Monitor Variability of Millimeter Lines in IRC+10216

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Abstract

A single dish monitoring of millimeter maser lines SiS $J = 14-13$ and HCN $\nu_2 = 1/ J = 3-2$ and several other rotational lines is reported for the archetypal carbon star IRC+10216. Relative line strength variations of $5\% \sim 30\%$ are found for eight molecular line features with respect to selected reference lines. Definite line-shape variations are found in limited velocity intervals of the SiS and HCN line profiles. The asymmetrical line profiles of the two lines are mainly due to the varying components. The dominant varying components of the line profiles have similar periods and phases to the IR light variation, though both quantities show some degree of velocity dependence; there is also variability asymmetry between the blue and red line wings of both lines. Combining the velocities and amplitudes with a wind velocity model, we suggest that the line profiles are due to SiS and HCN masers emanating from the wind acceleration zone. The possible link of the variabilities to thermal, dynamical, and/or chemical processes within or under this region is also discussed.

Key words: circumstellar matter – line: profiles – masers – stars: individual (CW Leo) – stars: variables: general – submillimeter: stars

1. Introduction

Variability studies of molecular emission lines in strongly pulsating carbon rich asymptotic giant branch (AGB) stars (carbon stars) are very rare, perhaps because of the lack of strong radio masers in them and the poor absolute millimeter-line flux calibration accuracy for most ground-based telescopes. Only few works contributed to this topic (Carlstrom et al. 1990; Groenewegen & Ludwig 1998; Cernicharo et al. 2014). The discovery of weak masers in millimeter wavelengths toward some carbon stars (see, e.g., Henkel et al. 1983; Turner 1987; Lucas & Cernicharo 1989; Cernicharo et al. 2000; Schilke et al. 2000; Fonfría Expósito et al. 2006; Gong et al. 2017) offers the possibility to monitor the low rotational transitions of circumstellar molecules with existing millimeter telescopes. These maser lines are usually emitted from the inner region of the circumstellar envelop (CSE). This makes them good tools for studying the properties of the dynamical atmosphere of the pulsating stars.

IRC+10216 (or CW Leo) is an archetypal carbon star that is very rich in molecular line emission (see the most recent examples in He et al. 2008; Cernicharo et al. 2010; Tenenbaum et al. 2010a; Neufeld et al. 2011; Patel et al. 2011; Decin et al. 2015; Gong et al. 2015, among others) and serves as a benchmark for molecular line studies in CSE. Most of the weak maser lines in carbon stars were also discovered in this object. For example, the first centimeter maser SiS $J = 1-0$ (18.155 GHz) was discovered in IRC+10216 by Henkel et al. (1983), confirmed by Nguyen-Q-Rieu et al. (1984), and newly explored by Gong et al. (2017). Later on, millimeter masers were found in more ground and vibrational levels of SiS, including $J = 11-10, 14-13$, and $15-14$ lines in the $\nu = 0$ state and $J = 12-11, 13-12$, and $14-13$ lines in the $\nu = 1$ state in this star (Turner 1987; Fonfría Expósito et al. 2006). Another molecule also versatile in maser emission is HCN. At least four maser lines have been found in the low lying vibrational states in IRC+10216: $(01^40), J = 2-1$ (Lucas & Cernicharo 1989); $(02^30), J = 1-0$ (Lucas & Guilloteau 1992); $(04^00), J = 9-8$ (Schilke et al. 2000); and $(01^00) - (04^00), J = 10-9$ (Schilke & Menten 2003). A maser phenomenon has also been reported for CS $\nu = 1, J = 3-2$ (Cernicharo et al. 2000; Hightberger et al. 2000) and possibly for the oxygen bearing molecular lines OH 1665/1667 MHz (Ford et al. 2003) and even H$_2$O 6$_{1,6} - 5_{2,3}$ (Han et al. 1998) in this star.

However, millimeter-line variability studies are relatively lacking for IRC+10216. Besides the earlier attempt of Carlstrom et al. (1990), the only work that successfully revealed the millimeter-line variability in this star is Cernicharo et al. (2014) who used Herschel HIFI spectra. Combining several sparsely sampled epochs, they found that some lines of spatially extended species such as the SiCC and low-J CO lines showed little variation, while some other molecular lines such as high-J CO, CS, SiO, SiS, HCN, CCH $N = 6-5$, and H$_2$O lines all show evident variability. In particular, the varying CCH $N = 6-5$ line was argued to be emitted from an extended region in the CSE, which, together with the far-infrared (IR) variability of dust emission found by Groenewegen et al. (2012), demonstrated the importance of IR excitation/Heating of dust and gas in the outer parts of the CSE.

In the inner CSE of IRC+10216, some molecular emission lines are also expected to vary with time because of the variation of IR light and gas temperature, the rise and fall of pulsation shocks, and the ensuing varying shock chemistry (see, in particular, the chemical simulations for the case of IRC+10216 by Cherchneff 2011, 2012), and possibly dust formation instability.
Masers are interesting phenomena in space and are one of the best tracers of variability due to their sensitive dependence upon the variation of pumping agents (Elitzur 1992). However, the lack of strong radio masers makes them almost useless to carbon stars. Weaker maser lines in millimeter wavelengths could regain their usefulness to carbon stars with large interferometers like ALMA. Identifying these maser lines and investigating their properties through variability studies is a good approach for both single dishes and interferometers.

The large flux calibration uncertainty that prevented us from detecting the line variation with ground-based telescopes can be greatly reduced by studying the relative variation of lines in the same side band. The relative line variations could provide us with important information regarding these processes.

We report in this work the discovery of relative line strength and line-shape variation for eight line features around 1.1 mm wavelength, including two candidate millimeter maser lines, SiS ν = 0, J = 14-13, and HCN ν2 = 1′′, J = 3-2, toward IRC+10216. The design of the monitoring, the observations and data processing are described in Section 2, the results and the characteristics of line intensity and line profile variabilities are presented in Section 3. We discuss the remaining uncertainties and how to understand the results in Section 4 and summarize the new findings in Section 5. Part of the results and some notes are given in the appendices.

2. Monitoring Strategy, Observation, and Data Processing

2.1. Observations

The monitoring observations were made during a period of 523 days from 2007 December 3 to 2009 May 9, with a gap of about a half year (169 days, from 2008 May 26 to November 11). Thus the monitoring period covers nearly a whole IR variation period (630 days, Menten et al. 2012). In total, 27 epochs are sampled. The first 17 epochs before the gap were sampled roughly once every 10 days, while the other 10 epochs were sampled roughly once every 20 days. However, there was an issue with the spectrometer on 2008 April 25 in the LSB, which lead to the LSB data being unusable at that epoch. Therefore, useful LSB data are available only for 26 epochs.

The ALMA band-6 receiver was used at the 10 m Submillimeter Telescope (SMT) of the Arizona Radio Observatory on Mt. Graham. Both the USB and LSB were observed simultaneously with Filter Banks that have a 1 GHz frequency coverage and 1 MHz resolution each (centered at 266.80 and 254.55 GHz respectively). The weather was better in the first period than in the second, with an average τ (1.3 mm) = 0.27 and 0.36 before and after the time gap respectively. The system temperatures were about 300 K in LSB and 350 K in USB on average. The average on-source integration time was about 51 minutes, ranging from 30 to 76 minutes at various epochs. This results in an average rms baseline noise of 12 mK at a spectral resolution of 1 MHz for both side bands. The observation was done in beam switch mode with a 2′ throw at 2 Hz frequency. The image rejection ratio was measured each time for both side bands and it was found to usually be in the range of 10–20 dB. When the image rejection was not very high, the strongest line SiS J = 14-13 in our LSB can emerge in the USB as a false feature at several epochs (see the details in the results below). The beam size is about 29″. A main beam efficiency of 0.75 can be adopted for both side bands.

2.2. Data Processing

The observational data were reduced using the GILDAS/CLASS software. The baseline is always straight and thus only a linear baseline was removed from each side band spectrum (after averaging together sub-scans). The spectra at individual epochs are also averaged together to yield very deep overall average spectra with an rms baseline noise of 1.6 mK in LSB and 2.0 mK in USB. The deep overall average spectra allows us to identify many weak line features in the two 1 GHz spectral windows that are usually invisible in individual epoch data.

Some detected line features are actually not single lines but groups of blended lines from different carriers or different transitions of the same molecules, we treat the blended lines as a whole in this work.

3. Results

3.1. Line Identification and Line Profile Examples

The very deep cumulative exposure in the spectra averaged over all epochs (overall average spectra hereafter) allows us to detect 47 lines in the two side bands (including blended lines, but hyper-fine splits are merged and counted as a single line). The line carriers are identified using the CDMS\(^7\) (Müller et al. 2001, 2005) and Splatalogue\(^8\) line lists. Besides the eight unidentified lines (U-lines; three in USB and five in LSB), the other 39 lines belong to 17 molecules. Rotational lines from excited vibration states are detected for C\(_2\)H, HCN, H\(^3\)CN, and SiS. The transition list is given in Table 2 in Appendix A. Some lines are partially or totally blended with each other and considered together as a single composite line feature in the variability analysis. In total, 30 line features are defined (18 in USB and 12 in LSB). The eight strongest line features used for light-curve analysis are summarized in Table 1. The plots of the overall average spectra, as well as more comments, are given in Appendix A.

As an example, we show in Figure 1 the spectral line profiles of selected stronger line features at three selected epochs to illustrate how they change with time. In particular, they include the three in-band calibrator lines in the top row and the two candidate maser lines of SiS and HCN (the left panels in the middle and bottom rows).

3.2. Relative Variation of Line Strength

The line strengths are calibrated using relatively stable lines in each side band as calibrators: SiCC12,10–10,19 (LSB), and the average strength of C\(_4\)H\(_2\)N = 28-27, J = 57/2-55/2, and J = 55/2-53/2 (USB). They are expected to be stable because they are from the vibrationally ground state and have extended emission regions in IRC+10216. Particularly, the Herschel observations by Cernicharo et al. (2014) have nicely confirmed the stability of the SiCC rotational lines in large beams.

An “in-band flux calibration factor” for each side band at each epoch is defined in two steps: first, we compute the average strength of the calibrator lines over all epochs; then the calibration factor is set to be equal to the average-to-individual flux ratio of the calibrator line. Each target line feature is in-band calibrated by multiplying with this factor. The calibration can be done either to integrated line strengths or to line profiles.

\(^7\)http://www.astro.uni-koeln.de/cdms/catalog

\(^8\)http://www.cv.nrao.edu/php/splat/
However, we note that if the reference lines are also varying their variations will be intricately involved in the calibrated line fluxes.

The relative line variation will be compared to the well established near-infrared (NIR) variations. We adopt the NIR light curve of IRC+10216 from Menten et al. (2012). They used the NIR photometry of Shenavrin et al. (2011) from 1999 December 10 to 2008 November 11 and found a weighted-mean period of 630.0 ± 2.9 days and a maximum epoch at JD 2454554.0 ± 7.4 from the light curves of H, K, L, and M bands. Their light curves are slightly different from the NIR light curves of Men’shchikov et al. (2001) who used photometry data during 1965 to 1998. Thus, the newer one is closer to our observation epochs. Men’shchikov et al. (2001) mentioned a K-band amplitude of about 15%. The amplitudes in Figure A.1 of Menten et al. (2012) range from about 0.76% in J-band to 0.55% in M-band. Thus, the NIR continuum flux variation amplitudes are in the range from 60% to a factor of 2.5. The variation amplitude of the stellar luminosity can be inferred from Equation (1) of Men’shchikov et al. (2001) to be about 44%.

The relative light curves of the eight strongest line features are compared to the extrapolated NIR light curve in Figure 2. The fluctuation of data points is larger in the second half of each light curve due to worse weather. The four light curves that closely follow the period and phase of the NIR variation are gathered in the left panel, while the other four that vary differently are in the right panel.

We can characterize the main properties of the relative light curves by fitting a sinusoidal light-curve model to each of them:

\[ I_{\text{fit}}(t) = A \cos[2\pi(t/P - \phi_0)] + Z. \]

Here \( t \) is the time, \( A, P, \) and \( \phi_0 \) are the amplitude, period, and phase of the fitted sinusoidal component and \( Z \) is the the average line strength. All four parameters are free parameters determined through \( \chi^2 \) minimization weighted by observation errors. For convenience, the phase \( \phi_0 \) is expressed in terms of the NIR phase.

The fitting results are shown in Table 1. The last column of the table gives the minimum \( \chi^2 \) values of the model fitting. They range from about 40 to 4390 and are always larger than the degree of freedom (22 or 23, the number of epochs minus the number of free independent parameters), indicating that either additional statistical errors in addition to basline rms noise exist or the observed relative light curves cannot be adequately represented by a single sinusoidal light curve. Thus, the 1σ statistical errors of the parameters in the parentheses in Table 1 could be underestimated to some extent.

Despite the possible underestimate of the parameter uncertainties, the fitting results in Figure 2 and Table 1 still reveal several important facts: (1) Most of the line features have fitted periods that are not far from the NIR period of 630 days, though longer (e.g., 1182 days for \(^{29}\)SiS + HCN \( \nu_2 = 2^0 \)) and shorter (e.g., 444 days for HCN \( \nu_2 = 1^0 \) J = 3-2) periods exist. (2) The relative amplitude (A/Z from Table 1) can reach about 30% for the weaker line features, but remains at only 5%–8% for the two strongest lines, SiS J = 14-13 and HCN \( \nu_2 = 1^0 \) J = 3-2. Therefore, the relative line variations in this work are no larger than the NIR or luminosity variation (higher than 40%).

### 3.3. Line-shape Variation

We mainly discuss the channel by channel line-shape changes of the two strongest lines, HCN \( \nu_2 = 1^0 \) J = 3-2 and SiS J = 14-13, in this subsection. The possible line-shape variation of several other weaker lines is discussed in Appendix B (online only) and is argued to be mainly due to pointing errors.

The variation of line shape can be investigated in two ways. One way is to directly normalize the line profile with respect to a specified reference velocity channel. The other way is to first apply the in-band calibration and then straightforwardly decompose the light curves of each velocity channel into three components: a “constant component” that does not change with time, a “co-varying component” that is entirely in-phase with the variation in the reference channel, and a “differential

### Table 1

| Freq (MHz) | Line Feature | \( V_a \) (km s\(^{-1}\)) | \( V_b \) (km s\(^{-1}\)) | \( P \) (day) | \( A \) (K km s\(^{-1}\)) | \( \phi_0 \) | \( Z \) (K km s\(^{-1}\)) | \( \chi^2_{\text{min}} \) |
|-----------|--------------|----------------|----------------|-------------|------------------|----------|----------------|----------------|
| LSB:      |              |                |                |             |                  |          |                |                |
| 254103.20 | SiS 14-13    | -4.10          | -11.0          | 680(18)     | 7.36(0.20)       | -0.03(0.01) | 136.000(1.5) | 4391           |
| 254216.14 | SiO 6-5      | -4.10          | -11.1          | 759(75)     | 0.460(0.04)      | +0.63(0.06) | 4.350(0.03)   | 143            |
| 254683.00 | Na\(^+\)Cl, CH\(_2\)NH, HC\(_3\)N | -63.1          | 10.4           | 708(50)     | 0.64(0.04)       | +0.56(0.05) | 4.55(0.03)    | 53             |
| USB:      |              |                |                |             |                  |          |                |                |
| 266500.88 | C\(_2\)H\(_3\)J\(_2\)J\(_2\) \( \nu_2 = 1^e \) | -4.10          | -11.0          | 695(50)     | 0.61(0.04)       | +0.00(0.02) | 2.080(0.03)   | 42             |
| 266771.19 | C\(_2\)H\(_3\)J\(_2\)J\(_2\) \( \nu_2 = 1^f \) | -4.10          | -11.0          | 678(40)     | 0.74(0.04)       | -0.01(0.01) | 2.91(0.04)    | 65             |
| 267120.00 | C\(_2\)N\(_3\)CCCN, HCN \( \nu_2 = 2^2 + 2^e \) | -45.0          | 7.7            | 586(31)     | 0.62(0.05)       | +0.01(0.02) | 2.13(0.05)    | 75             |
| 267199.28 | HCN \( \nu_2 = 1^f \) J = 3-2 | -4.10          | -9.0           | 445(9)      | 1.21(0.11)       | +0.61(0.01) | 14.84(0.09)   | 1412           |
| 267243.00 | \(^{29}\)SiS, HCN \( \nu_2 = 2^0 \) | -42.0          | -10.0          | 1182(58)    | 3.53(0.25)       | -0.01(0.05) | 11.66(0.25)   | 1242           |

**Note:** Average lab frequency is used to represent a blended line group and to define its systemic velocity −26.5 km s\(^{-1}\). The other quantities are the velocity range (\( V_a \sim V_b \)) for the integrated line strength, the four light-curve parameters (\( P, A, \phi_0, \) and \( Z \)) defined in Equation (1) and the minimum \( \chi^2 \) value for the best fit. The maximum phase is expressed in the IR variation phase and the zero IR phase corresponds to the IR maximum on JD 2454554.0. For the four line features in the right panel of Figure 2, the phase corresponds to the maximum of the fitted light curve after the time gap of our monitoring.

\(^9\) They originally mentioned \(^2\)n, which we assume to be the full range of variation, because otherwise it is too large compared to the light curves in Menten et al. (2012).
variation component” that is independent of the variation in the reference channel (see more details in the next paragraphs). The two ways involve the flux uncertainties differently, so that the comparison of their results can help us assess the successfulness of the in-band calibration procedure.

Here we explain the above decomposition approach in more detail. In a velocity channel, the minimum of the light curve (determined after a smoothing among five neighboring epochs) is taken as the constant component and removed from the light curve, leaving the purely varying component (with a minimum of zero). The purely varying component in the reference channel serves as the template of the co-varying component. It is scaled to other channels according to the strength of the constant component, and subtracted from the purely varying component to yield the differential variation component. The reference channel thus has no differential variation component by definition.

The decomposition approach, as compared to the normalization, has better links to the various contributing physical processes in the CSE: the constant component mainly reflects...
the contribution from the lines of some abundant species in the outer cooler part of the CSE that are mainly collisionally excited and the minimum emission level of some varying lines that do not entirely extinguish at their minimum epochs; the co-varying component roughly represents those globally varying processes that can be represented by the variation in the reference channel (e.g., those driven by the varying IR light); the differential variation component then wraps the remaining variation processes occurring locally in individual velocity (and also spatial) components (e.g., radially beamed masers or local density enhancements).

3.3.1. Results of the Normalization Approach

After the normalization with respect to the systemic velocity channel \((-26.5 \text{ km s}^{-1}\)) and the subtraction of the observed average line profile, we obtain the “line profile residual” as shown in Figure 3. In the left panel, the SiS \(J = 14-13\) line shows variability in two velocity intervals, with one in the blue wing and the other in the red wing. The variation in the blue wing is much stronger than in the red wing. The central part \((-30 \text{ to } -18 \text{ km s}^{-1}\)) of the spectrum shows little variation with respect to the systemic velocity channel, which means these velocity channels must be varying roughly in-phase with each other. In the right panel of the figure, the HCN \(\nu_2 = \frac{1}{2}\) \(J = 3-2\) line only shows variability in the blue wing of the line profile. However, the variation is visible in a broader range of velocity than the SiS \(J = 14-13\) line.

To quantify the channel by channel variability, we plot in Figures 4 and 5 the light curves of all velocity channels that show definite variability, together with their cosine function fits and fitting residual. The fittings are generally good. The minimum \(\chi^2\) values are about 20–60 for the HCN line. They are not too large compared to the number of freedom of 23 (=27 data points—4 free parameters), which means that the cosine light curve is an adequate model. For the SiS line, however, the minimum \(\chi^2\) values are still larger than several hundreds \((>22, \text{ the degree of freedom})\). This means that the offsets of the data point from the cosine fits still cannot be explained by the statistical errors from baseline noise. In the strongest channels (the top six curves in the right panel of Figure 4), smaller variability on shorter timescales of two to four weeks (earlier than the time gap) and large curvy shape (later than the time gap) can be seen. These additional variabilities and non-sinusoidal features are weaker by factors of four to seven than the major sinusoidal components.

The light-curve parameters, the amplitudes, periods, and phases, are useful for understanding the physical nature of these varying spectral features. They are plotted as functions of velocity channels in Figure 6. The following properties can be recognized.

1. (Top left panel) The maximum variation amplitude occurs around the velocity channel \(-35 \pm 0.6 \text{ km s}^{-1}\) in the blue wing of both SiS and HCN line profiles and around \(-16.2 \pm 0.6 \text{ km s}^{-1}\) in the red wing of the SiS line (the uncertainties are simply set to about one-half of

![Figure 2](image_url)

**Figure 2.** Light curves of integrated line intensity (after in-band calibration). (Left) line features that are (at least roughly) in-phase with the near-infrared light. (Right) line features that are varying differently than the NIR light. The gray curves are the cosine function fittings (the fitted parameters are in Table 1). The light curves are normalized to an average of unity and then shifted upward for clarity. The zero date is our first epoch (JD 2454438.0), while the nearest zero NIR phase (at maximum, see the upper axis and the top dotted curves) is at JD 2454554.0. The SiS and HCN line light curves are scaled up by a factor of four and two, respectively, for clarity.
the channel width). We call these velocity channels the peak channels hereafter. Thus, the blue and red-peak channels are at relative velocities of $V_{\text{sys}} - 8.5\text{ km s}^{-1}$ and $V_{\text{sys}} + 10.3\text{ km s}^{-1}$, indicating a left–right asymmetry of about 2 km s$^{-1}$.

2. (Left panel) The amplitude distribution of the HCN line is highly asymmetric with respect to the systemic velocity of the object. Variation only appears in the blue wing and extends to velocities very close to $V_{\text{sys}}$.

3. (Left panel) The full width at half maximum (FWHM, denoted as $\Delta V$) of the amplitude curve can be measured in the blue wing of the line profiles to be about 3 km s$^{-1}$ for both the SiS and HCN lines. This can be roughly converted into a characteristic velocity dispersion of $\sigma_v = \Delta V / \sqrt{8 \ln 2} \approx 1.3\text{ km s}^{-1}$ for the varying components of both lines.

4. (Left panel) The amplitude in the blue-peak channel of the SiS line is $2.456 \pm 0.004\text{ K}$, being $\sim 2.5$ times larger than that of its red-peak channel ($0.541 \pm 0.005\text{ K}$) and $\sim 13.6$ times larger than that of the blue-peak channel of the HCN line ($0.18 \pm 0.01\text{ K}$).

5. (Middle panel) The SiS line has a variation period of $\sim 610\text{ days}$ around its red-peak channel and $\sim 670\text{ days}$ around its blue-peak channel, while the HCN line has a longer period of $\sim 730\text{ days}$ around its blue-peak channel.

6. (Middle panel) The variation periods show a velocity dependence, with the SiS line periods decreasing in channels away from its blue/red-peak channels in both directions, while the HCN line periods are increasing away from its blue-peak channel in both directions. The SiS line periods are close to the NIR period of 630 days, while the HCN line periods are $\sim 100$–200 days longer.

7. (Right panel) The blue-peak channels of the SiS and HCN lines show similar phase delays of $0.04 \pm 0.01\text{ (} \sim 25 \pm 6\text{ days) with respect to the NIR light, while the red-peak channel of the SiS line shows an additional phase delay of 0.053 \pm 0.001\text{ (} \sim 33.4 \pm 0.6\text{ days) with respect to its blue-peak channel.}$

8. (Right panel) The variation phases also show velocity dependence, with the SiS line phases increasing in channels farther away from its blue/red-peak channels in both directions, while the HCN line phases decreasing in channels farther away from its blue-peak channel in both directions.

In summary, the variability properties of the blue and red line wings are not symmetrical and a velocity dependent period as well as phase variation trends exist. The SiS and HCN lines show both similar and different, or even opposite, behaviors.
3.3.2. Results of the Decomposition Approach

We first show the constant components of SiS $J = 14-13$ and HCN $\nu_2 = \frac{10}{3}$ $J = 3-2$ in Figure 7. Compared with the average line profiles in the same figure, the constant component profiles look more left–right symmetrical, as expected for a typical thermal line in this star. Therefore, the asymmetry in the average line profiles of the two lines mainly originates from the varying components.

Different from the normalization approach, the decomposition approach provides information on the variation in the reference channel at $V_{\text{sys}}$ (after in-band calibration): the co-varying component. The period and phase of this component of both the SiS and HCN lines are shown in Figure 8 to be significantly different from the NIR light variation (NIR phase marked on the top axis).

The channel-by-channel light curves of the differential variation components look very similar to the light curves in the normalization approach (in Figures 4 and 5). We do not show the similar light curves, but show in Figure 9 the parameters from sinusoidal light-curve fitting. The light-curve parameters of the co-varying component is also plotted at the $V_{\text{sys}}$ channel for comparison.

Comparing the parameters of the co-varying components (at $V_{\text{sys}}$) with that of the differential variation components (in line wings) in Figure 9, we see the following new facts.

1. (Left panel) The peak amplitudes of the differential variation components are significantly larger (SiS line) or slightly larger (HCN line) than that of the co-varying component.
2. (Middle panel) The period of the co-varying component (464 ± 16 day) of the SiS line is much shorter than that of the differential variation components and the NIR light (630 day). The period of the co-varying component of the HCN line (1139 ± 1061 day) looks much longer than that of the differential variation components and the NIR light, though its uncertainty is quite large.
3. (Right panel) The phase of the co-varying component of the SiS line is also very different from that of the differential variation components. The phase of the co-varying component of the HCN line is very noisy.

The varying component to constant component ratios (relative amplitudes) are found to be smaller than unity in all velocity channels, as shown in Figure 10. The SiS line has a peak relative amplitude of 56.4 ± 0.5% in the blue wing and 14.1 ± 0.4% in the red wing for its differential variation components, while its co-varying component has a much smaller relative amplitude of only 4.8 ± 0.4%. The HCN line has a peak relative amplitude of 38 ± 4% for its differential variation components in its blue wing, while its co-varying component has an noisy relative amplitude of 19±40%.
4. Discussion

4.1. Uncertainties in the Relative Light Curves

Although the traditional flux calibration uncertainty (typically \(\sim 20\%\)) has been greatly reduced in the in-band calibrated relative light curves and the line-shape light curves, there could be remaining effects of the uncertain factors that are neither completely removed nor fully reflected by the baseline noise of the spectral line data. They may prevent us from understanding the astrophysical origin of the relative light curves.

The most important additional source of uncertainties is the telescope pointing fluctuation. Different molecular lines can be excited in different regions of the CSE (e.g., compact, extended, or shell-like regions) and the gas density and chemical abundances are not necessarily homogeneously or smoothly distributed. Thus, the different lines and the different velocity channels of the same line can respond to the random telescope pointing offsets differently. The pointing uncertainty of the telescope is usually better than 3\(''\) (3\(\sigma\)), being small compared to the beam size of 29\(''\). The intensity variation of a point source is only about 2\% at such a beam offset, being much smaller than the intensity variation (usually 10\%–20\%) found in this work. An extended smooth emission region would be even less sensitive to such small pointing offsets. For those molecules with a shell-like emission structure that has a comparable size to our telescope beam (e.g., our in-band calibrator lines of SiCC and \(\text{C}_2\text{H}\) belong to this case), both their strengths and line shapes may be more sensitive to the telescope pointing offsets. However, as we discuss in detail in Appendix B (online only), the effect of this to their line strengths is no larger than 3\%. In addition, the pointing error should be random in nature and thus cannot explain the large regular long-period variation found in this work.

The other additional uncertainty sources are less important. There is no strong telluric line in the bandpass. The side band leakage is not an issue in our data, because the strong lines in the image side bands were all known before hand and were carefully arranged to avoid overlapping with lines in the signal side band. The image rejections were also high (10–20 db). The spectral baselines are also very straight and thus are largely free of baseline problems.

Therefore, we conclude that the observed regular long-period variations of both line strengths and line shapes are not due to observational error, but are physical in the object.

4.2. Interpretation of the Line Strength Variation

We have no reliable evidence to prove how and where the observed in-band calibrated line variations (Section 3.2) are produced. However, we can discuss one possibility: they very likely originate from the inner part of the CSE. The line emission in the outer cooler part of the CSE is usually dominated by collisional excitation by \(\text{H}_2\), which is not very sensitive to the central-star pulsation. However, observable line emission variation could arise through various mechanisms in the inner hot part of the CSE through larger changes of dust and gas temperatures due to the varying heating by IR light, pulsation shock propagation in the extended atmosphere, variation of chemical abundances due to periodically varying shock chemistry, dynamical instability of the dust formation.
processes (Fleischer et al. 1995), and maser effects. Particularly, the shock propagation can result in diverse variation periods and phases (see, e.g., Bessell et al. 1996; Hoefner et al. 1998; Loidl et al. 1999; Höfner et al. 2003; Gautschy-Loidl et al. 2004; Nowotny et al. 2005, 2010). The fluctuating chemistry in the shock regions (e.g., Cherchneff 2011, 2012; Gobrecht et al. 2016; Marigo et al. 2016) can produce temporal variation of abundances in the shock regions and at larger downstream radii to produce observable effects in line emission and this process could have periods and phases that are different from the IR light.

The feasibility of attributing the observed line variations to small regions within or under the wind acceleration zone can be tested by checking the possible brightness temperatures of the varying components of the line features at various assumed size scales. From Table 1, the amplitudes of all eight line features range from 0.46 to 7.36 K km s$^{-1}$. Assuming a line width of 29 km s$^{-1}$ (for those blended lines, we assume one line dominates), the absolute amplitudes in main beam temperature in our beam of 29” is about 16–254 mK. If the varying line emission all comes from the wind acceleration region (diameter of 22 $R_*$ or 0’.44; Decin et al. 2015), the brightness temperatures are 70–1103 K, which is in a reasonable range. If, however, some of the varying line emission would directly come from the small shock region (diameter of 6 $R_*$ or 0’.12; Nowotny et al. 2010; Marigo et al. 2016), the line width would be much narrower (e.g., two times the sound speed: 4 km s$^{-1}$; Marigo et al. 2016), the similarly scaled line brightness temperatures become $(6700–1) \times 10^5$ K. This is too high for thermal line emission. Thus, the observed line variations cannot solely come from the small shock region, unless some of them are masers.

Furthermore, literature data and excitation considerations also support that the line variation can originate from the inner CSE. Five of the eight varying line features are rotational transitions in vibrationally excited states and thus are mainly excited in the inner hot dense regions of the CSE. For the remaining three line features, SiS $J = 14-13$ ($E_{\text{up}} = 91$ K), $^{30}$SiO $J = 6-5$ ($E_{\text{up}} = 43$ K), and the blended line feature Na$^+$Cl+CH$_3$NH+HCN ($E_{\text{up}} = 116, 18, 165$ K respectively), all of the involved molecules have a strong compact emission component near to the central star, as revealed by the submillimeter imaging spectral line survey of Patel et al. (2011) or recent ALMA observations (e.g., Velilla Prieto et al. 2015).

Therefore, the in-band calibrated millimeter-line light curves very possibly originate from the small region before the terminal wind velocity is reached. They have the potential to be used as tracers of the dynamical processes in this region around all AGB stars.

### 4.3. Interpretation of Line-shape Variation

The good agreement of the channel-by-channel line-shape light curves between the normalization and decomposition approaches has demonstrated that the in-band line flux calibration is successful and thus the light-curve parameters from the decomposition approach (Figures 9 and 10) can be trusted. Figure 10 shows that the relative variation amplitudes in the strongest varying lines in the line wings are larger than that in the $V_{\text{sys}}$ channel, which explains why we see the variation of line shape of the SiS $J = 14-13$ and HCN $\nu_2 = 1^{14}J = 3-2$ lines. Because the variation in the $V_{\text{sys}}$ channel has a different period and phase than in the line wings (Figures 8 and 9), the light curves in the normalization approach in Section 3.3.1 should be the combined effect of the intrinsic variations in both the line wings and the $V_{\text{sys}}$ channel.

Below we combine the velocities of the peak channels, the absolute peak amplitudes, and a wind velocity model from the literature to demonstrate that only masers can produce the observed SiS and HCN line profile variations. We will discuss this problem for three cases: the emission region of the varying components of the two lines are at the outer edge of the wind acceleration zone ($\sim 11 R_*$), inside the outer steady wind zone ($> 11 R_*$), or inside or under the wind acceleration zone ($< 11 R_*$), according to the wind velocity model of Decin et al. (2015).
If the varying region is located at the outer edge of the wind acceleration zone, its radial direction must make an angle of $\sim 54^\circ$ to the sight line to project the terminal wind speed of $V_{\text{exp}} = 14.5 \, \text{km s}^{-1}$ to the blue-peak channel at $V_b \approx -8.5 \, \text{km s}^{-1}$. This corresponds to a linear shift of $b = 8.9 \, R_e$ from the central-star position on the sky plane. As discussed in Section 3.3.1, the FWHM of the variation amplitude around the peak channels is $\Delta V = \sim 3 \, \text{km s}^{-1}$, corresponding to a length $\Delta l$ of the varying region as

$$
\Delta l = \frac{\Delta V}{\sqrt{V_{\text{exp}}^2 - V_b^2}} \approx 0.255 \, b \approx 2.27 \, R_e \approx 0.045. \quad (2)
$$

For a round region, the blue-peak amplitudes of 2.46 and 0.18 K of the SiS and HCN lines in our telescope beam of 29″ (Section 3.3.1) can be scaled into brightness temperatures of about $1.0 \times 10^6 \, \text{K}$ and $7.5 \times 10^4 \, \text{K}$, respectively. They are far higher than the thermal temperature of less than 2000 K in the CSE. The varying components must be masers. The weaker varying maser emission in the redshifted line wing could be due to occultation of the radio photosphere of the central star.

Is it possible that the varying regions are at larger radii so that their emission is still thermal? Let us assume a thermal line brightness temperature of 2000 K. This requires a varying region size of $\Delta l = \sim 50 \, R_e$ (≈1″) for the blue peak of the SiS line or $\Delta l = \sim 14 \, R_e$ (≈0.9″) for the blue peak of the HCN line. Reversing Equation (2) yields offsets of the varying regions from the central star of $b = \sim 196 \, R_e$ (3.9″ for SiS) and $b = \sim 55 \, R_e$ (1.1″ for HCN) on the sky plane. The larger thermal line variation amplitudes in these regions perhaps mean higher local densities. The much smaller variation amplitudes in the red line wings of both the SiS and HCN lines mean that the corresponding density enhancements at the far side of the CSE should be much weaker. However, such strongly asymmetric density enhancements at $>1''1-3''9$ offsets were never observed in high-resolution mappings of this star (e.g., the ALMA observations by Decin et al. 2015; Velilla Prieto et al. 2015; Quintana-Lacaci et al. 2016). In addition, it is also lacking driving mechanisms for the larger line variation amplitudes in so far regions from the central star. Therefore, thermal emission is not able to interpret the observed line profile variations.

Because the varying SiS and HCN masers peak in line wings, they are most probably located along the direction of the central star so that they are beaming radially, just like the case of the OH 1612 GHz masers around oxygen-rich AGB stars. The fact that the peak channel velocity is smaller than steady wind velocity indicates that the maser regions must be located within the wind acceleration zone. Taking the wind velocity curve in the one step wind acceleration model from Decin et al. (2015; the wind velocity linearly increases from 2 km s$^{-1}$ at $\sim 5 \, R_e$ to the terminal wind velocity of 14.5 km s$^{-1}$ at $\sim 11 \, R_e$), we find the maser radius to be 8.1 $R_e$ for the blue-peak channel of both SiS and HCN lines$^{10}$ and 9.0 $R_e$ for the red-peak channel of the SiS line. The velocity range of the varying channels ($\Delta V = \sim 3 \, \text{km s}^{-1}$) corresponds to a radial maser length of only $\sim 1.44 \, R_e$ (7.2 $\times 10^{13}$ cm or 0.029″), which is typical for a maser (Elitzur 1992). The maser region is usually elongated along the radial beaming direction. Conservatively, assuming spherical maser regions, the peak variation amplitudes in our 29″ beam can be scaled to brightness temperatures of $>2.5 \times 10^6 \, \text{K}$, $>5.4 \times 10^5 \, \text{K}$, and $>1.8 \times 10^5 \, \text{K}$ for the blue and red-peak channels of the SiS line and the blue-peak channel of the HCN line, respectively.

$^{10}$ Interestingly, Shinnaga et al. (2009) used eSMA to find that the emission of the $\lambda$-doubling conjugate line, HCN (01$^1\nu_0$) $J = 3-2$, is distributed in a very small shell-like structure that has a radius of about 23 $R_e$ (0.38″) and a thickness of about 15 $R_e$ (0.25″). The size of the shell is about two to three times larger than the estimated radius of the HCN (01$^1\nu_0$) $J = 3-2$ maser region in this work. However, it is not clear if that shell structure has anything to do with the varying masers.
2015; Kim et al. 2015 system has been proposed 

2014; Jeffers et al. 2014; Decin et al. 2015 

maser-region size 
explained by central-star occultation, because the estimated 
line wing for both the SiS and HCN lines. This can be naturally 

The co-varying components are at the systemic velocity 

Jeffers et al. 2012 

amplitude to constant component ratio 

Figure 10. Channel-by-channel distribution of relative amplitudes (the absolute amplitude to constant component ratio) of the co-varying and differential variation components of the SiS $J = 14-13$ and HCN $\nu_2 = 1^1 J = 3-2$ lines. The co-varying components are at the systemic velocity (the vertical line). 

...We stress that the central region of the CSE of IRC+10216 has complex structures (see, e.g., Murakawa et al. 2005; Tuthill et al. 2005; Leão et al. 2006; Menut et al. 2007; Fonfría et al. 2014; Jeffers et al. 2014; Decin et al. 2015) and even binary system has been proposed (Cernicharo et al. 2015; Decin et al. 2015; Kim et al. 2015). It is desirable to perform high-resolution observations to confirm the masers directly. 

4.4. Maser Properties 

The variation amplitude (and thus maser line strength) is much weaker in the redshifted line wing than in the blueshifted line wing for both the SiS and HCN lines. This can be naturally explained by central-star occultation, because the estimated maser-region size ($1.44 R_*$) is comparable to the measured diameter (4 $R_*$) of the radio photosphere of the star (Menten et al. 2012). On the other hand, the amplification of the radiation from the central star by the maser system could also contribute. 

The blue-peak channel velocity of the SiS line is closer to the systemic velocity than the red-peak channel by $\sim 2 \text{ km s}^{-1}$. This could also be the consequence of the occultation of the redshifted maser component by the star. The elongated maser region should be smaller at a smaller radius (thus smaller velocity shift). The star has blocked more maser emission from the inner smaller maser sub-regions, resulting in a redder maser velocity to be seen in the red line wing. On the other hand, the self-absorption to the blueshifted maser line emission by the SiS molecules in the outer CSE is also able to shift the blue maser peak to a velocity closer to $V_\text{lsr}$ (Huggins & Healy 1986). 

In the strongest blueshifted velocity channels of the SiS $J = 14-13$ line profile, additional variation with shorter periods of about two to four weeks and flat light curves are also found in different parts of the light curves (Figure 4). It could be interpreted by the instability of strong masers during the NIR maximum time and the dying out of the strongest maser spots near the NIR minimum light. 

The variation of the HCN (0$^1\text{IF}0$) $J = 3-2$ line profile shows extreme asymmetry. The lack of variation in the red wing of the HCN line profile can be explained with at least two possible mechanisms: (1) the HCN maser region could be much smaller than that of the SiS maser so that the red part has been totally obscured by the star; (2) the HCN maser is unsaturated and the observed blueshifted masers are the magnified stellar radiation. The much broader velocity range of varying velocity channels (in the blue line wing) than the SiS line indicates that the HCN maser transition is inverted at almost all radii within the maximum radius of $\sim 8.1 R_\ast$. This salient difference indicates some differences in the maser pumping processes of the two molecules. 

4.4.1. Comparison with Other SiS Masers in IRC+10216 

Millimeter maser lines of SiS in IRC+10216 have been reported in previous works, e.g., the $v = 0 J = 1-0$ line by Henkel et al. (1983), the $J = 5-4$ and 15-14 lines by Sahai et al. (1984), and more higher rotational maser transitions interferometrically mapped by Fonfría Expósito et al. (2006) and Fonfría et al. (2014). These masers are possibly pumped through line overlap (Fonfría Expósito et al. 2006). Our new results in this work confirm the variability of the SiS $J = 14-13$ line and its maser nature in IRC+10216. Below we briefly compare the velocities of SiS maser lines found in this star by other authors with the varying velocity channels identified from this work. 

Fonfría Expósito et al. (2006) found multiple candidate maser features in the line profiles of three ground state transitions of SiS: $J = 11-10$, 14-13, and 15-14. We adopt the five major maser features from them and plot them with our average line profile in Figure 11; “a” ($-35.3 \text{ km s}^{-1}$), “d” ($-30.2 \text{ km s}^{-1}$), “f” ($-25.62 \text{ km s}^{-1}$), “i” ($-20.2 \text{ km s}^{-1}$), and “j” ($-18.1 \text{ km s}^{-1}$). It agrees to our findings that maser features appear in both blue and red wings of this line. However, only their SiS $J = 14-13$ and 15-14 maser components “a” and “j” are in the varying velocity channels discovered in our data. The other small line features could be stable local density structures related to the complex non-spherical structures of the inner CSE. The SiS $J = 1-0$ maser of Henkel et al. (1983) is also shown as “h” ($-40 \text{ km s}^{-1}$). It is outside of our varying velocity ranges and appears to be near the blue edge of the line. Perhaps this maser is pumped in the steady wind region by IR light (Gong et al. 2017).
velocities agree to our findings that maser lines only appear in the blue line wing. The two HCN maser lines with smaller vibrational quantum numbers ("l" and "k") are within the varying velocity channels, while the other two HCN maser lines that involve hotter vibrational levels ("m" and "n") are not in the varying channels but are very close to \( v_{\text{sys}} \), indicating that they are inverted very close to the central stars, perhaps in the hottest pulsation shock regions.

5. Summary

We have monitored the SiS \( J = 14-13 \) and HCN \( \nu_2 = \nu_l / J = 3-2 \) maser lines together with several other millimeter lines toward IRC+10216 during a time span of 523 days. Relative light curves of line intensity with respect to specified reference lines are obtained for eight molecular line features (single lines or blended line groups); line-shape light curves are also obtained for the two strongest lines.

The relative line intensity light curves show regular long-term variations on timescales of several hundred days with amplitudes of 5%-30%. The amplitudes are smaller than that of IR light and bolometric luminosity variations. Variation periods and phases can be either similar to or different from the NIR light. They possibly originate from the inner dense part of the CSE, particularly the region within or under the wind acceleration zone. Therefore, these varying lines have the potential to be developed into new probes of the wind launching processes in AGB stars.

The SiS \( J = 14-13 \) and HCN \( \nu_2 = \nu_l / J = 3-2 \) show line-shape variability mainly in two narrow velocity ranges and roughly follow the variation of the NIR light. However, the HCN line-shape variation periods are generally longer by 100–200 days than the NIR light period (630 day). There exist blue-red asymmetries: the variation amplitude is larger in the blue line wing than in red line wing for both lines. There is also a velocity dependence of the periods and phases for both lines. The varying components are the main causes of the asymmetrical average line profiles of the two lines. Their velocities and amplitudes support that they are masers in the zone where the wind is still accelerating, with brightness temperatures higher than \( 10^5–10^6 \) K. In particular, the HCN maser may be inverted all the way down to radii close to the photosphere, as indicated by the velocities of its varying channels.

The line profile variation of the two maser lines is also analyzed by two approaches: line profile normalization and light-curve decomposition. The results from the two methods are very similar, which supports that the remaining flux uncertainties after the in-band calibration are not very large. The decomposition approach provides new insights: the co-varying component in the systemic velocity channel has a smaller amplitude than the differential variation components in the line wings; the amplitudes of both varying components are smaller than the strength of the constant components; the periods and maximum phases are also quite different between the co-varying and differential variation components.

In the strongest blueshifted velocity channels of the SiS \( J = 14-13 \) line profile, additional variation with shorter periods of about two to four weeks near the maximum time and flat light curves around the minimum time are also found. They could be interpreted by the instability of strong masers during the NIR maximum light and the dying out of the strongest maser spots near the NIR minimum light.

4.4.2. Comparison with Other HCN Masers in IRC+10216

HCN maser lines in IRC+10216 were also found decades ago, e.g., the \( (0^2P_0) J = 1-0 \) line by Guilloteau et al. (1987), Lucas et al. (1988), and Lucas & Guilloteau (1992), \( (0^1\Sigma^+\,0) \) \( J = 2-1 \) (originally assigned as \( 0^1\Pi\,0 \)) by Lucas & Cernicharo (1989), \( (0^4\Pi\,0) J = 9-8 \) by Schilke et al. (2000), and even in the cross-vibration ladder transition \( (1^1\Sigma^-\,0)–(0^4\Pi\,0) J = 10-9 \) by Schilke & Menten (2003). Various maser pumping mechanisms, such as IR light pumping plus line overlap (Lucas & Cernicharo 1989; Dinh-V-Trung & Nguyen-Q-Rieu 2000; Shinnaga et al. 2009) and chemical pumping (Schilke et al. 2000; Schilke & Menten 2003), have been discussed. Our line variability data offer several new insights to the HCN maser properties.

The velocities of other known HCN maser lines in IRC+10216 are compared with our velocity range of line variability in the bottom panel of Figure 11: HCN \( (0^2P_0) J = 1-0 \) at \(-30 \text{ km s}^{-1} \) ("l," Guilloteau et al. 1987; Lucas et al. 1988), \( (0^1\Pi\,0) J = 2-1 \) at \(-31.5 \text{ km s}^{-1} \) ("k," Lucas & Cernicharo 1989), \( (0^4\Pi\,0) J = 9-8 \) at \(-27.3 \text{ km s}^{-1} \) ("m," Schilke et al. 2000), and \( (1^1\Pi\,0)–(0^4\Pi\,0) J = 10-9 \) at \(-26.3 \text{ km s}^{-1} \) ("n," Schilke & Menten 2003). Their
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Facility: ARO SMT.  
Software: GILDAS/CLASS.  

Appendix A  
Line Identification Results  

The detailed list of line carriers of each detected line feature is given in Table 2, while the line profile averaged over all epochs are plotted in Figure 12. Concerning the format of quantum numbers for the vibrational states, there is some divergence in the literature. For example, the works of Ziurys & Turner (1986) and Tenenbaum et al. (2010b) used letters “d” and “c” to differentiate the two parity cases of the λ-doubling states of linear molecules, while others (e.g., Zelinger et al. 2003) used “e” and “f,” which were recommended by Brown et al. (1975). In this work, we will follow the convention of Brown et al. and the λ-doublets of HCN is adopted from Zelinger et al. (2003) and that of C2H from Yamamoto et al. (1987). Here are some comments about the line carriers:

1. CH3NH 4\(0,4 - 3,0\), line at 254685.20 MHz shows a double peaked line profile partially blended with the strong HC3N 28-27 and weaker Na\(^{17}\)Cl 20-19 lines. It was first detected in IRC+10216 by He et al. (2008) who took it as an unidentified line. Its identity was first recognized in this star by Tenenbaum et al. (2010a).

2. Hot C2H lines in bending states. At least three hot C2H lines in the bending state (\(v_\gamma = 1\)) are detected to be free of line blending. All of them show double peak line profiles, indicating that their emission regions are extended compared to the SMT beam size of 29\(''\) and are not very optically thick. Although the C2H 3\(P_{1/2}\) \(v_\gamma = 1\) line at 267316.33 MHz appears at the edge of the USB, the double peak shape of its partial line profile is still clear. Guelin et al. (1987) and Cooksy et al. (2015) have shown that the rotational transitions of C2H in the \(v_\gamma = 1\) state mainly arise from a ring-like structure of 15\(''\) radius, together with a much weaker component near the central star. The C2H 3\(P_{1/2}\) \(v_\gamma = 2\) line at 267116.98 MHz is blended with several other lines of C2H, 13C3CN and HCN. Thus its detection is only tentative.

### Table 2  
Detected Lines

| Freq(MHz) | Trans | Notes | Freq(MHz) | Trans | Notes |
|-----------|-------|-------|-----------|-------|-------|
| 254037.00 | U254037 | incomplete | 266283.63 | NaCN/NaNC | incomplete |
| 254103.20 | SIS 14-13 | ... | 266347.60 | NaCN/NaNC | ... |
| 254169.59 | U254170 | no-T2010 | 266389.92 | C2H N = 28-27 | ... |
| 254216.14 | ... | ... | 266428.18 | C2H N = 28-27 | ... |
| 254244.97 | Si\(^{13}\)CC 12,12 - 11,11 | blended | 266500.88 | C2H 3\(P_{1/2}\) \(v_\gamma = 1\) N = 28-27 | ... |
| 254245.40 | KCN/KNC 27,20 - 26,19 | blended | 266540.00 | HCN v2 = 3 \(J = 3-2\) | ... |
| 254245.40 | KCN/KNC 27,19 - 26,18 | blended | 266617.79 | U266618 | ... |
| 254310.37 | Si\(^{13}\)CC 11,7 - 10,6 | blended | 266674.40 | U266674 | ... |
| 254313.70 | Si\(^{13}\)CC 11,4 - 10,3 | blended | 266740.96 | Si\(^{13}\)CC 11,9 - 10,8 | ... |
| 254313.70 | Si\(^{13}\)CC 11,4 - 10,3 | blended | 266771.19 | C3H 3\(P_{1/2}\) \(v_\gamma = 1\) N = 28-27 | ... |
| 254324.42 | Si\(^{13}\)CC 1,6 - 10,5 | blended | 266904.99 | H13CN v2 = 1 \(J = 1\) \(J = 3\) | ... |
| 254358.87 | U254359 | no-T2010 | 266941.75 | SiS \(\nu = 4\) J = 15-14 | ... |
| 254399.56 | U254400 | no-T2010 | 266944.51 | PH1,10-0,0 | blended |
| 254663.46 | Na\(^{35}\)Cl 20-19 | blended | 267103.31 | C2CCN N = 27-26 J = 55/2-53/2 | ... |
| 254685.20 | CH2NH 4\(0,4 - 3,0\) | blended | 267109.14 | HCN v2 = 2 \(J = 3\) | ... |
| 254699.50 | HC3N 28-27 | blended | 267116.98 | C2H 2\(\Delta_{1/2}\) \(v_\gamma = 2\) N = 28-27 | ... |
| 254924.96 | U254925 | no-T2010 | 267117.89 | 13C3CN N = 28-27 J = 57/2-55/2 F1 = 29-28 | ... |
| 254945.21 | NaCN 16,15 - 15,14 | ... | 267120.10 | HCN v2 = 2 \(J = 3\) | ... |
| 254981.49 | SiCC 15,10 - 12,9 | blended | 267121.23 | C2CCN N = 27-26 J = 53/2-51/2 | ... |
| 254987.64 | c-C2H2 5,1 - 4,2 | blended | 267122.89 | 13C3CN N = 28-27 J = 57/2-55/2 F1 = 28-27 | ... |
| 255060.77 | Si\(^{13}\)CC 11,9 - 10,8 | incomplete | 267130.89 | 13C3CN N = 28-27 J = 55/2-53/2 F1 = 28-27 | ... |
| 255135.89 | ... | ... | 267135.89 | 13C3CN N = 28-27 J = 55/2-53/2 F1 = 27-26 | ... |
| 256199.28 | HCN v2 = 1 \(J = 3\) | ... | 267199.28 | HCN v2 = 2 \(J = 3\) | ... |
| 267242.14 | 2\(^{3}\)SiS J = 15-14 | ... | 267242.14 | ... |
| 267243.20 | HCN v2 = 2 \(J = 3\) | ... | 267243.20 | ... |
| 267263.48 | U267263 | ... | 267263.48 | ... |
| 267316.33 | C3H 3\(P_{1/2}\) \(v_\gamma = 1\) N = 28-27 | incomplete | 267316.33 | ... |

Note. no-T2010: the unidentified line was observed but not detected by Tenenbaum et al. (2010b).
3. **Narrow lines.** Beside the three unidentified narrow lines that will be discussed in the next paragraphs, there are another two identified narrow lines: HCN \( \nu_2 = 3^\nu R = J = 3 - 2 \) at 266540 MHz and SiS \( J = 15 - 14 \) at 266941.75 MHz. The former has an FWHM \( \pm 4.4 \) km s\(^{-1}\). The latter is a narrow spike on top of the broad PH\(_{1030}^3\) line. Both narrow lines should originate in regions within or under the wind acceleration zone.

4. **Unidentified lines.** All the eight U-lines have S/N ratios in terms of integrated line intensity higher than about 5. However, most of the eight U-lines have peak \( T_{\text{mb}} < 10 \) mK, except U266618, which has a peak \( T_{\text{mb}} = \sim 40 \) mK. U266618 only appeared at six epochs and is found to be anti-correlated with the light curve of the leaked image of the strong line SiS \( 14 - 13 \) from the image side band, indicating that it might be a false feature related to the side band leaking of SiS \( 14 - 13 \).

Three U-lines are definitely narrower than the majority of thermal lines: U254359 has a \( V_{\text{exp}} = 12.3 \pm 1 \) km s\(^{-1}\), U254400 has a \( V_{\text{exp}} = 5.9 \pm 0.5 \) km s\(^{-1}\), and U266674 has a \( V_{\text{exp}} = 1.9 \pm 0.6 \) km s\(^{-1}\), all being much narrower than the terminal envelop expansion velocity 15 km s\(^{-1}\). Thus they are either lines from regions inside or under the wind acceleration zone or weak maser lines. U267263 also looks like a narrow line, but because of the line blending, we cannot tell if it is the blue horn of a blended double peak line profile.

### Appendix B

**Notes on Line Profile Variation of Weaker Line Features**

Line-shape variation of four relatively strong line features other than the SiS and HCN maser lines are discussed in broader velocity ranges in this section. Roughly, velocity ranges of about 10 km s\(^{-1}\) wide are adopted so that a typical line from IRC\(+10216\) (\( \sim 29 \) km s\(^{-1}\)) can be divided into three parts: line center and blue- and redshifted line wings. The central velocity range is chosen as the reference to calibrate the other velocity ranges in the line wings to reveal their relative variabilities. For those blended line features, we carefully arrange the velocity ranges so that each range is dominated by the blue- or redshifted or central component of the blended lines. The central velocity range of the possibly strongest blended line is selected as the reference for normalization (the detailed division is given for individual line features below).

The normalized light curves of the four line features are shown in Figures 13 and 14. The main features are as follows.

1. \( ^{29}\text{SiS} \) and HCN \( \nu_2 = ^{0} \) line feature (Figure 13, left panel). The two blended lines only have a small velocity shift from each other of about 1 km s\(^{-1}\). Thus we define three velocity ranges for the line feature, with the central reference velocity range centered around their average frequency. The boundaries of the three velocity ranges are \((-42, -31, -21, -10)\) km s\(^{-1}\).
This line feature is weak and only shows marginal variability in both blue and red parts of the line profile. The variation amplitude is no larger than 20% (with large error bars). The blue and red wings have a weak trend to opposite variations so that the total line intensity in the top curve in the figure shows little variation.

2. SiCC$^{12}$ with $J = 3 - 2$ (Figure 13, right panel). This line is blended with c-C$_3$H$_2$ $5_{1,3} - 4_{2,2}$. We divide the line profile into four velocity ranges, with boundaries at ($-43$, $-34.76$, $-22$, $-10$, $-3.76$) km s$^{-1}$, so that the blue, central, and red parts of each of the two lines can be sampled as evenly as possible. As a result, the three bluest ranges cover 21%, 42%, and 37% (from blue to red) of the 29 km s$^{-1}$ wide full velocity range of the SiCC line, respectively, while the three reddest ranges cover 39%, 40%, and 21% (from blue to red) of the full velocity range of the c-C$_3$H$_2$ line. The reddest range turns out to be very weak and thus is omitted from Figure 13 (it also indicates that the c-C$_3$H$_2$ line is very weak). We select the middle range ($-34.76$, $-22$) km s$^{-1}$ of the remaining three velocity ranges (also the middle part of the SiCC line) as the reference for normalization.

Although this line is the calibrator line in the LSB for the in-band calibration, its line profile is found to be varying with time. The largest variation is about 8%. The blue and red parts of the line profile vary differently. The light curve of the blue part looks more or less similar to that of the USB calibrator lines in Figure 14, while the light curve of the red part looks different.

3. $\Sigma$ = 28-27 $J = 55/2-53/2$ and $J = 57/2-55/2$ (Figure 14). The two lines do not suffer from blending. We define three symmetrical velocity ranges with boundaries at ($-41$, $-31$, $-21$, $-11$) km s$^{-1}$. The central range is taken as the reference for normalization.

Although the two lines are taken as calibrator lines in the USB, their line profiles are found to be varying with time in a similar manner. The largest variation is about 17%. Both the blue and red wings of the line profiles show irregular variation patterns.

The line-shape variation in the broad velocity ranges in Figures 13–14 can hardly be interpreted with physical processes such as IR light or shock driven variation or masers. The three flux calibrator lines (of SiCC and c-C$_3$H$_2$) have a strong contribution from the extended cold part of the spherical CSE. Usually no line profile variation is expected with such a spherical emission region. Even if the inner hot and dense part of the CSE contributes a certain amount of variation to the central velocity range of the three lines, the resulting line profile variation in Figures 13–14 should be regular, blue-red symmetrical and periodical, which is contrary to the irregular behaviors seen in the figures. The $^{29}$SiS and HCN of blended line feature could have a considerable contribution from the inner hot CSE that is liable to variation. However, the contribution of the varying emission should also be blue-red symmetrical, which is not the case in Figure 13. We have no reasonable interpretation for the $^{29}$SiS and HCN line feature, but will give a possible interpretation for the line-shape variation in the broad velocity ranges.
variation in the three flux calibrator lines: random telescope pointing offsets.

It has been known that some rotational lines of both C4H and SiCC have a prominent extended ring-like component (a spherical structure in three-dimensions) with a diameter of about 30" in their emission maps (e.g., Gensheimer et al. 1992; Takano et al. 1992; Dayal & Bieging 1993; Guélin et al. 1993; Lucas et al. 1995; Cooksy et al. 2015). The ring size is comparable to the telescope beam size in this work. This is consistent with the double peak line profiles of all three of the calibrator lines in our Figure 12. The SiCC 4_2,3–2_2 line map from Lucas et al. (1995) and the maps of C4H lines in both ground and vibration states from Cooksy et al. (2015) also show a central emission component, however.

Therefore, the roughly blue-red symmetrical, but irregular, variation of the line shapes of the three lines can be self-consistently explained as follows: the contribution from the ring-like emission component varies sensitively with the random telescope pointing offsets and produce a variation in the central velocity channels of the line profiles; the central point-like component (perhaps also a smooth extended component) is not sensitive to the pointing fluctuation and thus contributes some unaffected emission to all velocity channels. In this case, the apparent variation of the double peaks with respect to the central velocity channels of the three lines is actually due to the variation of the central velocity channels themselves (the reference velocity ranges).

If the pointing fluctuation interpretation is true, the total line intensity of the three calibrator lines should also be affected to some extent. The impact of this effect on the in-band calibration of line intensity in Section 3.2 can be roughly estimated by assuming that only the central one-third portion of the line profiles is subjected to such variation with pointing fluctuation. For the two C4H calibrator lines in the USB, because of the sharp double peak profiles, the central velocity channels only contribute to about one-fifth of the integrated line intensity (two-fifths by the blue and two-fifths by the red part). The apparent profile variation amplitude of the blue and red parts (actually reflecting the variation of the central part) is at most 17% in Figure 14, corresponding to an integrated line intensity calibration error of at most 17% × 1/5 ≈ 3.4% for lines in USB. For the SiCC calibrator line in the LSB, the double peaks are not very sharp, thus the varying central part of the line profile may contribute to about one-third of the integrated line intensity. The maximum variation amplitude of the blue and red parts of its line profile amounts to about 8% in Figure 13. This can be transformed into a line intensity calibration error of at most 8% × 1/3 ≈ 2.7% for lines in the LSB. This kind of calibration error should randomly vary from epoch to epoch. These errors are relatively small and we do not try to make corrections for them. However, a lesson that can be learned is that the extended ring-like emission component can incur large errors through its sensitive response to the pointing fluctuation of a telescope beam comparable to the ring size.

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