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SUBMILLIMETER NARROW EMISSION LINES FROM THE INNER ENVELOPE OF IRC+10216

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ABSTRACT

A spectral-line survey of IRC+10216 in the 345 GHz band has been undertaken with the Submillimeter Array. Although not yet completed, it has already yielded a fairly large sample of narrow molecular emission lines with line widths indicating expansion velocities of ~ 4 km s^{-1}, less than three times the well known value of the terminal expansion velocity (14.5 km s^{-1}) of the outer envelope. Five of these narrow lines have now been identified as rotational transitions in vibrationally excited states of previously detected molecules: the $v = 1$, $J = 17$–16, and $J = 19$–18 lines of Si^{34}S and ^{29}SiS and the $v = 2$, $J = 7$–6 line of CS. Maps of these lines show that the emission is confined to a region within ~ 60 AU of the star, indicating that the narrow-line emission is probing the region of dust formation where the stellar wind is still being accelerated.

Key words: circumstellar matter – radio lines: stars – stars: individual (IRC+10216) – stars: late-type – submillimeter

1. INTRODUCTION

Massive circumstellar envelopes of asymptotic giant branch (AGB) stars are believed to be a major contributor of molecules and grains to the interstellar medium (ISM). IRC+10216 (CW Leo), at a distance of 150 pc, is the archetypal AGB carbon star with a high mass-loss rate (greater than 10^{-5} $M_\odot$ yr^{-1}; Young et al. 1993; Crosas & Menten 1997). Owing to its proximity, this star is an ideal target for detailed studies of physical and chemical processes in AGB circumstellar envelopes (e.g., Olofsson et al. 1982). Nearly 60 molecular species have been discovered in its circumstellar shell from single-dish spectral-line surveys (Kawaguchi et al. 1995; Avery et al. 1992; Groesbeck et al. 1994; Cernicharo et al. 2000; He et al. 2008).

Interferometric mapping allows us to check predictions of abundances of various molecular species as a function of radius in the circumstellar envelope. "Parent" molecules, such as CO, C_2H_2, CS, HCN, and SiS, are formed in the stellar atmosphere in thermochemical equilibrium (Tsuji 1964, 1973). Once they get levitated to a distance from the star at which the density is too low for chemical reactions, their abundances "freeze out" at the values prevailing in that region (McCabe et al. 1979). At around that distance ($\sim$ 20 AU), the temperature has dropped below the dust condensation value ($\sim$ 1200 K) and dust grains start forming (Monnier et al. 2000). Radiation pressure accelerates the grains and, by friction, the molecules too, in an outflow which, for IRC+10216, reaches a terminal velocity of 14.5 km s^{-1}. In the outer parts of the expanding envelope, a rich carbon-dominated photochemistry driven by the ambient ultraviolet field produces species such as CN and C_4H whose mostly optically thin emission can be observed as ring-like distributions with radii, at a few times 10^{16}–10^{17} cm, depending on the chemical reactions at work (see the reviews of Glassgold 1996; Ziurys 2006).

At submillimeter wavelengths, we can observe lines requiring elevated excitation conditions, allowing us to probe the physical conditions in the inner circumstellar envelope (radius $\lesssim 10^{16}$ cm) where densities and temperatures are relatively high (temperatures $\sim$ 100–1000 K, column densities $\sim 10^{22}$–10^{24} cm^{-2}; Keady & Ridgway 1993).

We have begun a spectral-line survey of IRC+10216 with the Submillimeter Array[5] (SMA; Ho et al. 2004). Previous 345 GHz single-dish line surveys include those done with the James Clerk Maxwell Telescope (JCMT; Avery et al. 1992) and Caltech Submillimeter Observatory (CSO; Groesbeck et al. 1994) in the frequency ranges of 339.6–364.6 GHz and 330.2–358.1 GHz, respectively. Our SMA line survey will eventually cover the frequency range of 300–355 GHz with higher sensitivity and spatial resolution than previous surveys; about 40% of the survey has so far been completed. The frequency range 300–330 GHz will be observed for the first time. Here, we present several new results, including the discovery of many lines having narrow widths, and detections of vibrationally excited rotational transitions in SiS, ^{29}SiS, Si^{34}S, and CS. A full account of the observed lines will be presented on completion of the survey.

2. OBSERVATIONS AND DATA REDUCTION

We observed IRC+10216 with the SMA in 2007 February in the subcompact configuration with baselines from 9.5 m to 69.1 m in the frequency range of 300–355 GHz. To follow up on some of the detected narrow lines with higher angular and spectral resolution, we repeated the observations at 337.5 GHz with the SMA in the extended configuration on 2008 February 19. The baseline lengths in this configuration range from 44.2 m to 225.9 m. The synthesized beam sizes were $3'' \times 2''$ and $0''.8 \times 0''.6$ in the subcompact and extended array observations, respectively. Table 1 summarizes the observational parameters on the five tracks of observations which are relevant for the data presented here. The duration of each track was from 7 to 9 hr. The phase center was $\alpha(2000) = 09^h47^m57^s.38$, $\delta(2000) = +13^\circ16'43''.70$ for all observations. All the tracks in subcompact configuration

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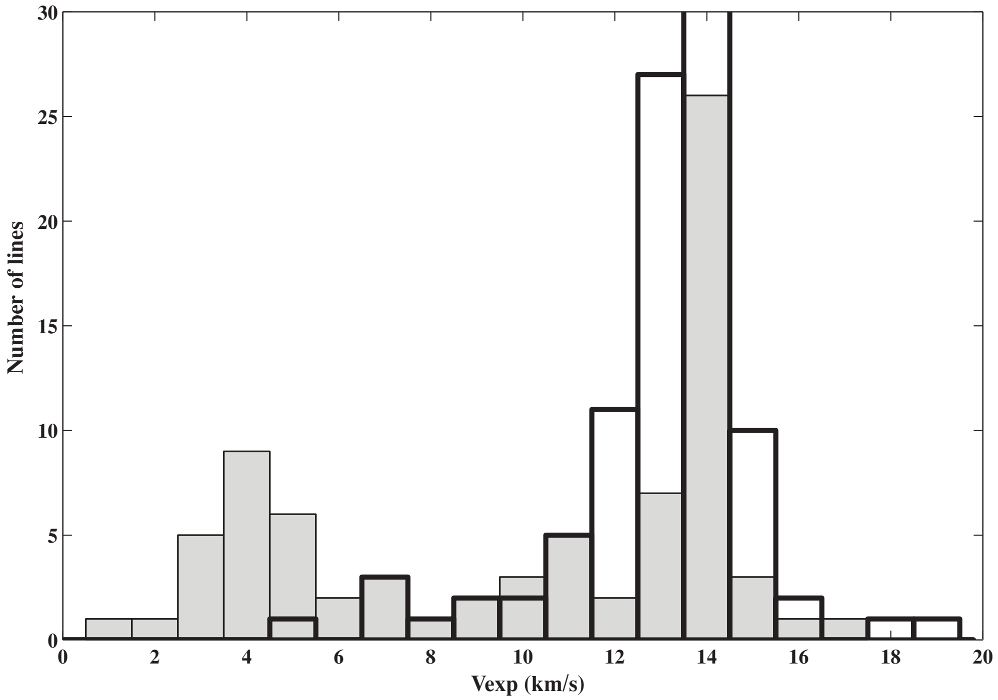

Figure 1. Distribution of expansion velocities derived from lines detected in the circumstellar envelope of IRC+10216. The uncertainty in $V_{\rm exp}$ is ~ 0.2 km s^{-1}(1σ). The white bars with bold outlines are from the recent line survey of He et al. (2008) which is representative of all single-dish line surveys toward IRC+10216 at cm to submm wavelengths. The bin at 14 km s^{-1} is shown truncated here; it actually consists of 170 lines. The gray bars represent SMA observations, showing a new population of narrow lines which peaks at ~ 4 km s^{-1}.

Table 1
Summary of Observations

Date	SMA Configuration	Tuning	Synthesized Beam	$\tau_{225\rm GHz}$	$T_{\rm sys}$ (SSB, K)
2007 Feb 7	Subcompact	299.1 GHz (LSB)	$3\farcs2 \times 2\farcs4$, P.A. = $-4°$	0.08	180–270
2007 Feb 8	Subcompact	301.1 GHz (LSB)	$3\farcs3 \times 2\farcs4$, P.A. = $-6°$	0.09	160–230
2007 Feb 9	Subcompact	337.5 GHz (LSB)	$3\farcs0 \times 2\farcs4$, P.A. = $-8°$	0.08	180–350
2007 Feb 12	Subcompact	334.4 GHz (LSB)	$3\farcs0 \times 2\farcs2$, P.A. = $-3°$	0.05	130–260
2008 Feb 19	Extended	337.5 GHz (LSB)	$0\farcs8 \times 0\farcs6$, P.A. = $-88°$	0.03	100–250

were carried out in mosaiced mode, with five pointings with offsets in R.A. and decl.: $(0'', 0'')$ and $(\pm 12'', \pm 12'')$. The extended configuration observations were carried out with single pointing toward IRC+10216. Titan and the quasars 0851+202 and 1055+018 were observed every 20 minutes for gain calibration. The spectral bandpass was calibrated using observations of Mars and Jupiter. Absolute flux calibration was determined from observations of Titan and Ganymede.

The visibility data were calibrated using the *Miriad* package (Sault et al. 1995). The mosaiced images are deconvolved using the Miriad task *mossdi*; the resulting synthesized beams are summarized in Table 1. Maps of continuum emission show the peak to have a position offset of $(\Delta\alpha, \Delta\delta) \approx (0\farcs7, 0\farcs2)$ from the phase center position quoted above. The absolute position measurements in the continuum emission are estimated to be accurate to $\sim 0\farcs1$. Taking into account the proper motion of IRC+10216 of $(\dot{\alpha}, \dot{\delta}) \approx (26, 4)$ mas yr^{-1} determined by Menten et al. (2006) our position is, within the mutual uncertainties, consistent with that determined by those authors. The continuum emission was unresolved at the highest angular resolution of $\sim 0\farcs8$. The integrated continuum flux density was 0.84 Jy at 301.1 GHz and 1.17 Jy at 337.5 GHz, with an uncertainty of about 15% in the absolute flux calibration. All the spectra shown below were produced by integrating the continuum-subtracted line intensity in a $2'' \times 2''$ rectangle centered on the continuum peak (by means of the Miriad task *imspec*).

3. EXPANSION VELOCITIES

Within a $3''$ beam a total of 92 lines were detected in the first phase of the SMA line survey of IRC+10216 at the central position. Truncated parabolic line profiles were fitted using the CLASS package (using the *shell* model for the line profile) with one of the fitted parameters being $V_{\rm exp}$, the expansion velocity of the circumstellar shell. From this sample, 25 lines have $V_{\rm exp} \leqslant 7$ km s^{-1}and of these, 12 are as yet unidentified. Several are tentatively identified to be lines of salts such as KCN, NaCl, and NaCN. Some of the lines may result from known molecules in vibrationally excited states, such as the $\nu_3 = 1$ $15_{7,9} - 14_{7,8}$, $15_{7,8} - 14_{7,7}$ doublet of SiCC at 345727.3 MHz. Figure 2 shows a sample spectrum toward IRC+10216 observed on 2008 February 9 over a 2 GHz wide band centered at 337.5 GHz. A comparison with the line survey of Groesbeck et al. (1994) (see their Figure 1) shows that only the C^{34}S $J =$ 7–6 line at 337.396 GHz was detected in their observations. All of the new narrow lines were missed in this previous survey due to poorer sensitivity. Here, we present results on the lines which

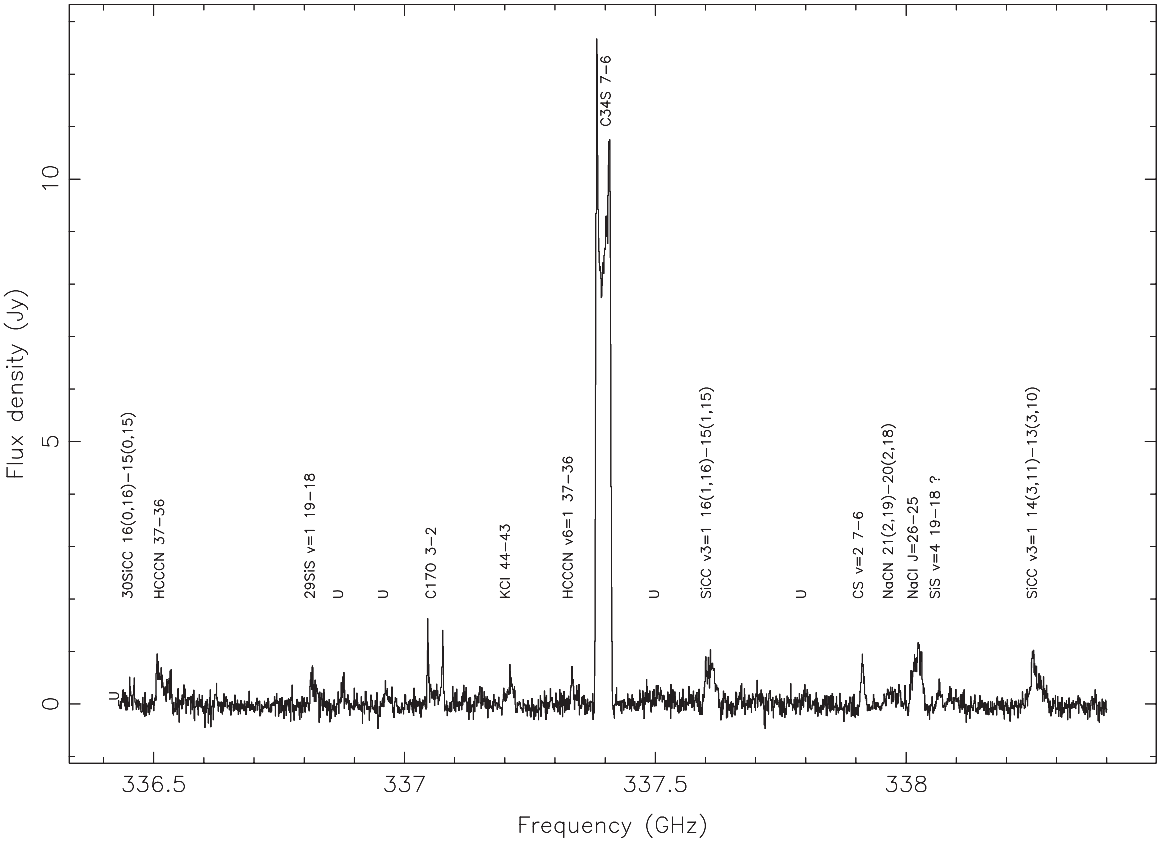

Figure 2. Sample spectrum toward IRC+10216 showing several examples of narrow lines. Over this frequency range, the only line detected in a previous line survey (Groesbeck et al. 1994) was the $C^{34}S$ $J = 7$–6 line at 337.396 GHz. This line has a $V_{\rm exp} = 13.9$ km s^{-1}. All the other lines are new detections and several of them are narrow ($V_{\rm exp} < 7$ km s^{-1}).

Table 2
Summary of Narrow Lines

Species	Transition	Rest Frequency[a] (MHz)	Catalog Frequency[b] (MHz)	$V_{\rm exp}$ (km s^{-1})	Peak Flux Density[d] (Jy)	Integrated Flux Density (Jy km s^{-1})	Deconvolved Size	T_B[c] (K)
CS	$v = 2$ $J = 7$–6	337913.246 ± 0.18	337912.189	5.1 ± 0.1	0.78	7.0	< 0″.2	>237.0
$Si^{34}S$	$v = 1$ $J = 17$–16	298630.441 ± 0.69	298629.989	4.5 ± 0.4	0.36	2.6	< 1″.9 × 0″.2	>138.7
$Si^{34}S$	$v = 1$ $J = 19$–18	333733.581 ± 0.32	333731.998	5.7 ± 0.1	0.49	4.5	< 2″.3 × 0″.5	>183.3
^{29}SiS	$v = 1$ $J = 17$–16	301390.406 ± 0.25	301388.939	4.8 ± 0.2	0.52	3.8	< 1″.9 × 0″.8	>198.3
^{29}SiS	$v = 1$ $J = 19$–18	336819.842 ± 0.32	336814.954	7.5 ± 0.1	0.50	4.6	< 0″.9 × 0″.6	>152.9

Notes.
[a] Assuming a systemic velocity of −26.2 km s^{-1}.
[b] From the Cologne Database of Molecular Spectroscopy.
[c] Lower limit in brightness temperature assuming source size of 0″.2 × 0″.2.
[d] Typical uncertainty is 0.1 Jy.

are securely identified as rotational transitions in vibrationally excited states of molecules that are well known to be abundant in IRC+10216's envelope.

In previous single-dish line surveys of IRC+10216 (Cernicharo et al. 2000; Kawaguchi et al. 1995; Avery et al. 1992; Groesbeck et al. 1994) $V_{\rm exp}$ is not tabulated, but it can be seen from published spectra to be ∼ 14.5 km s^{-1} for all lines. From the latest published line survey by He et al. (2008) (see their Table 9), we can plot a distribution of $V_{\rm exp}$ which is shown in Figure 1 as empty bars with bold outlines. This histogram peaks at 14 km s^{-1}. The distribution of $V_{\rm exp}$ from our line survey is shown in Figure 1 as grey bars. Our line survey shows a peak in the same bin of 14 km s^{-1} but reveals a significant number of narrow lines with velocities around ∼ 4 km s^{-1}. Both histograms show a continuous distribution of expansion velocities between these two peaks at 4 and 14 km s^{-1}.

Lines with $V_{\rm exp} \leqslant 10$ km s^{-1} from IRC+10216 have been reported by Highberger et al. (2000) and were assigned as vibrationally excited SiS and CS lines. He et al. (2008) found four lines with $V_{\rm exp} = 7$–10.2 km s^{-1} (see their Table 14)—all from vibrationally excited SiS. Narrow maser lines in IRC+10216 from SiS and HCN were reported by Fonfría Expósito et al. (2006) and Schilke & Menten (2003), respectively. Ford et al. (2003) detected OH, which has a narrow width (5.8 km s^{-1}), but this line appears at −37 km s^{-1}, blueshifted with respect to the systemic velocity of the star of −26 km s^{-1}. All the narrow lines we have observed are centered at the systemic velocity of about −26 km s^{-1} to within ∼ 2 km s^{-1}.

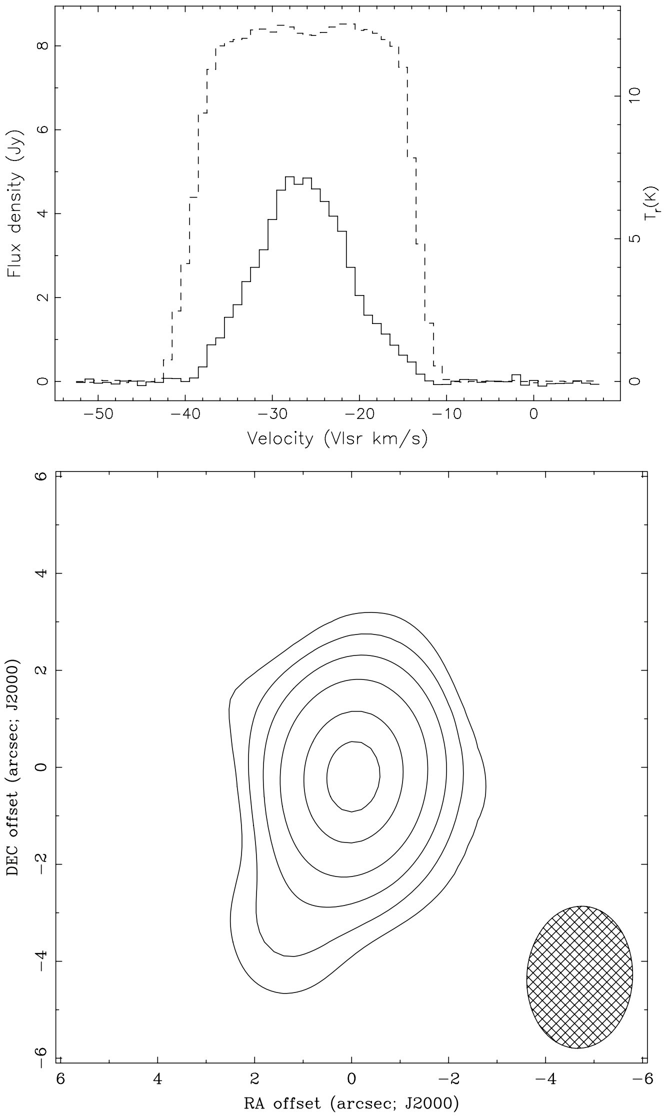

Figure 3. Upper: spectrum of SiS $v = 1$, $J = 19$–18 line obtained from a 2 arcsec^2 square centered on the star, with $V_{\rm exp} = 10.6$ km s^{-1}. For comparison, the SiS, $v = 0$, $J = 19$–18 line is shown by the dashed line (scaled down by a factor of 10). The $v = 0$ line has an expansion velocity of 13.5 km s^{-1}. Note that the intensity values for this line are scaled down by a factor of 10 in this figure. Lower: integrated intensity emission from the SiS $v = 1$, $J = 19$–18 line. The contours levels are −5, 5, 10, 20, 40, 80, 120 × 0.45 Jy beam^{-1} km s^{-1}. The coordinate offsets are with respect to $\alpha(2000) = 09^{\rm h}47^{\rm m}57\overset{\rm s}{.}43$, $\delta(2000) = +13°16'43\overset{''}{.}98$. The synthesized beam is shown in the lower right corner. See also Table 2.

Infrared molecular line profiles in the 10 μm band were observed and analyzed by Keady & Ridgway (1993). They proposed (see their Figure 3) an expansion velocity as a function of radius with: (1) $V_{\rm exp} = 3 \sim 4$ km s^{-1} from $1\sim 8R_*$, (2) rapid acceleration from 4 to 11 km s^{-1} from 8 to 10 R_*, and (3) slower acceleration from 11 km s^{-1}to the terminal velocity of 14 km s^{-1} from 10 to 20 R_*. The histogram of expansion velocities (Figure 1) peaks at ∼ 4 km s^{-1} and ∼ 14 km s^{-1}, consistent with this velocity structure.

4. VIBRATIONALLY EXCITED SiS, ^{29}SiS, AND Si^{34}S

SiS is an abundant molecule in IRC+10216, one of the parent molecules found close to the star (Glassgold 1996), and an important source of Si for the formation of silicon carbides such as SiC, SiC$_2$, and SiC$_4$ (e.g., McCarthy et al. 2003). Figure 3 (top) shows the spectrum of SiS $v = 1$, $J = 19$–18 emission at 343100.98 MHz (rest frequency), observed on 2007 February 12. This line was previously detected (but not mapped) in the single-dish line survey of Groesbeck et al. (1994), where it is significantly weaker than here because of poorer sensitivity (we have longer integration time as well as larger collecting area with the SMA). Figure 3 (bottom) shows a map of the integrated intensity emission over the velocity interval of −40 to −10 km s^{-1}. The total integrated flux density is 69.1 Jy km s^{-1}. The deconvolved source size is $1\overset{''}{.}1 \times 0\overset{''}{.}5$ with P.A. of −27°.6. Assuming a size of $0\overset{''}{.}5 \times 0\overset{''}{.}5$, we estimate a lower limit to the brightness temperature of 200 K.

The emission appears to have an extended weak feature toward the southeast. High angular resolution near-IR adaptive-optics images of IRC+10216 show evidence of azimuthally asymmetric structures in the inner circumstellar envelope, over angular scales of ∼ 2″ (Menut et al. 2007). The 3″ angular resolution of our observations is insufficient to allow a detailed comparison between the submillimeter line emission maps and near-IR images.

The expansion velocity of the SiS $v = 1$, $J = 19$–18 line is 10.6 km s^{-1}. This is an example of a line of intermediate expansion velocity (see Figure 1), in the rapidly accelerating zone of the envelope where presumably dust has already been formed.

Figure 4 shows spectra of Si^{34}S and ^{29}SiS $v = 1$, $J = 17$–16 and 19–18 lines, detected toward IRC+10216 for the first time. This emission is unresolved and the source-size upper limits are shown in Table 2. Assuming that the size of the emitting region is $0\overset{''}{.}2$, we estimate the brightness temperature to be 140–200 K, which should be considered as lower limits. We estimate a column density of 7×10^{17} cm^{-2} and abundance of 7×10^{-7} for ^{29}SiS for an assumed excitation temperature of 550 K.

From the observed integrated intensities of SiS, ^{29}SiS, and Si^{34}S $v = 1$, $J = 19$–18 emission, we derive the isotopic abundance ratios $[^{28}{\rm Si}/^{29}{\rm Si}] = 15.1 \pm 0.7$ and $[^{32}{\rm S}/^{34}{\rm S}] = 19.6 \pm 1.3$ (uncertainties are 1σ). For comparison, previously published values from single-dish observations (Kahane et al. 1988; He et al. 2008) are 20.2 ± 2 for $[^{32}{\rm S}/^{34}{\rm S}]$ (in good agreement with our estimate here) and 18.7 ± 1 for $[{\rm Si}/^{29}{\rm Si}]$ (marginally larger than our value). A possible cause for disagreement might be non-negligible optical depths.

5. VIBRATIONALLY EXCITED CS

Vibrationally excited CS radio emission in IRC+10216 was first detected by Turner (1987) in the $v = 1$, $J = 2$–1 and 5–4 transitions. These lines were re-observed along with new detections of the $J = 3$–2, 6–5, and 7–6 transitions by Highberger et al. (2000). The $J = 7$–6 emission reported here is the first detection in the $v = 2$ state (Figure 5). The triangular line profile is indicative of spatially unresolved emission from accelerating gas (Bujarrabal et al. 1986). In subcompact configuration observations with angular resolution of ∼ 3″, the emission appears highly concentrated and unresolved. There is no emission detected at the angular radius of ∼ 12″ (where several other species have shown a peak in abundance in previous interferometric maps). The observations of this line were repeated in the extended configuration of the SMA at a beam size of $0\overset{''}{.}8$, confirming that the emission is unresolved. The deconvolved source size is less than $0\overset{''}{.}2$. The lower limit for brightness temperature is 237 K. Assuming an excitation temperature of 550 K, we estimate a column density of 7×10^{17} cm^{-2} and a lower limit for

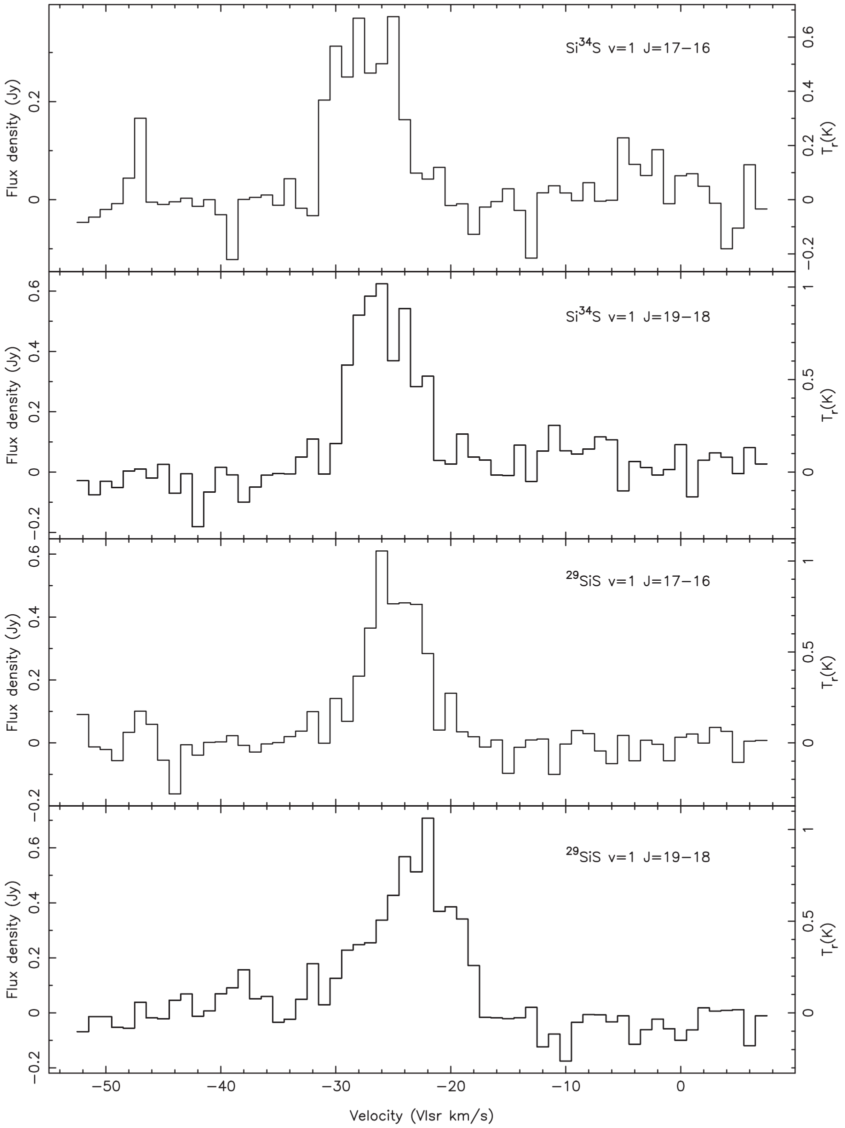

Figure 4. Spectra of vibrationally excited rotational lines in isotopes of SiS obtained from the imaged data cube. The flux density was calculated over the area enclosed in a 2 arcsec^2 square centered on the star. See also Table 2.

CS abundance with respect to H_2 of 9.3×10^{-6} within a radius of $\sim 4.5 \times 10^{14}$ cm ($\sim 7\ R_*$).

Previous interferometric observations of the $v = 1$, $J = 5$–4 line show the emission to be within a radius of 0.″35 ($\sim 10\ R_*$ or $\sim 7 \times 10^{14}$ cm) (Lucas & Guelin 1999). Young et al. (2004) derived a lower limit on the CS abundance to be 3.4×10^{-9} within $\sim 34 R_*$. From single-dish observations of CS $v = 1$, $J = 3$–2, 6–5, and 7–6 lines, Highberger et al. (2000) estimate an abundance of 3–7×10^{-5} relative to H_2. From comparison with the CS radial abundance predicted by chemical models, we conclude, as did Young et al. (2004), that the model of Millar et al. (2001) predicts too low a value ($\sim 10^{-11}$) at the radius of $\sim 10^{16}$ cm. In this model, assuming CS to be a parent molecule (see Figure 1, right panel, in Millar et al. 2001), the initial abundance is still lower by about an order of magnitude relative to that derived from submillimeter observations. Moreover, the drop in CS abundance with radius (owing to the production of other sulfur-bearing molecules), is too small, and not consistent with the compact distribution of CS seen in the SMA observations. There is better agreement in a more recent study of nonequilibrium chemistry of the inner wind, which takes into account shocks induced by stellar pulsation (Cherchneff 2006), although these models seem more relevant for S stars (C/O $\approx$ 1).

The CS $v = 2$, $J = 7$–6 transition requires extreme excitation conditions since it corresponds to an energy $E_u/k = 3707$ K. As noted by Highberger et al. (2000), even for the $v = 1$ line, collisional excitation with H_2 would require very high gas densities (~ 1–5×10^{14} cm^{-3}). This line emission is most plausibly excited by 8 μm stellar thermal radiation.

6. CONCLUSIONS

Preliminary results from the SMA line survey of IRC+10216 have yielded a population of narrow lines with expansion velocities of ~ 4 km s^{-1}. About half of these can be assigned to vibrationally excited rotational transitions of abundant species such as CS, SiS, and their isotopomers. The emission is found to occur in a very compact region smaller than 0.″2 around the star. This is thought to be the region where dust is forming in the envelope, and in which the material has just begun accelerating and has yet to attain the terminal velocity of ~ 14 km s^{-1}. The

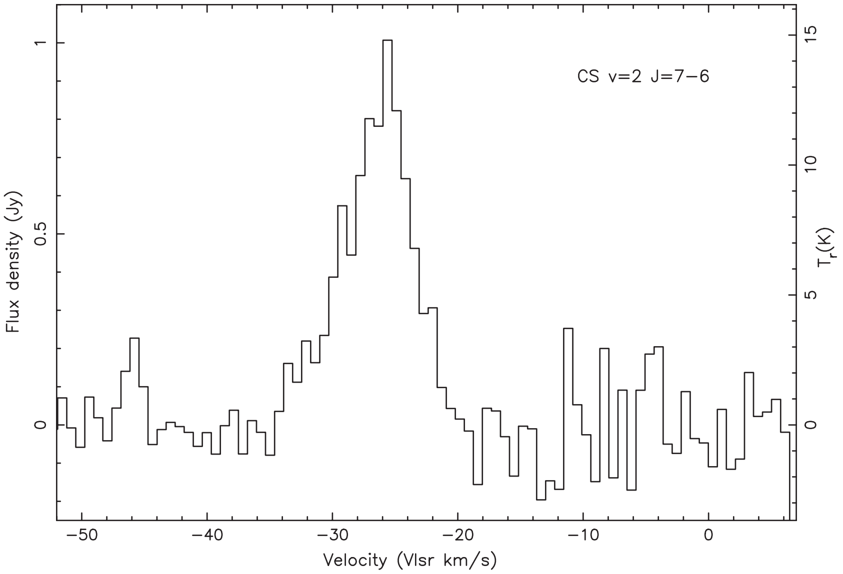

Figure 5. Spectrum of CS $v = 2$, $J = 7$–6 emission at 337912.19 GHz. See Figure 4 caption and also Table 2.

CS $v = 2$, $J = 7$–6 line is most likely radiatively excited, because collisional excitation would require an unrealistically high gas density and abundance of CS.

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