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HIGH-EXCITATION SiO MASER EMISSION IN VY CANIS MAJORIS: DETECTION OF THE $v = 4$ $J = 5$–4 TRANSITION

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ABSTRACT

We report the detection of the $v = 4$ $J = 5$–4 transition of SiO in VY CMa, together with 13 maser lines of the same molecule corresponding to the rotational lines $J = 1$–0 to $J = 6$–5 of the vibrational levels 1–3. This is the first time that maser emission arising from a level of about 7000 K has been observed. The line profile from this transition has two different peaks at extreme velocities, in contrast to the strong $v = 1$ $J = 2$–1 maser, which has an intense emission peak at 22 km s^{-1}, i.e., closer to the velocity of the star. The density necessary to produce these high-excitation masers is $\approx 10^{10}$ cm^{-3}, and the SiO column densities have to be higher than or about 10^{20} cm^{-2}. The maser chains inside a given vibrational level predicted by standard large velocity gradient models (radiative or collisional pumping) are not observed for $v = 3$ and $v = 4$, indicating that nonlocal effects and infrared line overlaps could play an important role in the pumping of these high-excitation masers.

Subject headings: masers — radio lines: stars — stars: circumstellar matter — stars: late-type

1. INTRODUCTION

Masers in rotational transitions of vibrationally excited states of SiO are usually observed associated with O-rich long-period variables. Although a relatively large number of SiO transitions have been detected, only the $v = 1$ $J = 1$–0, $J = 2$–1 and the $v = 2$ $J = 1$–0 transitions have been studied in depth so far. In the $v = 1$ state, emission from all the rotational transitions up to $J = 6$–5 has been found (e.g., Jewell et al. 1987). The situation is similar for $v = 2$, except that the $J = 6$–5 transition was not detected and the $J = 2$–1 line appears to be anomalously weak (Olofsson et al. 1981). In the $v = 3$ state, only the $J = 1$–0 transition was found (Scalise & Lepine 1978; Alcolea, Bujarrabal, & Gallego 1989; see a tentative detection of $v = 3$ $J = 5$–4 in the red supergiant VX Sgr by Jewell et al.). No emission had been found from $v = 4$ (e.g., Alcolea et al. 1989).

The comparison of the intensities of the different SiO maser lines is a fundamental key to understanding the physics underlying the SiO maser phenomenon. In particular, the observation of transitions arising from high energy levels strongly constrains the location of the masers, the volume density, and the SiO column density of the emitting clumps. The major problem when comparing the relative emission of several maser lines is that they have often been detected by different observers, at various epochs and with different telescopes. In the most complete published study (in this sense), Schwartz, Zuckerman, & Bologna (1982) only reported the detection of at most seven masers in the same star. Today large telescopes and better receiver performances allow significant improvements to these results.

The late (M5) supergiant VY CMa is a well-known star showing intense SiO maser emission. The SiO spectra in this object are unusually complex and broad, presenting several strong peaks spread between $V_{\rm LSR} \approx 0$ and $V_{\rm LSR} \approx 50$ km s^{-1}. In this *Letter* we report the detection of 14 maser transitions in VY CMa, most of them observed at the same time and with the same instrument (the 30 m IRAM telescope); our observations include the detection for the first time of the transitions $v = 2$ $J = 6$–5; $v = 3$ $J = 4$–3, $J = 5$–4; and $v = 4$ $J = 5$–4 (§ 2). The observation of such lines would be a probe for the physical conditions of the densest clumps in the inner envelopes around evolved stars (§ 3).

2. OBSERVATIONS AND RESULTS

The observations of the $v = 1$–4 $J = 2$–1 to $J = 6$–5 lines of SiO were carried out in 1991 September and 1992 January with the 30 m IRAM radio telescope. Three SIS receivers at 1, 2, and 3 mm were tuned to the frequency of different maser lines and were used simultaneously. The main-beam single-sideband (SSB) system temperatures were typically 900, 400, and 300 K, respectively. The spectrometers connected to the receivers were a 2 × 256 and a 1 × 512 1 MHz filter bank, a 2 × 128 100 kHz filter bank, and an autocorrelator with 1024 channels and a total bandwidth of 20 MHz. The pointing was monitored every 30 minutes using a Schottky receiver tuned to the frequency of the strong $v = 1$ $J = 2$–1 line of SiO. The same line was also used to check the focus of the telescope every 2 hr. The relative pointing of the four receivers was found to be better than 2″. The 3 and 1 mm receivers are sensitive to the same linear polar component on the sky, while the 2 mm receiver is sensitive to a linear polarization perpendicular to that of the other receivers. The factors to transform main-beam antenna temperature in janskys are 4.5, 5.0, and 6.0 for the 3, 2, and 1 mm receivers, respectively. The calibration was performed using two absorbers at different temperatures. Sky opacities were derived from measurements of the sky emissivity. Calibration errors, as determined from observation of standard sources, were $\approx 15\%$ and 25% at low and high frequency, respectively (for more details see Cernicharo, Bujarrabal, & Lucas 1991). We note that the differences between the observed spectra discussed below are much larger than these uncertainties. These differences are also much larger than the maser flux variations expected from the monitoring with the 14 m Yebes radio telescope of the $v = 1$–3 $J = 1$–0 lines of SiO in VY CMa (see, e.g., Alcolea 1993). In addition, several lines of SiO were observed in 1991 September and 1992 January, showing, within the experimental errors, similar intensities.

The $v = 1$–4 $J = 1$–0 lines were observed with the 13.7 m radio telescope of the Centro Astronómico de Yebes. The telescope was equipped with a cooled Schottky receiver with a SSB system temperature of 260 K. The back end was a 256 × 50 kHz filter bank. A polarizer was installed in front of the receiver allowing the observation of circular polarization (for more details see Barcia et al. 1985; Alcolea & Bujarrabal 1992). Main-beam antenna temperatures have to be multiplied by 25 to get the maser flux in janskys.

The observed spectra of the SiO $J = 1$–0 to $J = 6$–5 transitions of the vibrationally excited states $v = 1$–4 are shown in Figure 1. All the lines in the $v = 1$ level are characterized by a strong emission peak at 22 km s^{-1} and the presence of a broad plateau of emission covering the velocity range 0–50 km s^{-1}. Over this plateau other narrow features are also clearly visible. The $J = 2$–1 line of the $v = 2$ level is not detected down to a 3 σ level of 0.03 K. However, the $J = 3$–2 line of this vibrational level is detected again, but at a velocity of 18 km s^{-1}, while the $J = 4$–3 line has two features, at 22 and 33 km s^{-1}. The intensities of the different low-J transitions in $v = 2$ are one to two orders of magnitude weaker than the corresponding ones of the $v = 1$ level, except for the $J = 1$–0 line, for which the emission is comparable in both vibrational levels. However, the high-J lines have similar intensities or are even larger than the corresponding transitions of the $v = 1$ level (see, e.g., the case of the $J = 6$–5 line). The emission from the rotational transitions of the $v = 3$ level is markedly different from those of $v = 1$ and $v = 2$. The $J = 1$–0 line has only a strong feature at 33 km s^{-1}. Although the $J = 2$–1 line of $v = 3$ is not detected down to a 3 σ level of 0.03 K, the $J = 4$–3 line has two

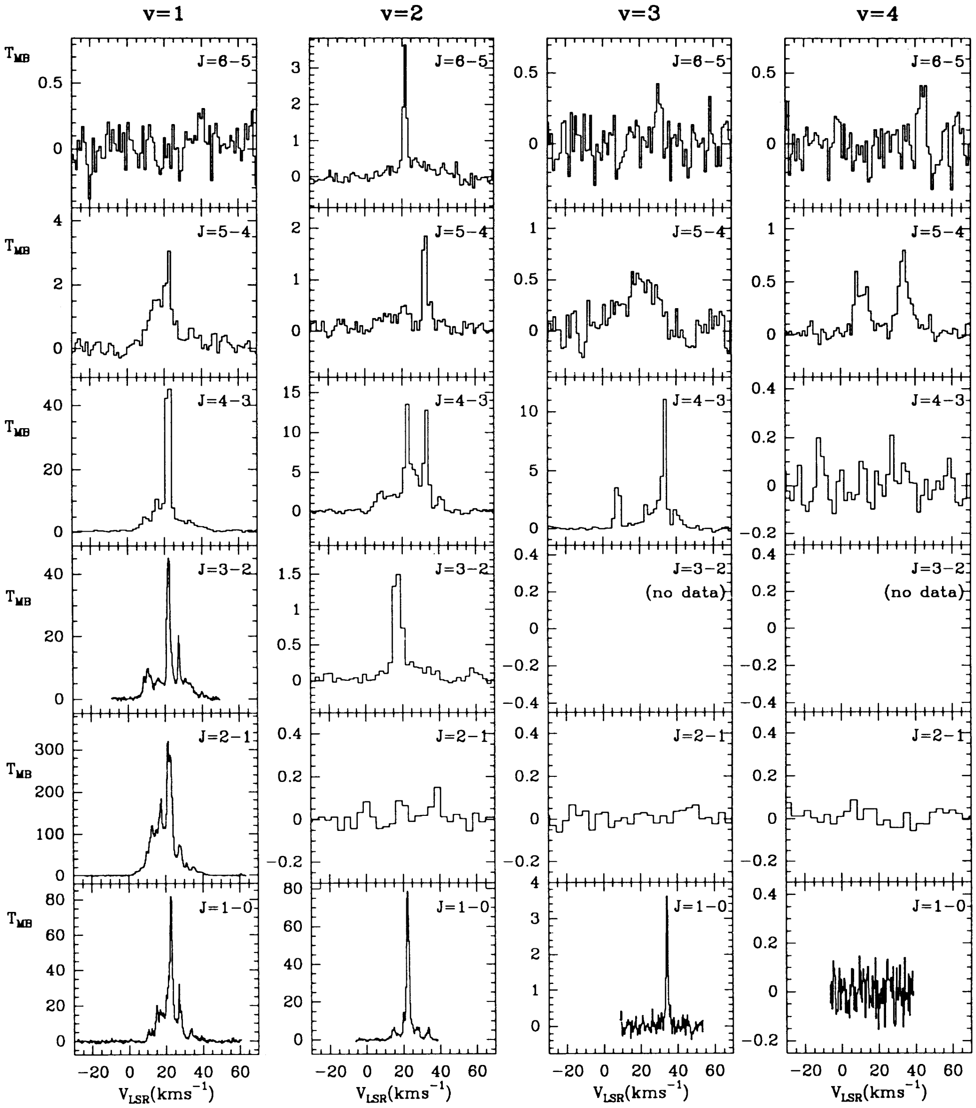

FIG. 1.—Observed transitions of SiO in VY CMa. Intensity is given in units of main-beam antenna temperature (K), and abscissa is $V_{\rm LSR}$ (km s^{-1}). Note the broad emission plateau in the $v = 1$ lines, while the high-excitation lines show only one or two emission peaks (see the case of $v = 4$ $J = 5$–4).

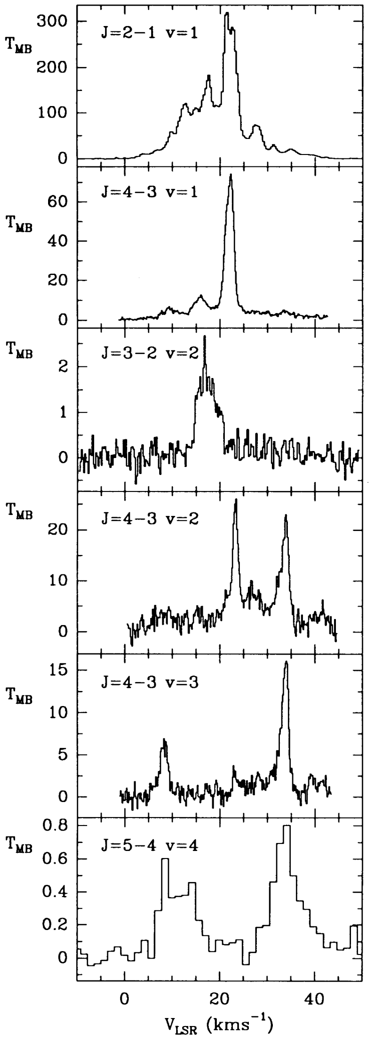

FIG. 2.—Selected rotational transitions of SiO in different vibrational states. Note the lack of a systematic line profile pattern among the different lines.

emission peaks at 8 and 33 km s^{-1}. Finally, in the $v = 4$ level, only the $J = 5$–4 line has been observed, having three features at velocities of 8, 15, and 33 km s^{-1}. The rotational transitions of the different vibrational levels seem to be composed of emission arising from clumps at different velocities, although only two or three of these clumps produce strong SiO masers. All the transitions with $v > 1$ show maser emission at one or two of these velocities, but without a repetitive pattern and with strong differences from one rotational transition to the next (see Fig. 2).

3. DISCUSSION

We have performed calculations of the pumping of the $v = 4$ maser using a large velocity gradient (LVG) model similar to that described by Cernicharo et al. (1991), except for the treatment of the collisions, which is similar to that proposed by Lockett & Elitzur (1992). The adopted kinetic temperature of the gas is 1500 K, and that of the central star is of 2800 K. The radius adopted for the star in our calculations was 10^{14} cm, and the distance of the maser region to the star 2×10^{14} cm, since the least restrictive conditions for the maser pumping are predicted for a short distance to the star. The logarithmic velocity gradient, ε, was equal to 3 to allow radiative pumping in our models. Under these conditions (see Fig. 3), a SiO column density of at least 10^{20} cm^{-2} (for a velocity width of 1 km s^{-1}) is needed to explain the maser output of the $v = 4$ $J = 5$–4 line. For a SiO molecular abundance of 4×10^{-5}, the local density must be higher than 5×10^{9} cm^{-3}. On the other hand, for densities higher than 5×10^{10} cm^{-3} the maser is quenched by collisional thermalization and, consequently, the density must be $\approx(0.5$–$5) \times 10^{10}$ cm^{-3}. The pumping can also be collisional, but in this case the inversion often requires still higher column densities to produce strong masers (see results in Fig. 3 for $R/R_* = 10$). The maser quenching is produced for similar densities to those in the radiative case. Only for distances of the order of 3×10^{15} cm can the collisional model predict the observed masers with substantially lower volume densities. However, the collisional pumping needs temperatures of the order of 1500 K, and such high values are not expected at these distances. In addition, McIntosh (1987) derived a radius for the maser-emitting region of VY CMa of about $4R_*$ from VLBI observations.

Our calculations fail to explain same observational facts. The contrast predicted by our model for different rotational transitions inside a given vibrational state is often smaller than a factor ≈ 3–5 for contiguous transitions (maser chains inside a given vibrational state). However, the observed contrast for $v = 3$ and $v = 4$ transitions is very high. This situation is similar to that reported by Cernicharo et al. (1991) and Cernicharo & Bujarrabal (1992) for the $v = 1, 2$ masers of ^{29}SiO and ^{30}SiO and could arise as a result of infrared line overlaps between ^{28}SiO, ^{29}SiO, and ^{30}SiO. The number of overlaps, not only between ^{28}SiO and ^{29}SiO but also between ^{28}SiO and ^{30}SiO and between ^{29}SiO and ^{30}SiO, is really impressive. SiO maser emission results probably from the combined effect of radiation and collisions close to the central star. But, at least for $v > 1$ in ^{28}SiO and for all vibrational states in the rare isotopes, line overlaps, which affect mainly the radiative population of the levels, are certainly of great importance in explaining the observations.

Another aspect that our model cannot explain is the occurrence of maser emission for all the v states at certain velocities. Figure 3 indicates that the inversion of different-v lines cannot be produced simultaneously at the same column density, a well-known problem in all SiO maser models (in radiative or collisional maser pumping).

Zhou Zhen-pu & Kaifu (1984) have proposed a kinematic model for the inner envelope of VY CMa based on the result that the most intense SiO masers are often composed of three main features, of which the central peak at about 22 km s^{-1} is in general dominant. They consider the presence of rotation and expansion in the inner shell of the molecular envelope surrounding VY CMa. This model predicts that the central peak comes from the innermost layers (at 3×10^{14} cm from the center) and the peaks at velocities around 10 and 30 km s^{-1} come from outer regions [at $(4$–$5) \times 10^{14}$ cm]. Our data do not support this prediction, since it is observed that high-energy transitions tend to be detected at the two extreme velocities. Because these transitions certainly require a high excitation to be detected, the observations suggest that they must come from regions closer to the central star than those responsible for the central peak. On the other hand, a single rotating structure cannot explain the full velocity pattern of the maser emission shown in Figure 1, and some clumps at

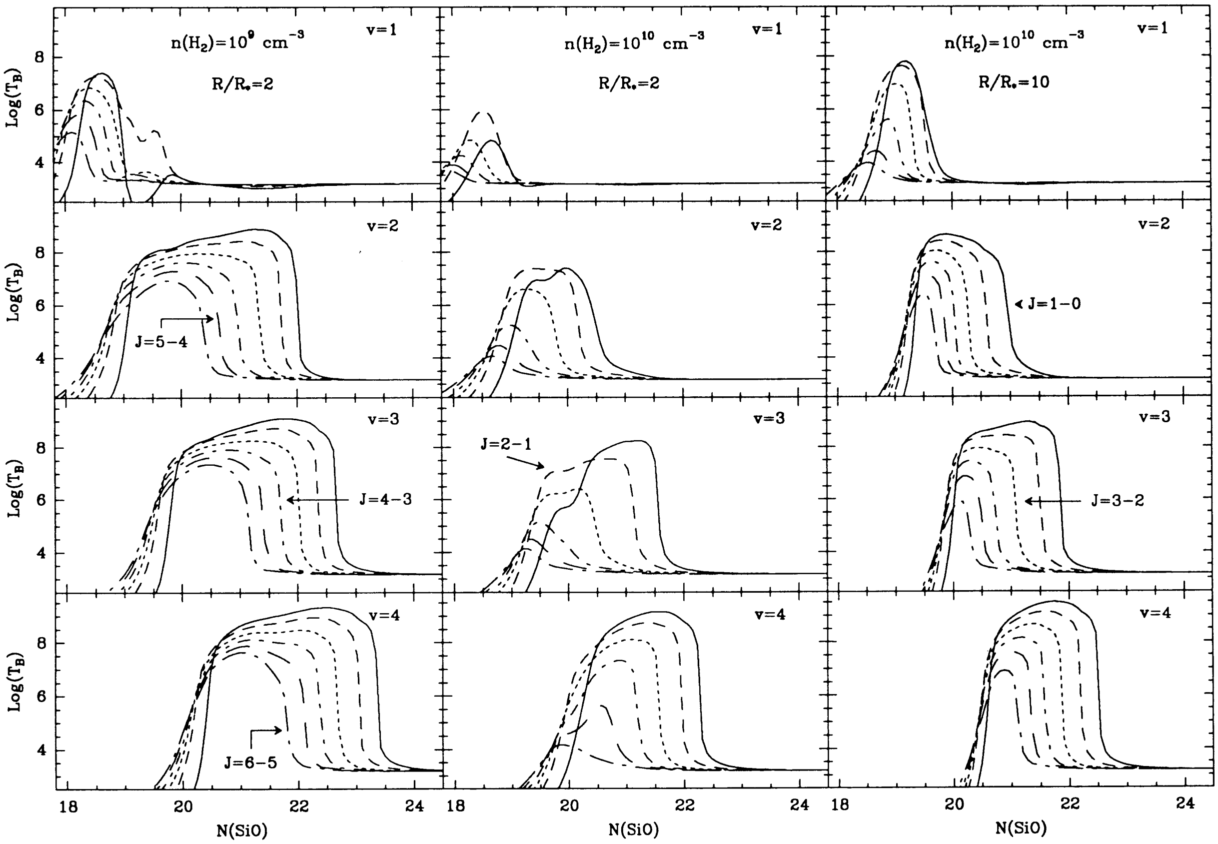

FIG. 3.—LVG calculations of the maser output (logarithm of the brightness temperature, log T_B) for the J = 1–0 to J = 6–5 lines in the v = 1 to v = 4 vibrational states as a function of the SiO column density, and for different volume densities and distances to the central star. The kinetic temperature of the gas is 1500 K, and the temperature of the central star is 2800 K. The value adopted in these calculations for the logarithmic velocity gradient ε is 3. The left-hand panels correspond to $R/R_* = 2$ and $n(H_2) = 10^9$ cm^{-3}, while the center panels corresponds to $n(H_2) = 10^{10}$ cm^{-3} and the same values for the other parameters. The right-hand panels correspond essentially to the pure collisional case ($R/R_* = 10$) with $n(H_2) = 10^{10}$ cm^{-3}.

different velocities are needed to explain the velocity structure of the SiO maser emission in this star.

We then conclude that the detection of the $v = 4$ J = 5–4 transition implies the presence of very dense clumps in the innermost envelope of VY CMa, with densities of $\approx 10^{10}$ cm^{-3}. We favor the location of these clumps at a few stellar radii, where the conditions to pump these high energy levels are more easily fulfilled. The large number of maser spots raises difficulties for the interpretation of the observed velocities in terms of a simple velocity field. Standard LVG calculations fail to explain some of the peculiarities shown by the high-excitation lines, and it is possible that nonlocal effects and infrared lines overlaps between the different isotopes of SiO could play an important role in the pumping of these high-v levels.

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