Part II. Stellar MASERs

Cosmic MASERs: From Protostars to Blackholes
IAU Symposium, Vol. 206, 2002
V. Migenes and M. J. Reid, eds

Stellar masers: A review

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Abstract. I review the current state of studies of masers in the circumstellar envelopes of Asymptotic Giant Branch stars.

1. Introduction

The study of masers in the circumstellar envelopes of evolved stars has been the subject of extensive observational interest over the past three decades. Such studies have accelerated with the advent of modern interferometers with the resolution, both spatial and spectral, required to produce detailed images of the molecular maser and thermal lines that abound in such objects.

The availability of such instruments has resulted in an explosion of results over the last few years. The purpose of this review is to explore the major results in the field published in the last two to three years and hopefully provide readers with the references to enable them to delve deeper into the subject.

1.1. Setting the scene

Stars with mass $< 8M_{\odot}$ evolve along the Asymptotic Giant Branch (AGB) to become variable giants and supergiants. As they evolve, they develop large ($R_{*} \sim 1-3$AU), cool ($T \sim 2000-3000$K) convective photoshperes. They begin to pulsate and produce envelopes of dust and molecular gas. The pulsation (periods of 100-1000 days) produces shock waves that generate complex gas motions in the inner regions of the envelope. As the dust condenses, at radii of a few AU, it becomes momentum-coupled to the gas and stellar radiation pressure then accelerates the material to velocities that typically range from 10-20 km/s. Excellent general reviews of the current state of knowledge of AGB stars can be found in Habing (1996) and the proceedings of IAU Symposium 191, 'Asymptotic Giant Branch Stars'.

Figure 1 is a schematic view of an idealized maser environment around an AGB star. Depending on the densities, temperatures and excitation conditions we can observe SiO, H_2O and OH masers at distances of a few AU to a few thousand AU respectively from the central, pulsating, mass-losing star. Rarely do we find a star which exhibits the theoretical ideal shown in Figure 1; however, there are exceptions. The beautiful CO ring observed by Olofsson et al (2000) in the carbon star TT Cygni (Figure 2) reminds us that occasionally nature does provide us with a treat. TT Cyg is not without its surprises though, the radius of the ring is large (2.7×10^{17}cm) and it is circular to within 3% implying that it is expanding into a region of remarkably uniform density. Olofsson et

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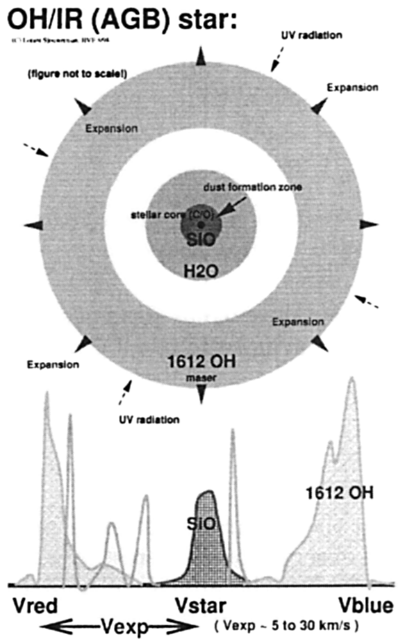

Figure 1. A cartoon of the maser environment around an AGB star, courtesy Lorant Sjouwerman. The upper picture shows the relationship of the common molecular masers, the lower picture is an idealized composite spectrum of the various masers.

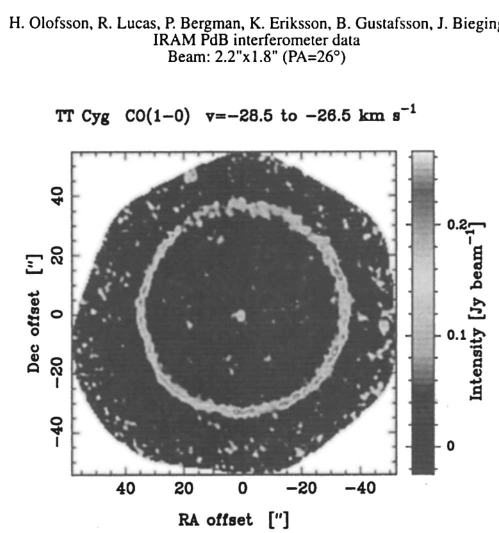

Figure 2. An image of the detached CO shell around TT Cyg (Olofsson et al, 2000). Data from the Plateau de Bure interferometer.

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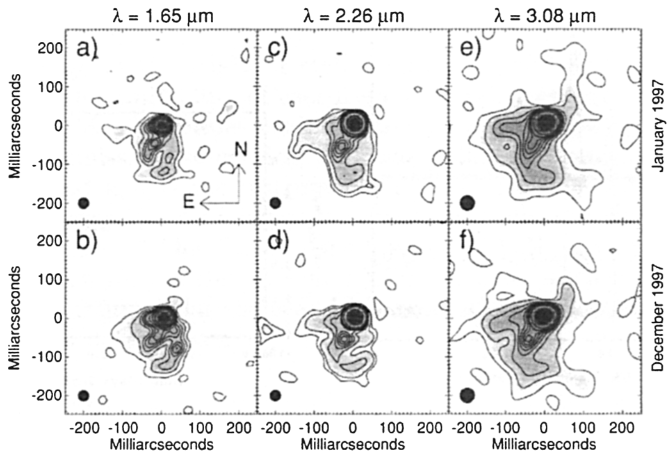

Figure 3. IR images of the dust shell around VY CMa, from Monnier et al (1999).

al interpret their data as being indicative of TT Cyg undergoing a period of dramatically varying mass-loss within the last 10^4 years.

At the opposite extreme, an example of an AGB star which contains strong masers and whose nature has not been satisfactorily explained, despite many years of study, is that of VY CMa. Figure 3 shows recent IR images of the dust shell around VY CMa obtained by Monnier et al (1999). The images demonstrate the complexity of the structure of the circumstellar envelope. Although VY CMa is an attractive target for observers due to its high luminosity, its complexity is such that our understanding of AGB stars as a whole is more likely to improve through observations of a larger number of hopefully simpler sources.

2. Surveys

The bedrock of observational astronomy lies in surveys of the sky. Statistically complete surveys offer the chance to understand the nature of classes of sources and from such samples astronomers can select individual sources for more detailed studies. Over the last few years several major surveys of masers have been undertaken. The most complete has been the combined ATCA/VLA 1612 MHz survey of the Galactic Plane by Sevenster et al (1997a, 1997b, 2001). This unbiased survey covered the region between $|l| \leq 45°$ and $|b| \leq 3°$ and discovered a total of 766 sources. This database will be a crucial tool for the investigation of Galactic structure (e.g. Sevenster, 1999) and the global properties of OH/IR stars.

Surveys for H_2O masers have been relatively rare. However, Takaba et al (2001) have conducted a survey of late-type stellar objects at 22.235 GHz with the 34-m telescope at Kashima. Of 643 sources observed, they detected 179. They found the highest detection rate for stars with a thin dust envelope (e.g. Miras and semi-regulars) as expected.

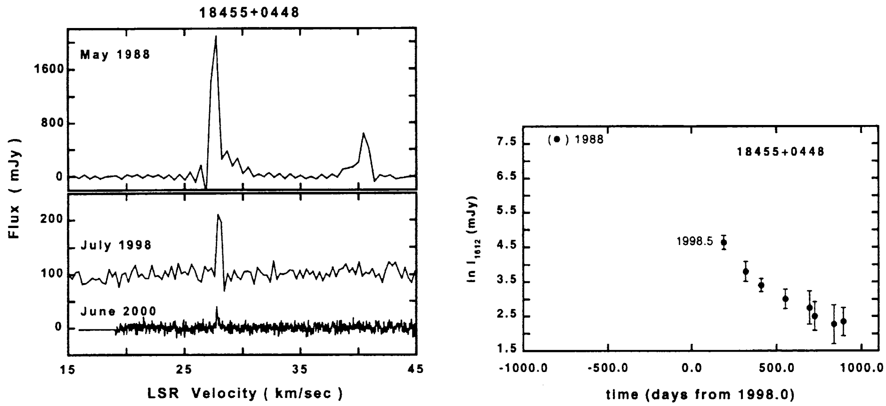

Figure 4. Left frame: Arecibo spectra of the 1612 MHz OH maser from IRAS 18455+0448. Right frame: Decay of the 1612 MHz feature at 27.5 km/s. Both figures from Lewis et al 2001.

Surveys of SiO masers have been a major activity at the Nobeyama Observatory. Several surveys (e.g. Izumiura et al, 1999; Deguchi et al, 2000a; Deguchi et al 2000b) have been undertaken at 43 GHz towards colour-selected IRAS sources in the longitude range $-10° < l < 25°$ and $|b| \leq 3°$. Several hundred sources have been detected and an analysis of the overall characteristics of the data have shown evidence of a streaming motion of stars in the bulge bar. Multi-transition surveys of SiO maser sources have also been undertaken at Nobeyama and are described in Cho et al (1996) and references therein. Other surveys at 86 GHz have also been performed in recent years (e.g. Deguchi et al 2001, Messineo et al, these proceedings).

3. Single dish monitoring

The monitoring of individual sources are analagous to the survey programs discussed above. Rather than searching in the spatial domain such observations study the time domain and can produce fascinating results. One major result is that of the well documented decline of the OH maser IRAS 18455+0448 (Lewis et al, 2001: Figure 4). Although the 1665 MHz emission remains largely unaffected the 1612 MHz has faded by a factor of 20 since 1988. Lewis et al suggest that we may be witnessing the early stage of the expansion of a fossil circumstellar shell, prior to the star becoming a planetary nebula.

A Russian group have been conducting extensive, long time-base monitoring of various stellar H_2O masers sources (e.g. Berulis et al, 1998; Esipov et al, 1999; Rudnitskij et al, 1999). Recent observations of the maser in U Ori (Rudnitskij et al, 2000) show 20 years of data and demonstrate well the correlation of the flux of the radio emission with the stellar light curve, with the radio having a phase delay of between $0.2 - 0.4$ of the period. Rudnitskij et al explain the maser variability as the result of periodic shocks driven by the stellar pulsation.

4. Interferometry

A massive change in the study of stellar maser sources over the last decade has arisen from the availability of user-friendly interferometers. The VLBA has led the way in this revolution, enabling astronomers to routinely study H_2O and SiO maser emission, something that was difficult in earlier decades. The EVN has followed and is the instrument of choice for high-resolution studies of stellar OH masers (and uniquely, various transitions and molecular species of interstellar masers). The United Kingdom's MERLIN array, with its unique resolution between that of the VLA and VLBI, is well matched to the detailed study of OH in circumstellar shells and has revolutionized our ability to obtain polarization data on such sources.

4.1. SiO Masers

Early work by the North-East US VLBI group in the 1970s and early 1980s (e.g. Moran et al 1979) demonstrated that VLBI observations of stellar SiO masers at 43 GHz was possible but also, in retrospect, revealed the limitations of the equipment available at that time. The maps produced demonstrated that the SiO emission was clustered in regions similar in size to that of the star but suggested that, in general, the masers were physically large. In 1990 Colomer et al (1992) detected compact SiO maser structure in several stars, this was soon followed by the first images of stellar SiO masers (Diamond et al, 1994). Diamond et al used 5 antennas of the VLBA to demonstrate that the SiO masers around the Mira variables TX Cam and U Her lay in ordered ring-like structures and were not randomly distributed. The masers were shown to be tangentially beamed. Other groups (e.g. Miyoshi et al, 1994; Greenhill et al, 1995) soon showed that such structures were common.

Since the discovery of the ordered structures in the envelopes of such stars and the recognition that VLBI was superbly capable of following the evolving structure of the masers, there has been considerable effort expanded in monitoring observations. The most complete set of data exists for TX Cam (Diamond & Kemball, 2001). At the time of writing 80 epochs of imaging data have been taken, the first 44 epochs cover a period of 1.1 stellar phases can be seen at:

`http://www.jb.man.ac.uk/~pdiamond/txcam44.gif`

There has been some suggestion that rotation of the gas in which the SiO is embedded is detected. There are, as yet, no clear cut cases of rotation except possibly NML Cyg. Boboltz & Marvel (2000) detected a new SiO peak which made NML Cyg unique amongst evolved stars in having a double peaked spectrum. Their VLBA image shows an elongated ring of masers which appears to be rotating with a velocity $V sini \sim 11$ km/s about an axis aligned NW-SE.

Polarization observations of the SiO masers in TX Cam were also surprising. Kemball & Diamond (1997) demonstrated that the linear polarized emission was even more ordered than the total intensity emission (Figure 6). The electric vectors were predominantly aligned tangential to the maser ring. A detection of a circularly polarized component was interpreted as evidence for a magnetic field of 5-10 G at the $\sim$ 5AU radius of the SiO masers.

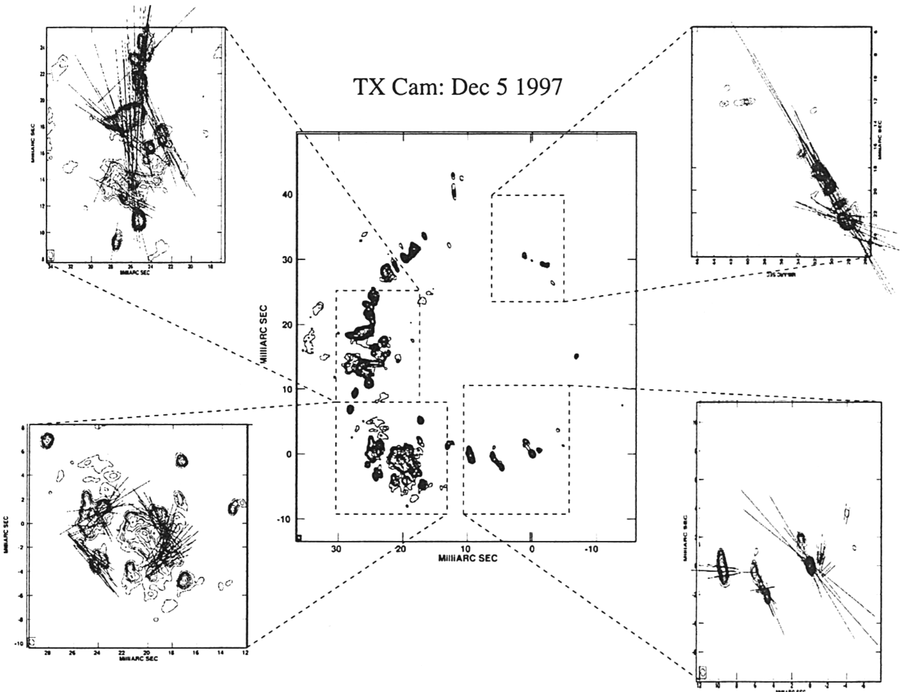

Figure 5. A montage of images of TX Cam. The central image shows the total intensity structure as seen on Dec 5 1997. The four surrounding images show the linear polarization structure of the regions marked.

Studies of other transitions of SiO have also been performed. Doeleman et al (1988) have produced an image with a single interferometer of the v=1, J=2-1 transition at 86 GHz towards VX Sgr while Phillips & Boboltz (2000) observed the same transition towards Mira. The data on VX Sgr shows that this transition exhibits a similar ordered structure to that at 43 GHz, that on Mira was inconclusive. Miyoshi et al (1994), Desmurs et al (2000), Imai et al (2001), Yi et al (these proceedings) and Doeleman et al (in prep) have all observed the v=1 and v=2, J=1-0 transitions at 43 GHz. The aim of such observations is to determine the relationship of the maser structures and address questions concerning the maser pumping. The jury is still out, although Desmurs et al (2000) make a strong case for radiative pumping based on the non-coincidence of spots from the different transitions.

4.2. H_2O Masers

Before the advent of the VLBA high-resolution studies of H_2O masers in circumstellar envelopes were limited. The opportunity to observe proper motions and to study the polarization characteristics of the masers has transformed the ability of astronomers to sample this relatively under-studied area.

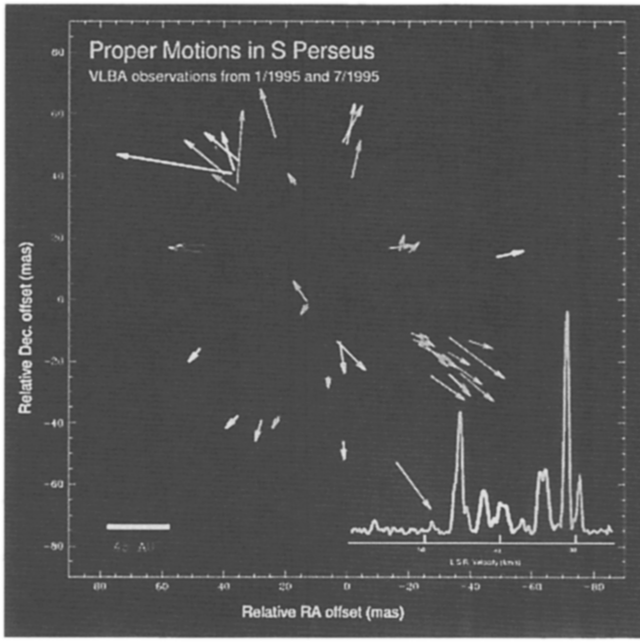

Figure 6. An image showing the results of three epochs of VLBA observation, each separated by 6 months, of the H_2O masers around S Per. Courtesy Kevin Marvel.

Marvel (1996) has shown the power of multi-epoch VLBI observations in revealing the structures and kinematics of the circumstellar envelopes in the intermediate regions between the SiO and OH. The observations of S Per shown in Figure 7 clearly show the outward expansion of the maser emission, however a detailed examination of the maser motions (Marvel & Diamond, in prep) reveal departures from a smooth, symmetric outflow.

MERLIN has also observed proper motion of H_2O masers in VY CMa (Richards et al, 1998) and NML Cyg (Richards et al, 1996). Interestingly, the motions seen in NML Cyg imply expansion predominantly along a NW-SE direction.

Recent advances in instrumentation and analysis tools have made possible the first detection of circularly polarized emission from a stellar H_2O maser (Vlemmings et al 2001). Vlemmings et al determine a magnetic field value of $\sim$ 280mG at the position of the H_2O masers in S Per, although see Watson & Wyld (2001, in press).

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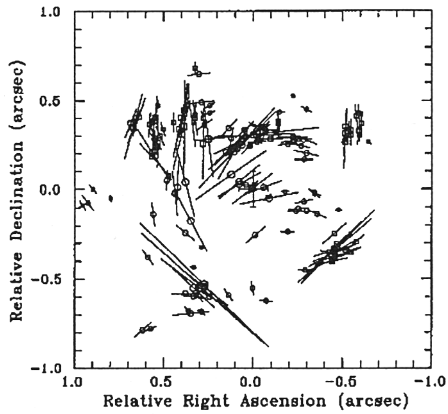

Figure 7. Relative positions of the OH 1612 MHz masers and their associated polarization vectors. The circles and squares represent the blue- and red-shifted components, respectively. Figure from Szymczak et al (2001).

4.3. OH Masers

Some of the more fascinating advances in the study of OH stellar masers in recent years have come from the ability of MERLIN to obtain routine polarization data. Szymczak et al (2001 and references therein) have studied the polarization structure of the 1612 MHz OH masers towards VX Sgr (Figure 8). The polarization vectors are generally tangential to the circumstellar envelope, indicating a globally ordered magnetic field. Szymczak et al (2001) interpret these results as being indicative of a dipole field tilted at $20 - 30°$ to the line of sight with a strength in the vicinity of the masers of $\sim$ 1.1mG. Similar MERLIN images of the OH 1612 MHz masers in NML Cyg (Diamond & Etoka, in prep) reveal a different picture; in that the polarization vectors lie predominantly in a NW-SE direction, similar to the H_2O expansion direction and the suggested SiO rotation axis.

Monitoring of structural changes in OH masers is less easy than for H_2O and SiO masers. The transition frequency is lower and that translates to less angular resolution for the same length of baseline. In addition, the OH masers tend to lie in the more quiescent parts of the circumstellar envelopes and exhibit less violent and dramatic motions. Nevertheless, observations of such changes can be made. van Langevelde et al (2000) reported on VLBI astrometric monitoring of the 1667 MHz OH masers towards the Mira U Her. These are the most accurate such measurements to date and have resulted in the determination of the stellar proper motion and the annual parallax ($\pi = 5.3 \pm 2.1$ milliarcsec). The observations also revealed structural changes in the blue-shifted maser spots which are probably amplifying the stellar disc of U Her. Palen & Fix (2000) have also observed U Her over more than a decade with Arecibo and the VLBA. Their aim was to study the long-term variation in the OH emission and its structure.

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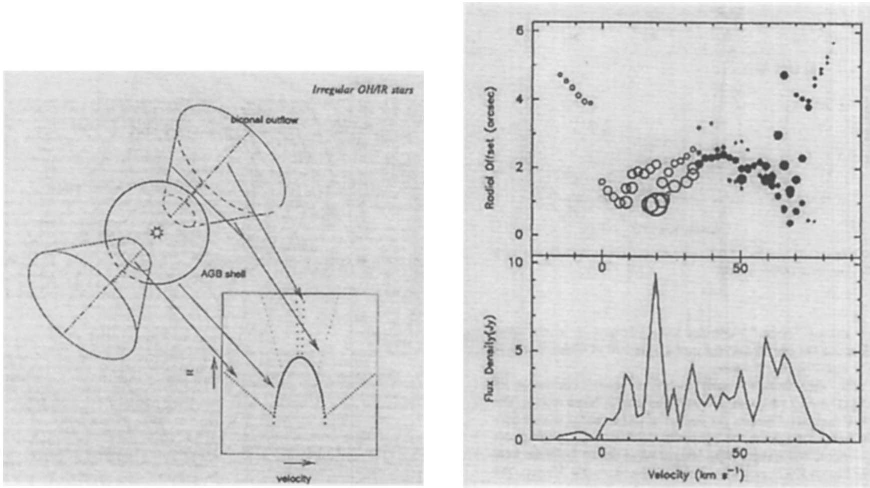

Figure 8. Left frame: Predicted velocity-radius relations for the model of an hourglass-shaped bipolar nebula. Right upper frame: The projected radial offsets of the OH 1667 MHz masers from the stellar position of OH231.8+4.2. Right lower frame: The OH 1667 MHz spectrum of OH231.9+4.2. Both figures from Zijlstra et al, 2001.

They concluded that the most likely mechanism of the changes observed arises through the turbulent magnetic field.

5. Getting older

When mass-loss ceases the central star heats up and begins to ionize the expanding envelope. At this stage a fast wind from the newly hot star sweeps up the earlier, slower AGB wind to form a planetary nebula. Approximately 50% of all planetary nebulae show bipolar structure, which is presumed to be the result of the formation of a dense, slowly expanding equatorial torus and a faster outflow confined to two polar cones. It is possible that IRAS 18455+0448 (Lewis et al, 2001) is a star observed just at the stage of the cessation of mass-loss.

Zijlstra et al (2001) have performed a comprehensive imaging survey of 10 OH/IR stars which exhibit the signs of old-age, namely irregular OH spectra and unusually large expansion velocities. Their survey offers the chance to investigate the development of bipolar outflows. Zijlstra et al developed a model that predicts the nature of the velocity-radius diagram (Figure 9a) for sources undergoing the bipolar flow described above. Their VLA data of OH231.8+4.2 (Figure 9b) is a dramatic confirmation of the geometry of the OH in this particular source.

Dyer et al (2001) have published a comprehensive ATCA study of the three principal OH transitions towards Roberts 22. Their study (Figure 10) confirmed previous suggestions that this object is a proto-planetary nebula and exhibits the bipolar structure seen in other sources by Zijlstra et al (2001).

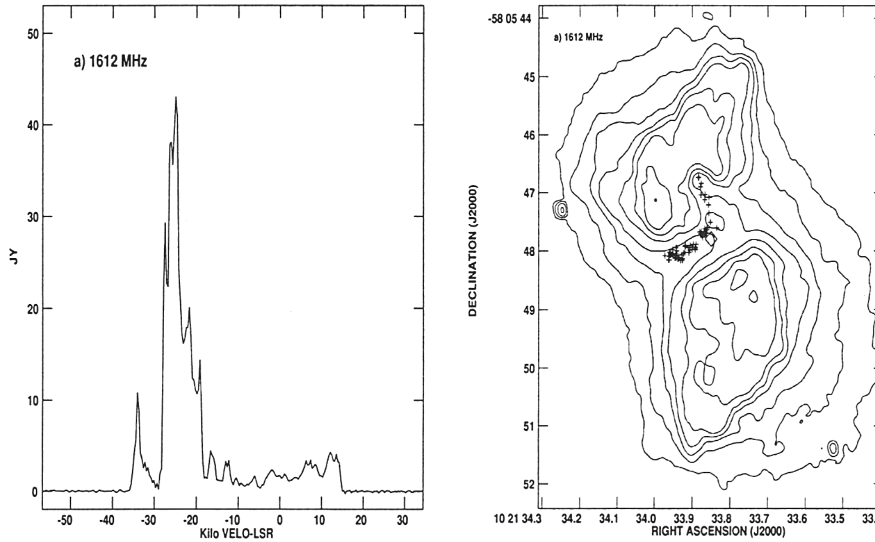

Figure 9. Left frame: ATCA spectrum of the OH 1612 MHz emission from Roberts 22. Right frame: HST H_α image of Roberts 22 (Sahai et al (1999), the crosses represent the location of the 1612 MHz masers. Both figures from Dyer et al, 2001.

The exact mechanism for the formation of the bipolar flows from the relatively circularly symmetric structures that are seen at earlier stages of the stars' evolution is unclear. However, the intriguing observations of an axis of symmetry seen in the rotating SiO, expanding H_2O and polarized OH emission in NML Cyg may offer the hints required.

Early surveys demonstrated that OH 1720 MHz emission was not detected towards AGB stars, although Lo & Bechis (1973) did detect it towards the FU Orionis star V1057 Cyg. It is therefore a surprise to see the detection of OH 1720 MHz maser emission towards OH009.1-0.4 (Sevenster & Chapman, 2001: Figure 11). The authors argue that such unusual emission can be explained if the star is an early post-AGB object and that the 1720 MHz emission is collisionally excited in a region where the interaction of the remnant AGB wind with the hotter, faster post-AGB wind can cause shocks.

6. The Future

This review has, I hope, demonstrated the impressive progress in the study of stellar masers over just the last few years. With the increased capabilities of modern interferometers and the plans for their upgrades coupled with the introduction of new, and the improvement of existing, monolithic radio telescopes, the prospects for future advances are huge.

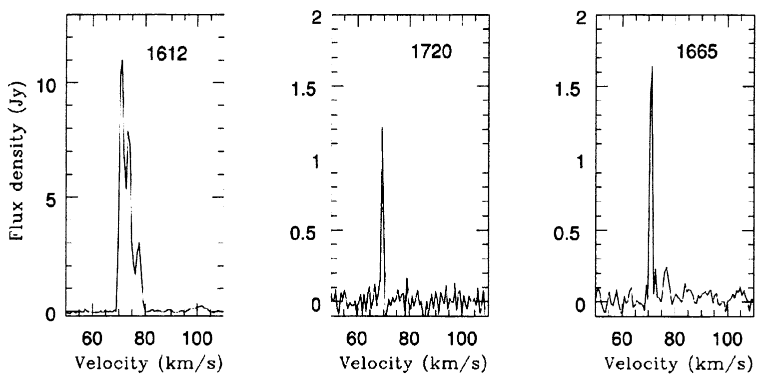

Figure 10. ATCA spectra of OH towards OH009.1-0.4 (Sevenster & Chapman, 2001).

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