SiO emission from the Orion KL region

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Summary. Statistical equilibrium and radiative transfer equations of SiO emission are solved for Orion IRC2. A model of a spherical expanding shell, which is exposed to the radiation from IRC2, dust and the cosmic background, is suggested and the collisional rates recently reported by Bienik and Green (1983) and Langer and Watson (1984) are used. It seems that under some specific physical conditions the SiO masers may turn on in a star formation region. The physical conditions of Orion IRC2 fit the specific requirements. The results of the calculations show that there is a region of $V = 1$ and 2 masers at the distance of $2 - 5 \times 10^{14}$ cm from IRC2, and farther at $10^{16}$ cm, a region of weak $V = 0$ masers. Therefore we can explain why Orion IRC2 is the only star formation region displaying the SiO masers.

Key words: SiO masers – radiation transfer – formation of stars

1. Introduction

Unlike most of the sources of SiO maser emission, which have been identified with late-type stars, Orion KL is known as the only star formation region displaying SiO masers. It was the first discovered source of SiO maser emission (Snyder and Buhl, 1974); however, since then, all efforts to search SiO masers at other star formation regions have failed (e.g. Genzel et al., 1980). Recently, Jewell et al. (1984) reported a sensitive search for $V = 1$, $J = 1 - 0$ SiO masers using the 100 m telescope at Effelsberg towards galactic star formation regions, 35 sources in total. The results are still negative.

The SiO masers in Orion KL have been identified with the infrared source IRC2 by Baud et al. (1980). Genzel et al. (1980) suggested that there is either an evolved giant or supergiant in the Orion Molecular Cloud, or that, else, the Orion SiO maser source is a unique object in the Galaxy. Later, Downes et al. (1981) argued that IRC2 may be a young, massive star in the last stage of its formation rather than an evolved star. Elitzur (1982) constructed an expanding shell model. To obtain agreement with observations the model requires a narrow range of physical parameters. This may provide an explanation for the uniqueness of the Orion SiO maser.

SiO emission of $V = 1$ and 2 in Orion-KL has been found to be a strong maser. However, the question whether there is a maser in the silicon monoxide ground vibrational state has been posed by Buhl et al. (1975), Genzel et al. (1980), and Wilson et al. (1983).

In this paper, we attempt to construct a model and to select the optimum parameters which are needed for agreement with the observations (Table 1). By solving the statistical equilibrium and radiative transfer equations we study the properties of SiO emission and the conditions for population inversion to understand the Orion source.

2. Model and calculation

Elitzur's suggestions (1982) are helpful to study the SiO maser emission in Orion. In our model, IRC2 may be a young and luminous star ($10^{4} - 10^{5} L_{\odot}$) with a high mass loss rate ($10^{-4} - 10^{-3} M_{\odot} \text{yr}^{-1}$) in the last stage of its formation. At a distance of about $10^{16}$ cm from IRC2, the expansion velocity exceeds the mean turbulent velocity and the temperature drops to about 1500 K. In this area some material, such as corundum ($Al_{2}O_{3}$), perovskite ($CaTiO_{3}$) and gehlenite ($Ca_{2}Al_{2}Si_{2}O_{7}$), of high melting point may condense under the pressure (Salpeter, 1977). Farther from IRC2, the temperature decreases continuously. The transitions of SiO are affected by the radiation fields from IRC2, dust and the cosmic background.

The statistical calculation covers 32 energy levels including $J = 0 - 7$ of $V = 0, 1, 2, 3$. The equilibrium equation for level $j$ is

$$
\sum_{i} n_{i} C_{ij} + \sum_{i} n_{i} (B_{ij} U_{ij}) + \sum_{i} n_{i} A_{ij}
$$

$$
= \sum_{j} n_{j} C_{ji} + \sum_{j} n_{j} (B_{ji} U_{ji}) + \sum_{j} n_{j} A_{ji} \quad j = 1, 2, ..., 32.
$$

(1)

$A_{ij}$, $B_{ij}$ are the Einstein radiative transition probabilities, and $C_{ij}$ is the collision transition probability, $U_{ij}$ is the radiation field at frequency $v_{ij}$ corresponding to the transition from level $i$ to level $j$. $n_{i}$ is the density of SiO molecules in level $i$.

For the calculations of collision rates we refer to Bienik and Green (1983) and Langer and Watson (1984). For the energy levels $E_{i}$ and Einstein A-values of the IR and microwave lines we refer to Langer and Watson (1984). According to the profiles and the separation between the double peaks of the $V = 1, 2$ emission lines, the SiO maser region may be located in an expanding shell of...
velocity 12 km s⁻¹ (Wilson et al., 1983). The Sobolev approximation is used to describe the radiation transfer, since the expanding velocity is much larger than the Doppler width even at $T_p = 1500$ K. By using the escape probability method the radiation field $U_{ij}$ is obtained from

$$U_{ij} = 2\hbar v_\nu (1 - \beta_{ij}) \left( \frac{\exp(hv_\nu/KT_{ex}) - 1}{\exp(hv_\nu/KT_{ex}) - 1} + \frac{\beta_{ij}f}{\exp(hv_\nu/KT_{ex}) - 1} \right),$$

(2)

where $\beta_{ij}$, $T_{ex}$, and $\eta_{ij}$ are the escape probability and excitation temperature in the transition from level $i$ to level $j$, $T_{ex}$, and $f$ are the radiation temperature and the dilution factor of the IRC2 radiation field. $T_{ex}$ is the cosmic background radiation temperature, $T_{ex} = 2.7$ K. $T_{ex}$ is the dust temperature and $\eta_{ij}$ is the dust opacity at frequency $v_\nu$. We also assume two forms of $\eta_{ij}$ by following Kwan and Thuan (1974).

$$\eta_{ij}(v_\nu) = \frac{v_\nu}{v_0} \quad \text{if} \quad v_\nu < v_0$$
$$= 1 \quad \text{if} \quad v_\nu \geq v_0 \quad (v_0 = 8565 \text{ GHz})$$

and

$$\eta_{ij}(v_\nu) = (v_\nu/v_0)^2 \quad \text{if} \quad v_\nu < v_0$$
$$= 1 \quad \text{if} \quad v_\nu \geq v_0 \quad (v_0 = 2711 \text{ GHz}).$$

$v_0$ was chosen in consideration of the 350 μ observations of Gezari et al. (1974). $T_{ex}$, $f$, and $T_d$ are assumed to be constants for any transition.

The optical depth in the transition from level $i$ to $j$, $\tau_{ij}$, is given by

$$\tau_{ij} = \frac{A_{ij}C^3 n_i}{8\pi v_\nu^2 F_{gr}} \left( \frac{n_i g_i - n_j g_j - 1}{n_i g_i} \right)$$

(5)

for the large velocity gradient theory (Goldreich et al., 1974). Where $V_{gr}$ is the mean velocity gradient. The calculation needs the parameters $T_{ex}$, $T_{ex}$, $f$, $T_d$, molecular hydrogen density $n(H_2)$, and $F_{ab}/V_{gr}$. $F_{ab}$ is the abundance of SiO relative to H₂ by number, $F_{ab} = n(\text{SiO})/n(H_2)$. With a set of parameters, a self-consistent solution for the relative population of level $i$ to the ground level will be obtained, and $T_{ex}$, $\tau_{ij}$, $\beta_{ij}$ for the transition from level $i$ to level $j$ can be calculated. If the calculated results are in agreement with the observational data, the corresponding parameter set may well describe the real physical conditions.

3. Results of calculations and discussion

As mentioned above, the model includes 6 parameters and some uncertain factors. Some of these strongly influence the results but others may not. Table 2 shows that the difference caused by using (3) or (4) to describe the opacity of the dust covering the wave length ranges of microwave, far infrared (above dotted line) and infrared (below dotted line). It demonstrates that the difference only exists at microwave and far infrared wavelengths, while the radiation of the dust at this range compared with that at infrared range is very weak. Therefore the difference is not significant. Indeed we
have computed the statistical equilibrium and radiation transfer equations by using opacity laws (3) and (4). It is evident that the quantitative difference of the results may be neglected.

The radiation field due to IRc2 depends on $T_{rd}$ and $f$. Since the Orion SiO maser is located in an expanding shell and not in the upper parts of the stellar atmosphere, the dilution factor (6)

$$f = \frac{1}{4} \left( \frac{r_0}{r} \right)^2$$

is comparatively smaller. $r_0$ is the radius of the source IRc2 and $r$ is the radius of the expanding shell. For an estimate of $r_0 \sim 10^{11}-10^{12}$ cm and $r \sim 10^{15}$ cm suggested by Downes et al. (1981), the dilution factor $f$ should be much smaller than 0.001. $T_{ri}$ is an approximate estimate of the line temperature,

$$T_{ri} = T_{eq}(1 - \exp(-\tau_{ij})).$$

Figure 1 shows that the variation of $f$ would not influence the maser obviously below $f = 0.001$. The results of the calculations also demonstrate that if $f < 0.001$, $T_{ri}$ would not sensitively depend on $T_{eq}$.

The ratio $F_{eq}/V_{gr}$ is another parameter of the model. Elitzur (1982) assumed the upper limit of $6 \times 10^{-5}$ as the value of $F_{eq}$, i.e. all of Si is in SiO. But in our model, Si may exist in dust and SiO may be removed by reactions, e.g. with positive ions. Therefore $F_{eq}$ should be less than $6 \times 10^{-5}$. The rough estimate of $V_{gr}$ may be done by two ways: 1) assuming that at distance $10^{14}$ cm from IRc2 the velocity field changes from chaotic to ordered and at $2 \times 10^{14}$ cm the expanding velocity is $12$ km s$^{-1}$, then, estimate the mean velocity gradient; 2) estimate the velocity gradient at $r = 2 \times 10^{14}$ cm by using a velocity law (see e.g. Langer and Watson, 1984). We obtain a value for $V_{gr}$ of the order of $10^3$ km s$^{-1}$ pc$^{-1}$ in both ways. Of course, either $V_{gr}$ or $F_{eq}$ will decrease in the outer parts of the shell. On this basis of the discussion above we select the range of $F_{eq}/V_{gr} = 10^{-11}-10^{-10}$ pc s$^{-1}$ km$^{-1}$ to study.

Figures 2-4 illustrate results of the model calculations in the plots of $n(H_2)$ versus $T_{eq}$, where $F_{eq}/V_{gr} = 10^{-11}$ pc s$^{-1}$ km$^{-1}$, $f = 0.001$, $T_{rd} = 2000$ K, and $T_\nu$ equals 550 K (Fig. 2), 700 K (Fig. 3), and 1000 K (Fig. 4) respectively. Shown are the circumstances where maser emission is visible in different $V$ states. We conclude from Fig. 2 to 4, that $V = 1$ masers are present in a narrow range of physical conditions. Figure 2, where $T_\nu = 550$ K, has a ● region of $V = 1$ and 2 masers shaped as a triangle located at $4 \times 10^9$ cm$^{-3}$ $< n(H_2) < 4 \times 10^{10}$ cm$^{-3}$, $1200$ K $< T_\nu < 1500$ K. Figure 3, where $T_\nu = 700$ K.
$T_d = 700$ K, only has a very small region where $T_d$ is about $1500$ K. We do not think this region is significant, because $T_d = 1500$ K is the limit of our model. If $T_d > 1500$ K, dust would hardly be present under the pressure which exists there. Figure 4 of the dust temperature $1000$ K does not have a region of $V = 1$ maser. There is only a small triangle region of $V = 2$ masers. In summary, if $V = 2$ masers, then $T_d = 2000$, among the dust temperatures $T_d = 550, 700, 1000$ K, the region of $V = 1$ maser only appears in the $n(H_2)$ versus $T_d$ diagram of $T_d = 550$. According to the covered range of $n(H_2)$, the mass loss rate ($10^{-3} M_\odot$ yr$^{-1}$) and the expanding velocity ($12$ km s$^{-1}$), and assuming a density distribution suggested by, e.g., Eilts (1982), it is estimated that the masers of $V = 1$ are located in the shell at $r = 2.5 \times 10^{14}$ cm. This roughly agrees with the observations of Genzel et al. (1979) or Wright et al. (1983). The $V = 2$ maser may be located in the same shell or at somewhat larger distances from the central source than the $V = 1$ maser. The $V = 3$ masers are very weak and undetectable although present in most circumstances.

Next, we have to examine the effects caused by changing the value of $V = 2$. Figure 5 illustrates a comparison of the $V = 1$ and $2$ maser regions between $V = 3$ (solid line) and $10^{-11}$ (dotted line), and $10^{-11}$ (dotted line) (solid line), and $T_d = 2000$ K. $T_d = 550$. The outlines of the solid and dotted areas are similar, but when the value of $V = 3$ increases, the region of $V = 1$ and $2$ masers moves toward the direction of lower density and higher temperature. Our numerical computations also show that the line temperatures of the masers depend on $F_{\text{ab}}/V_{\text{gr}}$. For example, $T_d (V = 1, J = 1 - 0)$ has a maximum value at $F_{\text{ab}}/V_{\text{gr}} = 6 \times 10^{-11}$ s pc km$^{-1}$ if $T_d = 350$ K, $n(H_2) = 10^{10}$ cm$^{-3}$, $T_d = 1400$ K, $f = 0.001$, $T_d = 2000$ K.

Figures 2–4 demonstrate that for a set of values of $F_{\text{ab}}/V_{\text{gr}}, f$, and $T_d$, there is a $T_d^{\text{eff}}$, where if $T_d > T_d^{\text{eff}}$, the $V = 1$ masers disappear. Figure 6 illustrates that if $F_{\text{ab}}/V_{\text{gr}}$ is about $10^{-11} - 10^{-10}$ s pc km$^{-1}$, $T_d^{\text{eff}}$ will be about $700 - 500$ K, when $T_d = 1400$ K, $n(H_2) = 10^{10}$ cm$^{-3}$, $f = 0.001$, $T_d = 2000$ K. The color temperature at $8-20$ µm of IRc 2 is $300-500$ K (Downes et al., 1981), which satisfies the requirement ($T_d < T_d^{\text{eff}}$) for the presence of $V = 1$ masers. The meaning of $T_d^{\text{eff}}$ may be understood as that the pumping is too strong to form the population inversions at lower vibration states.

When $n(H_2)$ goes down to about $10^8$ cm$^{-3}$, but the other conditions remain like in Figs. 2–4, we find a region of weak $V = 0$ masers, but except $V = 0, J = 1 - 0$, situated in a wide range of $T_d$. Here “weak” means the line temperature is less than the $1/1000$ of that of $V = 1$ masers. Therefore, the observed line temperatures of $V = 0$ transitions are contributed by the weak maser and thermal emission. According to the $n(H_2)$ of $10^7$ cm$^{-3}$, it is estimated that the weak $V = 0$ masers turn on at $r = 10^{16}$ cm. We have not found conditions for strong $V = 0, J = 1 - 0$ maser emission, although there are signs of a maser at $-5.5$ km s$^{-1}$ (Genzel et al., 1980).
4. Conclusions

Orion IrC2 is so far the only detectable source of SiO maser emission in star formation regions, because its physical conditions satisfy the special requirements for displaying SiO maser emission. The conditions needed really are exceptional or they are expected to occur in the formation of any star, however only during some very limited time. Adopting the parameters of $F_{\nu}/V_\nu = 1 \times 10^{-11} \text{ pc s km}^{-1}$, $T_\text{d} = 550$ K, $f = 0.001$, and $T_\text{d} = 2000$ K, the SiO $V=1$ and 2 masers turn on in the shell at $r = 2 - 5 \times 10^{14}$ cm; the $V=3$ masers are always very weak and undetectable; the $V=0$ masers turn on at $r = 10^{16}$ cm with the weak line temperatures hardly distinguishable from the thermal emission. The observational data are an integral along the radius within the beam. We could not find a set of parameters and obtain from these a set of line temperatures of various transitions which fit the simultaneous observation data quantitatively very well. Usually in a model calculation the complexity and the accuracy exclude each other. This paper presents some qualitative results which help us to know the nature of IrC2.

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