TRACING THE ASYMMETRY IN THE ENVELOPE AROUND THE CARBON STAR CIT 6

DINH-V-TRUNG1,2 AND JEREMY LIM1

1 Institute of Astronomy and Astrophysics, Academia Sinica, P.O. Box 23-141, Taipei 10617, Taiwan; trung@asiaa.sinica.edu.tw, jlim@asiaa.sinica.edu.tw
2 Center for Quantum Electronics, Institute of Physics, Vietnamese Academy of Science and Technology, 10 DaoTan, BaDinh, Hanoi, Vietnam

Received 2008 November 14; accepted 2009 June 5; published 2009 July 22

ABSTRACT

We present high angular resolution observations of HC$_3$N $J = 5 - 4$ line and 7 mm continuum emission from the extreme carbon star CIT 6. We find that the 7 mm continuum emission is unresolved and has a flux consistent with blackbody thermal radiation from the central star. The HC$_3$N $J = 5 - 4$ line emission originates from an asymmetric and clumpy expanding envelope comprising two separate shells of HC$_3$N $J = 5 - 4$ emission: (1) a faint outer shell that is nearly spherical which has a radius of 8$''$ and (2) a thick and incomplete inner shell that resembles a one-arm spiral starting at or close to the central star and extending out to a radius of about 5$''$. A comparison between the data and our excitation modeling results suggests an unusually high abundance of HC$_3$N in the envelope of CIT 6. We discuss the possibility that the envelope might be shaped by the presence of a previously suggested possible binary companion. The abundance of HC$_3$N may be enhanced in spiral shocks produced by the interaction between the circumstellar envelope of CIT 6 and its companion star.

Key words: circumstellar matter – ISM: molecules – stars: AGB and post-AGB – stars: individual (CIT 6) – stars: mass loss

Online-only material: color figures

1. INTRODUCTION

The circumstellar envelope around carbon-rich asymptotic giant branch (AGB) stars is well known to be the site of very active photochemistry and hence a rich source of molecular emission lines. The prime example is the massive carbon-rich circumstellar envelope of the nearby AGB star IRC+10216 (CW Leo), where more than 50 molecular species have been detected. Many spectral line surveys in the millimeter wavelength range have been conducted toward IRC+10216 (He et al. 2008, Cernicharo et al. 2000, Kawaguchi et al. 1995). These surveys show that the emission lines from cyanopolyne molecules such as HC$_3$N and HC$_5$N are very prominent in the millimeter wavelengths. Interferometric observations of HC$_3$N lines in the 3 mm band by Bieging & Tafalla (1993) with BIMA and by Guélin et al. (1999) with the IRAM PdBI show that the cyanopolyne molecules have a hollow-shell distribution, consistent with the predictions of chemical models for a carbon-rich circumstellar envelope (Cherchneff et al. 1993, Millar & Herbstr 1994, Millar et al. 2000, Brown & Millar 2003). Even higher angular resolution observations of HC$_3$N $J = 5 - 4$ and HC$_5$N $J = 16 - 15$ lines by Dinh-V-Trung & Lim (2008) with the Very Large Array (VLA), which are detectable over a more radially extended region, revealed the presence of a number of incomplete shells representing different episodes of mass-loss enhancement from the central AGB star. These observations show that the emission of cyanopolyne molecules can be used to trace the small-scale structures of the envelope.

The spatial distribution of cyanopolyne molecules in the circumstellar envelope around other carbon-rich stars has been much less studied at high angular resolution. Here, we present observations of the HC$_3$N $J = 5 - 4$ line around CIT 6 (RW LMi, GL 1403 or IRAS 10131+3049) with the VLA. CIT 6, a semiregular variable, is an extreme carbon star enshrouded in a massive molecular envelope, very similar to the archetypical carbon star IRC+10216. It has a pulsation period of 640 days, which, based on the period–luminosity relation for evolved stars, translates to a distance of $\sim$400 pc (Cohen 1980; Cohen & HITCHON 1996). Recently, Whitelock et al. (2006) using better infrared (IR) photometry and a much improved period–luminosity relation suggest a slightly larger distance of 460 pc, which is close to the value of 440 pc used in the modeling work of Schoeier et al. (2002). Therefore, for easy comparison with previous work, we will adopt a distance of 440 pc for CIT 6. High-resolution optical imaging of Schmidt et al. (2002) shows a series of arcs in the optical reflection nebula around CIT 6, within 4$''$ of the star. These arcs comprise the density enhancement in the envelope and indicate variations of mass loss on a timescale of several hundred years. Such dusty arcs have previously been seen in a number of other circumstellar envelopes around AGB and post-AGB stars such as IRC+10216 (Mauron & Huggins 1999), the Egg nebula (Sahai et al. 1998), and some protoplanetary nebulae (Hrivnak et al. 2001).

Interferometric observations of the CO $J = 1 - 0$ line by Neri et al. (1998) and Meixner et al. (1998) at angular resolutions of 3$''$–6$''$ reveal a bright central core surrounded by a more diffuse but roughly spherical envelope, expanding at a velocity $\sim$18 km s$^{-1}$. Using sophisticated radiative transfer models, Schoeier & Olofsson (2001) and Schoeier et al. (2002) estimated a mass-loss rate of $5 \times 10^{-6}$ $M_\odot$ yr$^{-1}$ for CIT 6 by fitting the strength of CO rotational lines. They also noted that a more satisfactory match between model predictions and observations could be obtained if mass-loss variation is introduced into the model. Teyssier et al. (2006) also reached a similar conclusion from modeling the single-dish observations of CO rotational lines in CIT 6. Apart from CO, several other molecules have been detected in CIT 6, including cyanopolynes (Zhang et al. 2009). The overall chemical makeup of its envelope is similar to that of the archetypical carbon-rich envelope IRC+10216, with the exception of enhanced SiC$_2$ and cyanopolyne emissions. The distributions of other molecules such as the cyanopolynes (HC$_3$N and HC$_5$N) and HCN and CN have been mapped at an angular resolution of about 3$''$ by Lindqvist et al. (2000).
Only the emission of cyanogen radical CN was well resolved into an incomplete and elongated expanding shell.

In this paper, we present our high angular resolution observations of HC$_3$N $J = 5 - 4$ emission from CIT 6 obtained with the VLA. The observations allow us to probe the structure of the envelope at arcsec scale or $\sim 6 \times 10^{15}$ cm.

2. OBSERVATION

We observed CIT 6 on 2003 April 13, using the VLA in its most compact configuration. The telescope was pointed at $\alpha_{2000} = 10^h16^m02^s27$, $\delta_{2000} = 30^d34^m18.6$, the location of the star as listed in the SIMBAD database (Loup et al. 1993). The rest frequency of the HC$_3$N $J = 5 - 4$ line as compiled by the Lovas/NIST database (Lovas 2004) is 45.490316 GHz. To observe this line, we configured the VLA correlator in the 2AC mode with a 6.25 MHz bandwidth over 64 channels, thus providing a velocity resolution of 0.65 km s$^{-1}$ per channel over a useful velocity coverage of $\sim 40$ km s$^{-1}$. The total on-source time was about 1 hr. We monitored the nearby quasar 0958+324 at frequent intervals to correct for the antennas’ gain variations caused primarily by atmospheric fluctuations. The stronger quasars 0927+390 and 1229+020 were used to correct for the shape of the bandpass and its variation with time. The absolute flux scale of our observations was determined from observation of standard quasar 3C 147 (0542+498).

We edited and calibrated the raw visibilities using the AIPS data reduction package. The calibrated visibilities were then Fourier transformed to form the DIRTY images. We employed the robust weighting to obtain a satisfactory compromise between angular resolution and sensitivity. The DIRTY images were deconvolved using the normal clean algorithm implemented in AIPS, providing a synthesized beam of $1.5 \times 1.4$ at position angle P.A. $= 24^\circ.8$. We also averaged the data over four channels to obtain a final velocity resolution of 2.6 km s$^{-1}$. The rms noise level in our channel maps of HC$_3$N $J = 5 - 4$ emission is 6.7 mJy beam$^{-1}$ in each velocity channel of 2.6 km s$^{-1}$. The corresponding conversion factor between the brightness temperature of the HC$_3$N $J = 5 - 4$ emission and the flux density is $\sim 4$ mJy K$^{-1}$.

We also configured the VLA in normal continuum mode at 7 mm. The on-source integration time for CIT 6 was about 10 minutes. The same calibrators as above were used for complex gain and absolute flux density calibration. We processed the continuum data in the same manner as the line data. The resulting synthesized beam is $2.3 \times 1.6$ at position angle P.A. $= 75^\circ$. The rms noise level of the continuum map is $\sim 0.4$ mJy beam$^{-1}$.

3. RESULTS

We detected an unresolved continuum source at 43.3 GHz with a flux density of $2.4 \pm 0.4$ mJy at $10^h16^m02^s27$ and $30^d34^m19.1$. This is coincident within the errors (about $0^\prime.4$) with the position of an unresolved continuum source at 90.7 GHz with a flux of $8 \pm 0.4$ mJy detected by Lindqvist et al. (2000). The position of the continuum source clearly indicates the location of the central AGB star within the envelope of CIT 6. From the detected fluxes, we estimate that the spectral index between 43.3 GHz and 90.7 GHz is $\sim 1.6$, which is shallower than the spectral index of 2 expected for the blackbody radiation (i.e., $S_\nu \sim \nu^2$) from the central AGB star in CIT 6. However, the low S/N of our continuum observation implies non-negligible uncertainty in the derived spectral index, making it difficult to ascertain whether the lower spectral index is real or simply due to measurement uncertainty. At shorter wavelengths, the spectral index is larger with $S_\nu \sim \nu^{2.1}$, indicating significant contribution from dust in the envelope around CIT 6 (Neri et al. 1998, Marshall et al. 1992).

Figure 1 shows the channel maps of the HC$_3$N $J = 5 - 4$ emission. Figure 2 shows the HC$_3$N $J = 5 - 4$ profile derived by integrating over a region where the emission is detected above

---

Figure 1. Channel maps of the HC$_3$N $J = 5 - 4$ emission (shown in false color and also in contours). The LSR velocity is indicated in the upper right of each frame. The contour levels are (3, 5, 7, 9, 12, and 15)$\sigma$ with $\sigma = 6.7$ mJy beam$^{-1}$. The synthesized beam is shown in the lower left corner of the upper left frame. The corresponding conversion factor between the brightness temperature and flux density is 4 mJy K$^{-1}$.

(A color version of this figure is available in the online journal.)
the 2σ level. The HC$_3$N $J = 5 - 4$ line has been previously observed by Fukasaku et al. (1994) with the Nobeyama 45 m telescope, which has a primary beam of about 40′′ at FWHM. Using the main beam efficiency provided by Fukasaku et al. (1994), we estimate a conversion factor of 4 Jy K$^{-1}$, thus giving a peak flux density of about 1.7 Jy for the HC$_3$N $J = 5 - 4$ line. This is comparable to the peak flux density of ~1.6 Jy measured in our observation (see Figure 2). Furthermore, the shapes of the line profiles in both observations are also very similar, suggesting that our VLA observation has recovered most of the emission in the HC$_3$N $J = 5 - 4$ line present in the above-mentioned single-dish observation.

The channel maps of HC$_3$N $J = 5 - 4$ emission show the usual pattern of an expanding envelope, with the emitting region being largest at the systemic velocity $V_{LSR} = -2$ km s$^{-1}$ and becoming progressively more compact at large blueshifted and redshifted velocities. From the velocity range covered by the emission in the channel maps we estimate that the expansion velocity of the HC$_3$N shell is about ~17 km s$^{-1}$, which is in good agreement with the expansion velocity of 18 km s$^{-1}$ inferred from previous CO observations (Neri et al. 1998, Meixner et al. 1998). Unlike the well defined hollow-shell structure seen in HC$_3$N $J = 5 - 4$ and HC$_3$N $J = 16 - 15$ for IRC+10216 (Dinh-V-Trung & Lim 2008), however, the spatial distribution of HC$_3$N $J = 5 - 4$ emission in CIT 6 is much more complex. In the velocity channel at $V_{LSR} = 13.5$ km s$^{-1}$, the emission appears roughly spherically symmetric. In the velocity channels between −17.4 and 8.3 km s$^{-1}$, however, the emission resembles an incomplete shell with a mostly complete eastern portion whereas the western part is missing. Previous observations of the HC$_3$N $J = 10 - 9$ line at lower angular resolution of ~3′′ by Lindqvist et al. (2000) also show a lopsided envelope that is strongly enhanced in the eastern portion together with significant emission at the stellar position.

To more clearly show the structures within the expanding envelope of CIT 6, we integrate the line intensity spanning velocities −7.1 to 5.7 km s$^{-1}$, namely the six velocity channels straddling the systemic velocity. The resulting integrated intensity map is shown in Figure 3. The envelope clearly does not resemble a spherical expanding hollow shell expected for molecules such as HC$_3$N. Instead, starting from the stellar position, the brightest portion of the emission extends to the south, curls to the east and north, and then curls again to the west and south, thus creating a structure resembling a one-arm spiral. In the channel maps, this spiral structure can most clearly be seen at a systemic velocity of ~2 km s$^{-1}$ and an adjacent channel at 0.6 km s$^{-1}$. Such a spiral distribution in molecular emission has never been seen before in any circumstellar envelope.

Beyond the outermost radius of the one-arm spiral, there is fainter emission tracing a nearly spherical shell with radius of ~8′′. This shell can be seen along with the one-arm spiral in the channel maps between velocities of 3.2 and 5.7 km s$^{-1}$. The faint outer shell is more visible in the integrated intensity map shown in Figure 3. The outer shell appears to be centered on the central AGB star as indicated by its continuum emission at 7 mm and seems to be even more clumpy than the one-arm spiral. For clarity, we sketch the location and the outline of these two structures in Figure 4.

Using the conversion factor of 4 mJy K$^{-1}$, we estimate that the brightness temperature of the HC$_3$N $J = 5 - 4$ emission in the channel maps around the systemic velocity (~2 and 0.6 km s$^{-1}$) ranges from about 5 K to 12 K. We note that the measured brightness temperature is smaller but quite significant in comparison to the kinetic temperature of the molecular gas in the range 20–80 K expected from the modeling of the envelope of CIT 6 (Schoeier et al. 2002), indicating that the optical depth in the HC$_3$N $J = 5 - 4$ line is significant if the line is close to thermalization.

4. DISCUSSION

4.1. Comparison with Previous Observations

The existence of spatially distinct and incomplete molecular shells in the carbon star CIT 6 as traced by the HC$_3$N $J = 5 - 4$ emission suggests that this phenomenon is not just confined to the archetypal carbon star IRC+10216 but appears to be quite common. In the case of IRC+10216, numerous incomplete
expanding shells have been detected and linked to different episodes of mass-loss enhancement from the central AGB star (Dinh-V-Trung & Lim 2008). In CIT 6 several dust arcs, which are located in the same inner region of the envelope as the molecular arcs. The fact that the faint outer molecular shell is nearly spherical and centered on the star seems to be consistent with the mass-loss enhancement hypothesis. We note, however, that the underlying mechanism responsible for the mass-loss enhancement and the thin spherical shell or arc structures is still not known with certainty (Zijlstra et al. 2002). From the radius of the outer shell of 8 arcsec and an expansion velocity of 18 km s\(^{-1}\) of the molecular envelope of CIT 6, we estimate that the episode of mass loss that might give rise to this thin shell could have happened about 10\(^3\) years ago. However, the one-arm spiral located inside the thin outer shell cannot be easily generated by the mass-loss enhancement. Thus, an alternative explanation is required. We will discuss this point further in Section 4.3.

High-resolution optical images of Schmidt et al. (2002) show a bipolar morphology for the nebula around CIT 6. Because the bipolar morphology is typical of post-AGB objects such as the Egg nebula or CRL 618, they suggested that CIT 6 has reached the end of the AGB phase. Our data, however, do not show any evidence of bipolar morphology in the molecular envelope. The bipolar morphology seen in the optical is, therefore, likely an illumination effect due to the peculiar distribution of the material close to star. For example, a spherical envelope with its polar caps removed will allow starlight to escape more easily in the polar directions, thus creating an apparent bipolar morphology in the reflection nebula.

4.2. Excitation of HC\(_3\)N

The existence of HC\(_3\)N \(J = 5 - 4\) emission close to the central star of CIT 6 is surprising given the commonly accepted formation pathway for HC\(_3\)N and also the excitation conditions in the envelopes. Chemical models for carbon-rich circumstellar envelopes predict that HC\(_3\)N molecules form from the reaction between CN, which is a photodissociation product of the parent molecule HCN, and acetylene, C\(_2\)H\(_2\):

\[
\text{CN} + \text{C}_2\text{H}_2 \rightarrow \text{HC}_3\text{N} + \text{H}.
\]

Therefore, very few HC\(_3\)N molecules are expected to exist in the inner region of the envelope as few interstellar UV photons can penetrate into the inner region to produce CN radicals through photodissociation of HCN. That conclusion can be seen in the predictions of the chemical models of Cherchneff et al. (1993), Millar & Herbst (1994), and Millar et al. (2000). Observations of high-lying transitions of HC\(_3\)N by Audinos et al. (1994), however, suggest that the abundance of HC\(_3\)N in the inner region of the envelope around the archetypical carbon star IRC+10216 is quite significant, nearly an order of magnitude higher than predicted by chemical models.

To obtain a rough estimate of the HC\(_3\)N abundance and to explore an alternative explanation for the observed HC\(_3\)N \(J = 5 - 4\) emission close to the AGB star of CIT 6, we have performed excitation calculations for HC\(_3\)N molecules in the envelope of CIT 6. The calculations were carried out using the large velocity gradient (LVG) approximation, which is justified for the case of CIT 6 where the expansion velocity (~18 km s\(^{-1}\)) is large. We use the HC\(_3\)N molecular data compiled by Lafferty & Lovas (1978) and Uyemura et al. (1982). We include in our model the radiative excitation of the molecule due to IR pumping through the \(v_5\) bending vibrational state. As suggested by Bieging & Tafalla (1993), this mode is strongest and its wavelength is close to the peak of the continuum spectrum of IRC+10216 and also CIT 6. Therefore, the \(v_5\) bending mode should play a dominant role in the radiative excitation process. We include all rotational levels in the ground state and \(v_5 = 1\) vibrational state up to \(J = 30\). Because the Q-branch ro-vibrational transitions do not effectively contribute to the radiative excitation of the HC\(_3\)N molecule, we consider only transitions in the \(P-\) and \(R-\)branches in our model. We also adopt the same dipole moment of 0.18 D for the vibrational transition between the \(v_5\) state and the ground state as used in Audinos et al. (1994). The collisional cross sections between HC\(_3\)N and H\(_2\) are assumed to follow the prescription of Deguchi & Uyemura (1984). From detailed modeling of the structure of the envelope, Schoeier et al. (2002) inferred a mass-loss rate of \(5 \times 10^{-6}M_\odot\) yr\(^{-1}\) for CIT 6. The gas temperature as a function of radial distance in the envelope as derived from the modeling can be approximated as \(T_k(r) = 33 K \left(r/3 \times 10^{16} \text{cm}\right)^{-0.6}\). We note that the predicted kinetic temperature in the envelope of CIT 6 is significantly lower in comparison to that in IRC+10216 (Bieging & Tafalla 1993; Audinos et al. 1994) mainly because of the difference in physical properties of the dust grains (Schoeier et al. 2002). Noting further that both CIT 6 and IRC+10216 share very similar properties such as the total luminosity and the overall shape of the SED (Lindqvist et al. 2000), we follow Bieging & Tafalla (1993) and adopt a blackbody IR continuum source having a radius of \(5.1 \times 10^{14} \text{cm}\) and a temperature of 600 K.

We adopt an abundance of HC\(_3\)N with respect to H\(_2\) of the form \(f_{\text{HC}_3\text{N}} = f_0 \exp[-4ln2(r - r_0)^2/FWHM^2]\), where \(f_0\) is the peak abundance, \(r_0\) is the radius of the peak abundance, and FWHM is the full width at half-maximum of the radial distribution. This functional form of the abundance distribution is similar to that used by Bieging & Tafalla (1993) to model the HC\(_3\)N \(J = 10 - 9\) line in the envelope of IRC+10216. Because
the HC$_3$N $J = 5 - 4$ emission in CIT 6 exists over a large range of radii, from $\lesssim 1''$ to $8''$, we use a representative value $r_0 = 4 \times 10^{16}$ cm or $\sim 6''$ in angular distance.

In order to reproduce the measured brightness temperature of the HC$_3$N $J = 5 - 4$ line in CIT 6, which is in the range of $5 - 12$ K for channel maps around the systemic velocity, we find that a peak abundance of $f_0 = 5 \times 10^{-6}$ is needed. In Figure 5, we show the results of our model. For the case with FWHM $\sim 2 \times 10^{16}$ cm, which reproduces the broad distribution of HC$_3$N derived by Audinos et al. (1994) for IRC+10216, the predicted peak brightness temperature of the HC$_3$N $J = 5 - 4$ line is $\sim 10$ K, comparable to the above-mentioned observed brightness temperature. The predicted brightness temperature is found to peak at a smaller radius in comparison to the underlying abundance distribution of HC$_3$N. That can be easily understood because the location of the peak in brightness temperature is determined not just by the abundance but by the overall balance between gas density, the abundance of HC$_3$N, and the gas temperature. At radii between $1''$ and $2''$, because of the very low abundance of HC$_3$N, the predicted brightness temperature is almost zero. To reproduce the brightness temperature of $\sim 5$ K seen close to the central AGB star in the inner envelope close to the systemic velocity, we need to broaden the abundance distribution of HC$_3$N by increasing the parameter FWHM to $3.5 \times 10^{16}$ cm. The peak abundance parameter $f_0$ is the same as in the previous case. As a result, the abundance of HC$_3$N in the inner envelope is then increased by more than two orders of magnitude as shown in Figure 4. The predicted brightness temperature between radii of $1''$ and $2''$, or $6.6 \times 10^{15}$ cm and $1.3 \times 10^{16}$ in linear scale, is now comparable to the observed value. The parameters used in our model are summarized in Table 1.

The especially elevated abundance in the inner envelope close to the central AGB star of CIT 6 cannot easily be explained by the current chemical models of carbon-rich envelopes.

### 4.3. The Binary Hypothesis

The inferred high abundance of HC$_3$N in the envelope around CIT 6, especially in the inner region close to the star, and the unusual spatial distribution of HC$_3$N $J = 5 - 4$ emission resembling a one-arm spiral suggest that mechanisms other than photochemistry might be at work to form the HC$_3$N molecules. Guélin et al. (1999) noted that many molecular species in IRC+10216 are co-spatial even though they are predicted by chemical models (Cherchneff et al. 1993, Millar et al. 2000) to form at different radial distances. A similar spatial distribution of different molecular species indicates that the molecules are all formed in a very short timescale, of the order of hundreds of years. They suggest that other mechanisms such as desorption from dust grains or release from the grain surface due to shocks might be responsible for the formation of molecules in carbon-rich circumstellar envelopes.

Binary companions around AGB stars have been suggested to play an important role in shaping the structure and influencing the wind dynamics within the circumstellar envelope. Indeed, in the hydrodynamic simulations of Mastrodemos & Morris (1999) and Edgar et al. (2008), the interaction with a binary companion can induce spiral shocks and enhance the density structure in the envelope around a mass-losing star. The density structure in the envelope is predicted to resemble a one-arm spiral (see Figures 1 and 2 in Edgar et al. 2008). Such spiral structure has recently been seen in the high-resolution optical image of an extreme carbon star CRL 3068 (Morris et al. 2006, Mauron & Huggins 2006). The elevated density and temperature expected in the spiral shocks (Edgar et al. 2008) might be conducive to the formation of large carbon chain molecules including HC$_3$N as suggested by Guélin et al. (1999).

In the case of CIT 6, optical spectropolarimetric observations of Schmidt et al. (2002) showed that its optical spectrum possesses a strong and featureless blue continuum excess. They attributed the blue continuum excess to the presence of a companion star of spectral type A–F buried in the envelope. Thus, the highly asymmetric envelope of CIT 6 as traced by the HC$_3$N emission might be caused by the binary companion. Assuming that the HC$_3$N emission traces the spiral shock produced by the companion, the period of the binary system might be estimated from the shape of the one-arm spiral. As can be seen from the sketch of the structures in the envelope around CIT 6 (see Figure 4), the spiral makes almost a complete turn, starting from the central AGB star in the southwest quadrant and ending in the northwest quadrant at a radial distance of about $5''$. The dynamical timescale corresponding to the inter-arm spacing of the spiral shock is directly related to the reflex motion of the AGB star, i.e., the orbital period of the binary system (Mastrodemos & Morris 1999). Using the expansion

---

**Table 1**

| Parameters                                      | Value                        |
|------------------------------------------------|------------------------------|
| Distance                                       | 440 pc ($1'' = 6.6 \times 10^{15}$ cm) |
| Mass loss rate $M$                             | $5 \times 10^{-6}$ $M\odot \text{yr}^{-1}$ |
| Expansion velocity $V_{exp}$                   | 18 km s$^{-1}$               |
| $f_0$ ([HC$_3$N]/[H$_2$])                     | $5 \times 10^{-6}$          |
| $r_0$                                         | $6'' (4 \times 10^{16}$ cm) |
| FWHM                                          | $2 \times 10^{16}$ cm and $3.5 \times 10^{16}$ cm |
velocity of 18 km s$^{-1}$ and the adopted distance of 440 pc, the orbital period of the binary system is about 600 yr. The long orbital period indicates that the companion must be in a wide orbit around the AGB star (the orbital separation is about 70 AU if the primary AGB star has a mass of 1 $M_\odot$). The estimate of orbital period for the binary system in CIT 6 is comparable to that (830 yr) inferred by Mauron & Huggins (2006) for the binary system in CRL 3068. Based on this argument, we think that the hypothesis of a binary system in CIT 6 is plausible as it could naturally account for the spatial distribution and the high abundance of HC$_3$N as seen in our observations. Future high angular resolution observations of dense and warm gas tracers such as high-$J$ transitions of CO or HCN molecules will tell whether the spiral shock induced by the binary companion really exists within the envelope of CIT 6.

5. CONCLUSION

We have imaged at high angular resolution the distribution of HC$_3$N $J = 5 - 4$ emission from the envelope around the carbon star CIT 6. We found that the emission of HC$_3$N $J = 5 - 4$ traces (1) a faint outer spherical shell located at a radial distance of 8 arcsec and centered at the position of the AGB star CIT 6 revealed by the detection of 7 mm continuum emission, and (2) a thick and incomplete inner shell resembling a one-arm spiral. The presence of multiple shells in CIT 6 suggests that the mass loss from this star is highly anisotropic and episodic. From excitation modeling of HC$_3$N molecules, we inferred that the abundance of HC$_3$N is unusually high in CIT 6 in comparison to the well known carbon star IRC+10216. We suggest that the observed spatial distribution of the emission and the inferred high abundance of HC$_3$N might be caused by the presence of a binary companion in a wide orbit around CIT 6.

We thank an anonymous referee for insightful and constructive comments that helped to improve the presentation of our paper. We also thank the VLA staff for their help with the observations. This research has made use of NASA's Astrophysics Data System Bibliographic Services and the SIMBAD database, operated at CDS, Strasbourg, France.

REFERENCES

Audinos, P., Kahane, C., & Lucas, R. 1994, A&A, 287, L5
Bieging, J. H., & Tafalla, M. 1993, AJ, 105, 576
Brown, J., & Millar, T. J. 2003, MNRAS, 339, 1041
Cernicharo, J., Guélin, M., & Kahane, C. 2000, A&AS, 142, 181
Cherchneff, I., Glassgold, A. E., & Mamon, G. A. 1993, ApJ, 410, 188
Cohen, M. 1980, ApJ, 238, L81
Cohen, M., & Hitchon, K. 1996, AJ, 111, 962
Deguchi, S., & Uyemura, M. 1984, ApJ, 285, 153
Dinh-V-Trung & Lim, J. 2008, ApJ, 678, 303
Edgar, R. G., Nordhaus, J., Blackman, E. G., & Frank, A. 2008, ApJ, 675, L101
Fukasaku, S., et al. 1994, ApJ, 437, 410
Guélin, M., Neininger, N., Lucas, R., & Cernicharo, J. 1999, in The Physics and Chemistry of Interstellar Medium, ed. V. Ossenkopf, J. Stutzki, & G. Winnewisser (Herdecke: GCA-Verlag), 326
He, J. H., Dinh-V-Trung, Kwok, S., Muller, H. S. P., Zhang, Y., Hasegawa, T., Peng, T. C., & Huang, Y. C. 2008, ApJS, 177, 275
Hrivnak, B. J., Kwok, S., & Su, K. Y. L. 2001, AJ, 121, 2775
Kawaguchi, K., Kasai, Y., Ishikawa, S. I., & Kaifu, N. 1995, PASJ, 47, 853
Lafferty, W. J., & Lovas, F. J. 1978, J. Phys. Chem. Ref. Data, 7, 441
Lindqvist, M., Schoier, F. L., Lucas, R., & Olofsson, H. 2000, A&A, 361, 1036
Loup, C., Forveille, T., Omont, A., & Paul, J. F. 1993, A&AS, 99, 291
Lovas, F. J. 2004, J. Phys. Chem. Ref. Data, 33, 177
Marshall, C. R., Leahy, D. A., & Kwok, S. 1992, PASP, 104, 397
Mastrodemos, N., & Morris, M. 1999, ApJ, 523, 357
Mauron, N., & Huggins, P. J. 1999, A&A, 349, 205
Mauron, N., & Huggins, P. J. 2006, A&A, 452, 257
Meixner, M., Campbell, M. T., Welch, J. W., & Likkel, L. 1998, ApJ, 509, 392
Millar, T. J., & Herbst, E. 1994, A&A, 288, 561
Millar, T. J., Herbst, E., & Bettens, R. P. A. 2000, MNRAS, 316, 195
Morris, M., Sahai, R., Matthews, K., Cheng, J., Lu, J., Claussen, M., & Sánchez Contreras, C. 2006, in Proc. IAU 234, Planetary Nebulae in Our Galaxy and Beyond, ed. M. J. Barlow & R. H. Méndez (Cambridge: Cambridge Univ. Press), 469
Neri, R., Kahane, C., Lucas, R., Bujarrabal, V., & Loup, C. 1998, A&AS, 130, 1
Sahai, R., et al. 1998, ApJ, 493, 301
Schoier, F. L., & Olofsson, H. 2001, A&A, 368, 969
Schmidt, G. D., Hines, D. C., & Swift, S. 2002, ApJ, 576, 429
Schoier, F. L., Ryde, N., & Olofsson, H. 2002, A&A, 391, 577
Teysier, D., Hernandez, R., Bujarrabal, V., Yoshida, H., & Phillips, T. 2006, A&A, 450, 167
Uyemura, M., Deguchi, S., Nakada, Y., & Onaka, T. 1982, Bull. Chem. Soc. Japan, 55, 384
Whitelock, P. A., Feast, M. W., Marang, F., & Groenewegen, M. A. T. 2006, MNRAS, 369, 751
Zhang, Y., Kwok, S., & Dinh-V-Trung, 2009, ApJ, 691, 1660
Zijlstra, A. A., Bedding, T. R., & Mattei, J. A. 2002, MNRAS, 334, 498