PUMPING MECHANISMS OF OH MASERS

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ABSTRACT

We analyze in detail the pumping of 18 cm OH masers by the overlap of far infra-red lines in HII/OH regions and in circumstellar shells. We present some results of a model of pumping of HII/OH masers by thermal overlap. Pumping by overlap appears to be quite general but very complicated. It can account for the different observed main-line masers. However, other types of pumping, mainly by collisions with H or by near infra-red radiation, are possible if certain conditions are met for the physical and astrophysical parameters.

1. INTRODUCTION

Although the pumping of type II OH masers appears to be well understood (Litvak 1969, Elitzur et al. 1976, Elitzur 1976), at least for the 1612 MHz line, the pumping mechanism of the OH main lines is still unclear. It is generally agreed that UV or chemical pumping is unlikely because the needed rates are unrealistically large (see e.g. Elitzur and de Jong 1978). Much progress has been made recently in the treatment of most of the other possible pumping mechanisms: collisional pumping (Shapiro and Kaplan 1979, Dixon and Field 1979a,b,c, Flower 1979, Elitzur 1979); and pumping by far infra-red radiation (Elitzur 1978, Lucas 1979a,b, Bujarrabel et al. 1979a,b, Nguyen-Q-Rieu et al. 1979), or by near infra-red radiation (Cimerman and Scoville 1979). Litvak 1974 and Cook 1977 give reviews of previous work. The purpose of this paper is to try to draw some conclusions about the most likely pumping mechanisms of OH masers in circumstellar envelopes and in HII/OH regions, with special emphasis on the details of the pumping by far infra-red line overlap and on its efficiency compared to collisional pumping by atomic hydrogen.

2. FAR INFRA-RED LINE OVERLAP

The hyperfine structures of the rotational far infra-red lines of

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OH (35-120 μm) range from a few tenths of km/s to a few km/s (see figure 1 of Lucas 1979b), and are thus of the same order of magnitude as the large scale and the thermal velocities in the masering regions. As a result the intensity in one infra-red line strongly depends on the absorption or emission in other lines either at the same location or in other parts of the region. As the hyperfine structures of the IR lines connected to the two halves of the Λ-doublet are quite different, the IR rates from and to the main-line masering levels can be completely different. The potentially high efficiency of this process has been pointed out a long time ago (Litvak 1969, Pelling 1977). However, because of the very large number of possible overlaps, the situation is very intricate and requires a detailed treatment of the different arrangements of the velocity fields in the masering regions.

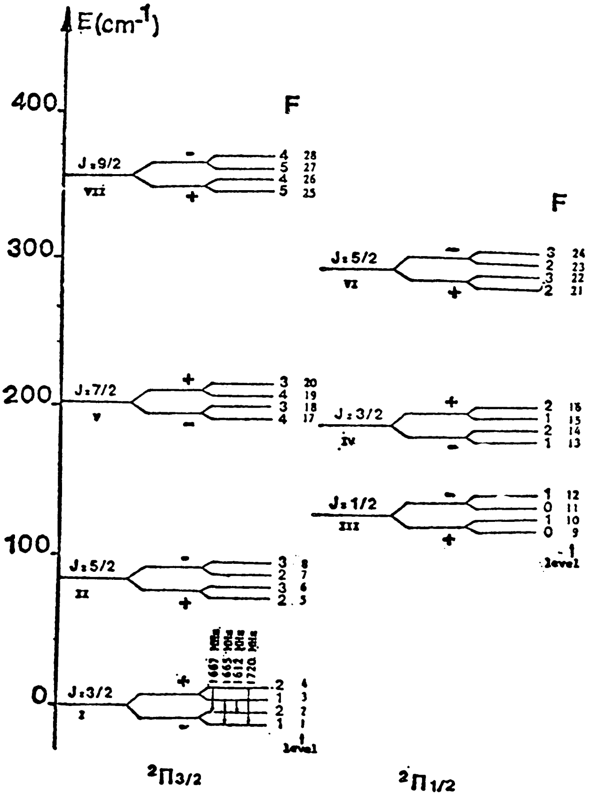

Figure. Levels of OH

2.1. Circumstellar Shells (Bujarrabal et al. 1979b).

In an expanding shell a line formed at one point on the shell is seen red-shifted by an observer located at another point. The results of a model for the pumping of circumstellar masers (Bujarrabal et al. 1979b) are presented in a communication at this Symposium by Nguyen-Q-Rieu et al. It can be seen in their figure that the inversion of the main lines by far-IR overlap appears to be quite general under the conditions of circumstellar main-line masers, and has a very good efficiency. We will measure the efficiency of a pumping mechanism by the value $\Delta n'/n=2(n_2-n_1)'/(n_2+n_1)$ of the inversion achieved by artifically setting to zero the intensity of the maser lines. In this case $\Delta n'/n$ can reach $7\ 10^{-2}$. A detailed analysis (Bujarrabal et al. 1979b) shows that a large number of overlaps are important for the pumping of each line: the 1667 MHz line is inverted mainly by the overlaps 5-2, 6-2 and 14-4, 13-3, while the pair 22-2, 21-1 has an important anti-inverting effect. On the other hand, the inversion of the 1665 MHz line is mainly due to the overlap 23-3, 24-4.

2.2. HII/OH Regions (Lucas 1979, Guilloteau et al. 1979)

As discussed by Lucas at this Symposium, very strong inversions ($\Delta n'/n \sim 1$) are easily achieved by pumping the OH in a small cloud ($N_{OH} \sim 10^{15} cm^{-2}$) by radiation from a larger cloud with a high excitation temperature (Lucas 1979a,b). At larger column densities ($N_{OH} \sim 10^{16}$-$10^{18} cm^{-2}$) at which this external pumping is less efficient, an alternative pumping mechanism is provided without any external cloud by the thermal overlaps of the IR lines within the masering cloud (Guilloteau et al. 1979). The overlap of the thermal profiles of the IR lines strongly perturbs the transfer of the IR radiation even when the gaussian widths of the lines correspond to temperatures as low as 100-200 K. These thermal overlaps have two main pumping effects: i) they increase the general trapping of the photons of the two overlapping lines, and hence they reduce the radiative repopulation of the two lowest levels, and ii) they mix the populations of the levels of the two lines; in particular they tend to equalize the populations of the two upper levels, and hence they overpopulate the lower level of the line which had the larger initial population in its upper level. Besides, the thermal overlaps in the masering cloud also obviously affect the pumping of the molecules by the external continuum IR radiation.

These intricate effects result in relatively efficient pumping. For instance, $\Delta n'/n$ is of the order 10^{-2} for typical conditions (spherical model, $n_{H_2} = 10^6 cm^{-3}$, $T = 200$ K) with $N_{OH} \sim 10^{16} cm^{-2}$ for the 1667 MHz line and $N_{OH} \gtrsim 10^{17} cm^{-2}$ for the 1665 MHz line. The corresponding brightness temperature of the 1665 MHz line ($T_B > 10^{10}$K) is comparable to the observed T_B. It is smaller in the 1667 MHz line. The power observed in this line can be accounted for either by a cylindrical maser, or by very large column densities ($N_{OH} \gtrsim 10^{18} cm^{-2}$), or by a relatively intense IR continuum ($T_R \sim 100$ K, dilution factor $W \sim 0.1$) which is not unlikely in HII/OH regions. Of course, the analysis of the details of these complicated maser mechanisms is not simple. However, it appears that the following effects are the most important: i) selective enhancement of the trapping of 120 μm photons at low density leading to the inversion of the 1667 MHz line, and ii) population mixing in the overlap 15-1, 16-2 (53 μm) inverting the 1665 MHz line.

In summary, because of the very rich level structure of the OH molecule, pumping by overlap appears to be both very general and very complicated. It is very sensitive, first to the velocity fields, but also to the other parameters of the masering regions: OH column density, total density, kinetic temperature, IR continuum, etc. Accordingly, detailed models of observed masers are very difficult to build, although we feel that this type of pumping could account for the different observed masers of type I.

3. COMPARISON WITH OTHER PUMPING MECHANISMS

3.1. Collisional Pumping

We can disregard collisional transitions between the components of the Λ-doublet which are caused by collisions with electron streams (Johnston 1967) or with ion streams (Elitzur 1979): the velocity required for electrons is very unlikely, and a collision rate asymmetry is unlikely for ions (Bouloy and Omont 1979). The possibility of pumping through rotational excitation by H_2 and e^- is less easily discounted: the asymmetries are probably small and possibly in the wrong sense, and the rotation rates are probably smaller than the Λ-doublet rates. Precise rates are urgently needed to clarify this question (see Bertojo et al. 1976, Shapiro and Kaplan 1979, Dixon and Field 1979a,b,c, Flower 1979).

It seems that atomic hydrogen can provide the most powerful collisional pumping. The asymmetry in the excitation rates to the first rotational level seems well established as 10% in the direction favouring 18 cm OH maser pumping (Shapiro and Kaplan 1979, Dixon and Field 1979a,b,c). However, there is a strong disagreement between these authors about the values of the rotation rates and hence about their ratio to the Λ-doublet rates. Shapiro and Kaplan's values result in a rather poor pumping efficiency ($\Delta n'/n < 3\ 10^{-3}$) which should disqualify this type of pumping. However, as discussed by Dixon and Field 1979a,b, the rotation rates are probably much larger. A pumping efficiency comparable to the one by overlap would require very strict conditions on the hydrogen abundance: $n_H/n_{H_2} > 20\%$, and collisional rates comparable to radiative excitation rates but not large enough to cause rotational thermalization (Elitzur 1979).

3.2. Pumping by Near Infra-red

Initially proposed by Litvak 1969, this mechanism has been recently revived for circumstellar masers by Cimerman and Scoville 1979, who point out that there are coincidences between IR transitions of H_2O and OH at 2.8 μm. The relative efficiencies of pumping by far-IR overlap and by 2.8 μm will depend on the amount of absorption by dust between the star and OH.

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DISCUSSION FOLLOWING OMONT

Field: The results of Shapiro and Kaplan on H + OH rotational excitation were obtained from calculations using a potential surface which did not include medium to long range anisotropy. They obtained such low cross-sections because these anisotropies are all-important in determining absolute rates of energy transfer. Furthermore in modelling H + OH it is important to note the gas kinetic rate of the atom exchange reaction H' + OH → OH' + OH.

Omont: Although Shapiro and Kaplan do not give the details of the potential they use, I probably agree with your comment. It should be noted that Dixon and Field do not take into account the long range part of the potential (R^{-4} dipole-quadrupole, R^{-6} dispersion, etc. (see Flower 1979)).

Field: With respect to high rates of transfer directly *across* the Λ-doublet, there are good experimental and theoretical grounds for believing that these should not be extremely large - indeed no larger than rotational excitation rates.

Omont: I agree that the question of the relative magnitude of Λ-doublet and rotational rates remains open, and should be checked experimentally and theoretically.

Elitzur: A problem arises from the line-overlap model in trying to explain all masers with the same underlying mechanism. The properties of mainline masers in IR/OH stars and HII/OH regions are very different. In one the 1667 line is stronger and in the other the 1665. Also, polarization is usually complete in HII/OH regions, but not in IR/OH stars. I think we should be guided by the observations with regard to the pumps.

In W3(OH) the maser spots appear in two distinct clusters, almost diametrically opposed. When we consider also the strong polarization, which is an inherent feature, it seems evident that we should always try to make the magnetic field a basic ingredient of the inversion mechanism.

Omont: It is obvious that IR/OH masers and HII/OH masers are very different, and their pumping mechanisms are not necessarily the same. The details of the operation of pumping by line overlap are quite different in the two situations. It seems quite possible for this pumping mechanism to reproduce in general terms the ratios of the two main lines in the different cases. I do not see any realistic mechanism where the magnetic field is a basic ingredient of the inversion mechanism itself. There are other ways to account for the polarization (e.g. Cook 1977).