OBSERVATIONS OF THE 6 cm LINES OF OH IN EVOLVED (OH/IR) STARS

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Received 2006 September 21; accepted 2006 October 24; published 2006 November 27

ABSTRACT

Recent observational and theoretical advances have called into question traditional OH maser pumping models in evolved (OH/IR) stars. The detection of excited-state OH lines would provide additional constraints to discriminate among these theoretical models. In this Letter, we report on VLA observations of the 4750 and 4765 MHz lines of OH toward 45 sources, mostly evolved stars. We detect 4765 MHz emission in the star-forming regions Mon R2 and LDN 1084, but we do not detect excited-state emission in any evolved stars. The flux density and velocity of the 4765 MHz detection in Mon R2 suggest that a new flaring event has begun.

Subject headings: ISM: individual (LDN 1084, Monoceros R2) — masers — radio lines: stars — stars: AGB and post-AGB — stars: late-type

1. INTRODUCTION

The standard model of the pumping mechanism behind 1612 MHz masers in OH/IR stars was developed by Elitzur et al. (1976). The masers are believed to be pumped by 35 μm radiation, which connects the ground states with the \( ^2\Pi_{\frac{1}{2}}, J = \frac{5}{2} \) states. Subsequent decays down the \( ^2\Pi_{\frac{3}{2}} \) ladder and back to the ground states invert the 1612 MHz transition when the infrared transitions are optically thick. Pumping by 53 μm radiation (via the \( ^2\Pi_{\frac{3}{2}}, J = \frac{3}{2} \) states) can also invert the 1612 MHz transition by this mechanism (Elitzur 1981).

More recent detailed modeling by Gray et al. (2005) offers greater insight into 1612 MHz inversion. The two primary ways of pumping the 1612 MHz maser are through collisional excitation within the \( ^2\Pi_{\frac{3}{2}} \) ladder and radiative excitation by 53 μm photons via the \( ^2\Pi_{\frac{3}{2}}, J = \frac{3}{2} \) states, with the latter being the dominant source of the inversion. In the case of a large population transfer through the \( ^2\Pi_{\frac{3}{2}}, J = \frac{3}{2}, F = \frac{1}{2} \) level, it is possible that the 4750 MHz (\( F = \frac{1}{2} \rightarrow \frac{1}{2} \)) and 4765 MHz (\( F = \frac{1}{2} \rightarrow 0 \)) A-doubling transitions will be seen in addition to the 1612 MHz transition.

An important detail in these models is whether the radiative pump operates primarily through the 35 μm infrared lines or the 53 μm lines. The former are more energetic and therefore require a larger far-infrared radiation field to produce an efficient maser pump. Detailed hot envelope models can include a large contribution from 35 μm radiation (M. D. Gray 2006, private communication). Unfortunately, infrared data are inconclusive as to the relative importance of these pumping routes. An analysis of archive data from the Infrared Space Observatory by He et al. (2005) produced three detections of 35 μm absorption in red supergiants, but it also produced 15 nondetections among stellar objects where the absorption line should be above the threshold of detectability, assuming the Elitzur et al. (1976) pump rates. All sources with detected 35 μm absorption also display 53 μm absorption with similar equivalent widths (He et al. 2005). The authors suggest that 53 μm absorption may play a role in pumping 1612 MHz masers in evolved stars, consistent with Gray et al. (2005).

2. OBSERVATIONS

Data were taken during three sessions during 2006 May 25–27 using the Very Large Array (VLA). The observations occurred near the end of reconfiguration between A and BnA configurations. Several antennas were out of the array due to the move as well as the Expanded VLA upgrade, leaving 22 antennas in operation.

The observed sources are drawn primarily from the Chen et al. (2001) catalog of OH/IR sources and were selected based on their range of observability in local sidereal time. Several of these sources are not actually evolved stars, likely due to incorrect Infrared Astronomical Satellite (IRAS) associations at the \( \frac{1}{2} \) level. The total time on each source was approximately 3 minutes, with 1 minute calibrator scans interspersed between sources. A significant amount of radio-frequency interference (RFI) was observed on two sources, IRAS 05437−0001 and IRAS 06053−0622, although simple flagging of the affected time ranges resulted in sufficient data apparently free of RFI to produce reasonable images.

The 4750.656 and 4765.562 MHz transitions of OH were observed simultaneously in both circular polarizations. The
1.5625 MHz bandwidth was centered at the local standard  
12207 kHz (0.77 km s⁻¹).  
Data reduction was performed in the Astronomical Image Processing System (AIPS; Greisen 2003). Image cubes measuring 10° in right ascension and declination and 80 km s⁻¹ in velocity were created using IMAGR. Each channel was visually scanned for maser emission and analyzed for the maximum pixel value and rms noise. Detections and upper limits for nondetections are listed in Table 1.

The snapshot observations provided a single-channel rms noise of ~20 mJy, which would allow for a 5 σ detection of a 100 mJy maser source. This is the flux density of the lone detection of a 4.7 Hz maser in the Mira variable AU Gem (Clausen & Fix 1981). The distance of this star, 2.4 kpc (Nguyen-Q-Rieu et al. 1979), is typical for our sample.

3. RESULTS
3.1. Detections

There were no detections among the OH/IR stars, but two previously known 4765 MHz masers were observed in star-
forming regions. The first of these sources, IRAS 21413+5442 (LDN 1084), is a region of massive star formation affiliated with an ultracompact H ii region (Cohen et al. 1988). From our observations, the detected maser has a flux density of 250 mJy in the channel centered at \(-61.80 \text{ km s}^{-1}\) and 260 mJy in the channel centered at \(-62.57 \text{ km s}^{-1}\). The data are consistent with a single point source at a velocity near \(-62.2 \text{ km s}^{-1}\) and located at \(21^\text{h}43^\text{m}01^\text{s}.452, +54^\circ 56^\prime 17^\prime\prime.87\) (J2000). This agrees with the position of the \(-62.10 \text{ km s}^{-1}\) feature detected by Harvey-Smith & Cohen (2005) to within 0\(^{\circ}\).25. The second detected source is IRAS 06053–0622 (Mon R2). Its flux density is approximately 2.5 Jy in the channel centered at 10.4 km s\(^{-1}\), located at \(06^\text{h}07^\text{m}47^\text{s}.845, -06^\circ 22^\prime 56^\prime\prime.61\), which agrees to within 0\(^{\circ}\)08 with the position of the brighter 10.62 km s\(^{-1}\) maser detected by Harvey-Smith & Cohen (2005).

Because the width of the channels used during the observations is larger than a typical maser width in a star-forming region, the quoted flux densities are lower limits. A closer approximation can be found by dividing the channel width by the estimated velocity range of the maser and then multiplying by the observed flux density. Assuming a single maser whose line width is 0.4 km s\(^{-1}\) (an average value for Mon R2; see Smits et al. 1998) yields flux densities of just under 1 Jy for LDN 1084 and 5 Jy for Mon R2.

### 3.2. Variability

As is common for masers, both LDN 1084 and Mon R2 have displayed a certain degree of variability in the past. The flux density of the 4765 MHz maser in LDN 1084 was observed to be 700 mJy in 1989 and again in 1991 (Cohen et al. 1991, 1995) but had dropped to 480 mJy by 1995 (Harvey-Smith & Cohen 2005). Our data suggest that the maser flux density has since increased. The velocity of this feature, \(-62.1 \text{ km s}^{-1}\), is in the middle of the range of 6035 MHz emission (Fish et al. 2006) and is consistent with our measurements given our coarse spectral resolution.

In Mon R2, 4765 MHz emission was first detected at 10.9 km s\(^{-1}\) by Gardiner & Martín-Pintado (1983). Cohen et al. (1995) confirmed its status as a maser and noticed variability, with a peak flux of 1.5 Jy in 1990. Subsequent monitoring caught two flares to a maximum of nearly 80 Jy, with the central maser velocity varying between about 10.55 and 10.85 km s\(^{-1}\) (Smits et al. 1998; Smits 2003). In 2000, Dodson & Ellingsen (2002) failed to detect any 4765 MHz emission in Mon R2 at the 80 mJy level, and Smits (2003) found no 4765 MHz emission in Mon R2 between 1998 December and the end of their observations in 2001 November despite monitoring the source at 2 week intervals.

It appears that emission from the 4765 MHz maser(s) in Mon R2 has returned. The LSR velocity of our detection is consistent with being near or just below the low end of the aforementioned velocity range. We detect strong emission in the channel centered at 10.44 km s\(^{-1}\) and possible weak emission in the next lower velocity channel (9.67 km s\(^{-1}\)), but not in the next higher channel (11.20 km s\(^{-1}\)).

### 4. DISCUSSION

We do not detect 4.7 GHz OH maser emission from any of the evolved stars in our sample. This is consistent with most previous surveys of evolved stars, in which no excited-state emission is detected (Thacker et al. 1970; Baudry 1974; Rickard et al. 1975; Jewell et al. 1985; Desmurs et al. 2002). Nevertheless, excited-state emission has been detected in two evolved stars. Zuckerman et al. (1972) report on 6035 MHz (and possibly 6030 MHz) maser emission in the red supergiant NML Cyg, although not at the same velocity as the 1612 MHz masers. Likewise, Claussen & Fix (1981) report on 4750 MHz emission from the Mira AU Gem; again, the velocities are not the same as in ground-state emission, although the authors note that the spectrum of the 4750 MHz emission appears to be centered at the same velocity, with peaks nearer the central velocity than at 1667 MHz. Both of these appeared to be convincing detections, yet the 6035 MHz emission in NML Cyg has disappeared (Jewell et al. 1985; Desmurs et al. 2002). The 4750 MHz emission in AU Gem was also not redetected in observations by Jewell et al. (1985), although the 100 mJy maser would only have been 1.5 times their rms noise, which does not conclusively establish that the maser had disappeared. Nevertheless, it appears that excited-state emission in late-type stars is both rare and time-variable.

There are several classes of theoretical models for OH pumping in circumstellar shells. The Elitzur et al. (1976) model of pumping via the 35 \(\mu\)m lines and subsequent decay down the \(^2\Pi_{1/2}\) ladder inverts the 1612 MHz line. Pumping via the less energetic 53 \(\mu\)m lines can also produce a strong 1612 MHz inversion (Elitzur 1981; Gray et al. 2005). Collisions may contribute a substantial fraction of the inversion (Gray et al. 2005). Far-infrared line overlaps can invert the 1612, 1665, and 1667 MHz lines because of asymmetries in the dipole matrix elements (Bujarrabal et al. 1980a, 1980b). Near-infrared line overlap, possibly with H\(_2\)O, also may be necessary to account for main-line maser emission (Cimerman & Scoville 1980; Collison & Nedoluha 1993, 1994).

A combination of several of these pumps may occur in evolved stars, either in the same spatial region or at different radii. Observational evidence supports several of these pumping models. Multiple infrared lines of OH have been detected (Sylvester et al. 1997; He & Chen 2004; He et al. 2005). Interferometric measurements indicate that main-line masers exist at smaller radii than 1612 MHz masers in circumstellar envelopes (Harvey et al. 1974). Substantial qualitative differences in variability confirm this (Etoka & Le Squeren 2000) and likely indicate that dust reprocessing of radiation is a critical element of the radiative pumping (Elitzur 1978). The spectrum of the lone 4750 MHz detection in AU Gem also suggests that the right conditions for masering in excited-state lines exist interior to the region producing main-line masers (Claussen & Fix 1981). This is analogous to H\(_2\)O and 1612 MHz OH maser observations in other stars, in which the H\(_2\)O masers are typically seen at smaller expansion velocities than the OH masers and are observed to exist at smaller radii as well (Habing 1996).

Why then are excited-state masers in late-type stars so rare? Three ingredients are essential to produce a detectable OH maser: a sufficient column density of OH, velocity coherence, and effective pumping conditions. The abundance of OH masers in the envelopes of evolved stars clearly shows that column density of OH is sufficient to produce maser activity. But velocity coherence may be a problem in the excited states. It appears that 4750 MHz masers are located at smaller radii than 1612, 1665, and 1667 MHz masers. It is possible that the velocity field at this radius is too irregular to support large coherent path lengths, due possibly to accelerations or turbulence.

It is also possible that the conditions necessary to pump excited-state masers are very fragile. Many pairs of far-infrared OH transitions overlap at different Doppler shifts on the order of several kilometers per second (see Table 2 of Collison & Nedoluha 1993). Small changes in the velocity structure of a
circumstellar envelope may therefore have large consequences in the pumping. When combined with other pump mechanisms, such as collisional excitation, these effects may be exaggerated. Detailed modeling, including the effects of multiple pump mechanisms, may be required to discover the precise physical conditions responsible for producing detectable excited-state maser emission.

More observations will be required in order to understand the narrow range of parameter space conducive to excited-state OH pumping. In particular, the two late-type stars in which excited-state maser emission was detected in one epoch (NML Cyg at 6035 MHz and AU Gem at 4750 MHz) should be reobserved with greater sensitivity. If they are redetected, their variability and spatial distribution will provide important clues as to the pumping mechanism responsible for excited-state maser emission in evolved stars.

The National Radio Astronomy Observatory is a facility of the National Science Foundation (NSF) operated under cooperative agreement by Associated Universities, Inc. L. K. Z. acknowledges support from the NSF Research Experiences for Undergraduates (REU) program. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

Facilities: VLA

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