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HIGH-EXCITATION ^{29}SiO AND ^{30}SiO MASER EMISSION

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ABSTRACT

We present the first detection of strong maser emission from high-J rotational levels of the $v = 1$, 2 vibrationally excited states of ^{30}SiO and of ^{29}SiO in the oxygen-rich supergiant star VY CMa. In addition, both isotopes present strong maser emission in the $J = 5$–4 line of the ground vibrational state ($v = 0$). The obtained results, in particular the strong variations in intensity and profile of the different rotational lines within a given vibrational state, favor the interpretation of these masers as due to thermal and/or nonlocal overlap of the infrared lines of ^{28}SiO with those of ^{29}SiO and ^{30}SiO, a mechanism that has been proposed by Cernicharo, Bujarrabal, & Lucas (1991) to pump the $J = 4$–3 $v = 1$ maser line of ^{29}SiO.
Subject headings: circumstellar matter — masers — stars: late-type — radiative transfer

1. INTRODUCTION

The current theory of SiO masers in oxygen-rich evolved stars predicts that, within a given vibrational state, several rotational transitions can have maser emission with a small variation in intensity from one rotational transition to the next (maser chains inside a vibrational level—see, e.g., Bujarrabal & Nguyen-Q-Rieu 1981; Langer & Watson 1984; Lockett & Elitzur 1992). While this behavior is observed for the $v = 1$ masers of ^{28}SiO, the observations indicate that for $v = 2$, 3, and 4 the maser lines lack of systematic pattern in intensity and in line profile (see, e.g., Cernicharo, Bujarrabal, & Santarén 1992, hereafter CBS). For the $v = 4$ state of ^{28}SiO, only one line is observed, and for the $v = 2$ and 3 states of the same molecule, the line profiles often show maser emission at very different velocities. Sometimes, the maser emission at a given velocity for a particular rotational transition, J–J', disappears in the next transition $(J + 1)$–$(J' + 1)$, but appears again in the $(J + 2)$–$(J' + 2)$ (see Fig. 1 of CBS). The situation for the high-v masers of ^{28}SiO, i.e., the lack of maser chains inside a given vibrational level, is somewhat similar to that shown by the masers of ^{29}SiO $v = 1$, where only the $J = 4$–3 line shows maser emission (Cernicharo, Bujarrabal, & Lucas 1991a, hereafter CBL).

^{29}SiO and ^{30}SiO are also known to present maser emission in the $J = 1$–0 and $J = 2$–1 transitions of the $v = 0$ vibrational state toward evolved stars (see Deguchi et al. 1983; Barcia, Alcolea, & Bujarrabal 1989; Alcolea & Bujarrabal 1991), as well as in the star-forming region Ori A (Olofsson, Hjalmarsonn, & Rydbeck 1981). The recent observations of CBL on the emission of ^{29}SiO $v = 1$ have been modeled by these authors as the result of the infrared line overlaps of ^{28}SiO and ^{29}SiO. The number of overlapping pairs for the three silicon substituted isotopes of SiO is really impressive, being larger than 300 for $J < 12$ $v < 5$ and $\Delta V < 10$ km s^{-1} and larger than 2300 for $J < 40$ and $v < 5$ with $\Delta V < 30$ km s^{-1}, where ΔV is the frequency shift in velocity units. Consequently, infrared line overlaps between the different isotopes of SiO can play a very important role in producing the observed maser behavior (see CBS and CBL). The observation of the rotational lines of ^{29}SiO and ^{30}SiO in different vibrational states and those of high-v ^{28}SiO could be an important clue in modeling the SiO masers (note that the solar abundances of these isotopes are 1:20:30; see, e.g., Cernicharo et al. 1986, 1991b). Whereas the first complete study up to $v = 4$ and $J_{up} = 6$ for ^{28}SiO has been recently reported by CBS, no systematic studies of the emission of the rare isotopes of SiO in vibrationally excited states had been carried out so far.

In this *Letter* we report the first detection of the $J = 4$–3 $v = 1$ and $v = 2$ transitions of ^{30}SiO, and of the $J = 6$–5 line of $v = 1$ and the $J = 2$–1 and $J = 6$–5 lines of $v = 2$ of ^{29}SiO, in the oxygen-rich supergiant VY CMa. In addition, both isotopes of SiO also show strong emission in the J = 5–4 line of the ground vibrational state. The $J = 2$–1 $v = 0$ line of ^{29}SiO, which was already known to be masing, was particularly strong during our observations (only a factor of 3 weaker than the strong $J = 2$–1 $v = 1$ line of ^{28}SiO). The observations are described in § 2. In § 3 we discuss the implications of the observed behavior of the SiO masers, and we stress the importance of the infrared line overlaps in pumping these masers. The implications of the ground vibrational state maser emission of the rare isotopes of SiO in the determination of silicon isotopic ratios are also discussed in this section.

2. OBSERVATIONS

The observations were done in 1991 September and 1992 January with the 30 m IRAM radio telescope. Three SIS receivers tuned at the different frequencies of ^{29}SiO and of ^{30}SiO ($v = 0, 1, 2, 3$) were used simultaneously. Pointing and focusing were performed on the source itself by using a Schottky receiver tuned to the frequency of the strong $v = 1$ $J = 2$–1 maser line of ^{28}SiO. For such a purpose, 16 100 kHz filters placed at the line center were averaged together as a pseudocontinuum detector; receiver and sky power fluctuations were corrected on-line by using another group of 16 100 kHz channels placed outside the velocity range of line emission. The SIS receivers and the Schottky receiver were aligned within 2″, and the best focus positions for the various receivers differed by less than 0.2 mm. Consequently, pointing errors during our observations were lower than 2″. During the January observations the weather was excellent, with sky opacities at zenith of 0.05, 0.07, and 0.1 at wavelengths of 3, 2 and 1 mm respectively.

Two backends of 512 × 1 MHz filter channels, one AOS with 1774 channels covering 512 MHz, a 256 × 100 kHz filter backend, and an autocorrelator with 1024 channels were con-

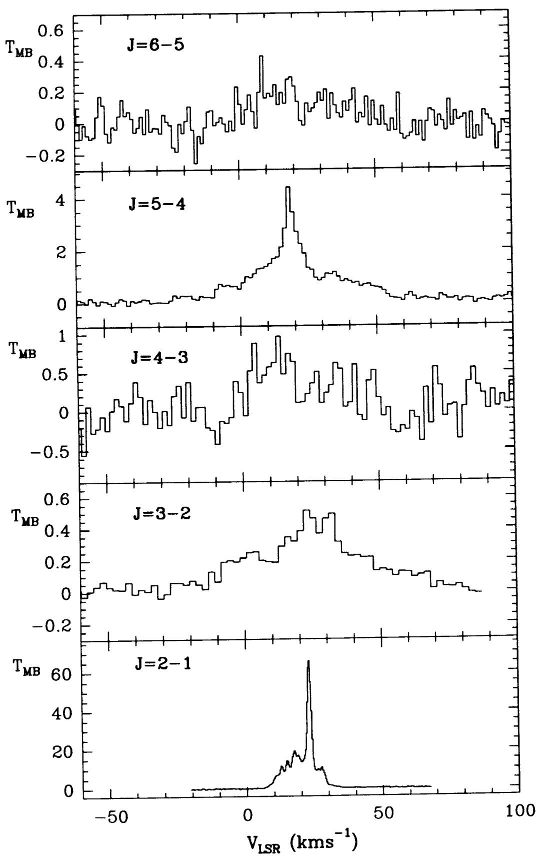

FIG. 1*a*

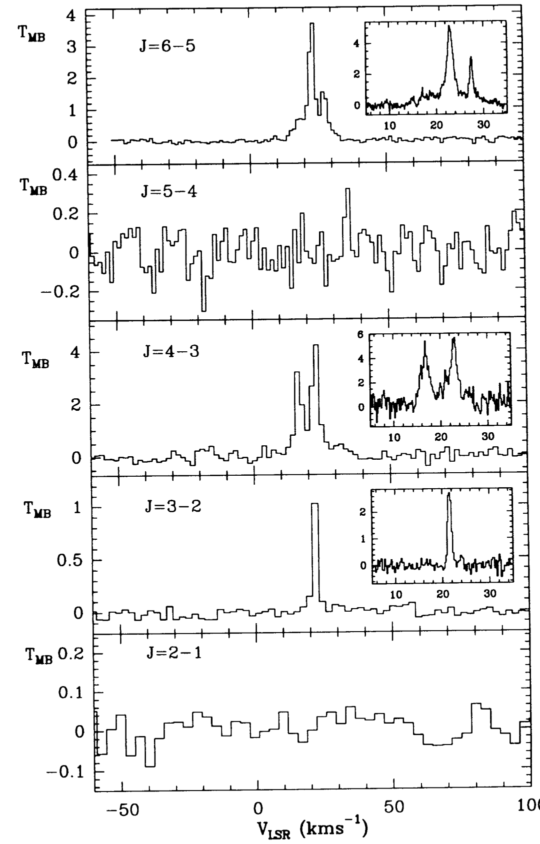

FIG. 1*b*

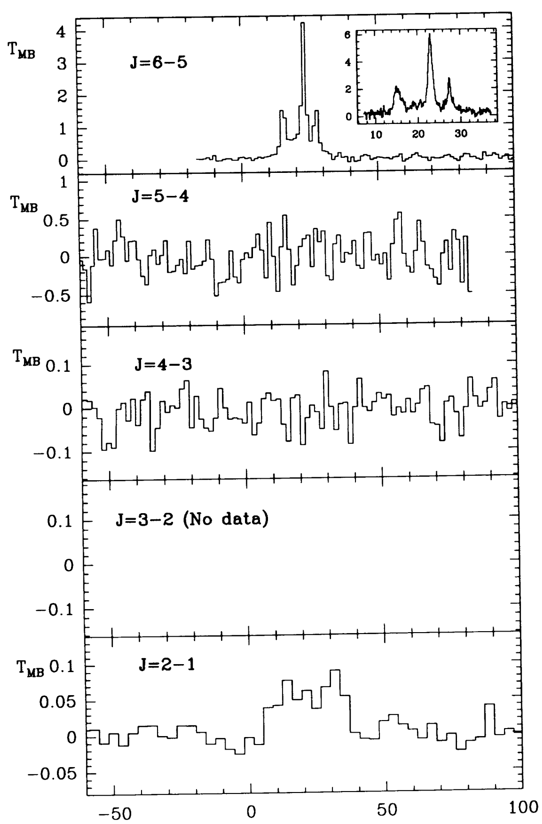

FIG. 1*c*

FIG. 1.—^{29}SiO $v = 0$ (Fig. 1*a*), $v = 1$ (Fig. 1*b*), and $v = 2$ (Fig. 1*c*) observed lines. Ordinate is main beam antenna temperature and abscissa is velocity (V_{LSR}). When strong maser emission was detected, the 100 kHz filters of the autocorrelator were connected to the receivers. These high-resolution data are shown in the corresponding inserts. In other cases, the resolution is 1 MHz.

nected to the three receivers. The 100 kHz filters and the autocorrelator were split into two halves in order to have a good velocity resolution for all the observed maser lines.

The observed ^{29}SiO $v = 0$, 1, and 2 lines ($J = 2$–1 to $J = 6$–5) are shown in Figure 1 (some $v = 1$ lines have been published previously by CBL). For ^{30}SiO the observed transitions of the different vibrational states are shown in Figure 2. We tried to detect the $J = 4$–3 $v = 3$ line of ^{29}SiO without success to an upper limit of 0.04 K (3 σ).

3. DISCUSSION

CBL reported the detection of the $J = 4$–3 $v = 1$ line of ^{29}SiO in several oxygen-rich evolved stars together with the relative absence of emission from the other rotational transitions of this vibrational state up to $J_{up} = 5$. Figure 1 shows that the $J = 6$–5 line of this state is also masing in VY CMa. This source also has maser emission in the $J = 3$–2 line of this state (the only star reported by CBL with maser emission in this line). However, the line profiles of the different maser lines in VY CMa are very different, with the $J = 3$–2 having only emission at 22 km s^{-1} (i.e., at the velocity of the strongest ^{28}SiO masers), and the $J = 4$–3 and $J = 6$–5 consisting of two peaks of similar intensity. Nevertheless, the velocities of the features of the $J = 4$–3 and the $J = 6$–5 lines are somewhat different, with a common feature at 22 km s^{-1} and a second

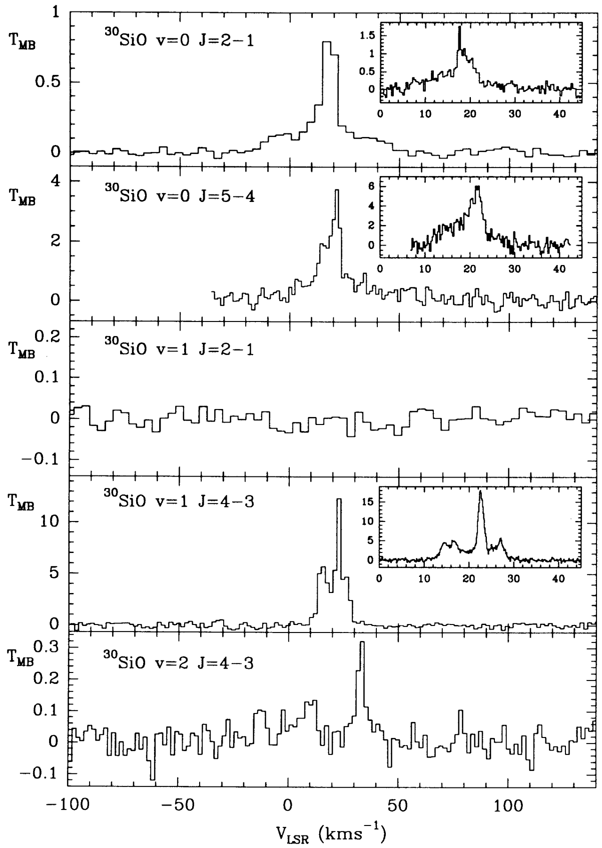

FIG. 2.—Observed spectra of ^{30}SiO toward VY CMa. Ordinate is main beam antenna temperature, and abscissa is velocity (V_{LSR}). The spectral resolution is 1 MHz and for the inserts is 100 kHz.

peak at 13 km s^{-1} for the $J = 4$–3 and at 28 km s^{-1} for the $J = 6$–5. It is noteworthy the absence of emission in the $J = 5$–4 line of this state, an observational fact impossible to explain within the standard theory of SiO masers. The $J = 6$–5 line also shows a broad plateau of emission similar to that presented by ^{28}SiO in the $v = 1$ and $v = 2$ states (see CBS), which is missing in the other rotational transitions. The situation is even more spectacular for the $v = 2$ vibrational level of ^{29}SiO where only the $J = 6$–5 line and the $J = 2$–1 line are masing. The $J = 6$–5 line has several features at the velocities covered by the $J = 3$–2, $J = 4$–3, and $J = 6$–5 lines of the $v = 1$ state. This $v = 2$ line also shows a broad emission plateau. The $J = 2$–1 line of this state is very weak but stronger than the corresponding line of the main isotope. Its peak velocity is 32 km s^{-1}, which corresponds to the velocity found in the $J = 5$–4 $v = 4$ line of ^{28}SiO (see CBS). Finally, the ^{29}SiO masers in the ground state constitute another interesting piece of the SiO maser problem. The $J = 1$–0 and $J = 2$–1 lines of the $v = 0$ state were known to be masering in many O-rich evolved stars (Alcolea & Bujarrabal 1992; Barcia et al. 1989; Deguchi et al. 1983). However, the $J = 3$–2 and $J = 4$–3 lines show thermal emission in VY CMa, which also applies to the $J = 6$–5 line (see Fig. 1). Unexpectedly, the $J = 5$–4 line is again showing strong emission, comparable in intensity to that of the thermal emission of the main isotope but with a different profile. The narrow peak shown by this line (see Fig. 1) and the increase in intensity by a factor of 10 as compared with the $J = 4$–3 and $J = 6$–5 lines indicate that this line is masering. The difference cannot be attributed to different observing dates because most of the lines were observed in the two runs with the 30 m IRAM telescope (see § 2; this comment also applies to the line shapes).

Trying to explain the observed ^{29}SiO maser emission one could think of asymmetries in the collisional cross sections that could favor the pumping of the observed $v = 0$, 1, and 2 masers. However, the LVG calculations carried out by CBL and CBS indicate that, with the Bieniek & Green (1983) cross sections, it is not possible to produce the noticed peculiarities of the ^{29}SiO and high-v ^{28}SiO masers. In addition, if the observed behavior of the masing lines were due to some selective effect in the collisional cross sections, then the influence on the pumping of the ro-vibrational levels should be almost identical for ^{29}SiO and ^{30}SiO (the abundance ratio between these two silicon isotopes is only of 1.5; see above) and for the high-v ^{28}SiO masers reported by CBS, which is not the case.

As already mentioned, the behavior of the ^{29}SiO masers and of the ^{28}SiO high-v masers is qualitatively similar and perhaps results from the similar column densities and the same physical processes necessary to pump their ro-vibrational levels. Note, however, that the vibrational level of ^{28}SiO that could have the same column density as ^{29}SiO in its ground state is $v = 2$, and that the lines from this level of ^{28}SiO and those of ^{29}SiO in $v = 0$ are very different in many aspects (line shape, intensities). The same applies to the $v = 1$ lines of this rare isotope and those of the $v = 3$ level of the main isotope of SiO.

Finally, from an observational point of view, the lines of ^{30}SiO can give us a very significant clue in trying to understand the SiO maser puzzle. Figure 2 shows the observed lines of this isotope (same observing dates as for ^{29}SiO and for those lines of ^{28}SiO reported by CBS—many of them can be observed even simultaneously within the 500 MHz bandwidth of the receivers). The first important difference between ^{29}SiO and ^{30}SiO is the intensity of the $J = 2$–1 $v = 0$ line. While in ^{29}SiO this line is a strong maser, in ^{30}SiO it is two orders of magnitude weaker and probably has a thermal character plus a weak maser at the velocity of 22 km s^{-1}, i.e., the velocity of the strong masers of ^{28}SiO. However, the $J = 5$–4 line is masing for ^{30}SiO, as it is for ^{29}SiO and with similar intensity though with a slightly different profile. As discussed above, we could expect to find maser emission of ^{30}SiO in $v = 1$ and $v = 2$ in the same lines as ^{29}SiO. Figure 2 shows that this is the case for the $v = 1$ $J = 4$–3 (the $J = 5$–4 line of the $v = 1$ was not detected to an upper limit of 0.5 K). However, the $J = 4$–3 $v = 1$ maser of ^{30}SiO is stronger than that of ^{29}SiO and has a different line profile, which is surprisingly similar to that of the $J = 6$–5 $v = 2$ line of ^{29}SiO. In addition, the $J = 4$–3 line of the $v = 2$ level of ^{30}SiO has been detected while the same line of ^{29}SiO is not detected to a 3 σ level of 0.1 K.

Taking into account the large number of infrared overlaps between the ro-vibrational lines of ^{28}SiO, ^{29}SiO, and ^{30}SiO, we believe that they strongly affect the pumping of the energy levels of these molecules. CBL suggested that the $J = 4$–3 $v = 1$ maser line of ^{29}SiO was produced by the overlap of the $J = 9$–10 $v = 1$–0 line of ^{28}SiO and the $J = 4$–5 $v = 1$–0 line of ^{29}SiO, which are separate by $\Delta V \approx 4.8$ km s^{-1}. CBS also suggest that the pumping of the high-v ^{28}SiO masers is strongly affected by these overlaps. As indicated by CBL, line overlaps affect the pumping of a rotational level in three different ways. First, the local opacity in a given point of the envelope is increased at the frequency of the overlapped line, thereby reducing the escape probability of the photons emitted at this point. Second, the most abundant of the overlapping species will absorb the photons emitted from the central star as they travel across the envelope. The infrared flux observed by the other line will consequently be reduced. Third, the most abundant species may emit photons at other points in the envelope that will be absorbed by the isotopic species partially compensating the reduction of continuum photons from the star. In addition, different points in the envelope may be radiatively connected even if a velocity gradient is present in the envelope.

In the case of silicon monoxide, the number of overlaps, not only between ^{28}SiO and ^{29}SiO, but also between ^{28}SiO and ^{30}SiO, and ^{29}SiO and ^{30}SiO is really impressive (the number of overlaps is of 2312 for $|\Delta V| < 30$ km s^{-1} $J_{up} < 40$ and $v < 5$). 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. Our data suggest (see also CBL and CBS) that SiO maser emission in oxygen-rich evolved stars must be analyzed as the result of a combined pumping in three molecular species. Collisional effects, although important, are probably less efficient than thermal or nonlocal line overlaps in explaining the occasional maser lines of ^{29}SiO and ^{30}SiO within a given vibrational level, as well as those of ^{28}SiO for $v = 3$, 4. We recall, however, that only the calculations of Bieniek & Green (1983) are available so far and that they just cover the $\Delta v = 1$ transitions up to $v = 2$.

Finally, the observed maser emission of the rotational levels of the ground state of ^{29}SiO and ^{30}SiO makes difficult a correct determination of the silicon isotopic ratios from the observation of the SiO lines. As an example, while in VY CMa the $J = 2$–1 and $J = 5$–4 $v = 0$ lines of ^{29}SiO are strong masers, in W Hya the $J = 4$–3 $v = 0$ line is very strong ($T_{MB} =$ 3.5 K) when compared with the $J = 3$–2 $v = 0$ line, which is 10 times weaker (the $J = 2$–1 $v = 0$ line of ^{29}SiO was also very strong, being clearly maser emission, during our observations in NML Tau; however, it was undetected in W Hya and U Ori, and very weak in RX Boo and R Leo). Consequently, in order to derive isotopic ratios from SiO ground state emission, several rotational lines should be observed to discriminate which of them are suffering a maser action and which have a thermal origin.

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REFERENCES

Alcolea, J., & Bujarrabal, V. 1992, A&A, 253, 475
Barcia, A., Alcolea, J., & Bujarrabal, V. 1989, A&A, 215, L9
Bieniek, R. J. & Green, S. 1983, ApJ, 265, L29; erratum, ApJ, 270, L101
Bujarrabal, V., & Nguyen-Q-Rieu. 1981, A&A, 102, 65
Cernicharo, J., Bujarrabal, V., & Lucas, R. 1991a, A&A, 249, L27 (CBL)
Cernicharo, J., Bujarrabal, V., & Santarén, J. L. 1992, ApJ, submitted (CBS)
Cernicharo, J., Guélin, M., Kahane, C., Bogey, M., & Destombes, J. L. 1991b, A&A, 246, 220
Cernicharo, J., Kahane, C., Gómez-González, J., & Guélin, M. 1986, A&A, 167, L9
Deguchi, S., Good, J., Fan, Y., Mao, X., & Wang, D. 1983, ApJ, 264, L65
Langer, S. H., & Watson, W. D. 1984, ApJ, 284, 751
Lockett, P., & Elitzur, M. 1992, ApJ, 399, 704
Olofsson, H., Hjalmarson, A., & Rydbeck, O. E. H. 1981, A&A, 100, L30