Dense Molecular Clumps in the Envelope of the Yellow Hypergiant IRC+10420

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Abstract

The circumstellar envelope of the hypergiant star IRC+10420 has been traced as far out in 28SiO ($J = 2–1$) as in 12CO $J = 1–0$ and 12CO $J = 2–1$, in dramatic contrast with the centrally condensed (thermal) SiO- but extended CO-emitting envelopes of giant and supergiant stars. We present an observation of the circumstellar envelope in 28SiO ($J = 1–0$) that, when combined with the previous observation in 28SiO ($J = 2–1$), provides more stringent constraints on the density of the SiO-emitting gas than hitherto possible. The emission in 28SiO ($J = 1–0$) peaks at a radius of $\sim$2′′ whereas that in 28SiO ($J = 2–1$) peaks at a smaller radius of $\sim$1′′, giving rise to its ring-like appearance. The ratio of brightness temperature between 28SiO ($J = 2–1$) and 28SiO ($J = 1–0$) decreases from a value well above unity at the innermost measurable radius to about unity at a radius of $\sim$2′′, beyond which this ratio remains approximately constant. Dividing the envelope into three zones as in models for the 12CO $J = 1–0$ and 12CO $J = 2$–Dinh–1 emissions, we show that the density of the SiO-emitting gas is comparable with that of the CO-emitting gas in the inner zone but is at least an order of magnitude higher by comparison in both the middle and the outer zones. The SiO-emitting gas therefore originates from dense clumps, likely associated with the dust clumps seen in scattered optical light, surrounded by more diffuse CO-emitting interclump gas. We suggest that SiO molecules are released from dust grains due to shock interactions between the dense SiO-emitting clumps and the diffuse CO-emitting interclump gas.

Key words: circumstellar matter – radiative transfer – stars: mass-loss – supergiants

1. Introduction

Yellow hypergiants are thought to be post-red supergiant stars that are evolving along the blueward loop in the Hertzsprung–Russel diagram toward higher effective temperatures. They define the empirical upper limit in luminosity at intermediate stellar effective temperatures (Humphreys & Davidson 1994; de Jager 1998). These stars are surrounded by massive circumstellar envelopes composed of warm dust and molecular gas, providing evidence for increased dynamical instabilities during this poorly understood phase of stellar evolution. By offering a historical record of their mass loss, studies of the circumstellar envelopes of yellow hypergiants can shed light on the physical processes that drive the mass ejection and affect the evolution of these stars.

One of the best-studied yellow hypergiants is IRC+10420. Based on photometric, spectroscopic, and polarimetric measurements, Humphreys et al. (2002) argue for a distance to this star in the range of 4–6 kpc. For convenience, we adopt a distance of 5 kpc for IRC+10420 so that the results reported in this paper can be directly compared with those of both Castro-Carrizo et al. (2007) and Dinh-V-Trung et al. (2009) for its molecular envelope. In the optical, IRC+10420 was initially classified as F8 II∗ in 1973 (Humphreys et al. 1973) but by the 1990s had evolved to spectral type A (Oudmaijer et al. 1996; Klochkova et al. 1997). Such a rapid change in stellar spectral type is unlikely to reflect an actual change in the stellar surface temperature but is instead attributed to variations in its optically thick wind that obscures the stellar surface from view (Humphreys et al. 2002). Evidence for such a wind comes from optical lines such as the prominent Hα and Ca II triplets, suggesting a strong outflow close to the stellar surface (Humphreys et al. 2002).

Ranking among the brightest infrared sources in the sky, the infrared emission of IRC+10420 constitutes reprocessed stellar radiation by dust in a massive circumstellar envelope ejected over the last ~4000 years. Observations in the optical with the Hubble Space Telescope (HST) reveal a highly complex and clumpy envelope as seen through scattered light from dust (Humphreys et al. 1997, Tiffany et al. 2010). Features such as knots and arcs or loops reveal that on relatively small scales, the mass loss from the star is highly inhomogeneous. By combining line-of-sight velocities measured using slit spectroscopy by Humphreys et al. (2002) with proper motions measured from multi-epoch HST images, Tiffany et al. (2010) infer that the dust clumps with measurable proper motions are moving preferentially on the plane of the sky with typical velocities of ~100–200 km s$^{-1}$. They suggest that the dust is ejected preferentially in an equatorial outflow (i.e., IRC+10420 is viewed closely along its pole), which is also consistent with the measurements of high degrees of linear polarization in the infrared emission from the dust ejecta by Shenoy et al. (2015).

The circumstellar envelope of IRC+10420 is also a source of strong molecular line emission. Interferometric observations at a high angular resolution in 12CO $J = 1–0$ by Castro-Carrizo et al. (2007) and 12CO $J = 2–1$ by Dinh-V-Trung et al. (2009) reveal an envelope that is, on a global scale, approximately spherically symmetric, in stark contrast with the equatorial outflow proposed by Tiffany et al. (2010) for the dust clumps. Through modeling of the 12CO emission, both Castro-Carrizo et al. (2007) and Dinh-V-Trung et al. (2009) find that the molecular envelope of IRC+10420 was produced predominantly during two major mass-loss episodes: a more recent and stronger mass-loss episode lasting for less than 1000 years with a strong decrease in mass-loss rate over the last...
approximately 300 years, and an older and weaker mass-loss episode lasting roughly 4000 years. The radial ranges of these high and low mass-loss episodes correspond roughly (to the same order of magnitude) with those derived by Humphreys et al. (1997) from mid-infrared images of the dust emission. Recently, using high-resolution mid- and far-infrared imaging data Shenoy et al. (2016) found two distinct episodes of mass loss in IRC+10420 with a high average mass-loss rate of $2 \times 10^{-3} M_\odot$ yr$^{-1}$ until about 2000 years ago followed by an order of magnitude decrease in the more recent past, thus confirming the strong variation of mass loss of the central star.

In addition to $^{12}$CO, molecular lines such as HCN and $^{28}$SiO that have much higher critical densities also have been detected toward IRC+10420 (Quintana-Lacaci et al. 2007). Interferometric observations at high angular resolutions in $^{28}$SiO ($J = 2\rightarrow1$) by Castro-Carrizo et al. (2001) reveal a roughly spherically symmetric envelope with a pronounced central depression, i.e., a ring-like shell. Surprisingly, the $^{28}$SiO ($J = 2\rightarrow1$) emission can be traced out to a radius of $\sim 4''$ (~20,000 au). Such a large radial extent in $^{28}$SiO ($J = 2\rightarrow1$) emission is unexpected because SiO molecules ought to condense onto dust grains relatively close to the stellar surface. For a typical evolved star, the condensation of SiO molecules onto dust grains is expected to occur at a temperature of about 900 K (Gail et al. 2013), so that essentially all SiO molecules are locked in solid form as silicates beyond a radius of $\sim 10^3$ au (e.g., Bujarrabal et al. 1989; Lucas et al. 1992). The extent of SiO emission in the envelope of a typical AGB star is an order of magnitude smaller than the radial extent of the $^{28}$SiO ($J = 2\rightarrow1$) emission from IRC+10420. Indeed, for the vast majority of evolved stars, SiO emission is observed to arise from just the innermost regions of their envelopes—e.g., in the archetypical envelope of the AGB star IRC+10216 (Schöier et al. 2006), the size of the SiO-emitting portion of the envelope is many times smaller than that of the CO-emitting envelope. If the same situation holds for IRC+10420, then at a distance of 5 kpc the SiO-emitting region of its envelope should have a radius of $\sim 0''/2$, far smaller than the angular resolution employed in the observation by Castro-Carrizo et al. (2001).

The $^{28}$SiO ($J = 2\rightarrow1$) transition has a critical density of $\sim 10^{3.5}$ cm$^{-3}$. The latter is significantly higher than the gas density in much of the molecular envelope of IRC+10420 as deduced from the modeling of $^{12}$CO lines, in which the gas density is inferred to decrease outward from $\sim 10^5$ cm$^{-3}$ at an inner radius of $\sim 2.5 \times 10^{16}$ cm to $\sim 10^2$ cm$^{-3}$ at an outer radius of $4.5 \times 10^{17}$ cm (e.g., Castro-Carrizo et al. 2007; Dinh-V-Trung et al. 2009; Teysseyer et al. 2012). If the spatially extended $^{28}$SiO ($J = 2\rightarrow1$) emission originates from the same gas as is traced in $^{12}$CO, then the gas temperature must be elevated to a level not normally found in the envelopes of evolved stars so as to significantly excite the SiO molecule. Assuming local thermal equilibrium (LTE) and an SiO abundance characteristic of the inner regions of evolved star envelopes where SiO is not locked in dust grains, Castro-Carrizo et al. (2001) found from radiative transfer modeling that if $^{28}$SiO is excited by the same gas as traced in $^{12}$CO $J = 1\rightarrow0$, a gas temperature of at least $\sim 55$ K is required to produce $^{28}$SiO ($J = 2\rightarrow1$) emission at its observed brightness temperature.

To explain the large spatial extent of the SiO emission around IRC+10420, Castro-Carrizo et al. (2001) argue that large-scale shocks must be prevalent in the envelope of this star. Such shocks can be produced when an inner (recently ejected) faster-moving part of the wind plows into an outer (ejected in the more distant past), slower-moving part of the wind. By compressing and heating the gas, shocks can elevate both the gas density and the temperature. Furthermore, shocks can evaporate SiO molecules from silicate dust grains. The existence of shocks in the envelope of IRC+10420 is supported by the detection of H$_2$O and NH$_3$ lines, which typically arise from hot and dense gas behind shock fronts (Teysseyer et al. 2012). In addition, the detection of OH masers within $\sim 2''$, corresponding roughly to the angular radius of the observed $^{28}$SiO ($J = 2\rightarrow1$) shell, also suggests a density enhancement in the envelope of IRC+10420 (e.g., Bowers 1984; Nedoluha & Bowers 1992).

In this paper, we report interferometric observations of $^{28}$SiO ($J = 1\rightarrow0$) emission from the envelope of IRC+10420. By comparing our maps with those in $^{28}$SiO ($J = 2\rightarrow1$) obtained by Castro-Carrizo et al. (2001), we also derive the ratio of the brightness temperature of $^{28}$SiO ($J = 2\rightarrow1$) to $^{28}$SiO ($J = 1\rightarrow0$) as a function of radius through the stellar envelope. From radiative transfer modeling, we show that the measured line ratios cannot arise from the same gas that emits in $^{12}$CO but require gas at much higher densities (if not also temperatures, although the latter are not strongly constrained by our measurements). We compare the inferred physical properties of the envelope with the dust features seen in optical images to determine the likely sources of the SiO emission and discuss the implications of our results for the nature of the mass loss from IRC+10420.

The paper is organized as follows. Readers interested in the observation and data reduction should proceed to Section 2. Those interested only in the results can skip ahead to Section 3. In Section 4, we present our model for the SiO-emitting envelope of IRC+10420. The implications of the results for our understanding of the molecular gas and dust envelope of IRC+10420 are discussed in Section 5. A concise summary of our work can be found in Section 6.

\section{Data}

\subsection{Observations}

We observed IRC+10420 with the Karl G. Jansky Very Large Array (VLA) on 2010 April 19 in its most compact (D) configuration. The observation spanned $\sim 1$ hr, with $\sim 25$ minutes on the source. The correlator was configured to span the $^{28}$SiO ($J = 1\rightarrow0$) line (a rest frequency of 43.423853 GHz) over a bandwidth of 32 MHz ($\sim 220$ km s$^{-1}$), sufficient to span the entire line width of $\sim 80$ km s$^{-1}$ observed for the $^{28}$SiO ($J = 1\rightarrow0$) emission toward IRC+10420. To correct for gain errors introduced by atmospheric fluctuations, which can be quite problematic at high observing frequencies at the VLA, the telescope was switched alternately between IRC+10420 and a nearby secondary calibrator, J1924+1540 (lying 4''36 away). In each 5-minute cycle, we integrated for $\sim 160$ s on IRC+10420 and $\sim 100$ s on J1924+1540. Another strong quasar, J1642+3948 (also known and referred to hereafter as 3C 345), was observed at the start of the observation for bandpass calibration.

\subsection{Absolute Flux Calibration}

Due to restrictions imposed by dynamic scheduling, the selected flux calibrator, J0137+3309 (3C 48), was not observed
during the session. We therefore searched the data archive for other observations of the bandpass calibrator used in our observation, 3C 345, taken in the same telescope configuration. Provided that these observations were accompanied by observations of a standard absolute flux calibrator, we could then use 3C 345 as an absolute flux calibrator (in addition to it serving as a bandpass calibrator). In Table 1, we list the three such observations that we found taken close in time (within 9 days) to our observation. One observation (labeled as observation 1) was taken before our observation (observation 2), and another two (observations 3 and 4) were taken after our observation. The data quality in observation 3 was poor and we therefore excluded it from further consideration. We reduced the data taken in observations 1 and 4 to determine the flux density of 3C 345 in those observations; the data reduction scheme used is the same as that used for reducing our data as described below in Section 2.3. In both these observations, the flux calibrator observed was J1331 +3030 (also known, and hereafter referred to, as 3C 286). Monitoring of 3C 286 by the observatory has shown that its flux density has remained constant (within ~2%) over the past few decades in all the VLA frequency bands. Note that at the time of all the aforementioned observations, the switched power (SY) table containing information of system gain variations was not available. Without the SY table, the uncertainty in the flux bootstrapping is roughly 10%.

As listed in Table 1, the flux density of 3C 345 increased by about 38% (much larger than the uncertainty in flux bootstrapping) between observations 1 and 4, separated by just 16 days. The corresponding average daily increase in flux density is ~0.14 Jy/day. Historically, 3C 345 has been found to undergo periodic major flaring events at radio wavelengths every 8–10 years (Klare et al. 2005), Larionov et al. (2009) and Schinzel et al. (2011) have shown that 3C 345 was undergoing a major flaring episode beginning in 2008 and lasting until at least mid-2010. Observations of 3C 345 with the Very Long Baseline Array (VLBA) in the months around 2010 April, as tabulated in Table 2, show that 3C 345 was varying especially rapidly in flux density during 2010 April. From a linear interpolation between the observations, we find that the average daily rate in flux density variations as measured with the VLBA was sometimes even higher than that measured with the VLA as described above. Schinzel et al. (2011) attribute the flux density variations observed with the VLBA to newly identified “moving emission features” in the radio-emitting jet of 3C 345. Notice that the flux density of 3C 345 as measured with the VLBA appeared to decrease in the interval from 2010 April 6 to June 14, whereas that measured with the VLA appeared to increase in the interval from 2010 April 10 to 26. This difference could reflect the vastly different angular scales of the emitting regions probed by the VLA and VLBA. On the other hand, the flux density of 3C 345 could have varied over shorter timescales than can be tracked with the available observations.

If we assume that the flux density of 3C 345 varied linearly in time between observations 1 and 4, then from a linear interpolation we obtain a flux density of 7.38 Jy for this source during our observation. Assuming that the flux density of 3C 345 did not vary beyond the range used in the interpolation, the uncertainty in the estimate flux density is ≤20.

### 2.3. Data Reduction

We reduced our VLA data using the NRAO Astronomical Image Processing System (version 31DEC11). First, we corrected for changes in the atmospheric opacity as a function of elevation, for which the default seasonal atmospheric opacity model was used to estimate the zenith atmospheric opacity at 43 GHz. We also corrected for the changes in the collecting area of the antennas with elevation due to gravity-induced deformation, as well as errors in antenna positions based on measurements made by the observatory. We then corrected for errors in the geometrical delay between antennas by fitting a slope to the visibility phase measured for 3C 345 (the bandpass calibrator) across the passband of each antenna.

To solve for the bandpass and complex gain of each antenna, we adopted an iterative approach where we first solved for the complex gain at short time intervals over a limited bandwidth and applied the complex gain solutions to solve for the bandpass. We then solved for the complex gain again but now over the entire bandwidth and applied the complex gain to refine the solution for the bandpass. We repeated this process until successive solutions showed little change in either the bandpass or the complex gain. The final bandpass solution was applied to both the secondary calibrator and the source. After that, we solved for the complex gain of the secondary calibrator and derived its flux density with reference to 3C 345 (see Section 2.2). Finally, we applied the complex gain solutions derived for the secondary calibrator to the target source by interpolating between scans of the secondary calibrator.

Averaging the visibilities over frequency to a velocity resolution of 4.86 km s⁻¹, we first applied a Fourier transform to the calibrated visibilities to form DIRTY maps. We then deconvolved the point-spread function of the telescope from the DIRTY maps using the CLEAN algorithm (Clark 1980) to obtain the final CLEAN maps. We made maps using ROBUST weighting (ROBUST = 0) of the visibilities to achieve a good

### Table 1

| Observation | Date      | Project | Scientific Object(s) | Q-band Flux (7 mm) of 3C 345 (VLA) |
|-------------|-----------|---------|----------------------|-----------------------------------|
| 1           | 2010 Apr 10 | S2053   | Quasars              | 6.0672 ± 0.0004 Jy                 |
| 2           | 2010 Apr 19 | AD621   | IRC+10420            | 7.38 Jy (interpolated)             |
| 3           | 2010 Apr 22 | AD621   | AFGL2343             | ...                               |
| 4           | 2010 Apr 26 | AD621   | AFGL2343             | 8.355 ± 0.001 Jy                   |

### Table 2

| Date        | Q-band Flux (7 mm) of 3C 345 (VLBA) |
|-------------|-----------------------------------|
| 2010 Mar 6  | 5.470 ± 0.005 Jy                   |
| 2010 Apr 6  | 6.180 ± 0.005 Jy                   |
| 2010 Apr 14 | 5.836 ± 0.004 Jy                   |
| 2010 May 19 | 5.049 ± 0.004 Jy                   |
| 2010 Jun 14 | 5.077 ± 0.004 Jy                   |
compromise between the angular resolution and the root mean square (rms) noise fluctuations. The synthesized beam thus obtained is 1.878 × 1.36 with a position angle (PA) of −44°51. The rms noise level, estimated from the DIRTY maps in the line-free channels, is ~5.9 mJy/beam, corresponding to ~1.1 K; i.e., a conversion factor of 185.63 K Jy\(^{-1}\).

Previously published maps of the \(^{28}\)SiO (J = 2–1) emission from IRC+10420 made with the Plateau de Bure Interferometer (PdBI; Castro-Carrizo et al. 2001) were kindly provided to us by Castro-Carrizo. To be able to compare these maps with ours so as to derive the line ratio of \(^{28}\)SiO (J = 2–1) to \(^{28}\)SiO (J = 1–0), we first regridded the \(^{28}\)SiO (J = 2–1) maps to the same velocity resolution as our \(^{28}\)SiO (J = 1–0) maps. In addition, we convolved our \(^{28}\)SiO (J = 1–0) maps to the slightly larger synthesized beam of the \(^{28}\)SiO (J = 2–1) maps of 2′53 × 1′38 and a position angle of PA = 25°98. From these maps, we derived the line ratio of \(^{28}\)SiO (J = 2–1) to \(^{28}\)SiO (J = 1–0), hereafter referred to as \(^{28}\)SiO (J = 2–1)/\(^{28}\)SiO (J = 1–0), as a function of radius averaged over circular annuli.

3. Results

Figure 1 shows our channel maps of the \(^{28}\)SiO (J = 1–0) emission from IRC+10420. For comparison, Figure 2 shows the channel maps of the \(^{28}\)SiO (J = 2–1) emission made by Castro-Carrizo et al. (2001) after being regridded to the same velocity resolution as our \(^{28}\)SiO (J = 1–0) maps. For reference, the cross marks the location of the central star as detected in the millimeter continuum by Dinh-V-Trung et al. (2009). In both maps, the emission has the characteristic signature of an expanding spherical envelope, as also seen previously in \(^{12}\)CO: the emission exhibits the largest spatial extent in velocity channels around the systemic velocity of 74 km s\(^{-1}\) and contracts in size toward the center of the envelope (the position of the star) at progressively higher blueshifted and redshifted velocities. The \(^{28}\)SiO (J = 1–0) emission spans a velocity range of between 38 and 120 km s\(^{-1}\), corresponding to an expansion velocity of about 41 km s\(^{-1}\). The inferred expansion velocity in \(^{28}\)SiO (J = 1–0) is similar to that found previously in \(^{28}\)SiO (J = 2–1) (Castro-Carrizo et al. 2001) as well as in \(^{12}\)CO (Castro-Carrizo et al. 2007; Dinh-V-Trung et al. 2009). The diameter of the \(^{28}\)SiO (J = 1–0) emission as shown in Figure 1 is about 8″, comparable to that mapped in \(^{28}\)SiO (J = 2–1) by Castro-Carrizo et al. (2001) and in \(^{12}\)CO J = 2–1 by Dinh-V-Trung et al. (2009). The combined single-dish and interferometer map in \(^{12}\)CO J = 1–0 by Castro-Carrizo et al. (2007) traces the envelope somewhat farther out to a diameter of about 12″.

The higher angular resolution maps in \(^{28}\)SiO (J = 1–0) reveal more internal structure than was previously seen in \(^{28}\)SiO (J = 2–1). At and near the systemic velocity, the \(^{28}\)SiO (J = 1–0) emission exhibits a clumpy ring-like structure centered approximately at the position of the central star. The emission from the south–east part of the shell is clearly weaker than that from the north–west part, indicating a departure from spherical symmetry at least in \(^{28}\)SiO (J = 1–0). A ring-like structure also is seen in the \(^{28}\)SiO (J = 2–1) maps of Castro-Carrizo et al. (2001) at and near to the systemic velocity. However, the \(^{28}\)SiO (J = 2–1) ring is significantly smaller than the \(^{28}\)SiO (J = 1–0) ring. The asymmetry in brightness around the ring is not as conspicuous in the \(^{28}\)SiO (J = 2–1) maps as in the \(^{28}\)SiO (J = 1–0) maps, although this difference may be related to the different angular resolutions of the two maps. At extreme blueshifted velocities (43.3–53.6 km s\(^{-1}\)), the centroid of the \(^{28}\)SiO (J = 1–0) emission is located to the south–west of the central star. By comparison, at extreme redshifted velocities (105.4–110.6 km s\(^{-1}\)), the centroid of the \(^{28}\)SiO (J = 1–0) emission is located to the north–east of the
In Figure 2, we show a position–velocity diagram of the VLA observation on $^{28}$SiO ($J = 1 - 0$) along PA = 70°. The horizontal axis represents the LSR velocity in km s$^{-1}$; the vertical axis represents the relative offset from south–west (0°) to north–east (15°) along the 70°-axis. The grayscale represents the intensity of emission in mJy. The position and systemic velocity of IRC +10420 (R.A.=19h26m48s.09, V$_{LSR}$ = 73.9 km s$^{-1}$) are indicated by the horizontal and vertical reference lines, respectively. The velocity gradient of the $^{12}$CO envelope observed by Castro-Carrizo et al. (2007) is indicated by the yellow line.

In Figure 4, we show the radially averaged brightness temperature profiles in $^{28}$SiO ($J = 1 - 0$) and $^{28}$SiO ($J = 2 - 1$) from maps regridded to the same velocity resolution and convolved to the same angular resolution in both lines (Section 2.3). These profiles are obtained by azimuthally averaging the line emission over successive annuli of 0.2°, which corresponds approximately to Nyquist sampling. The error bars indicate only random uncertainties and do not include systematic uncertainties in the flux calibration of either the $^{28}$SiO ($J = 1 - 0$) or the $^{28}$SiO ($J = 2 - 1$) lines. The brightness temperature in $^{28}$SiO ($J = 1 - 0$) peaks at a radius of $\sim$2″, whereas that in $^{28}$SiO ($J = 2 - 1$) peaks at a significantly smaller radius of $\sim$1″. Throughout the inner $\sim$2″, the brightness temperature in $^{28}$SiO ($J = 2 - 1$) is significantly higher than that in $^{28}$SiO ($J = 1 - 0$). Figure 5 shows the ratio of the brightness temperature between $^{28}$SiO ($J = 2 - 1$) and $^{28}$SiO ($J = 1 - 0$) as a function of radius, computed from the brightness temperature profiles of these two lines as shown in Figure 4. As can be seen, the line ratio $^{28}$SiO ($J = 2 - 1$)/$^{28}$SiO ($J = 1 - 0$) reaches its highest value of 2.2 ± 0.2 at the innermost annuli. On the other hand, at larger radii, both lines have comparable brightness temperatures such that $^{28}$SiO ($J = 2 - 1$)/$^{28}$SiO ($J = 1 - 0$) is practically unity at radii beyond $\sim$2″. The different line ratios over different radial ranges indicate a difference in the excitation of the $^{28}$SiO ($J = 1 - 0$) and $^{28}$SiO ($J = 2 - 1$) lines at the inner compared to the outer regions of the envelope.

Systemic errors in the flux calibration, as described in Section 2.2 for our observation in $^{28}$SiO ($J = 1 - 0$), may affect the measured brightness temperatures of both the $^{28}$SiO ($J = 1 - 0$) and the $^{28}$SiO ($J = 2 - 1$) lines and hence their measured ratio of brightness temperatures. Such errors, however, do not change the observed trends or the ratio of the brightness temperatures of both these lines as a function of radius as we have described. In our model for reproducing the azimuthally averaged brightness temperatures and the ratio of
the brightness temperatures of these lines as a function of radius as described in the next section, systematic errors in flux calibration may lead to a quantitative change in the physical parameters derived but not to a qualitative understanding of the differences in physical properties between the SiO-emitting and the CO-emitting envelopes.

4. Model

In Section 4.4, by combining our measurements in $^{28}$SiO ($J = 1$–0) with those in $^{28}$SiO ($J = 2$–1) by Castro-Carrizo et al. (2001) as described in Section 3, we are able to better constrain the density of the molecular hydrogen (H$_2$) gas responsible for exciting the observed SiO lines than was possible from the $^{28}$SiO ($J = 2$–1) line alone.

4.1. Qualitative Assessment

As a preliminary and qualitative assessment of how $^{28}$SiO ($J = 2$–1)/$^{28}$SiO ($J = 1$–0) varies with physical conditions within the envelope of IRC+10420, we make use of the simple radiative transfer code RADEX (van der Tak et al. 2007). RADEX adopts the large velocity gradient (LVG) or Sobolev approximation (Sobolev 1960), whereby photons emitted by molecules at a given location will not be absorbed by those elsewhere along the line of sight due to a Doppler shift caused by a velocity change. As a consequence, radiative transfer can be treated as a local problem, vastly simplifying the computation of radiative transfer through a parcel of gas. Assuming a constant H$_2$ gas density and a constant SiO abundance, Figure 6 shows how $^{28}$SiO ($J = 2$–1)/$^{28}$SiO ($J = 1$–0) is predicted by RADEX to vary with H$_2$ gas density, $n_{H_2}$ (cm$^{-3}$), and SiO column density, $N_{SiO}$ (cm$^{-2}$), at a gas temperature of 100 K, which is within the range of temperatures previously estimated for the inner envelope of IRC+10420. Two general trends are apparent in this figure, such that $^{28}$SiO ($J = 2$–1)/$^{28}$SiO ($J = 1$–0) increases as (1) $n_{H_2}$ increases and (2) $N_{SiO}$ decreases. As $n_{H_2}$ increases, collisional excitation by H$_2$ molecules increasingly populates the $J = 2$ level at the expense of the $J = 1$ level, leading to an increase in $^{28}$SiO ($J = 2$–1)/$^{28}$SiO ($J = 1$–0). As $N_{SiO}$ increases, the optical depth increases and the excitation temperature of $^{28}$SiO more closely approaches the gas kinetic temperature as radiative trapping contributes increasingly to the excitation. As a consequence, $^{28}$SiO ($J = 2$–1)/$^{28}$SiO ($J = 1$–0) approaches a value of unity as $N_{SiO}$ increases.

Attaining $^{28}$SiO ($J = 2$–1)/$^{28}$SiO ($J = 1$–0) in the range ~1–2, as is observed, requires $n_{H_2} \gtrsim 10^{4.5}$ cm$^{-3}$. Except in the inner region of the envelope, such H$_2$ gas densities are significantly higher than that required to produce both the $^{12}$CO $J = 1$–0 and the $^{12}$CO $J = 2$–1 (Dinh-V-Trung et al. 2009) lines according to the models proposed by both...
Castro-Carrizo et al. (2007) and Dinh-V-Trung et al. (2009). Note that RADEX predicts $^{28}$SiO ($J = 2–1$)/$^{28}$SiO ($J = 1–0$) to be quite insensitive to the gas temperature, hence our measurements do not provide strong constraints on the temperature of the SiO-emitting gas.

4.2. Radiative Transfer Code

To better constrain the physical conditions in the $^{28}$SiO-emitting envelope of IRC+10420, we used the one-dimensional radiative transfer code developed by Dinh-V-Trung & Nguyen-Q-Rieu (2000) that was previously used to model the CO-emitting envelope of this star. Instead of using the LVG approximation as in RADEX, we directly solved the coupled problem of radiative transfer and SiO level population throughout the envelope as a whole. To represent the stellar envelope, we used a grid of 90 radial mesh points. The intensity of the radiation field was calculated for each grid point through solving the radiative transfer equation, and the level population of SiO molecules in each grid point was computed by solving the statistical equations. This process was repeated iteratively until convergence was reached, using the accelerated iteration method to speed up the calculations. Once the level population at each grid point was determined, the resultant intensity of a given $^{28}$SiO line was found by integrating the radiative transfer equation along a large number of rays through the envelope.

To simulate the observations, we convolved the predicted intensity profile in the sky plane with a circular Gaussian beam. The diameter of the convolving beam is $1''78$, which is equal to the geometric mean of the major and minor axes of the synthesized beam ($2''53 \times 1''38$). Collisonal cross-sections between $^{28}$SiO and $H_2$ were taken from Schöier et al. (2005), who scaled (by 1.38) and interpolated the collisional cross-sections of $^{28}$SiO with He as computed by Dayou & Balança (2006). We included in our calculations all rotational transition levels of $^{28}$SiO up to $J = 20$ in the $v = 0$ and $v = 1$ vibrational states. Collisional excitation to the $v = 1$ vibrational state requires unrealistically high densities and temperatures and was therefore ignored in our calculations. On the other hand, strong infrared emission by hot dust located close to the star can contribute significantly to exciting $^{28}$SiO; in particular, $^{28}$SiO molecules in any rotational level $J$ in the $v = 0$ vibrational state may be excited to levels $J \pm 1$ in the $v = 1$ vibrational state by absorbing infrared photons at 8 $\mu$m emitted by the hot inner dust shell. These molecules are then de-excited very rapidly through spontaneous radiative transitions to rotational levels of $J \pm 2$ in the $v = 0$ vibrational state. For the sake of simplicity, we assume that all the infrared photons at 8 $\mu$m come from an optically thick shell with a temperature of $T = 400$ K located near the stellar surface, as in Dinh-V-Trung et al. (2009). The estimated temperature of the dust shell is based on fitting the spectral energy distribution from the near-infrared to millimeter wavelengths. From the observed flux density at 8 $\mu$m from IRC +10420, we estimate the radius of this dust shell to be $\sim 8 \times 10^{15}$ cm ($\sim 500$ au), which is a factor of three smaller than the inner radius of the SiO envelope.

4.3. Model Assumptions

Despite modeling efforts and recent constraints from observations with the Herschel telescope, the temperature profile in the gaseous envelope of IRC+10420 remains highly uncertain. In their model of the CO-emitting envelope, Castro-Carrizo et al. (2007) adopted an analytical profile for the temperature of the stellar envelope. This profile leads to a relatively high temperature at the inner region of the envelope, reaching about 1200 K at its innermost boundary (within which the density drops off dramatically due to the drastic decrease in the stellar mass-loss rate over the last $\sim 300$ years). In contrast, by considering the energy balance between the heating and the cooling processes, Dinh-V-Trung et al. (2009) derived a self-consistent manner the gas temperature throughout the envelope of IRC+10420. The temperature derived by Dinh-V-Trung et al. (2009) for the inner region of the envelope is significantly lower than that adopted by Castro-Carrizo et al. (2007). However, in relying on matching single-dish observations of $^{12}$CO from $J = 1–0$ to $J = 6–5$ and $^{13}$CO from $J = 1–0$ to $J = 2–1$, the temperature derived by Dinh-V-Trung et al. (2009) for the inner region of the envelope is not well constrained (the observed CO transitions arise primarily from the outer, cooler region of the envelope). More recently, from observations in the $J = 6–5$, $J = 10–9$, and $J = 16–15$ transitions of $^{12}$CO and $^{13}$CO with the Herschel telescope, Teyssier et al. (2012) inferred a gas temperature at the innermost layers of the envelope that is higher than that derived by Dinh-V-Trung et al. (2009) and closer to that adopted by Castro-Carrizo et al. (2007).

As mentioned in Section 4.1, our simple calculations using RADEX indicate that the line ratio $^{28}$SiO ($J = 2–1$)/$^{28}$SiO ($J = 1–0$) does not depend sensitively on the gas temperature. Thus, for the sake of simplicity, we adopted the temperature profile proposed by Teyssier et al. (2012) for the inner region and the analytical profile adopted by Castro-Carrizo et al. (2007) for the outer region of the envelope, parameterized as:

$$
\left( \frac{T_{\text{kin}}}{K} \right)_{\text{inner}} (r) = 170 \cdot \left( \frac{r}{10^{17} \text{ cm}} \right)^{1.2}
$$

for $0.25 \leq \left( \frac{r}{10^{17} \text{ cm}} \right) \leq 1.24$ (1)

$$
\left( \frac{T_{\text{kin}}}{K} \right)_{\text{outer}} (r) = 100 \cdot \left( \frac{r}{10^{17} \text{ cm}} \right)^{-0.8}
$$

for $1.24 \leq \left( \frac{r}{10^{17} \text{ cm}} \right) \leq 5.20$. (2)

As emphasized by Dinh-V-Trung et al. (2009), the gas temperature in the envelope of IRC+10420 is relatively high compared with that in the envelopes of AGB stars. They suggest that due to the high stellar luminosity and hence radiation pressure, dust grains are driven outward at a relatively high velocity. Collisions between gas molecules and the dust grains then heat up the gas in the envelope to a relatively high temperature.

To account for the smooth line profile of the envelope despite its unusually large expansion velocity of $\sim 38$ km s$^{-1}$, we adopted a local turbulent velocity of 3 km s$^{-1}$ as in Dinh-V-Trung et al. (2009). By comparison, the typical expansion velocity in the envelope of AGB stars is $\sim 10$ km s$^{-1}$, where the turbulent velocity is $\sim 1$ km s$^{-1}$. We find that our model results do not change significantly for reasonable values of the local turbulent velocity.
4.4. Model Results

The radial dependence in $H_2$ gas density and SiO abundance are free parameters that we varied until a satisfactory match was found to both the measured radial dependence in $^{28}\text{SiO} (J = 2–1)/^{28}\text{SiO} (J = 1–0)$ and the brightness temperatures of both $^{28}\text{SiO} (J = 1–0)$ and $^{28}\text{SiO} (J = 2–1)$. We emphasize at this point that our model strives to match the azimuthally averaged measurements in $^{28}\text{SiO} (J = 1–0)$ and $^{28}\text{SiO} (J = 2–1)$ and makes no attempt to reproduce the clumpiness and departure from circular symmetry seen in both lines. Our model also predicts the intensity of the SiO $J = 3–2$ and $J = 5–4$ lines as observed by Quintana-Lacaci et al. (2007), helping us to assess the viability of the selected model parameters.

4.4.1. Different Physical Parameters for SiO- and CO-emitting Gas

Using the $H_2$ gas densities derived by either Castro-Carrizo et al. (2007) or Dinh-V-Trung et al. (2009) for the CO-emitting envelope and assuming a reasonable SiO abundance (ratio of SiO to $H_2$ molecules) in the range between $10^{-2}$ to a few at $10^{-6}$, we found that the predicted brightness temperatures of both $^{28}\text{SiO} (J = 1–0)$ and $^{28}\text{SiO} (J = 2–1)$ are much lower than are observed except in the innermost region (radius $<2''$) where the $H_2$ gas density is close to the critical density of both $^{28}\text{SiO} (J = 1–0)$ and $^{28}\text{SiO} (J = 2–1)$. This result, assuming a gas temperature for the envelope as described in Section 4.3, is simple to understand. Although radiative excitation by infrared photons emitted from hot dust near the star is significant, collisions with $H_2$ molecules nevertheless dominate the excitation of both $^{28}\text{SiO} (J = 1–0)$ and $^{28}\text{SiO} (J = 2–1)$. Because the critical densities of both these lines are much higher than that of either CO ($J = 1–0$) or CO ($J = 2–1$) on the models of both Castro-Carrizo et al. (2007) and Dinh-V-Trung et al. (2009) are based, $^{28}\text{SiO} (J = 1–0)$ and $^{28}\text{SiO} (J = 2–1)$ are only weakly excited at the densities inferred for the CO-emitting envelope. In this situation, both these lines are very optically thin, yielding a line ratio well above unity along all lines of sight through the envelope. Such a high line ratio is in clear contradiction with that measured along lines of sight at angular radii $>2''$ ($>10^4$ au) from the star. Now, increasing the gas temperature can potentially boost the brightness temperatures of both lines to a level that matches the values observed, as in the model of Castro-Carrizo et al. (2001) for the $^{28}\text{SiO} (J = 2–1)$ line. However, the dramatic increase in gas temperature required would result in much brighter CO lines than are observed (for the gas temperature required to produce the observed CO lines, see the calculations of Dinh-V-Trung et al. 2009).

Our central conclusion therefore is that except at the innermost regions ($<2''$), the same gas component cannot be responsible for both the SiO and the CO emission from the envelope of IRC+10420. Instead, the SiO-emitting gas must have a significantly higher density or temperature, or both, than the CO-emitting gas.

4.4.2. Physical Parameters of SiO-emitting Gas

Here we explore the situation in which the SiO-emitting gas has a temperature that is comparable with that of the CO-emitting gas; i.e., a radial dependence in temperature as described in Section 4.3. In Section 5, we explain the physical motivation for making this assumption. Irrespective

of the exact gas temperature, as demonstrated in Section 4.1, the $H_2$ gas density required for producing the observed $^{28}\text{SiO} (J = 1–0)$ and $^{28}\text{SiO} (J = 2–1)$ emission must be close to or exceed the critical densities of these lines throughout the envelope. As a matter of convenience for inputting the model parameters as well as to provide an instructive comparison with the CO-emitting envelope, we express the required $H_2$ gas density in the SiO-emitting envelope in terms of a corresponding mass-loss rate (which can change as a function of time) from the central star. Implicit in this expression is that the mass-loss rate is computed for a unity filling factor for the SiO-emitting gas. The required $H_2$ gas density for producing the CO-emitting envelope is also expressed as a corresponding mass-loss rate, again implicitly assuming a unity filling factor for the CO-emitting gas, in the models of Castro-Carrizo et al. (2007) and Dinh-V-Trung et al. (2009). Of course, a star cannot have two different mass-loss rates at the same time, so any difference in this rate simply indicates different $H_2$ gas densities for the SiO- and CO-emitting gases at a given radius. The total mass-loss rate of the star is the sum of the individual contributions from the SiO- and CO-emitting parts of the envelope and depends on their individual filling factors.

As mentioned in Section 1, the CO-emitting gas originates from two shells: an inner detached shell and an outer shell, separated by a gap. Similarly, we divide the SiO-emitting envelope into three zones: an inner zone coinciding with the inner detached shell, an outer zone coinciding with the outer detached shell, and a middle zone corresponding to the gap between these two shells, chosen to specifically match the model for the CO-emitting envelope proposed by Castro-Carrizo et al. (2007) (given that we adopt their temperature profiles beyond the inner zone). In the inner zone, spanning a radius of $\sim 0''/3$ to $\sim 1''/5$, the $^{28}\text{SiO} (J = 2–1)$ emission peaks in brightness temperature. However, the $^{28}\text{SiO} (J = 1–0)$ emission peaks in brightness temperature farther out, in the middle zone. Thus in the inner zone $^{28}\text{SiO} (J = 2–1)/^{28}\text{SiO} (J = 1–0)$ is relatively high and consistently above unity, implying that both lines are optically thin. As a consequence, the $^{28}\text{SiO}$ column density is required to be relatively low and hence also the $^{28}\text{SiO}$ abundance. In the middle zone spanning $\sim 1''/5$ to $\sim 2''/5$, $^{28}\text{SiO} (J = 2–1)/^{28}\text{SiO} (J = 1–0)$ is close to but consistently above unity, indicating that both lines have a greater optical depth than in the inner region. Therefore the $^{28}\text{SiO}$ column density and the abundance must be higher than their corresponding values in the inner zone. In the outer zone, ranging from $\sim 2''/5$ to the outer edge of the envelope at $\sim 6''/0$, the brightness temperatures of both $^{28}\text{SiO} (J = 1–0)$ and $^{28}\text{SiO} (J = 2–1)$ decrease smoothly with an increasing radius and have values much lower than those in the middle or inner zone. Throughout this zone, $^{28}\text{SiO} (J = 2–1)/^{28}\text{SiO} (J = 1–0)$ has a value consistent with unity, indicating that both lines are somewhat more optically thick than in the middle zone. Given the relatively large depth of the outer zone but the much lower brightness temperatures in both $^{28}\text{SiO} (J = 1–0)$ and $^{28}\text{SiO} (J = 2–1)$ by comparison with the middle zone, the $^{28}\text{SiO}$ abundance in the outer zone must be much lower than that in the middle zone.

Assuming a constant mass-loss rate in each of the three zones of the SiO-emitting envelope just as for the CO-emitting envelope, we found a satisfactory match between our model and the results in both $^{28}\text{SiO} (J = 1–0)$ and $^{28}\text{SiO} (J = 2–1)$ if
The SiO-emitting envelope has the following mass-loss rate in the three zones:

\[
\dot{M}(M_\odot \text{ yr}^{-1}) = \begin{cases} 
1.2 \times 10^{-3} & 0.25 < \left( \frac{r}{10^3 \text{ cm}} \right) < 1.24 \\
7.5 \times 10^{-4} & 1.24 < \left( \frac{r}{10^3 \text{ cm}} \right) < 2.20 \\
5.2 \times 10^{-3} & 2.20 < \left( \frac{r}{10^3 \text{ cm}} \right) < 5.20
\end{cases}
\]

The corresponding \( \text{H}_2 \) gas density as a function of radius is plotted in Figure 7. For comparison, we also plot in this figure the dependence in \( \text{H}_2 \) gas density with radius as derived by Castro-Carrizo et al. (2007) and Dinh-V-Trung et al. (2009) for the CO-emitting gas. The \( ^{28}\text{SiO} \) abundance in each of these three zones is

\[
\frac{[\text{SiO}]/[\text{H}_2]}{10^{-8}} = \begin{cases} 
9 \times 10^{-7} \left( \frac{r}{10^3 \text{ cm}} \right) & 0.25 < \left( \frac{r}{10^3 \text{ cm}} \right) < 1.24 \\
4.5 \times 10^{-6} & 1.24 < \left( \frac{r}{10^3 \text{ cm}} \right) < 2.20 \\
4.8 \times 10^{-8} (4.8 - \left( \frac{r}{10^3 \text{ cm}} \right)) & 2.20 < \left( \frac{r}{10^3 \text{ cm}} \right) < 5.20
\end{cases}
\]

as plotted in Figure 8. For a constant mass-loss rate as assumed in each of the three zones, the \( ^{28}\text{SiO} \) abundance is required to increase with increasing radius in the inner zone, be approximately constant in the middle zone, and decrease with radius in the outer zone. An alternative, more physical way to interpret the change in \( ^{28}\text{SiO} \) abundance with radius is a corresponding change in the filling factor of the SiO-emitting gas as a function of radius. The predicted radial profiles in the brightness temperatures of the \( ^{28}\text{SiO} \) \((J = 1-0)\) and \( ^{28}\text{SiO} \) \((J = 2-1)\) lines are shown in Figure 9, and their corresponding line ratios are shown in Figure 10. Figure 11 compares our model predictions for the integrated spectra in \( ^{28}\text{SiO} \) \((J = 2-1), ^{28}\text{SiO} \) \((J = 3-2), \) and \( ^{28}\text{SiO} \) \((J = 5-4)\) (solid line) compared with measurements (histogram) made with the IRAM 30 m telescope by Quintana-Lacaci et al. (2016).
4.5. Caveats

The $^{28}\text{SiO} (J = 1–0)$ and $^{28}\text{SiO} (J = 2–1)$ measurements used in our model are separated in time by more than 10 years, raising the possibility that one or both lines have changed in intensity during the intervening period. A comparison between single-dish observations of the $^{28}\text{SiO} (J = 2–1)$ and $^{28}\text{SiO} (J = 3–2)$ lines in 1993 by Bujarrabal et al. (1994) and those in 2006 by Quintana-Lacaci et al. (2007) indicates a possible change in the intensity of the $^{28}\text{SiO} (J = 3–2)$ line at the level of $\sim 20\%$. From line surveys of IRC$+10420$ at 3 and 1 mm, Quintana-Lacaci et al. (2016) found that while most of the molecular lines observed seem to be stable over time, relatively high $J$ transitions of SiO and HCN such as $^{28}\text{SiO} (J = 3–2)$ and HCN ($J = 3–2$) show noticeable variations over time. Recently, de Vicente et al. (2016) reported that the $^{28}\text{SiO} (J = 1–0)$ emission from IRC$+10420$ is slightly variable in intensity, changing by roughly 20% over an interval of 1 year. We note, however, that the uncertainty in flux calibration for single-dish telescopes is quite large, about 10% at the lower frequency of the $^{28}\text{SiO} (J = 1–0)$ line and about 30% at the higher frequency of the $^{28}\text{SiO} (J = 5–4)$ line (Quintana-Lacaci et al. 2016). Systematic uncertainties in the flux calibration, a problem that also plagues our observation in $^{28}\text{SiO} (J = 1–0)$ as described in Section 2.2, can dominate over any intrinsic changes in line intensity.

By fitting the spectral energy distribution of IRC$+10420$ measured with the Infrared Space Observatory, Quintana-Lacaci et al. (2016) inferred an equivalent blackbody temperature of 300 K for the dust shell around this star. The derived temperature is significantly lower than that used in our model of 400 K, as described in Section 4.3; we note that the higher temperature was inferred by fitting the spectral energy distribution of IRC$+10420$ over a much broader range in wavelengths from infrared to millimeter. To estimate the sensitivity of our model to changes in the infrared radiation field inside the envelope, we have rerun our calculations for a lower equivalent blackbody temperature of 300 K for the dust shell but kept all the other physical parameters for the SiO-emitting envelope the same as described in Section 4.4. In Figure 12, we show our model predictions for the integrated intensity profiles of $^{28}\text{SiO} (J = 1–0)$, $^{28}\text{SiO} (J = 3–2)$, and $^{28}\text{SiO} (J = 5–4)$. As can be seen, the lower transitions of $^{28}\text{SiO}$ are much less affected by changes in the infrared radiation field than are the higher transitions, as radiative excitation contributes more strongly to the overall excitation of $^{28}\text{SiO}$ at higher than at lower transitions. Specifically, the peak intensity of $^{28}\text{SiO} (J = 2–1)$ weakens by only $\sim 10\%$, whereas that of...
of an oversimplified outer CO-emitting shells inferred by Castro-Carrizo et al. 28SiO emission, gives rise predominantly to the observed CO. Our model only provides the azimuthally averaged radial density profile and the SiO abundance of the envelope. In regions where the brightness temperature in either 28SiO (J = 1–0) or 28SiO (J = 2–1) or both differ from the azimuthally averaged value, the physical conditions may well be different from those indicated by our model.

5. Discussion

5.1. Dense SiO-emitting Clumps within Diffuse CO-emitting Gas

Our modeling results clearly show that the SiO-emitting gas has a much higher molecular (primarily H2) gas density than that derived by either Castro-Carrizo et al. (2007) or Dinh-V-Trung et al. (2009) for the CO-emitting gas throughout much of the envelope. The most striking difference is found for the middle zone, which corresponds to a gap devoid of CO-emitting gas between the inner and outer CO-emitting shells in the models of both Castro-Carrizo et al. (2007) and Dinh-V-Trung et al. (2009). In this zone, the inferred density of the SiO-emitting gas is ~104 cm−3 (Figure 8), only somewhat lower than that in the inner and outer zones. In the outer zone, the density of the SiO-emitting gas is about an order of magnitude higher than that obtained by Dinh-V-Trung et al. (2009) and about two orders of magnitude higher than that obtained by Castro-Carrizo et al. (2007) for the CO-emitting gas. In the inner zone, corresponding to the inner CO shell, the density of the SiO-emitting gas is comparable to or only somewhat elevated compared to that of the CO-emitting gas.

Despite the obvious differences in gas density responsible for 28SiO and CO emission throughout much of the envelope of IRC+10420, the SiO-emitting gas spans essentially the same radius from the star as does the CO-emitting gas. We therefore conclude that the 28SiO emission, particularly that from the middle and outer zones, must originate from relatively dense clumps. By comparison, the relatively diffuse gas between these clumps, which contribute little to the observed 28SiO emission, gives rise predominantly to the observed CO emission. At this point, we note that the gap between the inner and outer CO-emitting shells inferred by Castro-Carrizo et al. (2007) and Dinh-V-Trung et al. (2009) may be a consequence of an oversimplification of their models for reproducing the overall CO-emitting envelope (i.e., a minimum parameter model). The observed CO emission shows no such gap but instead just a weak local depression at the angular radius of the purported gap (see Figure 10 of Castro-Carrizo et al. 2007 or Figures 10 and 14 of Dinh-V-Trung et al. 2009). Decreasing the stellar mass-loss rate for producing the inner and/or outer CO-emitting shells in the models of Castro-Carrizo et al. (2007) and Dinh-V-Trung et al. (2009) would necessitate increasing the stellar mass-loss rate during the interval between the production of these two shells. In short, the CO observations indicate a drop, but not necessarily a null, in the stellar mass-loss rate between the production of the inner and outer shells. By contrast with the middle and outer zones, in the inner zone where the density of the CO-emitting gas is relatively high and comparable to the critical density of 28SiO (J = 1–0) if not of 28SiO (J = 2–1), the same gas component may be responsible for both the observed CO and the observed SiO emission. In Figure 13, we sketch a qualitative model for the origin of the CO and 28SiO emission from the envelope of IRC+10420.

Which component has the higher filling factor—the dense, primarily SiO-emitting gas or the diffuse, primarily CO-emitting gas? At a given radius, the azimuthally averaged brightness temperatures in 28SiO (J = 1–0) and 28SiO (J = 2–1) are roughly comparable (within a factor of ~2) to those in CO (J = 1–0) and CO(J = 2–1) (see Figures 13–14 of Dinh-V-Trung et al. 2009). These roughly comparable brightness temperatures suggest roughly comparable filling factors for the two components, assuming that both components have the same temperature (as we have in our model for the SiO-emitting envelope). If the dense clumps also have higher temperatures, a possibility we explore in section 5.2 to explain the presence of SiO in the gas phase so far out in the envelope of IRC+10420, then their filling factor decreases. A more detailed estimate of the filling factor of the two gas components would require modeling of the CO emission from both the dense clumps and the diffuse interclump gas.

As can be seen in Figure 7, the SiO abundance is highest in the middle zone. By comparison, the SiO abundance is dramatically lower in the inner and outer zones, with the outer zone having the lowest abundance. The modeled SiO abundance implicitly assumes a unity filling factor for the SiO-emitting gas and therefore represents a lower limit in the intrinsic SiO abundance (i.e., the intrinsic SiO abundance scales in proportion to the inverse of the filling factor). If the intrinsic SiO abundances in the three zones are similar, then the different SiO abundances inferred in our model imply different filling factors for the dense SiO-emitting clumps in these zones. As mentioned above, in the inner zone the same gas is likely responsible for both the SiO and the CO emission. If the gas filling factor is unity in this region, then the SiO abundance inferred in our model for the inner zone reflects the intrinsic SiO abundance in this zone. In that case, the intrinsic SiO abundance must be much higher in the middle zone than in the inner zone.
5.2. Shock Origin of SiO

According to current chemical models, SiO molecules form in stellar atmospheres under LTE (Cherchneff 2006). These (and other) molecules are then ejected through collective collisional coupling with dust grains driven outward by radiation pressure from the star. As the temperature drops with radial distance, SiO molecules are expected to condense onto dust grains, leading to an abrupt decrease in SiO abundance beyond a certain radius. In the model proposed by Jura & Morris (1985), the SiO abundance depends on the competition between SiO molecules sticking onto and evaporating from the surface of dust grains. The SiO evaporation rate has an approximately exponential dependence on the grain temperature, so that at low temperatures and high gas densities, SiO molecules mainly stick to dust grains.

Jura & Morris (1985) found that the condensation of molecules becomes dominant when the grain temperature drops below \( T_{\text{bind}}/50 \), where \( kT_{\text{bind}} \) is the binding kinetic energy of molecules on the grains. For SiO molecules, \( T_{\text{bind}} = 29,500 \) K, implying that SiO condenses onto dust grains when the grain temperature drops below \( \sim 600 \) K. In AGB stars, temperatures above the SiO condensation temperature are usually found only at the inner region of their envelopes. As a consequence, SiO emission is confined to a relatively small radial distance (by comparison with CO emission) from these stars. Farther out, the SiO abundance drops dramatically as condensation becomes dominant and almost every molecule that sticks onto the grain remains there. Beyond the radius where evaporation becomes negligible, the fractional abundance of SiO molecules as a function of radius, \( f_{\text{SiO}}(r) \), can be determined from the equation given in Jura & Morris (1985):

\[
f_{\text{SiO}}(r) = f_{\text{SiO}}(r_0) \exp \left[ -\delta \left( \frac{1}{r_0} - \frac{1}{r} \right) \right],
\]

where \( f_{\text{SiO}}(r_0) \) is the fractional abundance at \( r_0 \), the condensation radius, and \( \delta \) is the characteristic scale length. The latter is defined as

\[
\delta = \frac{\alpha N_d \sigma_{\text{gr}} v_{\text{dr}}}{4\pi \nu_{\text{c}}^2},
\]

where \( \alpha \) is the sticking probability of SiO onto dust grains, \( N_d \) is the dust mass-loss rate in terms of dust grain number, \( \sigma_{\text{gr}} \) is the grain cross-section, and \( v_{\text{dr}} \) is the drift velocity of the dust grains with respect to the gas. The condensation radius \( (r_0) \) is determined from the manner in which the temperature of the dust grains decreases with increasing radius. This simple model was used by González Delgado et al. (2003) to successfully explain the observational characteristics of SiO emission from both C-rich and O₂-rich circumstellar envelopes.

Using the parameters of the CO-emitting envelope as derived by Dinh-V-Trung et al. (2009), we estimate a condensation radius of \( r_0 \sim 4 \times 10^{15} \) cm (\( \sim 300 \) au) for IRC+10420, significantly smaller than the inner radius of the inner zone in our model. The estimated condensation radius is about an order of magnitude larger than that for AGB stars, as a consequence of the higher temperature in the envelope of IRC+10420 (given its much higher luminosity) at a given radius from the central star. Assuming a sticking probability of \( \alpha \sim 1 \) (as is adopted for and which explains the radial extent of the SiO emission around AGB stars), the characteristic scale length is therefore \( \sim 1.8 \times 10^{17} \) cm, which is much larger than the condensation radius (note that the larger the scale length, the more quickly the SiO abundance decreases beyond the condensation radius). Thus the SiO abundance is predicted to drop precipitously beyond the condensation radius, in stark contrast with the dramatic outward increase in the SiO abundance inferred from our model between the inner and middle zones. Indeed, the SiO abundance is predicted to become vanishingly small within the inner zone of the SiO-emitting envelope, let alone within the middle and outer zones.

The much higher SiO abundance throughout the SiO-emitting envelope of IRC+10420 than expected due to condensation onto dust grains makes necessary a mechanism for evaporating SiO molecules from the surfaces of these grains. The most obvious such mechanism is sputtering (collisions between gas and dust due to their slightly different outflow velocities) or shocks, as is conjectured for SiO emission detected from protostellar outflows as well as fast outflows from post-AGB stars (where, once again, any SiO in the gas phase is expected to condense onto dust grains near the star). Shocks may also explain the relatively high turbulent velocity in the envelope of IRC+10420, as noted by Nedoluha & Bowers (1992), based on the broad and irregular line shapes of OH masers observed from this star. We note that the sound speed in the molecular envelope is only \( 1 \) km s\(^{-1}\), and hence a difference in velocities of just a few km s\(^{-1}\) or higher between the SiO-emitting clumps and the surrounding CO-emitting gas is sufficient to generate strong shocks.

5.3. Relationship of Dense SiO-emitting Dust Clumps to Optical Dust Clumps

The inference of dense gas clumps responsible for the \( ^{28}\text{SiO} \) emission of IRC+10420 naturally suggests a connection with the dust clumps seen in optical scattered light around this star (Humphreys et al. 1997 and Tiffany et al. 2010). Indeed, such dust clumps are detectable out to an angular radius of \( \sim 2'' \) from the star, roughly comparable in angular extent to the middle zone at or near where the SiO emission is brightest. Humphreys et al. (1997) and Tiffany et al. (2010) suggest that these clumps are ejected as a consequence of violent global events on the surface of the star, probably related to convective or magnetic activities. We speculate that as these dense clumps move outward, shocks can form due to interaction between these clumps and the surrounding diffuse CO-emitting gas where the difference in their bulk velocities is as low as just a few km s\(^{-1}\). Heating due to such shocks leads to an increase in the temperature of the dust grains, releasing the SiO molecules from the surfaces of these grains back into the gas phase.

From dual-epoch observations with the HST, Tiffany et al. (2010) determined the proper motion and thus the transverse velocity for a number of dust clumps in the envelope of IRC+10420. By combining the transverse velocity and the line-of-sight velocity (Humphreys et al. 2002), they found a space motion for these clumps close to the plane of the sky. As a consequence, Tiffany et al. (2010) suggest that the ejecta is viewed nearly pole-on. Indeed, imaging polarimetry by Shenoy et al. (2015) reveals a concentric pattern in the linear polarization of the scattered light, with a fractional linear polarization of up to 30% at distance of 1"–2" from the star. Such high degrees of linear polarization requires a scattering...
angle close to 90°; i.e., the bulk of the scatterers are distributed near the sky plane. In addition, optical interferometric observation of Brγ emission by Oudmaijer & de Wit (2013) is found to be consistent with a bipolar outflow confined within \( \sim 10 \) au around the central hypergiant star and viewed nearly pole-on. Therefore, all previous observations in the optical and near-infrared seem to suggest a strong departure from spherical symmetry of the envelope. By contrast, the dense SiO-emitting clumps inferred from our observations and analysis are distributed throughout a roughly spherical envelope. The reason for such a discrepancy between optical and radio observations currently remains unresolved, and clarification will require further investigation.

6. Summary and Conclusion

We presented an image, taken with the VLA, of the circumstellar envelope of the yellow hypergiant IRC+10420 as traced in \(^{28}\)SiO \((J = 1–0)\). Like that traced in \(^{28}\)SiO \((J = 2–1)\) as reported by Castro-Carrizo et al. (2001), the global kinematic structure of the envelope traced in the SiO lines is similar to that traced in both CO \((1–0)\) by Dinh-V-Trung et al. (2009) and CO \((2–1)\) by Castro-Carrizo et al. (2001), including a weak velocity gradient along the north–west to south–east direction apparent in all the aforementioned molecular lines. By contrast with the envelope traced in CO, however, both the \(^{28}\)SiO \((J = 1–0)\) and the \(^{28}\)SiO \((J = 2–1)\) emissions show a pronounced central depression that gives rise to their ring-like appearance. The ring traced in \(^{28}\)SiO \((J = 1–0)\) is clumpy and brighter on the north-western than on the south-eastern side, along the same direction as the aforementioned velocity gradient in the envelope. Other than that, on a global scale the envelope is approximately spherically symmetric as traced in both \(^{28}\)SiO \((J = 1–0)\) and \(^{28}\)SiO \((J = 2–1)\), as is the case as traced in both \(^{13}\)CO \(J = 1–0\) and \(^{12}\)CO \(J = 2–1\). A detailed comparison between the \(^{28}\)SiO \((J = 1–0)\) and \(^{28}\)SiO \((J = 2–1)\) images reveals that:

1. The \(^{28}\)SiO \((J = 1–0)\) emission peaks at a radius of \( \sim 2'' \), whereas the \(^{28}\)SiO \((J = 2–1)\) emission peaks at a significantly smaller radius of \( \sim 1'' \).

2. The ratio of the brightness temperature between \(^{28}\)SiO \((J = 2–1)\) and \(^{28}\)SiO \((J = 1–0)\), \(^{28}\)SiO \((J = 2–1)\) / \(^{28}\)SiO \((J = 1–0)\), is significantly higher within a radius of \( \sim 2'' \), rising to a value of as high as about 2.2 at the innermost region, than farther out, where the line ratio is approximately constant at about 1.0.

Although systematic errors in the flux calibration introduce unknown uncertainties in the measured brightness temperature of both the SiO lines, such errors do not change the observed radial trends in the brightness temperature or the ratio of the brightness temperature of both these lines. While such errors may lead to a quantitative change in the physical parameters we derive for the SiO-emitting envelope, they do not change our conclusions on the qualitative differences in physical properties between the SiO-emitting and the CO-emitting parts of the envelope.

We constructed a model that reproduces both the measured radial dependence in \(^{28}\)SiO \((J = 2–1) / ^{28}\)SiO \((J = 1–0)\) and the brightness temperatures in both \(^{28}\)SiO \((J = 1–0)\) and \(^{28}\)SiO \((J = 2–1)\). Because these measurements do not provide meaningful constraints on the gas temperature, with \(^{28}\)SiO \((J = 2–1) / ^{28}\)SiO \((J = 1–0)\) in particular being relatively insensitive to temperature, we assumed a temperature profile for the envelope as inferred by Teyssier et al. (2012) from CO observations (for the inner region of the envelope), or as adopted by Castro-Carrizo et al. (2007) for the modeling of the CO emission (for the outer region of the envelope), in the manner parameterized by Equation (3). In our model, we divided the SiO-emitting envelope into three zones as is inferred for the CO-emitting envelope in the models of both Castro-Carrizo et al. (2007) and Dinh-V-Trung et al. (2009). In the model of Castro-Carrizo et al. (2007), the inner zone spans the radial range of \( \sim 0''3–1''5 \), the middle zone spans the radial range of \( \sim 1''5–2''5 \), and the outer zone spans the radial range of \( \sim 1''5–6''0 \). The middle zone is essentially devoid of CO-emitting gas in the models of both Castro-Carrizo et al. (2007) and Dinh-V-Trung et al. (2009), indicating a dramatic drop in H\(_2\) gas density or its filling factor in this zone. We find the following:

3. Except at the inner zone, the H\(_2\) gas density inferred for the CO-emitting envelope is far too low to produce the observed brightness temperatures in both \(^{28}\)SiO \((J = 1–0)\) and \(^{28}\)SiO \((J = 2–1)\).

4. In the outer zone, the H\(_2\) gas density traced by \(^{28}\)SiO \((J = 1–0)\) and \(^{28}\)SiO \((J = 2–1)\) is an order of magnitude higher than that inferred by Dinh-V-Trung et al. (2009) and two orders of magnitude higher than that inferred by Castro-Carrizo et al. (2007) for the CO-emitting envelope.

5. In the middle zone, where \(^{28}\)SiO \((J = 1–0)\) peaks in brightness temperature, the H\(_2\) gas density traced by \(^{28}\)SiO \((J = 1–0)\) and \(^{28}\)SiO \((J = 2–1)\) is no more than an order of magnitude lower than that of the outer zone, by contrast with the lack of CO-emitting gas in this zone as inferred by both Castro-Carrizo et al. (2007) and Dinh-V-Trung et al. (2009).

We conclude that the \(^{28}\)SiO emission, particularly that from the middle and outer zones, must originate from relatively dense clumps. By comparison, the relatively diffuse gas between these clumps, which contribute little to the observed \(^{28}\)SiO emission, gives rise predominantly to the observed CO emission. If both gas components are at the same temperature, as in our model, then the filling factors of the two gas components must be roughly comparable; a more detailed estimate of the filling factor of the two gas components would require modeling of the CO emission from both the dense clumps and the diffuse interclump gas. On the other hand, a higher temperature for the dense \(^{28}\)SiO-emitting clumps implies a lower filling factor for these clumps. Our model requires the \(^{28}\)SiO abundance to change with radius in each zone. In interpreting this change as an actual change in the filling factor of the SiO-emitting gas having a constant intrinsic \(^{28}\)SiO abundance throughout the envelope, we find that:

6. The filling factor of the SiO-emitting gas increases with radius in the inner zone, is nearly an order of magnitude higher and remains approximately constant with radius in the middle zone, and is lowest and moreover decreases with increasing radius in the outer zone.

Despite the relatively high effective temperature and luminosity of IRC+10420, we show that SiO molecules are expected to condense onto dust grains just beyond the inner radius of the inner zone and to become vanishingly small
within this zone. We speculate that SiO molecules are subsequently released from dust grains due to shock interactions between the dense SiO-emitting clumps and the diffuse CO-emitting interclump gas, where differences in bulk velocity as small as a few km s$^{-1}$ are sufficient to generate strong shocks. We associate the dense SiO-emitting clumps with dust clumps seen in scattered optical light. Such dust clumps are detectable out to an angular radius of $\sim 2''$ from the star, roughly comparable in angular extent to the middle zone at or near where the SiO emission is brightest.

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Facility: VLA.

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