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A SHOCK–EXCITED OH MASER IN A POST–AGB ENVELOPE ?

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ABSTRACT

We have observed a sample of OH 1612–MHz masing objects in all four OH ground–state transitions with the Australia Telescope Compact Array. One likely post–AGB object is found to emit in the 1612–MHz, 1665–MHz and 1720–MHz transitions. We discuss the evidence that this object may be an early post–AGB object and the possibility for such a circumstellar envelope to harbour a 1720–MHz maser. We argue that during a very brief period, just after the star has left the thermally–pulsing phase of the AGB and the wind velocity starts to increase, post–AGB objects might show 1720–MHz emission. The best objects to search for such emission would be those that are masing at 1612 MHz and 1665 MHz, but not at 1667 MHz nor in the 22–GHz H_2O transition.

Subject headings: masers — shock waves — ISM: jets and outflows — stars: AGB and post-AGB

1. INTRODUCTION

OH maser emission from the four ground-state transitions at 1612.231, 1665.402, 1667.359 and 1720.530 MHz occurs in a wide range of objects. Extra–galactic OH–maser emission is associated with active galactic nuclei and enhanced central star formation (Baan & Haschick 1987; Randell et al. 1995), with strongest emission, in general, from the main lines at 1665/1667 MHz. OH maser emisson from galactic star forming regions (SFRs) is also strongest in the main lines, with dominant emission mostly at 1665 MHz.

The satellite line at 1720 MHz is best known for its occurence in supernova remnants, whereas that at 1612 MHz is strongest in the optically–thick envelopes of oxygen–rich asymptotic–giant–branch (AGB) stars. Mainline OH emission may be present in optically–thin envelopes; from nearby Mira variables, with low mass-loss rates around 10^{-7} $M_\odot$ yr^{-1}, only mainline emission is detected.

At the end of the AGB evolutionary phase, the star undergoes a transformation which takes a couple of thousand years, during which it evolves to become a planetary nebula (PN). During this post-AGB stage, the mass-loss rate decreases by a factor of 1000 or more whilst the stellar surface temperature rises by a factor of 10 or 20 to above 50,000 K. The star changes from losing mass in a cool, dense wind to losing mass in a much hotter, lower density wind.

Strong changes also occur in the envelope kinematics and morphologies. In particular, whilst the circumstellar envelopes of AGB stars are generally spherically symmetric, images of planetary nebulae show axi-symmetric morphologies in over 50% of cases (Manchado et al. 2000).

During the initial searches in the 1970s it was quickly found that 1720–MHz emission was not detected from AGB stars. As this agreed with theoretical expectations (eg. Elitzur, Goldreich & Scoville 1976), there have been no systematic searches for this maser in stellar sources. However, it is imaginable that the shocks in some post–AGB stars could temporarily induce 1720–MHz maser emission. We therefore decided to observe, for the first time, a modest sample of 1612–MHz–selected sources, including post–AGB objects, at 1720 MHz. A total of 18 objects were selected from Sevenster et al. (1997a,b) on the basis of their unusual OH 1612–MHz profiles. Observations in all four ground–state OH transitions were taken with the Australia Telescope Compact Array (ATCA) in November 1998 (1612, 1665 and 1667 MHz) and September 1999 (1720 MHz). Eleven of the sources are likely post–AGB objects.

The full results from this study will be published separately. Here we report the detection of 1720 MHz from the source OH009.1−0.4 (IRAS 18043−2116). In Section 2, we present the observations and in Section 3 the evidence that OH009.1−0.4 is a post–AGB object. In Section 4 we discuss a possible scenario for the 1720–MHz excitation. Conclusions are given in Section 5.

2. COMPACT ARRAY RESULTS

Figure 1 shows the OH spectra for OH009.1−0.4 (18:07:20.9, −21:16:10.9 (J2000)), observed with a channel width of 0.7 $km\,s^{-1}$. The maser emission is strongest at 1612 MHz, with a peak flux density of 11.0 Jy at 71.2 $km\,s^{-1}$. The spectral profile has a 'one-sided' peak and a much weaker feature at 101 $km\,s^{-1}$. The 1665–MHz emission covers the same velocity range as the 1612–MHz emission (Figure 2), with a peak flux density of 1.64 Jy at 71.3 $km\,s^{-1}$. No emission was detected at 1667 MHz with a detection limit of $\sim$ 80 mJy.

The 1720–MHz emission is seen as a single narrow peak at a slightly more blue-shifted velocity than the 1612–MHz and the 1665–MHz peaks. The peak flux density is 1.22 Jy at 69.4 $km\,s^{-1}$, with no linear polarization. The positional coincidence ($0''.3$) of the emission in all three lines is consistent with a single point source, given the ATCA resolution ($\sim 3''$).

We also searched for radio–continuum emission at 4.8 and 8.6 GHz with no detection at the source position, re-

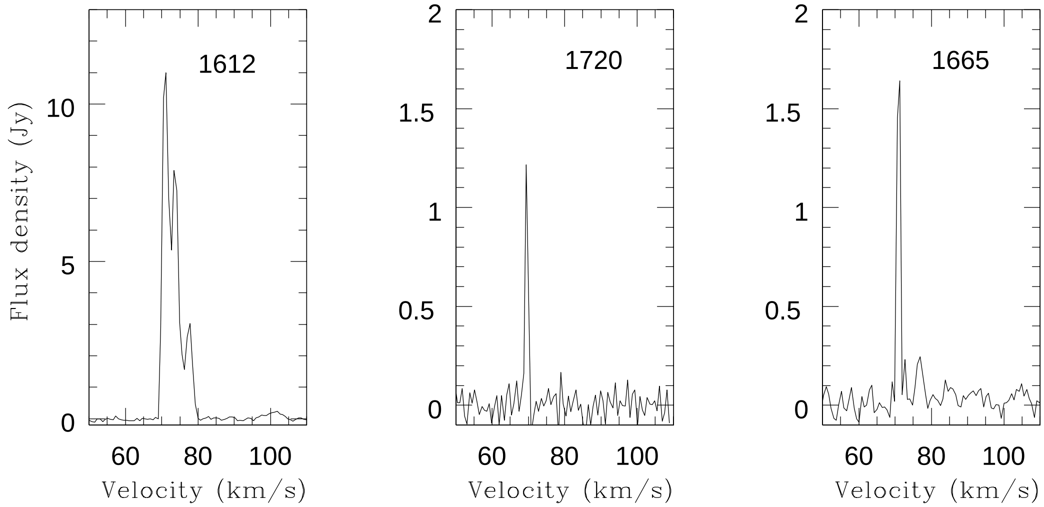

FIG. 1.— The 1612–MHz, 1720–MHz and 1665–MHz spectra for OH009.1−0.4, as observed in November 1998 (1612,1665 MHz) and September 1999 (1720 MHz). The stellar velocity is likely to be around 85 km s^{-1}. The 1720–MHz peak is slightly offset from the 1612–MHz and 1665–MHz peak velocities (see Section 3). All spectra were observed with a channel width of 0.7 km s^{-1}.

sulting in an upper flux limit of 1.5 mJy (five-σ).

3. THE EVOLUTIONARY STATUS OF OH009.1−0.4

We consider it extremely unlikely that OH009.1−0.4 is associated with either a SFR or a supernova remnant. No known supernova remnant is associated with the 1720–MHz position and the presence of the other two OH masers precludes such a classification (eg. Koralesky et al. 1998).

The non–detection of radio continuum is unfavourable to a classification as a SFR, since most SFRs with OH masers are also strong ($\gtrsim$100mJy) ultra–compact HII regions (Caswell 1998). Furthermore, a non–detection in methanol at 6668 MHz at the position of OH009.1−0.4 (Jim Caswell, private communication) provides an upper limit for methanol–maser emission at which 90% of SFRs would be detected if they show 1720–MHz maser emission (Caswell 1999).

The far-infrared MSX and IRAS colours of R_{21}=log(S_{25}/S_{12})=0.53 and R_{32}=log(S_{60}/S_{25})=0.4[1] are consistent with a classification as a "high–outflow" source (Zijlstra et al. 2000). These sources include both young stellar objects and bipolar post–AGB stars with optically thick envelopes. In the two–colour diagram presented by Pottasch et al. (1988), of the eight nearest neighbours to OH009.1−0.4, five are PNe, one is an OH/IR star and two are galaxies. For OH009.1−0.4, the R_{32} is bluer than for typical HII regions and far redder than for Mira variables. The high R_{21} indicates a (recent) mass–loss rate of $> 10^{-5}\,M_\odot\,yr^{-1}$ (Van der Veen et al. 1995), consistent with an AGB or post–AGB classification.

The OH spectral profiles strongly suggest that the source is a young post–AGB star. The steep outer edge of the bright 1612–MHz peak is characteristic of OH/IR stars and indicates that the emission arises in a thin, expanding shell. The raggedness on the inside of the peak suggests that the star is transiting off the AGB, with irregular or intermittent mass loss. A very large flux–density ratio between the blue– and the red–shifted peak has previously been seen in post–AGB stars, where the red–shifted emission, from the back of the circumstellar envelope, is absorbed in the small ionized region around the star, as noted by Lewis (1989). A similar spectrum is found for OHPN 9 (Zijlstra et al. 1989), which shows radio–continuum emission of 1.4 mJy, that could have gone undetected with our limit of 1.5 mJy. Approximately 50% of PNe have radio–continuum emission weaker than this (e.g. Pottasch et al. 1988). For an object with an optical depth of one, a $T_{\rm eff}$ of 3000 K, a distance of 5 kpc and an ionization radius of 10^{15}cm, we estimate that the 6–cm flux density would be $\sim$ 1 mJy.

Also consistent with a classification as a young post–AGB star are the non–variability of the IRAS and MSX emission from OH009.1−0.4 and the detection of mainline OH emission that is weaker than the 1612–MHz emission (Lewis 1989). Here we suggest that the absence of 1667–MHz emission may be a signature of the earliest stages of post–AGB evolution. In circumstellar envelopes, the 1665–MHz emission can be stronger than that at 1667 MHz in regions with dust temperatures below 300 K, if the far–infrared spectral index is $\gtrsim$2 (Elitzur 1978). Pavlakis & Kylafis (1996) find that, at lower temperatures, the 1665–MHz emission can be stronger also for spectral indices of $\sim$1. For envelopes which have only dilated enough for ambient H_2O–dissociating photons to reach regions with $T_{\rm d}$ <300 K, the 1667–MHz maser emission is expected to be weak or absent. With further dilation, the 1667–MHz emission should increase and the 1612–MHz emission weaken.

[1] S_{12} is taken from the Midcourse Space Experiment infrared satellite (MSX), see http://www.ipac.caltech.edu/ipac/msx/msx.html. S_{25} and S_{60} are IRAS point–source values.

From the infrared and OH maser properties and the non-detections of methanol–maser and continuum emission, we conclude that OH009.1−0.4 is almost certainly a young post–AGB star.

4. DISCUSSION

It is very unlikely that the 1720–MHz emission originates from exactly the same regions as the other lines (see Lockett, Gauthier & Elitzur 1999). In the few SFRs that have been imaged in both satellite masers, they come from spatially separate clumps (Caswell 1999). However, the two satellite transitions require conditions similar enough to compete directly, as is seen very clearly by their conjugate behaviour in Centaurus A (van Langevelde et al. 1995). During the transition from the AGB to the PN phase, temperatures, densities, wind velocity and irradiation change rapidly by orders of magnitude. A variety of environments must be present in the circumstellar envelope and it is possible that locally conditions could favour the 1720–MHz over the 1612–MHz maser.

We hypothesize that the 1720–MHz transition is collisionally excited in a region where shocks are present, at the interaction region between the remnant of the AGB superwind phase and the hotter, fast post–AGB wind. Interacting–wind models usually assume a spherical fast wind colliding with an equatorially–enhanced density distribution of the AGB remnant; another possibility is that a bipolar fast wind pierces into a spherical AGB remnant. Indeed, Weintraub et al. (1998) argue that it is likely that shocks occur after the onset of bipolarity and before the nebular envelope is ionized and the masers are destroyed.

A C–type of shock is the only way to create the right conditions for the 1720–MHz maser to exist (Lockett et al. 1999). The process could be as follows. In the very early post–AGB evolution (see Schönberner & Steffen 2000), the wind picks up in velocity to $\sim$ 100 $\mathrm{km\,s^{-1}}$, while the mass–loss rate drops significantly. In the first $\sim$1000 years, a shock front of $\sim$50 $\mathrm{km\,s^{-1}}$ would travel $\sim 2{\times}10^{17}$ cm (see Frank & Mellema 1994, their Fig.2: "swept–up shell"; cf. Bujarrabal et al. 1997, M1−92). This is well into the regions of the AGB envelope where the external radiation field dissociates and ionizes most molecular material ($n{\lesssim}10^4\mathrm{cm^{-3}}$, $T{\lesssim}100$ K). (Note that $2{\times}10^{17}$ cm is not resolved by ATCA at distances beyond 5 kpc.)

The passage of a C–type shock would change the chemistry in this region, forming H_2O and increasing the density by a factor of 10 (see Wardle 1999). Subsequent dissociation of the water by the ambient radiation field sufficiently enhances the OH abundance, while collisions with preferentially ortho–H_2 (see Lockett et al. 1999) leave OH in the proper excited state to decay via the 1720–MHz transition, provided cooling has also decreased the post–shock temperature to below 125 K (Lockett et al. 1999). With an ionizing rate of $\sim 10^{-17}\mathrm{s^{-1}}$ (solar vicinity $2{\times}10^{-17}\mathrm{s^{-1}}$, IRC+10216 $2{\times}10^{-18}\mathrm{s^{-1}}$, Glassgold 1999) and other parameters as given before, it is feasible that the necessary column density of $>2.5{\times}10^{15}$ $\mathrm{cm^{-2}}$ can be achieved (Lockett et al. 1999; Wardle 1999). For this, we assume the relevant layer has a thickness of $\sim 10^{17}$ cm (the outer radius of the 1612–MHz masing shell of an OH/IR star is typically 10^{17} cm, Cohen 1989), the post–shock density is $\lesssim 10^5$ $\mathrm{cm^{-3}}$ with OH abundance of $10^{-5.5}$ (in the 1612–MHz layer this is $\sim 10^{-4}$, Cohen 1989) and the magnetic field at these radii is of the order of 100μG (e.g. Chapman & Cohen 1986). These values are realistic, as well as in good agreement with those used by Wardle (1999). Note that the resulting 1720–MHz maser optical depth would be low, of the order of 4 (Lockett et al. 1999).

In this scenario, the 1720–MHz masing regions are located well outside the layers where the 1665–MHz masers arise and along a different line of sight than the 1612–MHz masers. This means that the usual argument that the 1720–MHz maser cannot co–exist with these lines in one circumstellar stellar envelope (see footnote Lockett et al. 1999) is not necessarily valid. The formation of extra water at large radii is not in disagreement with the observation that post–AGB objects with main–line emission do not have 22–GHz water masers (Lewis 1989) as no maser emission is expected from the shock–produced H_2O (Lockett et al. 1999).

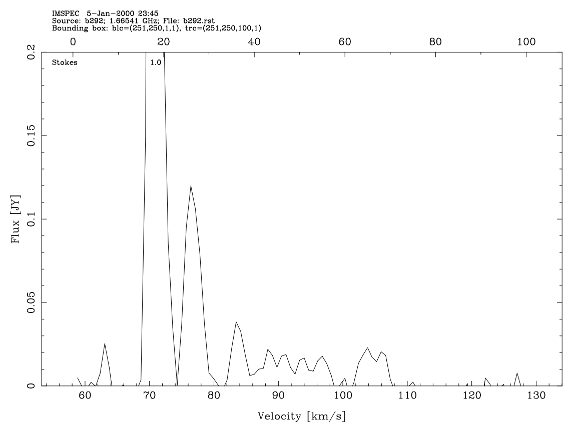

FIG. 2.— The hanning–smoothed cleaned–image spectrum at 1665 MHz, at the position of the star (maximum pixel). The 1665–MHz emission is seen over the same range of velocities as 1612 MHz, but the detection is only significant around 72 $\mathrm{km\,s^{-1}}$.

The high–density ($>10^7$) regime for 1720–MHz maser emission, as presented in Pavlakis & Kylafis (1996), requires strong velocity gradients ($\sim$2 $\mathrm{km\,s^{-1}}$; see Caswell 1999 for such spectra). As the linewidth for the 1720–MHz maser is $\lesssim$0.5 $\mathrm{km\,s^{-1}}$ ((Figure 1), typical for velocity gradients in circumstellar envelopes, such a regime appears to be unlikely.

The detection probability for 1720–MHz maser emission from post–AGB stars is almost certainly very low for several reasons. Firstly, a C–type shock has to form. Because of the geometry of the shock front and maser beaming effects, it is likely that only around 10% of sources with such shocks will show 1720–MHz emission, as is found for supernova remnants (Lockett et al. 1999; Koralesky et al. 1998; Claussen et al. 1997). In addition, the interstellar radiation field has to be strong enough, but not so strong as to increase the electron density (Lockett et al. 1999). Finally, in many objects a bipolar flow is traced by the 1612–MHz line (eg. Zijlstra et al. 2000, Sahai et al. 1999). In such cases, the physical conditions in the interaction region cannot be suitable for 1720–MHz emission, probably due to large column density or the strength of the local infrared radiation field (Lockett et al. 1999).

Circumstellar 1720–MHz maser emission was previously detected from the star V1057 Cygni (Lo & Bechis 1973;

Winnberg et al. 1981), following an optical/infrared flare in 1970. It has been suggested that the 1720–MHz flares occured when shells ejected at different velocities collided with remnant star–forming material and that the masers were collisionally excited (Elitzur 1976). The maser flares only lasted for ~ 18 months, showing that the right conditions for 1720–MHz maser emission may be very short–lived.

4.1. *Predictions*

Long–baseline interferometry of OH009.1−0.4 will be carried out with MERLIN in the near future and may help establish whether it is the AGB superwind or the proto–planetary wind that is aspherical and causes the wealth of morphologies observed in PNe. In our scenario, in the former case, the 1720–MHz masers would be preferentially on the equator of the OH shell, in the latter on its poles. We predict that this is more likely, given the very narrow width of the 1720–MHz line, compared to the 1612–MHz profile. On average, the 1720–MHz maser will be located outside the 1612–MHz and 1665–MHz layers, which is in agreement with its slightly higher velocity in an accelerating outflow (see Bujarrabal et al. 1997). The absence of the red–shifted peak at 1720 MHz suggests that we see the bipolar outflow nearly end–on (cf. Claussen et al. 1997).

If the object is a post–AGB star, measuring Zeeman splitting of the narrow 1720–MHz lines would give a measurement of the magnetic field, as has been done for several supernova remnants (eg. Brogan et al. 2000; Koralesky et al. 1998), and provide interesting boundary conditions for magneto–hydro–dynamic models (see Garcia–Segura, Franco & Lopez 2000).

Finally, we predict that no H_2O–maser emission will be found in this object, but that thermal emission should be detectable given the large column density. Several H_2O transitions in the far infrared (eg. 179.5μm,174.5μm) could provide conclusive evidence in favour of the shock–formed water scenario (Kaufman& Neufeld 1996), but other shock indicators, such as near–infrared H_2 transitions may be more practical for observations.

5. CONCLUSIONS

We have detected an OH 1720–MHz maser in a likely post–AGB envelope. From theoretical as well as observational arguments, it is possible that this maser exists briefly in such environments, at least in some sources. We argue that the 1720–MHz maser could arise in the region where the AGB– and the starting PN winds collide. We expect that this is a short-lived event and that our detection rate of 1/11 is due to favourable small number statistics. The most likely objects to show this emission may be those that have fairly strong emission at 1612 MHz, with weaker 1665–MHz and possibly SiO maser emission, but no 1667–MHz and certainly no H_2O 22–GHz maser emission.

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