HIGH-J \( v = 0 \) SiS MASER EMISSION IN IRC +10216: A NEW CASE OF INFRARED OVERLAPS

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ABSTRACT

We report on the first detection of maser emission in the \( J = 11–10, J = 14–13, \) and \( J = 15–14 \) transitions of the \( v = 0 \) vibrational state of SiS toward the carbon-rich star IRC +10216. These masers seem to be produced in the very inhomogeneous region between the star and the inner dust formation zone, located at \( \approx (5–7)R_\ast \), with expansion velocities below 10 km s\(^{-1}\). We interpret the pumping mechanism as being due to overlaps between \( v = 1–0 \) rovibrational lines of SiS and mid-IR lines of \( \text{C}_2\text{H}_2 \), HCN, and their \(^{13}\text{C} \) isotopologues. The large number of overlaps found suggest the existence of strong masers for high-J \( v = 0 \) and \( v = 1 \) SiS transitions, located in the submillimeter range. In addition, it could be possible to find several rotational lines of the SiS isotopologues displaying maser emission.

Subject headings: circumstellar matter — masers — AGB and post-AGB — stars: carbon

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1. INTRODUCTION

The detection of strong maser emission at the frequencies of pure rotational transitions of some molecules is a common phenomenon in circumstellar envelopes (CSEs) of evolved stars (Elitzur 1992; Gray 1999). The maser is usually produced in a small region of the envelope and sometimes provides valuable information on the physical conditions of the emitting region.

Because of the different chemistry, masers are produced by different molecules in O- and C-rich stars. In O-rich stars, SiO exhibits strong maser emission in different rotational transitions within several vibrational states, from \( v = 1 \) to \( v = 4 \) (Cernicharo et al. 1993; Pardo et al. 1998). These masers are formed in a region of the CSE very close to the stellar surface and seem to be driven by near-IR radiation (Pardo et al. 2004). In C-rich stars, although SiO is present with similar abundances to those in O-rich stars (Schöier et al. 2006), no SiO maser has been detected. The explanation could be that SiO is formed at \( \approx (3–5)R_\ast \) (Agúndez & Cernicharo 2006), where the angular dilution of the star is high and the density and temperature are lower than in the regions where SiO masers are produced in O-rich stars. In C-rich stars, only HCN shows strong maser emission, in several pure rotational lines within vibrational states from \( \nu_1 = 1 \) to \( \nu_2 = 4 \) (Lucas & Cernicharo 1989; Schilke & Menten 2003). These masers must be formed in the innermost regions of the CSE. SiS has been previously found to show weak maser emission in the \( v = 0, J = 1–0 \) transition in IRC +10216 (Henkel et al. 1983).

In this Letter, we report on the first detection of maser emission from the \( J = 11–10, J = 14–13, \) and \( J = 15–14 \) transitions in the \( v = 0 \) vibrational state of SiS (hereafter \( M_2, M_3, \) and \( M_4 \)) observed toward the C-rich star IRC +10216. We have also obtained observations of \( v = 1 \) rotational lines that exhibit thermal emission. We propose that overlaps of \( v = 1–0 \) rovibrational transitions of SiS with mid-IR lines of \( \text{C}_2\text{H}_2 \) and HCN could provide the pumping mechanism for these masers, as well as higher \( J, v = 0 \) SiS masers in the submillimeter range. This discovery is interesting because this species could play a role in C-rich stars similar to that of SiO in O-rich stars: the energy level pattern of both molecules is similar, and it is also formed close to the star, as chemical equilibrium and interferometric observations imply (Bieging & Nguyen-Q-Rieu 1989).

2. OBSERVATIONS

The observations of the \( v = 0, J = 6–5 \) and \( J = 8–7 \) to \( J = 15–14 \) transitions of SiS (see Fig. 1, left) were carried out on 2004 June 19 with the IRAM 30 m radio telescope, at phase \( \phi_u = 0.05 \) (Monnier et al. 1998). Four SiS receivers operating at 3, 2, 1.3, and 1 mm were used simultaneously. System temperatures were 120–225 K for the 3 and 2 mm receivers and 200–600 K for the 1 and 1 mm receivers. Atmospheric opacities ranged between 0.08 at 108 GHz and 0.2 at 272 GHz. For the \( J = 10–9 \) SiS line at 181.5 GHz, the system temperature was significantly higher, \( \approx 10^7 \) K, because of proximity to the atmospheric water line at 183.3 GHz. The intensity scale was calibrated using two absorbers at different temperatures according to the atmospheric transmission model ATM (Cernicharo 1985; Pardo et al. 2001). Pointing and focus were regularly checked on the nearby quasar OJ 287. The observations were made in wobbling mode, with 180° offset and the secondary nutating at a rate of 0.5 Hz. The back ends were a filter bank with 256 MHz bandwidth and 1 MHz resolution and an auto-correlator with 80 kHz resolution (\( \Delta v = 0.08–0.2 \text{ km s}^{-1} \)). The lines of SiS in the \( v = 1 \) state (see Fig. 1, right) were also observed with the IRAM 30 m telescope between 1989 and 2001.

In addition, we show some spectra corresponding to rovibrational lines of SiS (see Fig. 1, center) from a mid-IR high-resolution spectrum (11–14 \( \mu \)m) obtained in 2002 December with the TEXES spectrometer mounted on the 3 m Infrared Telescope Facility (observational procedures described in Lacy et al. 2002; J. P. Fonfría Expósito et al. 2006, in preparation).

3. RESULTS AND DISCUSSION

The \( v = 1 \) rotational lines show single-cusped profiles, and their relative intensities indicate that the rotational levels are thermally populated. The line widths correspond to expansion velocities of 9–11 km s\(^{-1}\), lower than the terminal velocity of \( \approx 14.5 \text{ km s}^{-1} \) (Cernicharo et al. 2000), and thus the emission arises from the innermost region of the CSE, between the photosphere and the inner dust formation zone, located at \( \approx 5R_\ast \) (J. P. Fonfría Expósito et al. 2006, in preparation; Keady & Ridgway 1993). We can derive the SiS abundance in that region from the \( v = 1 \) lines assuming a uniform sphere at a distance of 180 pc with a radius of 10\( R_\ast \), illuminated by the central star.
Fig. 1.—Millimeter and mid-IR observations toward IRC +10216. The pure rotational transitions in the $v = 0$ state (left) and in the $v = 1$ state (right) are plotted as a function of the velocity with respect to the star ($v_{\text{lsr}} = -26.5$ km s$^{-1}$). The velocity structure of the three observed masers M1, M2, and M3 is shown in more detail at bottom center, where the upper lines have been increasingly shifted by 10 K. The middle insets present some mid-IR spectra at the frequencies of several rovibrational $v = 1$–0 SiS lines, whose labels and frequencies are also shown. The zero of the velocity scale is set to the SiS frequency corrected for the local standard of rest. The observed spectrum is plotted as a histogram. The curves above these correspond to a radiative transfer model that only considers C$_2$H$_2$, HCN, and their isotopologues (J. P. Fonfria Expósito et al. 2006, in preparation). The vertical lines indicate the position of maximum absorption for the transitions of SiS (thick lines), C$_2$H$_2$ (thin lines), H$^{13}$CCH (dot-dashed line), and HCN (dashed lines). [See the electronic edition of the Journal for a color version of this figure.]
\( R_r = 5 \times 10^{13} \text{ cm}, T_e = 2300 \text{ K} \), with \( T_i = 1000 \text{ K} \) and \( n_{H_2} = 1.6 \times 10^9 \text{ cm}^{-3} \) (mean values for this region derived in J. P. Fonfría Expósito et al. 2006, in preparation) and an expansion velocity of 11 km s\(^{-1}\). We solve the statistical equilibrium for SiS considering 100 rotational levels and three vibrational states and apply the large velocity gradient (LVG) radiative transfer formalism using a code developed by J. Cernicharo. With the assumed \( n_{H_2} \), the column density for \( H_2 \) is \( \approx 7 \times 10^{23} \text{ cm}^{-2} \) and the derived one for SiS is \( \approx 5.0 \times 10^{18} \text{ cm}^{-2} \). Hence, the SiS abundance is \( \approx 7 \times 10^{-6} \). The derived abundance is compatible with a high SiS abundance in the innermost CSE (from LTE chemistry models, \( 3 \times 10^{-5} \); Agúndez \\& Cernicharo 2006), while the SiS abundance farther out in the CSE is considerably lower (\( 6.5 \times 10^{-7} \)) according to observations of \( v = 0 \) rotational lines over the outer CSE by Bieging \\& Nguyen-Q-Rieu (1989).

Most \( v = 0 \) rotational lines show a rounded or slightly double-peaked profile, with the blue part partially absorbed by cold SiS through the envelope. However, \( M_2 \), \( M_3 \), and \( M_5 \) show a large extra emission in the form of narrow peaks (FWHM = 1–3 km s\(^{-1}\)), suggesting that this emission is arising from very small regions. The velocities of these features, within the \(-10 \text{ to } 10 \text{ km s}^{-1} \) range, indicate that the SiS maser emission arises from different regions located between the star and the inner dust formation zone (\( r = 5 R_\ast \)). In addition, Carlström et al. (1990) found an out-of-phase oscillation in the intensity of the SiS lines \( v = 0 \), \( J = 6 \) and \( J = 5 \). In the latter, the blue- and redshifted peaks at nearly the terminal velocity appear and disappear, indicating that they could be maser features produced by an overlap involving the level \( J = 5 \). These facts suggest that overlaps of \( v = 1 \) rovibrational transitions of SiS with those of mode \( v_2 \) of \( C_2H_2 \) and mode \( v_6 \) of HCN could provide the pumping mechanism. \( C_2H_2 \) and HCN are abundant in the inner CSE of IRC +10216 and dominate the 11–14 \( \mu \)m spectrum (J. P. Fonfría Expósito et al. 2006, in preparation). Overlaps with these two species have been already proposed by Sahai et al. (1984) to explain the different profiles of adjacent- \( J \) lines of SiS. However, the SiS frequencies used in that work were not as accurate (\( \sigma \sim 10^{-4} \text{ cm}^{-1} \)) as those available today. We have calculated those frequencies from the Dunham coefficients determined by Sanz et al. (2003), for which the error of the band center is less than \( 10^{-7} \text{ cm}^{-1} \) (\( \approx 0.04 \text{ km s}^{-1} \); the relative accuracy of \( P \) and \( R \) lines is much better). The frequencies of \( C_2H_2 \), \( H^1CCH \), HCN and \( H^3CN \) lines have been taken from the HITRAN2004 database (Rothman et al. 2005), with an accuracy better than \( 10^{-8} \text{ cm}^{-1} \) (\( \approx 0.4 \text{ km s}^{-1} \)) for \( C_2H_2 \) and \( H^3CCH \), and \( 10^{-4} \text{ cm}^{-1} \) for HCN and \( H^3CN \).

Table 1 shows the mid-IR line overlaps of SiS with \( C_2H_2 \), HCN, and their most abundant isotopologues. For the overlap search, we selected coincidences within \( |\Delta v| < 10 \text{ km s}^{-1} \). However, since the CSE is expanding, every region of the envelope is receding from the others. Hence, if the population of the SiS levels is affected by an overlap with a strong line of another species, the frequency of this overlapping transition must be higher than the SiS one. This would restrict the condition to positive \( \Delta v \). Nevertheless, because of the line width, lines at \( \Delta v < 0 \) can overlap the SiS lines. Hence, we have set the negative cutoff to one-half the typical line width in the innermost CSE (\( \approx 5 \text{ km s}^{-1} \); J. P. Fonfría Expósito et al. 2006, in preparation). Therefore, our search is restricted to \(-2.5 \text{ km s}^{-1} \leq \Delta v \leq 10 \text{ km s}^{-1} \). All the rovibrational SiS lines commented on hereafter refer to \( v = 1 \) \( \rightarrow \) 0 transitions and will be labeled with the usual spectroscopic nomenclature \( R, Q, P \) (see note to Table 1).
In order to qualitatively interpret the effects of IR overlaps on maser emission, we have used the same LVG radiative transfer code, modified to account for overlaps, changing the on maser emission, we have used the same LVG radiative velocities are less than 0.5 km s\(^{-1}\) corresponding to the vibrational transitions \(\nu = 0\). SiS molecules are easily excited from \(K_{\text{rot}} = P_{\text{rot}}(K, L, J)\) or odd \((J, L, K)\).

In Table 1, we present a list of SiS transitions that could overlap with other transitions in the mid-IR range. The table includes the following information: the line name, the frequency in cm\(^{-1}\), the molecule, the transition, and the velocity difference in km s\(^{-1}\). We have also looked for overlaps of \(v = 0\) higher J SiS lines with C\(_2\)H\(_2\), HCN, and \(^{28}\)Si\(_{32}\)S. With the adopted criteria for the overlap search (see note to Table 1), we have found 91, 93, 76, and 94 coincidences for \(^{28}\)Si\(_{32}\)S, \(^{29}\)Si\(_{32}\)S, \(^{30}\)Si\(_{32}\)S, and \(^{33}\)Si\(_{32}\)S, respectively. Consequently, although these species are less abundant than \(^{28}\)Si\(_{32}\)S, the population of some levels could be inverted, producing maser emission.

This study represents the discovery of three new SiS masers and should be complemented with future observations of higher \(J = 0\) and \(v = 1\) rotational transitions. Furthermore, a detailed multimolecule nonlocal radiative transfer model would help to understand the dust formation region and the role of SiS in C-rich evolved stars.

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