CO in OH/IR Stars Close to the Galactic Centre

(Research Note)

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ABSTRACT

\textbf{Aims.} A pilot project has been carried out to measure circumstellar CO emission from three OH/IR stars close to the Galactic Centre. The intention was to find out whether it would be possible to conduct a large-scale survey for mass-loss rates using, for example, the Atacama Large Millimeter Array (ALMA). Such a survey would increase our understanding of the evolution of the Galactic Bulge.

\textbf{Methods.} Two millimetre-wave instruments were used: the Nobeyama Millimeter Array at 115 GHz and the Submillimeter Array at 230 GHz. An interferometer is necessary as a ‘spatial filter’ in this region of space because of the confusion with interstellar CO emission.

\textbf{Results.} CO emission has been detected towards two of the stars with positions and radial velocities coinciding within the statistical errors with the corresponding data of the associated OH sources. However, for one of the stars the line profile is not what one expects for an unresolved expanding circumstellar envelope. We believe that this CO envelope is partially resolved and that therefore this star is a foreground star not belonging to the Bulge.

\textbf{Conclusions.} The results of the observations have shown that it is possible to detect line profiles of circumstellar CO from late-type stars both within and in the direction of the Galactic Bulge. ALMA will be able to detect CO emission in short integrations with sensitivity sufficient to estimate mass-loss rates from a large number of such stars.

\textbf{Key words.} late-type stars – OH/IR stars – mass-loss rates – galactic bulge

1. Introduction

Rapid stellar mass loss occurs at the so called red-giant (RGB) and asymptotic-giant branches (AGB). Due to high stellar density and rapid star formation, the Galactic Bulge contains large numbers of RGB and AGB stars. It is important to measure the mass loss rates of these stars in order to get a picture of the recirculation of matter and metal enrichment in this region of the Milky Way. In addition, stars in the central Bulge are at distances that differ from one another by merely a few percent leading to quite an accurate estimate of the mass-loss distribution.

The most accurate method of estimating the stellar mass-loss rates is based on the CO rotational spectral lines (cf. Olofsson, 2003). The first attempt to detect such circumstellar lines in the vicinity of the Galactic Centre (GC) was made by Mauersberger et al. (1988) using a single dish instrument. They detected the $J = 1 − 0$ and $2 − 1$ CO lines from the proto-planetary nebula (PPN) OH0.9+1.3 which has a high radial velocity ($−110 \text{ km s}^{-1}$) making it likely to be physically close to the GC. They proposed also to look for CO emission from OH/IR stars, since such stars are believed to be the progenitors of PPNs. Winnberg et al. (1991) used the same radio telescope to observe several OH/IR stars close to the GC but detected CO emission from one star only: OH0.3–0.2 (Baud et al., 1975). This star has a very high radial velocity ($−341 \text{ km s}^{-1}$) and therefore is not affected by the interstellar background emission that covers typically the velocity range $−200$ to $+200 \text{ km s}^{-1}$ None of the other candidate stars were detected because of confusion with interstellar emission.

The present project employs a different observing technique in an attempt to detect the circumstellar CO emission in the midst of interstellar CO emission. A radio interferometer with suitable baselines can be used as a ‘spatial filter’ by resolving most of the interstellar background but leaving the circumstellar emission as unresolved point sources.

In order to determine optimal baseline lengths and the most favourable CO lines, we started a pilot experiment. We chose three OH/IR stars close to the position of the GC with strong IR fluxes and with low-to-moderate radial velocities. In 2003–2004 we used the Nobeyama Millimeter Array (NMA) at 115 GHz (CO, $J = 1 − 0$) and in 2005 we used the SubMillimeter Array (SMA; Mauna Kea, Hawaii) at 230 GHz ($J = 2 − 1$).

This research note presents the main results of these two data sets and outlines the prospects for future systematic surveys of late-type stars in the Galactic Bulge using the Atacama Large Millimeter Array (ALMA). A conference report of this project appears in Winnberg et al. (2006).
2. Observations

The first observations in this project were done with the 6-element array (NMA) at Nobeyama Radio Observatory, Japan, in November 2003 and in January 2004 at 115 GHz. Three OH/IR stars were selected for observations on the basis of strong IR fluxes: OH359.117–0.169, OH359.762+0.120 and OH359.971–0.119 (Ortiz et al., 2002). The relevant data for these stars are listed in Table 1, where [15] denotes the magnitude at a wavelength of 15 μm as measured by the Infrared Space Observatory (ISO). A clear signal was obtained from OH359.117–0.169 (Ortiz et al., 2002). The test star OH0.3–0.2 was detected and showing properties in accordance with the single-dish data (Figure 1). In addition the stars OH359.762+0.120 and OH359.971–0.119 were detected (Figures 2 and 3).

Typical resolutions were $4'' \times 7''$ for the NMA and $3'' \times 4''$ for the SMA.

3. Data reduction

3.1. The NMA

The data were calibrated using the Nobeyama internal programme package and subsequently the Astronomical Image Processing System (AIPS) was used in a standard way to obtain images and spectra.

We found strong ripples in the images that could be eliminated by removing data from projected baselines shorter than 10 000 wavelengths (26 m). Due to atmospheric phase instability, we decided to remove all projected baselines longer than 40 000 wavelengths (104 m) and to introduce a gaussian baseline-length taper such that baselines of length greater than 40 000 wavelengths got a weight of 30 %.

Maps were made with 256 $\times$ 256 pixels of size 0.5” with uniform weighting. They were ‘cleaned’ using the standard Högborn/Clark algorithm with a gain of 0.1 and a minimum flux density per clean component being the product of the beam dynamic range (1/strongest sidelobe) and the expected rms noise fluctuations. This ensured that no ‘overcleaning’ took place in the rather noisy maps.

Data cubes were made consisting of images from the 20 central channels of the UWBC spectrometer covering 416 km s$^{-1}$. Channel 10 is the central channel, i.e. channel 64 in the original instrument. For the ‘New FX’ spectrometer similar data cubes were made consisting of the 255 central channels. Each channel resulted from averaging 4 original channels and channel 63 was the central channel, i.e. this channel was made up of the original channels 511, 512, 513 and 514.

3.2. The SMA

Data from this instrument were retrieved using software from the Radio Telescope Data Center (RTDC) of the Center for Astrophysics (CfA). Calibration was performed using the image processing package IDL-MIR at Academia Sinica Institute of Astronomy and Astrophysics (ASIAA). Further data reduction was made using both AIPS at Onsala Space Observatory (OSO) and Miriad (SMA version) at ASIAA.

The $\nu \nu$ data were investigated for the presence of spatially extended emission by plotting the visibility amplitude as a function of projected baseline length. Based on such plots it was decided to exclude baselines shorter than 25 000 wavelengths (32.5 m) for OH359.762+0.120 and shorter than 30 000 wavelengths (39 m) for OH359.971–0.119 in order to avoid, as far as reasonable, contamination by residuals of interstellar emission. For OH359.117–0.169 no evidence for significant interstellar emission was found. No interstellar emission, of course, was found in the IF band of the test source OH0.3–0.2 due to its high radial velocity.

As in the case of the NMA, map-cubes were made with 256 $\times$ 256 pixels of size 0.5”, however, this time with natural weight-
As observed with the NMA.

Fig. 3. Circumstellar CO(2–1) line profile of OH359.971–0.119. The definitions of the lines are given in the captions of Figures 1 and 2, except in this figure the dotted ‘staircase’ line is the CO(1–0) spectrum as observed with the NMA.

### 4. Results

Table 2 lists the measured parameters of the CO sources associated with the four stars observed. The 1-σ errors are given in parentheses after the values. For OH0.3–0.2 and OH359.762+0.120 (2→1) least-square fits of parabolas to the CO line profiles have been made, assuming that the data are from unresolved, optically thick emission:

\[
S = S_m \left[1 - \left(\frac{V - V_m}{V_e}\right)^2\right] \tag{1}
\]

where \(S_m\) is the maximum flux density at the radial velocity \(V_m\) and \(V_e\) is half the line width at zero intensity. These three parameters are given in the table together with the statistical errors from the fitting procedure. No CO sources associated with OH359.117–0.169 (1→0 and 2→1) and OH359.762+0.120 (1→0) were found and 3-σ upper limits are given for \(S_m\). The CO line profiles for OH359.971–0.119 (1→0 and 2→1) are incompatible with a parabola, although the CO positions are coincident with the OH position, and only approximate values of the maximum flux densities are given (Figure 3).

OH359.117–0.169 was not detected at any of the two CO lines and we do not know the reason for it. One guess would be that this is due to heavy self-absorption by interstellar CO clouds in front of the star. Such a case could possibly occur for a star that is situated at a distance beyond the GC.

OH359.762+0.120 was detected with a rather poor S/N. Therefore there are quite large errors associated with the elements of the fitted parabola (Figure 2 and Table 2). Within these errors, the mean radial velocity of the line and the line width are compatible with the systemic velocity of the star and its envelope expansion velocity as measured from the OH line profile. Notice that the exclusion of short baselines did not improve the detection of the line significantly. It merely improved the spectral baseline.

OH359.971–0.119 was detected with moderate to good S/N. However, the CO line is narrow and close to the ‘red-shifted’ OH line component, i.e. the backside of the envelope (Figure 3).

### References:

1.–Fix & Mutel (1984); 2.–Sevenster et al. (1997); 3.–Lindqvist et al. (1992)

## Table 1. Selected OH/IR Stars

<table>
<thead>
<tr>
<th>Name</th>
<th>RA</th>
<th>Dec</th>
<th>(V_{rad})</th>
<th>(V_{exp})</th>
<th>([15])</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>OH0.3–0.2</td>
<td>17° 47′ 06.95′</td>
<td>–28° 44′ 42.2″</td>
<td>–341.0</td>
<td>14.5</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>OH359.117–0.169</td>
<td>17° 47′ 21.79′</td>
<td>–29° 47′ 42.2″</td>
<td>–88.5</td>
<td>21.2</td>
<td>1.02</td>
<td>2</td>
</tr>
<tr>
<td>OH359.762+0.120</td>
<td>17° 44′ 34.95′</td>
<td>–29° 04′ 35.2″</td>
<td>–5.7</td>
<td>15.3</td>
<td>0.27</td>
<td>3</td>
</tr>
<tr>
<td>OH359.971–0.119</td>
<td>17° 46′ 00.94′</td>
<td>–29° 01′ 23.6″</td>
<td>–8.5</td>
<td>19.3</td>
<td>0.68</td>
<td>3</td>
</tr>
</tbody>
</table>

## Table 2. Results

<table>
<thead>
<tr>
<th>Name</th>
<th>Trans. (J)</th>
<th>RA</th>
<th>Dec</th>
<th>(V_m)</th>
<th>(V_e)</th>
<th>(S_m)</th>
<th>(M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OH0.3–0.2</td>
<td>2→1</td>
<td>17° 47′ 06.978′(0.009)</td>
<td>–28° 44′ 42.8″(0.2)</td>
<td>–340.1(0.6)</td>
<td>14.0(0.8)</td>
<td>1.8(0.1)</td>
<td>5 \times 10^{-4}</td>
</tr>
<tr>
<td>OH359.117–0.169</td>
<td>1→0</td>
<td>17° 47′ 06.978′(0.009)</td>
<td>–28° 44′ 42.8″(0.2)</td>
<td>–340.1(0.6)</td>
<td>14.0(0.8)</td>
<td>1.8(0.1)</td>
<td>5 \times 10^{-4}</td>
</tr>
<tr>
<td>OH359.762+0.120</td>
<td>2→1</td>
<td>17° 44′ 34.979′(0.012)</td>
<td>–29° 04′ 36.6″(0.2)</td>
<td>–11(1)</td>
<td>13(1)</td>
<td>0.6(0.1)</td>
<td>4 \times 10^{-4}</td>
</tr>
<tr>
<td>OH359.971–0.119</td>
<td>1→0</td>
<td>17° 46′ 00.75′(0.04)</td>
<td>–29° 01′ 21.5″(0.7)</td>
<td>–1(1)</td>
<td>1(1)</td>
<td>~0.4</td>
<td>~5</td>
</tr>
</tbody>
</table>

### Flux density vs Radial velocity

The figure shows the flux density plotted against the radial velocity for the OH359.971–0.119 profile. The line is CO(2–1).

### Radial velocity vs Flux density

The plot illustrates the relationship between radial velocity and flux density for the CO(2–1) line profile of OH359.971–0.119.
A similar line was observed with the NMA at 115 GHz (dotted line). Notice that the line profile obtained when all the uv data were included (thin solid line) shows a much stronger and broader ‘red-shifted’ line and even a ‘blue-shifted’ counterpart. The absorption near $-20 \text{ km s}^{-1}$ is probably caused by a ‘dip’ in the interstellar background, as discussed above, but in this case it is resolved.

Mass-loss rates have been calculated for OH0.3–0.2 and OH359.762+0.120 (2 $\rightarrow$ 1) using a new formula based on the original equation by Knapp & Morris (1985) but containing constants determined by least-squares fits to physical models (Ramstedt et al., 2008), and the values have been entered in Table 2. For these calculations a distance of 8 kpc to the GC (Reid, 1993) and a CO/H$_2$ abundance ratio of $2 \times 10^{-4}$ (Ramstedt et al., 2008) have been assumed for both stars. The values of $V_c$ have been taken as the expansion velocities of the CSEs. Both mass-loss rates are normal for OH/IR stars.

5. Discussion

5.1. OH359.762+0.120

There is little doubt, in spite of the poor S/N, that the detected CO source is a true circumstellar source associated with the OH/IR star. Because of the high bolometric magnitude of this star and its strong OH emission, some people doubt the association of this star with the Galactic Bulge (see discussion by Blommaert et al., 1998). However, as pointed out by Blommaert et al. (1998), the OH radiation is heavily scattered by interstellar free electrons (Frail et al., 1994) making it very likely that it resides close to the GC. Our result of a weak CO source leading to a normal mass-loss rate for an assumed distance of 8 kpc supports this conclusion.

5.2. OH359.971–0.119

The CO source associated with this star, on the other hand, is an enigma. The line profile is similar to that expected from a resolved stellar envelope where unresolved sources are left at the front and back sides (see for example the central CO source in U Cam, Lindqvist et al., 1999). For such a picture to be true, the star needs to be at a small distance and would not belong to the Galactic Bulge. For example, assuming that the diameter of the CO envelope is $2 \times 10^{17}$ cm (which might be an overestimate for the $2 \rightarrow 1$ transition) and that the angular diameter is 10$''$, the distance would be only about 1.4 kpc. The IR properties of this star also are such that it is arguable whether it belongs to the Bulge (cf. Ortiz et al., 2002).

Another explanation of the line profile would be that it is heavily distorted through strong absorption of interstellar CO in front of the source. A third possibility - although improbable - is that the physical conditions in this CSE are such that they favour weak maser action along radial directions (Morris, 1980). Finally, there remains the (improbable) explanation that the source is an unresolved remnant of interstellar CO emission that happens to be at the same position and radial velocity as OH359.971–0.119.

Observations at higher-energy CO lines might be a possible way of revealing the true nature of this source. Such observations perhaps could be combined with careful single-dish observations using a stable 115 or 230-GHz receiver allowing a reference spectrum to be taken outside the Milky Way band.

However, given the available data, we favour the first alternative, i.e. that we have found a relatively nearby OH/IR star whose CO envelope is resolved by both arrays used. The salient points that support this conclusion are:

- There are two CO line components close to the two OH line components.
- The positions of both line components are compatible with the position of the OH/IR star.
- The redshifted CO line component grows stronger and the blueshifted line component emerges when all baselines (including the short ones) are included in the imaging.
- There is a weak line component at 115 GHz coinciding with the redshifted 230-GHz component.
- The position of the 115-GHz line component also coincides with the OH/IR star.

6. Conclusions

Our pilot project has shown that it is possible to detect circumstellar CO envelopes of OH/IR stars close to the GC: out of three stars selected, one was detected at both 115 and 230 GHz (OH359.971–0.119) and another one was detected at 230 GHz only (OH359.762+0.120). OH359.971–0.119 probably does not belong to the Galactic Bulge, but this fact is irrelevant for the issue at stake – this star too would have been hard to detect using a single-dish telescope.

We would have liked to observe the same three stars at 345 GHz ($J = 3 \rightarrow 2$) and to try out somewhat longer baselines, but both these requests require excellent atmospheric conditions and therefore the competition for observing time is strong.

We have no doubt that ALMA will be able to detect a large number of OH/IR stars in the inner Bulge (Olofsson, 2008).

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References