MASERS IN CIRCUMSTELLAR SHELLS

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1. INTRODUCTION

Presumably due to a cosmic accident, circumstellar masers are almost exclusively found in oxygen rich stars with [O/C] >1. The exception here is the SiS maser found towards IRC 10216 (Henkel et al. (1985)) but I will ignore this in what follows and concentrate this review upon the circumstellar shells where OH, H_2O, and SiO masers are found in profusion. Such objects are thought to be on the asymptotic giant branch (AGB) of the Herzsprung-Russell diagram and show evidence for rapid mass loss. The derived mass loss rates vary from approximately 10^{-7} solar masses per year for the optically well studied Mira variables in the solar neighbourhood (Distances <1 kpc) to as high as 10^{-4} solar masses per year for the optically invisible OH-IR stars and for some supergiants. Of these objects, the supergiants appear to be more luminous than the rest (10^5 $L_\odot$ rather than 10^4 $L_\odot$) and their central stars have masses of order 10 $M_\odot$ as compared to most Mira variables whose mass is probably in the range 1-2 $M_\odot$. Most OH-IR stars are likely to be a late stage in the evolution of solar mass type objects where the mass loss rate suddenly increases. As their name indicates, they are characterised by their strong OH-maser (1612 MHz) emission as well as by their radiation at far infrared wavelengths (20-50 μ). They may well be on the way to becoming planetary nebulae (see Pottasch, 1984 for an account of their probable evolution).

Molecular abundance determinations in such envelopes are of interest both from the standpoint of stellar evolution as also because one learns about the element abundance mix being returned to the interstellar medium. The amount of matter being returned to the interstellar gas due to mass loss from red giant envelopes is of the same order as that going into the formation of new stars (see Knapp and Morris (1985)). Hence, knowledge of the form which that matter takes is of importance to galactic evolution studies. However, it turns to be difficult to make good abundance determinations or even mass loss rate determinations for oxygen-rich circumstellar envelopes. This is partly because of the non-linear behaviour of the maser phenomenon itself which causes any estimates based upon observations of the maser lines themselves to be

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suspect. Another factor is that there simply are very few non-maser lines which can be observed towards oxygen rich stars. In fact, the only extensively observed non-maser transitions in oxygen rich objects are the $1 \rightarrow 0$ and $2 \rightarrow 1$ lines of CO (see Knapp and Morris (1985) as well as Zuckerman (this volume)). One is therefore dependent upon theoretical calculations (see Glassgold and Huggins (1985), Omont (this volume)) for most abundance estimates. This situation may however change in the near future as increased sensitivity becomes available at millimeter and sub-millimeter wavelengths.

Several of the subjects which I will discuss here are covered in more detail in other recent reviews. In particular, the article by Bowers (1985) concerning mass loss from maser stars gives a useful summary of the observational situation. The properties of the OH-IR stars, their evolutionary state, and their distribution in the galaxy are discussed by Herman and Habing (1985). Olofsson (1985) has reviewed the millimeter observations of both C-rich and O-rich envelopes. Finally, the article of Glassgold and Huggins (1985) reviews our observational and theoretical understanding of circumstellar chemistry. In this review section 2 will consider the general properties of OH, H_2O, and SiO masers and will mention briefly some attempts to understand their pump mechanisms. In section 3, I will discuss mass loss rate determinations and in section 4 I will briefly summarise what is known concerning circumstellar abundances in oxygen rich objects.

2. CIRCUMSTELLAR MASER PROPERTIES AND THEIR THEORETICAL INTERPRETATION

a) General Characteristics

Understanding circumstellar masers requires a model of the density distribution and dynamics of the circumstellar envelopes in which these maser lines form. Fortunately, the characteristic double-peaked line profiles seen in the 18 cm OH lines towards many oxygen rich stars can be easily understood in terms of an envelope expanding at constant velocity where the maser lines amplify preferentially along the radial direction. A rather simple theory (see Reid et al. (1977)) based upon the premise that the 1612 MHz masers observed in the OH-IR stars are saturated and that therefore the observed flux at a given velocity is proportional to the coherence path length at that velocity produces a satisfactory fit to observed line profiles. Moreover, simple dynamical models which assume that radiation pressure on grains is the driving force in the flow are in reasonable agreement with the observed flow prperties. In such models (see Goldreich and Scoville (1976), Elitzur (1981), Olnon (1981)), the grains are driven through the gas and the gas-grain friction is responsible both for heating the gas and for transferring momentum to the gas. The gas cools both due to its expansion and due to excitation of rotational and vibrational transitions of H_2O. In the outer parts of the shell (beyond 10^{16} cm), the ambient interstellar ultraviolet field can penetrate and photo-dissociate H_2O. This produces the observed OH shell and allows us to predict where in the envelope the OH is to be found even if it is difficult for us to say how much OH is present. It also allows a fair estimate to be made of the physical conditions (density and temperature) in the regions where the OH masers are found. A check upon these models is provided by interferometric measurements of the OH masers (e.g. Bowers et al. (1983), Diamond et al. (1985), Herman and Habing (1985)). These show the OH to be situated between 10^{16} and 10^{17} cm from the central star. The extreme red-shifted and blue-shifted gas is concentrated upon the stellar position whereas gas at intermediate velocities is found to be in a more extended shell-like structure.

The situation is less clear for H_2O although, here also, interferometer observations show where in the circumstellar envelope the maser lines form (see Bowers et al. (1983)). Water profiles are often double-peaked and similar to those observed in 1612 MHz OH suggesting in this case also radial maser amplification in the outflowing shell (Engels et al. (1986)). However, this is not always the case and rapid variability is observed. These variations show a rough correlation with the changes in optical or infrared luminosity but it is by no means clear for example that a radiative pump is operating. One concludes that most, but perhaps not all of the H_2O maser activity occurs approximately 10^{15} cm from the stellar surface.

SiO masers are certainly to be found close to the stellar photosphere. This is clear from the large degree of excitation required to excite the observed transitions. For example, the v = 3 level of SiO is more than 5000 K above ground and has been observed in a variety of objects. VLBI observations show however (see Lane (1984)) that the SiO masers are sometimes a few stellar radii above the photosphere. It is possible therefore that SiO masers form just inside the dust formation region where presumably much of the SiO is transformed into silicate solid particles. A loose correlation has been found between maxima of the integrated SiO maser flux and the infrared luminosity for some nearby Mira variables (Nyman and Olofsson (1986)). However, there is no obvious correlation between the velocities of SiO maser components and those measured in other wavelength ranges. More interferometric measurements are needed to clarify the spatial structure of SiO maser regions.

b) Models for Circumstellar OH Masers

For circumstellar OH masers, reasonably detailed pump models have been developed based upon the fact that the maser emission is observed to vary in phase with the far infrared luminosity. In fact for OH-IR stars, one finds that the luminosity in 1612 MHz OH photons is $\sim$1/10 - 1/4 of that which one expects to be emitted in the wavelength range of the $^2\pi_{1/2}$, J = 5/2 $\rightarrow$ $^2\pi_{3/2}$, J = 3/2 35 μm infrared transition of OH on the basis of broad band infrared measurements (see e.g. Engels et al. (1984)). Thus, there is strong evidence that the OH-masers are radiatively pumped by such infrared lines. Detailed models have been worked out (Elitzur et al. (1976)) which are in reasonable agreement with the observations. More problematic is the question of the origin of the main-line (1665, 1667 MHz) OH masers which are found preferentially in the nearby Mira variables (see e.g. Bujarrabal et al. (1980)).

c) Circumstellar H_2O Pump Models

Models for circumstellar H_2O masers have been developed by Deguchi (1977) and, more recently by Cooke and Elitzur (1985). Of these, the former seems inconsistent with recent observations in that the masers are predicted to be formed close to the stellar surface. In the Cooke-Elitzur model, the basic pump is collisional and inversion occurs due to trapping effects in the transitions which depopulate the maser levels. The pump is indirectly sensitive to the radiation field since the collisional excitation rates are temperature sensitive and the main heating process is grain-gas friction (see e.g. Engels et al. (1986)). The models can explain the observed maser power as well as it's dependence upon mass loss rate and the observed position of the masers relative to the central star. The rapid time-variability however is not clearly understood.

d) SiO Pump Models

Most SiO pump models are variations upon the theme of Kwan and Scoville (1974), where it was pointed out that the effective decay rate for an optically, thick $v \rightarrow v - 1$ transition is J (rotational quantum number) dependent. The escape probability is higher for low J and this can lead to inversion more or less independent of the process populating excited vibrational levels. However, the original suggestion by Kwan and Scoville of radiative excitation via overtone bands seems unlikely today. Elitzur (1981) has proposed that the maser form in large convection cells on the stellar surface. The difficulty here is that the VLBI measurements mentioned earlier seem to imply that the masers form at a distance of several stellar radii. However, Langer and Watson (1984) show rather conclusively that models placing the masers in the wind region of the circumstellar envelope cannot explain the observed maser power. Moreover, such models have difficulty in explaining the observation that the power in the $v = 1$ and $v = 2$ $J = 1 \rightarrow 0$ transitions is comparable. The more recent models use reliable estimates for the relevant collisional rates and it appears that the astrophysical rather than the physical assumptions may be in error.

3. MASS LOSS RATE DETERMINATIONS

There are a large variety of methods used to determine mass loss rates of maser stars. Some of these are discussed by Zuckerman (this volume) and by Bowers (1985). They are mainly indirect and, as a consequence, somewhat unsatisfactory. I here discuss very briefly the various possibilities.

a) Mass Loss Determinations based upon Measurements of $J = 1 \rightarrow 0$ and $2 \rightarrow 1$ CO

Measurements of the $J = 1 \rightarrow 0$ and $2 \rightarrow 1$ CO transitions are now available for a large number of stars. Extensive model calculations have also been carried out (Knapp and Morris (1985)) and one concludes that even when CO is moderately optically thick, there is a fair proportionality between integrated intensity in, say, the J = 1→0 transition and the CO loss rate f_{CO} $\dot{M}$ where f_{CO} = [CO]/[H_2]. More precisely, Knapp and Morris find that for $\dot{M}$ $f_{co}^{0.85}/V_e^2$ <6 10^{-11}, one has:

$$T_A^* \Delta V \quad \alpha \quad \dot{M} \, f_{co}^{0.85}/V_e^2$$

where V_e is the expansion velocity of the envelope in km s^{-1}, T_A^* ΔV is the integrated line intensity, and $\dot{M}$ is the mass loss rate in solar masses per year. The difficulty that evidently arises here is that f_{CO} is unknown and may vary considerably from object to object. One does know that [^{12}CO]/[^{13}CO] is of order 10 for many of these objects (Knapp and Chang (1985)) and hence one is dealing with processed material. Comparison with other mass loss rate determinations suggests that f_{CO} $\sim 10^{-4}$ is often a reasonable estimate.

b) Mass Loss Rate Determinations Based upon the Assumption of a Radiation Pressure Driven Wind

If winds in oxygen rich objects are indeed driven by radiation pressure, one expects (to within a factor of two) that

$$\dot{M} = \frac{L}{c \, V_e}$$

where L is the bolometric luminosity. Since the bolometric luminosities for most objects are known from IRAS and other infrared observations, this then allows a simple estimate of the mass loss rate. This certainly allows the most direct estimate of $\dot{M}$.

c) Dust-Loss Determinations

The mass of dust and hence the rate of dust loss in a circumstellar envelope can be determined by means of far infrared or sub-mm observations (e.g. Sopka et al. (1985)). The main uncertainty here is the sub-mm emissivity. Alternatively, one can model-fit the entire infrared spectrum. It is interesting to note in this context that there is a good correlation between IRAS colors (e.g. ratio of 60 and 75 micron fluxes) and mass loss rates determined, say, by method (b) (see Engels et al. (1986)). It is probably more reasonable to use dust-loss rates to determine the dust-to-gas ratio than to assume this ratio in order to derive the mass loss rate. Knapp (1985) finds in fact that one percent by mass is an average value for the dust-to-gas ratio.

d) Mass Loss rates from OH and H_2O Maser Fluxes

It has become apparent that at least for OH but probably also for H_2O, the maser output is well correlated with mass loss rate (Baud and Habing (1983), Bowers and Hagen (1984), Bowers (1985)). In fact the OH photon luminosity is approximately proportional to the square of the mass loss rate whereas the H_2O luminosity (at maximum light) seems to have a roughly

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linear dependence upon $\dot{M}$. One can therefore in principle use the measured maser fluxes to determine $\dot{M}$ in cases where other information is not available. In practice, it seems unlikely that this method gives more reliable results than, say, approach (b). This is partly due to uncertainties concerning the distances of the stars but more fundamentally because of our lack of detailed understanding of the maser pump (at least in the case of H_2O).

4. ABUNDANCE ESTIMATE FOR OXYGEN RICH STARS

For reasons discussed earlier, good abundance estimates for molecules in oxygen-rich envelopes are non-existent. However, it is encouraging that several species have now been detected in non-maser emission towards such stars. The current situation is that HCN and SO_2 have been detected towards separate pairs of oxygen rich objects (Deguchi and Goldsmith (1985), Lucas et al. (1986)). H_2S has been seen towards the peculiar object OH231.8+4.2 (Ukita and Morris (1983)). Additionally, NH_3 has been detected towards several stars in the infrared (see Betz, this volume). In all of these cases, the observed species appear to contain a relatively small fraction of the available elemental abundances. Thus, a small fraction of sulfur (few percent) is in either H_2S or SO_2. HCN contains a negligible amount of the available carbon and nitrogen. This is consistent with the available theoretical predictions (e.g. Scalo and Slavsky (1980)) which suggest that sulfur will remain mainly atomic in oxygen-rich envelopes. However, it is curious that SO_2 was not found in OH231.8+4.2 suggesting that there may be considerable composition differences between different objects.

As mentioned earlier, the size of the OH shell in oxygen rich stars can be predicted theoretically on the assumption that photodissociation of water molecules in the outflowing gas is the main source of OH. Calculations of the OH/H_2O balance have been carried out by Huggins and Glassgold (1982). These predict a correlation between OH shell size and mass loss rate which reproduces the observed variation rather well. The assumption made here, and in most calculations of this type, is that in oxygen rich objects, the oxygen at the base of the flow is divided between CO and H_2O. Most of the carbon is probably in the form of CO and one thus expects both CO/H_2 and H_2O/H_2 to be in the range $10^{-4} - 10^{-3}$.

The case of SiO is rather less clear. Observations of v = 0, J = 2 $\rightarrow$ 1 SiO suggest that non-maser emission from gas in the outflow has been detected. This interpretation requires approximately one percent of the available silicon to be in the form of SiO (Morris et al. (1979)). A complicating factor is that Jewell et al. (1985) find evidence towards two stars that the J = 1 $\rightarrow$ 0, v = 0 transition of SiO is a weak maser and it is not clear whether the J = 2 $\rightarrow$ 1 emission is "uncontaminated". Assuming this to be the case, one may ask where the rest of the silicon is and it seems plausible that it has been converted into silicate grains. This is bolstered by the fact that the 10 micron silicate feature is seen in many stars. It is also worth noting that in the regions where SiO v = 1 or 2 masers are seen, a large fraction of silicon must be in the form of SiO. Hence, it appears as if SiO is converted into silicate particles with 99 percent efficiency in a region at a few stellar radii from the photosphere. The details of this dust formation process are presumably of great importance for the molecular abundances at the base of the outflow region.

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DISCUSSION

SAHAI: This question has a bearing on where SiO masers form in red giants - why do we see SiO masers in O-rich objects and not in C-rich objects like IRC+10°216 even though the thermal v = 0 SiO lines in the latter are as strong as in the former? I have a possible explanation for this in my poster paper entitled "New Observational Constraints on Si Chemistry in Circumstellar Envelopes of Red Giants".

ZUCKERMAN: I suspect that the reason is related to the following: In both oxygen-rich and carbon-rich stars the observed "quasi-thermal" SiO emission, which originates fairly far out in the envelope, implies that, there, only a small fraction of the silicon is in the form of SiO. Closer to the photosphere of oxygen-rich stars, where the SiO masers are produced, the SiO partial pressures appear to be much larger. But in carbon-rich stars the amount of SiO is never large, not even near the photosphere. For example, according to the calculations of Tsuji (Astron. Astrophys. 23, 411, 1973), for all temperatures $\gtrsim$2000K, at a given atmospheric pressure, the partial pressure of SiO is at least two orders of magnitude smaller in carbon stars than it is in oxygen-rich atmospheres.

SAHAI: It is not sufficient to answer the above by saying that carbon rich chemistry of IRC 10216 prevents SiO from reaching large abundances, because chemical models (Tsuji 1976) show that though [SiO]/[SiS] is less than unity but only by a small factor. It is actually the condensation of SiC grains close to the photosphere in C-rich objects that prevents SiO abundance being large enough for masering to occur.

WALMSLEY: I don't think one can use the presence or absence of SiO masers as evidence that a certain type of grain condensation is occurring until SiO masers are properly understood. From the present models, it appears that a large fraction of silicon in the form of SiO is a necessary but not sufficient condition for SiO maser action.

VENUGOPAL: What is the physical significance of the correlation between the distance of the masers from the stars and the mass loss rates?
WALMSLEY: In the case of OH, the formation mechanism is thought to be photodestruction of H_2O and this is sensitive to the amount of shielding from interstellar UV radiation by the dust in the circumstallar shell. This will increase with the increasing mass loss rate, thus causing an increase of R(OH) with $\dot{M}$. For H_2O and SiO, the theoretical situation is much less clear and the observational evidence for a correlation of the distance of these masers from the central stars with $\dot{M}$ is also not conclusive.

VARDYA: We (Vardya, de Jong, Willem, Astrophys. J. Lett. 304, L29, 1986) see in a large number of M Mira variables SiO v = 1-0 line at 8 µm in LRS spectra of IRAS. In fact, we find that whenever 8 µm intensity (line + continuum) is $\geq$ 150 Jansky, we do see it as SiO mm maser as well, if that star has been looked into at that wavelength.

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