INTERPRETATION OF CIRCUMSTELLAR MASERS

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1. INTRODUCTION

In a short review paper one is often forced to survey the subject in a broad way and to ignore many, perhaps even important, details. Such is the case here. My remarks are intended to indicate how I view the current status of the field. In general, I shall avoid qualifying my statements, even when I am clearly guilty of oversimplification. If someone finds my paper provocative, so much the better.

My comments are strictly directed toward the interpretation of masers which operate in the circumstellar envelopes about oxygen-rich Mira variables. Most of them also apply to the masers associated with oxygen-rich supergiants.

1.1 Types of masers

Maser action in circumstellar envelopes has been observed in certain microwave transitions from the SiO, H_2O and OH molecules. There is a distinct possibility that additional types of masers await discovery.

The SiO, H_2O and OH masers form a sequence along which the excitation required to adequately populate the maser levels decreases. The same sequence also orders the masers in terms of increasing distance from the central star, increasing mass of the circumstellar envelope in which they operate most effectively, and decreasing variability.

1.2 Models of masers

Interstellar masers are both basic astronomical phenomena and probes of the physical conditions in regions where they operate. The latter aspect alone makes their study a valuable one. However, much effort has been and is continuing to be devoted to developing detailed models for maser pump cycles. I doubt whether this game is really worth playing in most cases.

B. H. Andrew (ed.), Interstellar Molecules, 551–558.

To accurately calculate a maser pump cycle, we require knowledge of the number densities of maser molecules, hydrogen molecules and dust grains; the kinetic temperature and velocity at each point in the maser cloud; the external radiation field incident upon the cloud; the surface area and wavelength dependent emissivity of the dust grains; the cross sections for all transitions of the maser molecules induced by collisions with hydrogen molecules. Given this information, we could solve the coupled equations of radiative transfer and statistical equilibrium to obtain at every point in the cloud the population in all of the levels of the maser molecule and the radiation field in each of the lines which couple these levels. To solve these equations would be an enormous undertaking, but in principal it would enable us to represent nature closely enough to reveal how the maser is pumped.

Of course, the program we have outlined cannot, in general, be carried out. We lack too much of the input information. However, masers associated with circumstellar envelopes of envolved stars are far more amenable to theoretical interpretation than those associated with regions of star formation. We know much more about the environment where the former operate than about that where the latter do. In particular, the radiation field, velocity, temperature and molecule and dust grain number densities in these envelopes may all be reasonably estimated. Lack of detailed knowledge of collision cross sections and limited computing power are among the more serious obstacles to determining the pump schemes.

2. CIRCUMSTELLAR ENVELOPES

2.1 Dynamics

Infrared and microwave observations imply that the maser stars are losing 10^{-6}-10^{-4} $M_\odot$ yr^{-1}. It is unclear whether the initial acceleration of material away from the star is primarily due to a periodic shock wave driven by the stellar pulsation (1,2) or to radiation pressure acting on dust grains (3,4).

VLBI observations of masers suggest that substantial acceleration of the circumstellar material continues until at least ten stellar radii. This far from the star the acceleration can only be due to radiation pressure and requires that the dust grains continue to grow out to at least $10R_*$ (5).

2.2 Thermodynamics

A crude model of the thermal structure of the circumstellar envelope (6) shows that the major heat input is due to collisions between gas molecules and dust grains which are driven by radiation pressure at supersonic speed through the gas. Adiabatic expansion and the emission of line radiation by abundant molecules, especially H_2O, are the principal sources of cooling. For a mass loss rate

$\dot{M} \approx 3 \times 10^{-5}$ $M_{\odot}$ yr^{-1} and $T \simeq 2 \times 10^3$ K, at $r = R_*$, the model yields $T \approx 10^3$ K at $r = 10R_*$ and $T \simeq 3 \times 10^2$ K at $r = 10^2R_*$.

The stellar luminosity variation forces a variation in the speed at which the dust grains stream through the gas. This in turn gives rise to a small variation in the gas temperature in the outer part of the circumstellar envelope. The temperature variation lags behind the luminosity variation by between $\pi/2$ and π radians.

2.3 Chemistry

In the atmospheres of cool, oxygen-rich Miras, most hydrogen exists as H_2. Silicon is predominately found in SiO. The oxygen which is not tied up in CO is bound in H_2O. Given this atmospheric composition, the source of the SiO and H_2O maser molecules is obvious. The origin of the OH maser molecules is less apparent.

At temperatures above 500 K, OH molecules are destroyed on the expansion timescale by the exothermic reaction $OH + H_2 \rightarrow H_2O + H$. However, an adequate supply of OH molecules may be produced in the cool outer part of the circumstellar envelope by the dissociation of H_2O molecules either by interstellar ultraviolet photons or by high speed dust grains (6).

3. MASER AMPLIFICATION

3.1 Basic questions

Short of determining a detailed model for the maser we might hope to obtain answers to the following questions

i) Where in the circumstellar envelope does the maser operate?

ii) What is the directionality of the maser gain and maser radiation?

iii) What is the principal input to the maser? Is it spontaneous emission, the stellar continuum or the cosmic background radiation?

iv) Is the maser unsaturated or saturated?

v) Is the maser radiatively, collisionally or chemically pumped?

3.2 Answers to basic questions

Only partial answers to the basic questions are available. They are given below.

i) VLBI observations of the spread in angular position of the different types of masers imply that the SiO and H_2O masers are located within a few radii of the central star (7,8). The SiO masers probably operate somewhat closer to the star than the H_2O masers do,as is indicated by observations of masers associated with supergiants. The OH masers are clearly very distant from the central star, $r \gtrsim 10^2 R_*$ (9). The available VLBI data shows that the main-line, 1665 and 1667 MHz OH masers are a bit closer to the star than the satellite line, 1612 MHz maser.

There is a hint from monitoring programs of the 1612 MHz OH maser variations that the high-velocity flux shows a phase-lag with respect to the low-velocity flux (10,11). If real, the time-lags imply that the masers are located between 10^{16} and 10^{17} cm from the central stars.

The maser locations determined from VLBI observations are in accord with the conclusions of theoretical models of maser pump cycles.

ii) The maser gain in direction $\vec{\ell}$ is proportional to the path length along which velocity coherence is maintained. In other words, the gain is inversely proportional to $dv/d\ell$. For a spherically symmetric flow

$$\frac{dv}{d\ell} = (1-\mu^2)\,\frac{v}{r} + \mu^2\,\frac{dv}{dr}$$

where $\mu = \hat{r}\cdot\hat{\ell}$. Thus the maximum gain path is radial if $dv/dr < v/r$ and tangential if $dv/dr > v/r$. Clearly, we expect dv/dr to be smaller than v/r except perhaps very close to the star where the major acceleration takes place.

The directionality of the maser radiation depends upon the directionality of both the gain and the radiation input to the maser.

iii) The relative importance of spontaneous emission, the cosmic background radiation and the stellar continuum as input sources for radial amplification may be assessed by comparing $|T_{ex}|$, T_{BB} and $T_*\Omega_*/\Omega_M$ (12). Here T_{ex} is the negative excitation temperature of the maser transition, $T_{BB} \simeq 2.7$ K, and $T_* \simeq 2000$ K is the stellar brightness temperature at the maser frequency. The solid angles are

$$\Omega_* \equiv \pi\left(\frac{R_*}{r}\right)^2 \quad \text{and} \quad \Omega_M \equiv \frac{\pi}{|\tau|}\,\frac{d\ln v}{d\ln r}$$

where τ is the negative optical depth in the radial direction.

Theoretical considerations indicate that spontaneous emission and the stellar continuum are the most important inputs to the SiO and H_2O masers. The principal input to OH masers is usually spontaneous emission, but both the background radiation and the stellar continuum may be significant as well.

The OH masers often have two velocity peaks which come from the front and back of the circumstellar envelope (2, 12, 13, 14). There is no tendency for the blue-shifted peak to be stronger than the red-shifted one. This proves that the stellar continuum is not the dominant source of input to these masers.

VLBI observers should look for the amplified image of the central star in their maps. This would be especially worthwhile for OH masers which usually have angular sizes large compared to that of the stellar disk.

iv) Theoretical calculations suggest that circumstellar masers are generally saturated. Observations of the variation of maser luminosity with stellar luminosity for OH and H_2O masers (15,16) support this conclusion.

v) There is little doubt that the OH masers are radiatively pumped. They vary in phase with the stellar luminosity unlike the local gas temperature. The situation for SiO and H_2O masers is less clear. In particular, theoretical considerations suggest that collisions as well as radiation are important in the SiO pump cycle.

4. PUMP MODELS

4.1 1612 MHz OH masers

Detailed models of these masers show that the maser radiation is narrowly beamed in the radial direction, both inward and outward (2, 12). The masers are pumped by far infrared radiation emitted by hot dust grains. The rotationally excited OH molecules radiatively decay down to the ground rotational state. If the lines which connect the $^2\Pi_{1/2}$ J = 1/2 state to the $^2\Pi_{3/2}$ J = 3/2 ground state are optically thick, the 1612 MHz transition is inverted (12). Numerical calculations predict that about 4 FIR photons are absorbed in each pump line for every 1612 MHz maser photon which is emitted. Recent observations have confirmed this prediction (17).

The 1612 MHz OH masers are a particularly good case for theory. The line strength of the 1612 MHz transition is much smaller than that of the main-lines at 1665 and 1667 MHz. Nevertheless, the 1612 MHz masers are the strongest ones in stars with dense circumstellar envelopes. Furthermore, these masers operate very far from the central star where the density is so low that collisionally induced transitions are negligible.

4.2 Main-line OH masers

Radiative pump models for these masers rely on the parity dependent hyperfine splitting which breaks the symmetry between the upper and lower halves of the lambda doublets (18-22). The most sophisticated models take into account the overlaps between different components of hyperfine-split rotational lines. In circumstellar envelopes, line overlap due to the expansion velocity may be modeled in considerable detail (22). A recent study indicates that pumping by FIR radiation together with the effects of line overlap probably accounts for the essential features of the main-line pump (22).

4.3 H_2O masers

The H_2O molecule has a far more complicated rotational spectrum than the OH molecule. Also, to date, it has been observed in a single maser line. These factors make the H_2O masers less attractive to model than the OH masers. Nevertheless, some models have been put forth (23,24). As far as I can see, it is not yet clear whether the basic excitation is due to collisions or to radiation.

4.4 SiO masers

The SiO masers involve rotational transitions in excited vibrational states. There are several different transitions which show maser action. Although the maser molecules are highly excited, the level structure of the SiO molecule is so simple that detailed modeling of the pump mechanism may be rewarding. An early model showed that radiative decays from excited vibrational levels would tend to invert the lowest rotational transitions in these levels, if the decay lines were optically thick (25). More recent studies (26, 27) indicate that both collisional and radiative transitions are of importance in the pump cycle. A definitive model of SiO masers has yet to appear.

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DISCUSSION FOLLOWING GOLDREICH

Dickinson: Your placing of the H_2O and SiO masers near the star is consistent with the emission velocities, which are near the stellar velocity, and with the familiar double-peaked OH, which is out in the shell at higher velocities. However, we often see in H_2O, and occasionally in SiO as well, "shell" components similar to the OH. Is there anything in your theory which would explain why there are two velocity domains - near the star and in the shell - with no intervening emission?

Goldreich: "Shell" components probably signify radial amplification, which can be important for the H_2O and SiO masers as well as for the OH masers. However, the H_2O and SiO masers may also operate so near the star that the best gain paths are tangential rather than radial because of the radial acceleration of the outflowing gas.

Elitzur: It is not difficult to show that a radiative pump cannot be the explanation of the SiO masers. From very general properties of cross-sections for vibration-rotation excitations, it follows that collisions can provide an adequate explanation. I propose that the SiO maser emission has two components; the weak maser pedestal and the broad v = 0 thermal emission are sampling the shell, whereas the strong maser spikes arise from the upper atmosphere, where the temperature is high enough. The velocity structure, the time variation of the spikes, and the general properties of polarization, can all be well explained if the emission arises from large convective cells of the type proposed by Schwarzchild in 1975, for other reasons.

Gold: If there is enough gain, then surely a line can be made to drift gradually in frequency by a medium with a radial velocity gradient. For each step, a small but finite velocity shift can be tolerated, and the emerging wave will have the additional power supplied at the frequency appropriate to the new velocity. Together with such gradual frequency shifts, there may be slight changes in direction of the wave. These effects will be particularly important in cases of saturated masers that may have a great deal more gain available than can be used in view of their total power limitation.

Goldreich: The effects you refer to are not significant in the masers associated with IR stars. Although such effects can exist in principal, the radiation field intensities in these masers are far too low for these nonlinear phenomena to be important.

Burdjuzha: Why do you not also discuss the pumping mechanism of OH masers through the J=5/2 level of the $^2\pi_{3/2}$ band? The optical depth is high, is it not?

Goldreich: We do include pumping through the J=5/2, $^2\pi_{3/2}$ level in our numberical calculations. The optical depths of the transitions between states in this level and the ground level are indeed high.