R.J. Cohen

Masers in the envelopes of supergiants, OH-IR sources and long period variables

ABSTRACT

Recent observational progress in mapping circumstellar masers is reviewed. Powerful masers of OH, water vapour and SiO enable physical conditions and kinematics to be probed in angular scales down to one milliarcsecond. The picture that emerges is one of turbulence and irregularity in the inner regions of the envelope where mass loss is established, giving way to regularity in the outer regions as the material approaches terminal velocity. The role of the magnetic field in the maser regions is also discussed.

INTRODUCTION

Maser emission is a powerful tool for studying circumstellar envelopes. Spectral lines from circumstellar molecules can be amplified milions of times by the maser process. This produces powerful beams of microwave radiation which can be detected from circumstellar envelopes throughout the Galaxy, and even in nearby galaxies (Wood *et al.*, 1986). Masers often highlight unusual phases of stellar evolution: the birth of stars, the late stages of heavy mass-loss that I will discuss, and also the subsequent transition to planetary nebulae (Cohen 1989; Shepherd *et al.*, 1990; and references therein). Using radio interferometers the masers can be mapped with very high angular resolution on scales down to one milliarcsecond.

But there is also a penalty. The highly nonlinear nature of the maser process means that it is often difficult to recover the physical conditions from the observations. Before showing you some of the recent radio data I would like to remind you what the difficulties are.

BASIC THEORY

Masers work by the process of stimulated emission, in which a photon with the right energy causes an excited molecule (in our case) to emit a second photon in the same direction as the incident photon. This is the inverse process to absorption. In order to get maser action we need a population inversion. As the energy levels for a microwave transition are very close together only a small population shift is required. The molecules in a circumstellar envelope are interacting with systems at several different temperatures - radiation from hot dust, radiation from cold dust, gas at one temperature and dust at another temperature. Thus population inversion of one or more transitions is not difficult to bring about. Once the inversion is set up then stimulated emission dominates. The absorption coefficient of the gas becomes negative and the gas becomes a maser, amplifying any background radiation or spontaneous emission from within the cloud. The intensity of the maser beam will continue to grow exponentially through the cloud until the maser photons began to destroy the population inversion faster than the pump processes can replenish it and the maser saturates.

An unsaturated maser gives a very distorted view of the gas cloud, exponentially amplifying any small irregularities. It can readily be shown that the radiation is highly beamed. For a uniform spherical cloud beaming reduces the apparent size of the maser by the square root of the optical depth, that is by a factor of typically 5 for a strong maser (Goldreich & Keeley 1972). In a similar way the maser linewidth is reduced by the same factor. Finally the maser intensity is a very sensitive function of the physical conditions, responding exponentially to small changes in the pump rate.

For a saturated maser the situation is little better. The maser intensity now responds linearly to the pump, but there are new complications when maser beams travelling in different directions come into competition for the limited number of excited molecules (Alcock & Ross 1986).

The most important circumstellar masers are listed in Table 1. We see that masers are a symptom of a non-thermal distribution which affects many energy levels of a molecule, and which can generate several maser transitions. I will concentrate on the strong masers of OH, water vapour and SiO for which we have detailed radio interferometer maps. These masers are found almost exclusively in oxygen-

Table 1. Widespread circumstellar masers

Molecule	Transition	Frequency (MHz)	E/k (K)
*OH	$^2\Pi_{3/2}$, $J={}^3/_2$, F=1→2	1612.231	0.08
*OH	$^2\Pi_{3/2}$, $J={}^3/_2$, F=1→1	1665.402	0.08
*OH	$^2\Pi_{3/2}$, $J={}^3/_2$, F=2→2	1667.359	0.08
*H_2O	$6_{16} \rightarrow 5_{23}$	22235.08	644
*SiO	V=2, J=1-0	42820.54	1772
*SiO	V=1, J=1-0	43122.03	1769
SiO	V=2, J=2-1	85690.37	3526
SiO	V=1, J=2-1	86293.35	3519
HCN	$V=(0\ 2^0\ 0)$, J=1-0	89087.90	2050
H_2O	$3_{13} \rightarrow 2_{20}$	183310.09	205
H_2O	$10_{29} \rightarrow 9_{36}$	321225.64	1861

*Radio interferometer maps

rich envelopes, although possible counter-examples to this are known (Little-Marenin *et al.* 1988).

Our basic picture of the circumstellar maser regions is due to Goldreich & Scoville (1976). The inner regions where mass-loss originates are the least well understood. Here shocks and cooling instabilities are likely to be important. Once the material cools sufficiently for dust to form then the physics becomes simpler. The dust is blown outwards by radiation pressure and sweeps the gas with it. Further out is a photo-dissociation zone where the interstellar ultraviolet radiation breaks up water in particular to produce OH in great abundance. Beyond this is the cooler extended molecular envelope probed by CO measurements.

The locations of the various masers in the circumstellar envelope form a natural sequence according to the excitation energies of the transitions (Table 1). Thus SiO masers are found within a few stellar radii of the star, water masers are found further out at about ten stellar radii, and OH 1612 MHz masers are found further out again at about one hundred stellar radii. This sequence has been confirmed observationally for the supergiant VX Sgr (Chapman & Cohen 1986). In the following sections I will discuss the masers in reverse order, working inwards.

OH 1612 MHz MASERS

OH 1612 MHz masers are the best understood circumstellar masers. It was suspected right from their discovery that these masers are pumped by infrared radiation (Wilson & Barrett 1968). The identification of the pump scheme by Elitzur *et al.* 1976, and its subsequent experimental verification form one of the major successes in this field. The 1612 MHz masers are saturated and vary linearly with the infrared pump. The twin-peaked OH spectrum characteristic of these sources was recognized as the signature of shell structure, and this was elegantly confirmed by the first radio interferometer maps (Booth *et al.* 1981). According to the photodissociation model the shell radius should increase with the mass-loss rate, as UV radiation cannot penetrate so far through a thicker envelope. Observational data on a number of sources confirm the expected dependence (Huggins & Glassgold 1982; Netzer & Knapp 1987; Szymczak 1989).

The photodissociation model also predicts two effects which have yet to be observed: a dependence of the shell radius on the strength of the UV field, and an increase in shell thickness with mass-loss rate. Migenes, Cohen & Bowers (in preparation) have recently obtained data which provide the first accurate measurements of the shell thickness. The combined MERLIN and VLA arrays were used to make a high quality image of the source OH 127.8 with a dynamic range of 400:1. A selection of the channel maps is shown in Figure 1. The OH shell radius is very accurately defined by these data. If we use

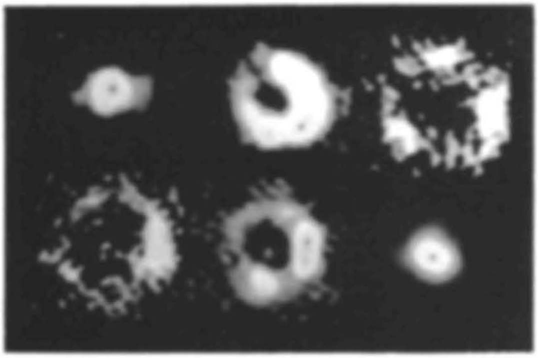

Fig. 1: A selection of channel maps of the OH 1612 MHz source OH127.8, showing the shell structure. The data were obtained with the combined MERLIN and VLA arrays (Migenes, Cohen & Bowers, in preparation).

this to estimate the mass-loss rate we find that the maser shell appears to be twice as thin as the OH shell predicted by the photodissociation models. There are several factors which might explain this result, some of which were discussed above. The maps also show much filamentary structure and "holes". These may reflect differences in the OH density and excitation, or velocity irregularities such as turbulence in the envelope. Evidently these data demand something more comprehensive than the simple thin-shell model.

The 1612 MHz maser shells provide a means of measuring distances to OH-IR sources. The long-term monitoring programmes such as that of Herman & Habing (1985) enable light-travel diameters to be measured from phase-lags in the OH spectrum, as the masers vary in intensity through the stellar cycle. These phase-lags can be combined with the angular diameter to yield the distance. The technique is very labour-intensive, but it has the advantage of being completely independent of other distance measurement techniques.

OH MAINLINE MASERS

OH mainline masers already show more irregularity than the 1612 MHz masers. The variations are larger in amplitude than those of 1612 MHz masers, and the profile is more likely to change in shape, particularly for Miras (Sivagnanam 1989). The mainline masers are predicted to lie nearer the star, in warmer denser regions than the 1612 MHz masers. This is confirmed in general. In some cases we see a well developed shell of mainline emission at a smaller radius than the 1612 MHz shell (e.g. Diamond *et al.* 1985). In other cases the mainline emission is more compact and more irregular (e.g. Chapman & Cohen 1986). However there is also at least one source, the supergiant IRC+10420, where OH mainline masers lie further from the star than the 1612 MHz masers (Bowers 1984).

Some remarkable new results on the source U Orionis may shed light on the mass-loss process. The source has been mapped at several epochs with MERLIN, on account of its unusual maser flare activity in the 1970s (Jewell *et al.* 1981; and references therein). The mainlines show a clear ring of emission first identified by Chapman & Cohen 1985, as well as other more irregular filaments (Chapman *et al.* 1991). Repeated mapping has revealed that the maser ring is expanding at a rate of a few milliarcseconds per year which corresponds to the terminal velocity of 8 km s^{-1}. This goes completely against the standard picture of a stationary photodissociation zone through which material flows at a steady rate. What we may be seeing in U Ori is an increase in the mass-loss rate, and perhaps a change in its character. If the outflowing material is in large blobs these can survive the external UV radiation for greater distances than would be the case for a uniform spherically symmetric mass-loss. As the blobs travel outwards we would measure proper motions at the flow velocity. Eventually the blobs would be dissociated but then, if the mass loss was continuous, new blobs would reappear further in. Further monitoring is essential of we are to distinguish among the various possibilities. It is salutory to realize that this behaviour was only uncovered because of interest in the maser flare activity. We do not know whether such effects are present in other sources.

H_2O MASERS

The pumping of the 22 GHz water masers is well understood in terms of collisional excitation and radiative decay (Cooke & Elitzur 1985). Strong inversion of the 22 GHz transition is obtained over a wide range of conditions, and in addition several other maser transitions are predicted. The observed intensities show very strong variations, following the period of the stellar cycle but with very irregular amplitudes (Gomez-Balboa & Lepine 1986).

Maps of the 22 GHz masers show a collection of maser spots whose structure is yet to be fully resolved. Reid & Menten (1990) have recently confirmed in a very elegant way that the maser spots cluster around the stellar position. They used the powerful maser signals as a phase-reference to correct wide-band continuum measurements and in this way were able to detect the radio continuum emission from the star WHya. The masers form a ring around the star, which suggests that they lie in a region of large velocity gradient. The model advanced by Chapman & Cohen (1986) is that the water masers lie in a thick shell region where the outflowing gas is accelerated to escape velocity. The size of the maser region increases with the mass-loss rate as predicted by the pumping model (Cohen 1987; Lane *et al.* 1987).

In the context of this meeting it is notable that the water masers frequently have an asymmetric distribution. They are also relatively close to the star and therefore probe earlier stages of mass loss than the OH masers. It is encouraging that several new water maser transitions have recently been detected in circumstellar envelopes (Cernicharo *et al.* 1990), including a submillimetre transition with an excitation of 1861K (Menten *et al.* 1990). Observations of several of these transitions may prove to be a powerful diagnostic of the physical conditions.

SiO MASERS

SiO is the least well understood of the circumstellar masers, although it has been observed as a maser in numerous transitions up to vibrational level V = 3 and rotation level J = 6 (Jewell *et al.* 1987). The SiO maser intensity varies strongly and there is evidence in at least one star for "superperiods" with alternately high and low maxima (Nyman & Olofsson 1986).

There has been only limited mapping of SiO masers so far, and this has mainly been by very-long-baseline-interferometry (VLBI). The masers form very irregular ensembles of hot-spots only a few stellar diameters in extent (Lane 1982). Wright *et al.* (1990) have established that the masers are centred on the stellar position as would be expected from their high excitation energies. Recent work by McIntosh *et al.* 1989 combined VLBI with single-dish polarization measurements to investigate the magnetic field structure close to the stellar surface. Fields of some 30G are implied by the polarization of SiO masers (Barvainis *et al.* 1987). These may be compared with fields of 3mG measured in the OH maser regions (Chapman & Cohen 1986; Cohen *et al.* 1987), implying that the field strength falls inversely as the square of the distance from the star. The magnetic fields which have been measured are strong enough to affect the dynamics of the envelope. Further investigations of this kind hold great promise.

CONCLUSIONS

Before giving this talk I asked myself "are masers really relevant to the subject of this meeting and can I really justify being here?" I hope I have convinced at least some of you in some respects. The masers are bright and readily detected probes of the circumstellar regions, and they can be studied very precisely with high angular resolution. The use of phase-lag techniques for distance measurement contributes at a very fundamental level, enabling us to determine what is a supergiant and what is not.

Radio interferometry enables us to study the structure of the mass-loss regions, and even in the case of U Orionis to follow mass-loss in real time. The masers give information on the velocity field as well. The general pattern is that the nearer we go to the star the more turbulent and the more asymmetric we find the maser regions to be. The polarization of maser radiation enables us to estimate the magnetic field strength in several zones, and may one day enable the three-dimensional field structure to be mapped out, and its dynamical evolution to be followed.

I have not had time to deal with several important topics, such as the use of maser line ratios as indicators of the mass-loss rate (Kirrane 1987; Lewis & Engels 1988), and the possibility of tracing evolutionary sequences using different maser transitions. Masers play an important role in identifying key stages in stellar evolution. As more maser transitions are identified and as the observational techniques continue to improve we can look forward to many exciting discoveries in the future.

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AUTHORS ADDRESS

Nuffield Radio Astronomy Laboratories, Jodrell Bank, Macclesfield, Cheshire SK11 9DL, U.K.