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SiO maser emission from late-type stars

ABSTRACT

We have performed an extensive study of both radiative and collisional pumping of the SiO masers associated with late-type stars. The physical conditions necessary to account for the observed maser emission are essentially pump independent. Our calculations show that collisional pumping creates the strongest masers and, in contrast with radiative pumping, does not require fine tuning of the physical conditions for its operation.

INTRODUCTION

SiO maser emission is commonly observed coming from late-type stars. Unlike the OH and H_2O masers, SiO maser emission is not produced in the wind. Instead, it occurs much closer to the star, inside the dust formation point. This conclusion is supported by interferometric observations which place the masers at 2 to 6 stellar radii (Lane 1982) and also by theoretical arguments (Elitzur 1980). These arguments show that the vibrational transitions must be optically thick in order for maser emission to occur. The detection of masers within the v = 2 and 3 levels for low mass loss rate stars precludes the production of these masers in the wind. In addition, most of the silicon goes into dust in the wind, leaving little to form SiO. SiO masers are also found to have complicated line profiles and erratic time variability. Recent observations indicate that the maser regions are large blobs of material that have specific velocities and often well defined polarization angles (McIntosh et al. 1989). This makes modeling the masers more difficult. However, accurate theoretical analysis of the masers offers an opportunity to learn a great deal about the physical conditions in this region. This may lead to a better understanding of the processes of dust formation and mass loss.

We have performed an extensive analysis of these masers. Our results indicate that while both collisions and radiation are important, collisional pumping is much less sensitive to the details of the model and to the physical conditions existing in the region. Perhaps more importantly, we found that certain conclusions can be reached concerning the physical conditions that are essentially pump independent.

PUMPING MECHANISMS

The dominant factor that affects all pumping mechanisms is the monotonic decrease of vibrational decay rates with J when the transitions become optically thick (Kwan and Scoville 1974). This produces inversion even if the pumping into the levels is "flat"; ie. pump rate is J independent. As a result, it is relatively easy to produce inversions with either collisions or radiation, but it is difficult to identify characteristic signatures to distinguish them.

RADIATIVE PUMPING

There are two different radiative pumps that have been proposed. The first inverts the rotational levels of state v by cycling molecules through state v+1 (Kwan and Scoville 1974). The inversion is due to the J dependent decay rate discussed above. A different and more efficient pump has been proposed that utilizes a large velocity gradient to create an asymmetry between the absorption of stellar pump photons and the escape of emitted radiation in the pump-cycle lines (Deguchi and Iguchi 1976). This creates a pump rate that increases with J. This pump operates over a narrower range of optical depths and its success is tied to a particular functional form of the escape probability. We have performed calculations for both cases and have found that while the second pump is more effective, it still produces less maser emission than the collisional pump described below.

COLLISIONAL PUMPING

Although collisional pumps are usually more difficult to model accurately due to the uncertainty in the cross sections, the conditions in the SiO maser region lead to collisional pumping that is "flat", independent of the specific details of the cross sections (Watson et al. 1980). Inversion results when the vibrational decays become optically thick. Although the basic inversion is independent of the cross sections, detailed modeling requires their availability. Theoretical cross sections are now available and we have used them in our work (Bieniek and Green 1983). We have also developed a procedure that accurately corrects for the necessary restriction to a finite number of rotational levels in the numerical calculations. This has a significant impact on collisional pumping because the relevant maser levels are connected by collisions to levels of high J that contain a significant population. Neglect of this seriously underestimates the collisional pump rate.

We have found that collisional pumping is robust and operates effectively for gas temperatures in excess of 1200 K. The masers become quenched at molecular densities larger than 10^{10} cm^{-3}, a limiting factor for both radiative and collisional pumps.

RESULTS

We found that collisional pumping alone produces the strongest masers. The calculated maser photon luminosities are in agreement with the typically observed value of 10^{44} s^{-1}. Radiation acting alone produces weaker masers. The combination of collisions and radiation tends to produce maser strengths that are between the values produced by the separate pumps acting alone. Although there are minor differences in the value of the SiO column density required for maximum maser emission, these values are typically 10^{19} cm^{-2} for the inversion of the v=1 masers. This sets a lower limit on the molecular density. Assuming that the masers are 10^{14} cm in size and that most of the silicon goes into SiO, this gives a lower bound of 10^9 cm^{-3}. This restricts the variation in molecular density to between 10^9 and 10^{10} cm^{-3}.

Our calculations show that different masers in the same vibrational state are produced in the same region. Although observations are not conclusive, the only study that has compared different J masers in the same vibrational state at the same time has reached this same conclusion (Schwartz et al. 1982). This has also been supported by recent observations of the polarization of the masers (McIntosh and Predmore 1991).

We also found that the higher v masers require a larger column density for inversion. There is a region of overlap, however, where the v=1 and 2 masers are both produced, in agreement with observations which indicate that these masers form in the same region. The v=3 maser is less commonly observed and in general is much weaker. This is because of the large densities required for its production.

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