SF16 would be useful in characterizing the variability of the water maser emission here. No doubt that the spectrum has again changed again in the past five years, but the magnitude of the change is unknown. Of particular interest is the maser SF16d, and it would be interesting to see if maser emission in this region has persisted, possibly indicating a change in the evolutionary state of a massive YSO. Follow-up archival Spitzer infrared data would be necessary to potentially identify the host YSO.

**SF23** The six masers toward SF23 are new detections. They all peak in the same velocity channel at 231.4 km s$^{-1}$ and follow an arc from north to south (see Fig. 5). The masers here have a velocity width of about 2 km s$^{-1}$. The strongest maser is SF23f, and its spectra can be seen in Fig. 6. Imai et al. (2013) indicate that there are only 23 known water masers associated with star formation toward 14 regions in the entire LMC. With the masers detected here and toward SF16, this would bring the number up to 33 masers toward 15 regions. Because of the high variability of water masers, the total number of maser spots may not be as significant as the fact that potentially two new YSOs with conditions to produce water masers have been discovered.

As is the case for SF16, archival Spitzer infrared data would be useful in identifying the host
Fig. 5.— New maser spots detected toward SF23

YSO for SF23. Follow-up observations in the ATCA 6 km array mode would produce higher-resolution images of the region, potentially disentangling one maser spot into collections of more compact, smaller spots.

N206 No masers were detected toward N206 (SF06 in the 2008 ATCA archival data). A more thorough investigation of the region was made with four additional pointings toward N206 in February 2013 toward specific YSO candidates as described above. No masers were detected toward any of these YSO candidates. A couple of radio continuum sources were detected and their properties are listed in Table 2. The continuum source N206A is associated with one of the high-mass YSO candidates.

This suggests the continuum emission may be from bremsstrahlung in the area around the YSO candidate. This suggests that it is indeed a YSO and that it has reached an evolutionary stage where a compact HII region has begun forming. Additional data at different frequencies would be required to determine a spectral index of the radio emission, which would confirm whether the phenomenon is thermal bremsstrahlung.

4.1. Characteristics of the LMC

The relatively low detection rate of water masers toward these sources in the LMC is consistent with previous results as noted in Ellingsen et al. (2010). Even though the star-formation rate in the LMC is higher than that of the Milky Way, the water maser detection rate is attributed to the lower metallicity. In addition, the higher ambient UV flux in the LMC may also contribute to a higher rate of molecule dissociation, and thus fewer molecules for masing. Since the strength of the maser is exponentially related to the path length, then even modest decreases in metallicity of molecular abundances can suppress maser signals. Fundamentally, more sensitive instrumentation is needed solely on the basis that the star-forming regions in the LMC are more distant than those in the Milky Way.

5. CONCLUSION

A search for 22.2 GHz water masers toward 25 massive star forming regions resulted in a detection of 11 masers toward two of the regions. Ten of the masers are new detections which increases the number of star formation water masers from 23 to 33 in 15 regions. N206 was observed recently to detect water masers toward massive YSO candidates, but yielded no detections. However, two continuum sources toward N206 were

<table>
<thead>
<tr>
<th>Source</th>
<th>RA 05:30:s</th>
<th>Dec -71:m:s</th>
<th>Peak Flux µJy</th>
</tr>
</thead>
<tbody>
<tr>
<td>N206A</td>
<td>20.150±0.031</td>
<td>7.50.25±0.15</td>
<td>667±100</td>
</tr>
<tr>
<td>N206B</td>
<td>27.442±0.031</td>
<td>6.30.90±0.15</td>
<td>473±71</td>
</tr>
</tbody>
</table>
detected, with one of the sources being associated with one of the massive YSO candidates. This continuum source could potentially positively identify the YSO and mark its evolutionary stage.

A proposal for ATCA time to search N206 and SF23 in the LMC for 6.7 GHz methanol maser emission is currently in preparation. Much of the LMC has been surveyed for methanol emission as part of the Methanol Multi-Beam Survey by Green et al. (2008), and only four methanol masers have been detected. This suggests an underabundance of methanol masers in the LMC. However, the survey toward N206 and SF23 went only to a 220 mJy rms, which would not have even been sensitive enough to detect most of the new water masers. The ATCA has been recently upgraded with new, more sensitive receivers, allowing for a high-sensitivity search toward these regions. Continuum data can simultaneously be acquired toward N206, allowing for a spectral index to be determined for the continuum source N206A and its nature determined. Archival Spitzer data will also be analyzed to determine the infrared properties of SF16 and SF23 and associated YSOs.

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