MAPPING THE CENTRAL REGION OF THE PPN CRL 618 AT SUBARCSECOND RESOLUTION AT 350 GHz

CHIN-FEI LEE1, CHUN-HUI YANG2, RAGHVENDRA SAHAI2, AND CARMEN SÁNCHEZ CONTRERAS3
1 Academia Sinica Institute of Astronomy and Astrophysics, P.O. Box 23-141, Taipei 106, Taiwan
2 Jet Propulsion Laboratory, MS 183-900, California Institute of Technology, Pasadena, CA 91109, USA
3 Astrobiology Center (CSIC-INTA), ESAC Campus, E-28691 Villanueva de la Canada, Madrid, Spain

ABSTRACT

CRL 618 is a well-studied pre-planetary nebula. We have mapped its central region in continuum and molecular lines with the Submillimeter Array at 350 GHz at ~0.3–0.5′′ resolutions. Two components are seen in the 350 GHz continuum: (1) a compact emission at the center tracing the dense inner part of the HII region previously detected in a 23 GHz continuum and it may trace a fast ionized wind at the base; and (2) an extended thermal dust emission surrounding the HII region, tracing the dense core previously detected in HC3N at the center of the circumstellar envelope. The dense core is dusty and may contain millimeter-sized dust grains. It may have a density enhancement in the equatorial plane. It is also detected in carbon chain molecules HC3N and HCN and their isotopologues, with higher excitation lines tracing closer to the central star. It is also detected in CH3CHCN toward the innermost part. Most of the emission detected here arises within ~630 AU (0.7″) of the central star. A simple radiative transfer model is used to derive the kinematics, physical conditions, and the chemical abundances in the dense core. The dense core is expanding and accelerating, with the velocity increasing roughly linearly from ~3 km s−1 in the innermost part to ~16 km s−1 at 630 AU. The mass-loss rate in the dense core is extremely high with a value of ~1.15 × 10−3 M⊙ yr−1. The dense core has a mass of ~0.47 M⊙ and a dynamical age of ~400 yr. It could result from a recent enhanced heavy mass-loss episode that ends the asymptotic giant branch phase. The isotopic ratios of 12C/13C and 14N/15N are 9 ± 4 and 150 ± 50, respectively, both lower than the solar values.

Key words: circumstellar matter – planetary nebulae: general – stars: AGB and post-AGB – stars: individual (CRL 618) – stars: mass-loss

1. INTRODUCTION

Most stars are of low and intermediate mass and they end their lives in the same way that the Sun will. They first evolve into red giant branch (RGB) stars and then asymmetric giant branch (AGB) stars with intense mass loss, producing atomic and molecular circumstellar envelopes around them. Eventually, they evolve into white dwarfs hot enough to photoionize the envelopes, forming spectacular emission nebulae called planetary nebulae (PNs). PNe are mostly bipolar and multipolar, but their shaping mechanism is still uncertain. Pre-planetary nebulae (PPNe) are transient objects in the transition phase but their shaping mechanism is still uncertain. Pre-planetary nebulae are mostly bipolar and multipolar, but their shaping mechanism is still uncertain. Pre-planetary nebulae (PPNe) are transient objects in the transition phase but their shaping mechanism is still uncertain. Pre-planetary nebulae are transient objects in the transition phase but their shaping mechanism is still uncertain. Pre-planetary nebulae are transient objects in the transition phase but their shaping mechanism is still uncertain. Pre-planetary nebulae are transient objects in the transition phase but their shaping mechanism is still uncertain. Pre-planetary nebulae are transient objects in the transition phase but their shaping mechanism is still uncertain. Pre-planetary nebulae are transient objects in the transition phase but their shaping mechanism is still uncertain. Pre-planetary nebulae are transient objects in the transition phase but their shaping mechanism is still uncertain. Pre-planetary nebulae are transient objects in the transition phase but their shaping mechanism is still uncertain. Pre-planetary nebulae are transient objects in the transition phase but their shaping mechanism is still uncertain. Pre-planetary nebulae are transient objects in the transition phase but their shaping mechanism is still uncertain. Pre-planetary nebulae are transient objects in the transition phase but their shaping mechanism is still uncertain. Pre-planetary nebulae are transient objects in the transition phase but their shaping mechanism is still uncertain. Pre-planetary nebulae are transient objects in the transition phase but their shaping mechanism is still uncertain. Pre-planetary nebulae are transient objects in the transition phase but their shaping mechanism is still uncertain. Pre-planetary nebulae are transient objects in the transition phase but their shaping mechanism is still uncertain. Pre-planetary nebulae are transient objects in the transition phase but their shaping mechanism is still uncertain.

CRL 618 is a nearby (~900 pc) well-studied PPN, with the morphological classification Mcw,m,hl(e,a) based on Hubble Space Telescope imaging (Sahai et al. 2007), where M—primary class is multipolar; c—outflow lobes are closed at their ends; w—obscuring waist; ml—minor outflow lobes are present; and h(e,a)—elongated halo is present around the nebula and shows (some) circular arc structures. The radio image in a 23 GHz continuum showed a compact HII region close to the central star (Kwok & Bignell 1984; Martin-Pintado et al. 1993), suggesting that this PPN has started evolving into a PN at the center. The optical image showed two pairs of collimated outflow lobes in the east–west direction expanding rapidly away from the star (Trammell & Goodrich 2002; Sánchez Contreras et al. 2002). Since CRL 618 is a C-rich star, single-dish molecular line surveys detected many lines from carbon chain molecules HC3N, HC5N, and their isotopologues at various vibrational states, arising from a circumstellar envelope that expands at ~5–18 km s−1 (Wyrowski et al. 2003; Pardo et al. 2004, 2007). A total of 1756 lines of HC3N, its isotopologues, and its vibrationally excited states have been previously reported by Pardo et al. (2004, 2007) and Pardo & Cernicharo (2007). This source is also the first one in which benzene and polyacetylenes were detected in space (Cernicharo et al. 2001a, 2001b; Fonfría et al. 2011). The envelope was found to have a 12C/13C ratio of 10–15 (Wyrowski et al. 2003; Pardo et al. 2004), which is much lower than the solar value.

In the interferometric observations in HCO+ J = 1–0 at ~2″ resolution, Sánchez Contreras & Sahai (2004) found in the envelope a large expanding torus with a diameter of ~11″ (10,000 AU) perpendicular to the outflow axis. In the interferometric observations in CO J = 2–1 and HC3N J = 25–24 at ~1″ resolution, the envelope was resolved into an extended round halo and a compact dense torus–like core near the central star aligned with the large expanding torus (Sánchez Contreras et al. 2004, hereafter Setal04). As argued by Setal04, the dense core may have resulted from a recent heavy mass loss from the central star and it may help shape the PPN. In order to check these possibilities, we present our observations of the central region at ~2–3 times higher resolution, obtained with the Submillimeter Array (SMA) in the 350 GHz band. In our observations, many lines are also detected in the dense core, arising from the carbon chain molecules, allowing us to refine not only the physical and kinematic properties, but also the chemical properties of the dense core at a higher resolution. In particular, our observations provide a much higher angular...
resolution than that of Pardo et al. (2004, 2007), allowing us to directly distinguish the different contributions to the molecular emission, study the detailed spatial distribution of HC$_3$N, and thus understand the chemical processes at work (Cernicharo 2004). Moreover, the dense core and the H ii region can also be seen and studied in the 350 GHz continuum.

2. OBSERVATIONS

The CRL 618 observations were carried out on 2011 January 23 and February 4 with the SMA in the very extended and extended configurations, respectively. Detailed information about the SMA can be found in Ho et al. (2004). In these observations, the receivers were set up to have the following two frequency ranges: 342.104–346.065 in the lower sideband and 354.115–358.068 GHz in the upper sideband. These frequency ranges covered the lines of CO, CS, HCO$^+$, HC$_3$N, and HCN and their isotopologues simultaneously with the 350 GHz continuum. The correlator was set up to have a velocity resolution of 0.35 to 1.41 km s$^{-1}$ per channel. One single pointing was used to observe the central region of CRL 618 with a field of view of 34′. Six and seven antennas were used in the very extended and extended configurations, respectively. The baseline length, after combining the two configurations, ranged from 45 to 460 m. The observations were interleaved every 5 minutes with nearby gain calibrators, 3C 84 and 3C 111, to track the phase variations over time. However, only 3C 111 was used for the gain calibration because it is much closer to the source and was already bright enough. The bandpass calibrator was the quasar 3C 279, and the flux calibrator was Titan. The total on-source time was ∼5 hr in each configuration. The system temperature ranged from 220 to 660 K and from 250 to 900 K in the very extended and extended configurations, respectively.

The visibility data were calibrated with the MIR package. The flux uncertainty was estimated to be ∼20%. The continuum band was obtained from the line-free channels. The calibrated visibility data were imaged with the MIRIAD package. The dirty maps that were produced from the calibrated visibility data were CLEANed using the Steer clean method, producing the CLEAN component maps. The final maps were obtained by restoring the CLEAN component maps with a synthesized (Gaussian) beam fitted to the main lobe of the dirty beam. With natural weighting, the synthesized beam has a size of 0′′.53 × 0′′.36 at a position angle (P.A.) of ∼83°. The rms noise levels are ∼60 mJy Beam$^{-1}$ for the channel maps with a velocity resolution of 1.4 km s$^{-1}$ and 3.7 mJy Beam$^{-1}$ for the continuum map. The velocities of the channel maps are local standard of rest.

3. OBSERVATIONAL RESULTS

3.1. Continuum: Dense Core and H ii Region

At 350 GHz, continuum emission is detected within 1″ of the central star elongated in the east–west direction along the main outflow axis (Figure 1(a)), with a total flux density of ∼3.3 ± 0.7 Jy. According to the previous model for the spectral energy distribution (SED) of the source, the continuum emission at this frequency consists of two components: free–free emission from the H ii region near the central star and thermal dust emission from the circumstellar envelope (see Figure 2 and also Wyrowski et al. 2003). Note that for the flux density in the frequency between 80 and 360 GHz, Pardo et al. (2004, 2007) have found that the total flux density from the lines represents less than 3%–5% of the continuum and thus will not affect the analysis of the SED. Our flux density is consistent with the previous model, arising from the two components. Since the emission detected here is within 1″ of the central star, the dust emission component here must be from the dense core of the circumstellar envelope, which has an outer radius of ∼1″2 (Setal04).

In order to distinguish the two components, we zoom into the emission peak at the center at a higher resolution in Figure 1(b). However, the emission peak there is still not resolved. Since it is detected with a signal-to-noise ratio (S/N) of more than 100, the structure can be studied with the CLEAN component map shown in Figure 1(c). On the map, a bright compact emission peak is seen at the center inside the H ii shell detected at 23 GHz in 1990 (Martin-Pintado et al. 1993). It has a brightness temperature of ∼800 K, but the actual value must be higher because it is unresolved. It has a flux density of ∼1.4 ± 0.3 Jy, roughly the same as that of free–free emission required to fit the SED of the continuum source (see Figure 2). As a result, both the brightness temperature and flux density indicate that it traces the H ii region.

Note that the 23 GHz continuum map has been shifted by ∼0′′.2 to the north in order to match the center of the H ii shell to the compact emission peak in our map. This position shift, if real,
The thermal dust emission from the dense core has a flux density of \( \sim \) extending to the northeast and southeast from the central star. There is a density enhancement in the equatorial plane perpendicular to the outflow axes, suggesting that the dense region was derived assuming a constant source size of \( \sim 0\prime 22 \). Previous OVRO (Owens Valley Radio Observatory) data from Sánchez Contreras & Sahai (2004) and Sánchez Contreras et al. (2004) are shown as open circles. Our SMA data at 350 GHz are also included and the flux density is consistent with the two-component model.

could be due to a proper motion of \( \sim 40 \text{ km s}^{-1} \) to the north. As argued by Martin-Pintado et al. (1993), the H\( \text{II} \) region is a filled region. Since the H\( \text{II} \) region has a turnover frequency <100 GHz (see Figure 2), the free–free emission at 350 GHz is optically thin. It appears as a peak at the center, indicating the presence of a dense inner part. At 23 GHz, the H\( \text{II} \) region is optically thick. It appears as a shell probably because of an increase in electron temperature (Martin-Pintado et al. 1993) or an increase in density (Kwok & Bignell 1984). At 350 GHz, the shell is optically thin and it is not detected here due to the fact that there is not enough column density.

In the CLEAN component map, two faint emission peaks, one in the north and one in the south, are seen at a radius of \( \sim 0\prime 14 \) (\( \sim 126 \text{ AU} \)) from the central star, roughly located in the equatorial plane perpendicular to the outflow axes and surrounding the H\( \text{II} \) shell. The peak in the north also extends to the east and west surrounding the H\( \text{II} \) shell. These morphological relationships clearly indicate that these emissions trace the limb-brightened edges of the innermost part of the dense core around the H\( \text{II} \) shell. The two emission peaks may arise from a density enhancement in the dense core in the equatorial plane that helps confine the H\( \text{II} \) region into a bipolar morphology. The radius of the two emission peaks can set an upper limit for the current radius of the H\( \text{II} \) region in the equatorial plane. Less emission is seen in the outflow axes, suggesting that the dense core material there is cleared by the outflow.

Now it is clear that the extended emission in Figures 1(a) and (b) traces the dense core. Since the free–free emission of the H\( \text{II} \) region has a flux density of \( \sim 1.4 \pm 0.3 \text{ Jy} \) as discussed above, the thermal dust emission from the dense core has a flux density of \( \sim 1.9 \pm 0.4 \text{ Jy} \). In Figure 1(b), the emission in the east is resolved, extending to the northeast and southeast from the central star (Figure 1(b)), likely tracing the dense core material around the outflow cavity walls. The emission is also seen extending \( \sim 0\prime 6 \) to the north from the central star, tracing the dense core that may have a density enhancement perpendicular to the outflow axes. However, no counterpart is seen extending to the south.

3.2. Molecular Lines: Dense Core

3.2.1. Spectra

Figure 3 shows the spectra toward the inner region averaged over a circular region with a diameter of 0\( \prime 5 \), from 342 to 346 GHz and from 354 to 358 GHz. The observed frequency has been converted to the rest frequency using the systemic velocity of \( -21.5 \text{ km s}^{-1} \) as found in Setal04. Many molecular lines are detected, as listed in Table 1. Most of them are from HC\( 3 \text{N} \) and its isotopologues and arise from rotational transitions at various vibrational states, as found at lower frequencies (Wyrowski et al. 2003; Pardo et al. 2007). As can be seen below, these molecules mainly trace the dense core. Most of their lines are isolated or almost isolated so that their line peak brightness temperature \( T_B^\prime \) and FWHM linewidth \( \Delta v \) can be measured, as listed in Table 2, allowing us to derive the properties of the dense core. With an upper energy level ranging from \( \sim 300 \text{ K} \) up to 2000 K, these lines can be used to probe the properties of the dense core from the outer part down to the very inner part enclosing the H\( \text{II} \) region. Note that sharp absorption dips are seen at \( \sim -16 \text{ km s}^{-1} \) in strong molecular lines, e.g., CO (deepest at \( -15.8 \text{ km s}^{-1} \)), CS (\( -15.8 \text{ km s}^{-1} \)), HCO\(^+\) (\( -15.5 \text{ km s}^{-1} \)), HCN \( v = 0 \) (\( -15.8 \text{ km s}^{-1} \)), and H\(^{13}\)CN \( v = 0 \) (\( -15.5 \text{ km s}^{-1} \)), due to an absorption by the extended halo, which is cold and expanding at that velocity (Seta10). In this paper, we study the dense core mainly with HC\( 3 \text{N} \) and its isotopologues. Other molecules mainly trace the outflow and will be studied in another paper.

3.2.2. Morphology

The integrated intensity maps of the isolated and almost isolated lines of HC\( 3 \text{N} \) and its isotopologues are shown in Figures 4 and 5, respectively, in order of increasing upper energy level of the lines. The figures show that for a given molecule, the structure of the emission shrinks closer to the central star as we go to the line with a higher upper energy level, indicating that the temperature of the dense core increases toward the central star. In addition, comparing the two figures we can also...
see that for a given similar upper energy level, the lines of the isotopologues trace closer and are thus warmer material than the HC$_3$N lines. This is because the isotopologues are less abundant and thus their lines are optically thinner. For the isotopologues with double substitutions of $^{12}$C with $^{13}$C, their abundances are very low, and their lines with low upper energy level mainly trace the dense core close to the central star (Figure 5).

For HC$_3$N and its single $^{13}$C substituted isotopologues, the lines with the lowest upper energy level trace the outer part of the dense core that can be resolved in our observations. Figure 6 shows the maps for two of these lines, one in HC$_3$N and one in its isotopologue, H$^{13}$CCCN, at a slightly higher angular resolution on top of the continuum map. Although the two lines have a similar upper energy level, the line of the isotopologue traces closer to the central star as discussed above. In these maps, two emission peaks, one in the north and one in the south of the central star, are seen surrounding the continuum emission peak and tracing the two limb-brightened edges of the dense core in the outer part. This two-emission peak structure was also seen before in a lower excitation line of HC$_3$N and was used to suggest an equatorial density enhancement (mimicking a torus-like structure) in the dense core farther out (Setal04).

The dense core is evacuated by the outflow lobes with the emission around the outflow cavity walls extending to the northeast, southeast, northwest, and southwest, but with less emission along the outflow axes. In addition, the SE and SW outflow lobes evacuate the southern part of the dense core more, reducing more of the emission there near the central star, as seen in H$^{13}$CCCN. The major axis of the dense core, defined as the axis passing through the two emission peaks and the central star position, has a P.A. of $\sim 3^\circ$, similar to that found by Setal04, and is almost perpendicular to the east–west pair (i.e., the major pair) of the outflow lobes. Thus, the dense core is likely to be perpendicular to this pair of outflow lobes and is thus assumed to have an inclination angle of $\sim 30^\circ$ (Setal04) with the near side tilted to the west and the far side to the east. Note that the outer part of the dense core is expected to show a tilted ring-like structure in the maps. Here we see more of a “C” structure because the emission is fainter on the western side of the central star due to a self-absorption to be discussed later.

Quite a few lines are also detected in HCN and its isotopologues (Figure 3). Some of them also mainly trace the dense core and maps of the isolated ones are shown in Figure 7. The HCN lines at the vibrational states $v_2 = 1$ and 2 trace the dense core because of their high upper energy level and thus low number density at low temperatures. The HCN line at the ground vibrational state traces the outflow and is thus not shown here. The lines of H$^{13}$CN $v = 0$ and $v_2 = 1$ and HC$^{15}$N $v = 0$ trace the dense core due to their low abundances. Like that of HC$_3$N, the line with a higher upper energy level traces the inner...
part of the dense core. We also detect many CH$_2$CHCN (vinyl cyanide) lines. A total of 120 lines of this molecule have been detected at a lower frequency from 80 to 270 GHz by Pardo et al. (2007, see their Table 2). In our frequency ranges, there are 12 lines with the line strength $S_{ij} > 96$ (a factor of three is included here for the spin-statistical weight of N). Here, 11 of them are detected and 1 at $\sim 356.247$ GHz is lost in a strong HC$_3$N line (Figure 3). These lines are weak, and thus we combine all of them to produce a map with a high S/N, as shown in Figure 7. It is clear from the figure that these lines trace the innermost part of the dense core due to the low abundance of the molecule. This molecule could result from the interaction of C$_2$H$_4$ and CN, as discussed in Cernicharo (2004).

### 3.2.3. Kinematics

The kinematics of the dense core can be studied with position–velocity (PV) diagrams using the same two lines that show the resolved structure of the dense core, as before. The axial PV diagrams, with the cut perpendicular to the dense core, show that the east side (or far side) is mainly redshifted and the west side (or near side) is blueshifted (see Figures 8(a) and (b)), which is opposite that seen for the outflow. Note that for HC$_3$N, the blueshifted emission with the velocity $\lesssim -10$ km s$^{-1}$ should be ignored because it is contaminated by another weak HC$_3$N line centered at $-20$ km s$^{-1}$. This PV structure clearly supports the fact that the core is expanding away from the central star. Negative contours are seen on the blueshifted side due to an absorption of the continuum emission and the line emission by a cold layer on the near side. Thus, the dense core appears fainter in the west of the central star, as seen above in Figure 6. The expansion velocity in each emission line is proportional to the maximum velocity, either redshifted or blueshifted. Since the blueshifted side is self-absorbed, the redshifted side is used, and the redshifted velocity is higher in the HC$_3$N line than in the H$^{13}$CCCN line. Since the HC$_3$N line traces the outer region rather than the H$^{13}$CCCN line, it seems that the expansion velocity increases with the distance from the central star. The equatorial PV diagrams with the cut along the major axis of the dense core show an incomplete ring-like PV structure due...
Figure 5. Same as in Figure 4 but for the lines of the HC$_3$N isotopologues. The contour levels are $A(1 - r^n)/(1 - r)$, where $A = 1$ Jy beam$^{-1}$ km s$^{-1}$, $r = 1.2$, and $n = 1, 2, 3, ...$.

Figure 6. Integrated intensity maps of the (a) HC$_3$N (0000) and (b) H$^{13}$CCCN (0000) lines on top of the continuum map shown in Figure 1(b), showing the structure of the dense core in the outer part. The cross marks the central star position and the arrows indicate the outflow axes. The solid line indicates the major axis of the dense core. The resolution is $\sim 0.42 \times 0.26$. The contour levels are $A(1 - r^n)/(1 - r)$, with $A = 2$ Jy beam$^{-1}$ km s$^{-1}$ and $r = 1.4$. In (b) $A = 1.2$ Jy beam$^{-1}$ km s$^{-1}$ and $r = 1.3$. 
### Frequency (MHz) | Species and Vibrational Statea | Rotational Transition J/QN |
|-----------------|--------------------------------|-----------------------------|
| 342123.5509     | CH3CHCN                         | J = 36(12,24)–35(12,23)   |
| 342123.5509     | CH3CHCN                         | J = 36(12,25)–35(12,24)   |
| 34204.9747      | H13CCN (0000)                   | J = 39–38                  |
| 342317.5544      | CH3CHCN                         | J = 36(5,32)–35(5,31)     |
| 342375.5639      | CH3CHCN                         | J = 36(5,31)–35(5,30)     |
| 342585.4708      | CH3CHCN                         | J = 36(4,33)–35(4,32)     |
| 342666.3834      | HC3C13CN (0000)                 | J = 38–37                  |
| 342882.8503      | CS                               | J = 7–6                    |
| 343446.5355      | CH3CHCN                         | J = 36(4,32)–35(4,31)     |
| 343737.3998      | H13CCCN (0000)                  | J = 39–38                  |
| 344142.9833      | H13CCCN (0000)                  | J = 38–37                  |
| 344176.1674      | HCC3CN (0000)                   | J = 38–37                  |
| 344198.9411      | HCC3CN (0100)/(0003)?           | J = 38–37                  |
| 344200.1089      | HCC3N                           | J = 4–3                    |
| 344302.9375      | H13CCCN (0010)                  | J = 39–38                  |
| 344385.3481      | HCC3C13N (0000)?                | J = 39–38                  |
| 344390.9656      | HCC3CN (0100)/(0003)?           | J = 38–37                  |
| 344565.1094      | H13CCCN (0010)                  | J = 39–38                  |
| 344590.0711      | H13CCCN (0001)                  | J = 39–38                  |
| 344694.4713      | H13CCCN (0010)                  | J = 38–37                  |
| 344719.4221      | HCC3CN (0100)                   | J = 38–37                  |
| 344955.5335      | HCC3C13N (0001)                 | J = 38–37                  |
| 344967.3969      | HCC3CN (0010)                   | J = 38–37                  |
| 344994.6742      | HCC3CN (0100)                   | J = 38–37                  |
| 345003.2278      | HCC3CN (0001)                   | J = 38–37                  |
| 345068.6323      | H13CCCN (0001)                  | J = 39–38                  |
| 345122.5871      | HC3N (1000)                     | J = 38–37                  |
| 345238.7103      | H13CN (v2 = 1)                  | J = 4–3                    |
| 345339.7694      | H13CN                           | J = 4–3                    |
| 345451.7567      | H13CCCN (0001)                  | J = 38–37                  |
| 345495.8736      | HCC3C13N (0001)                 | J = 38–37                  |
| 345609.0100      | HC3N (0000)                     | J = 38–37                  |
| 345632.1266      | HC3N (0100)/(0001)              | J = 38–37                  |
| 345795.9989      | CO                               | J = 3–2                    |
| 345797.0584      | H13CCCN (0002)                  | J = 39–38                  |
| 345824.6653      | HC3CCN (0001)/(0001)            | J = 38–37                  |
| 345862.0868      | HC3N (0102)/(0200)              | J = 38–37                  |
| 345917.7699      | HC3CCN (0002)                   | J = 39–38                  |
| 346010.5711      | HC3N (0001)                     | J = 38–37                  |
| 346041.2173      | H13CCCN (0002)                  | J = 39–38                  |
| 354127.5000      | U                                |                           |
| 354145.5000      | U                                |                           |
| 354197.5820      | HC3N (1000)                     | J = 39–38                  |
| 354460.4346      | HCN (v2 = 1)                    | J = 4–3                    |
| 354505.4773      | HCN                             | J = 4–3                    |
| 354535.7250      | HCC3C13N (0001)                 | J = 39–38                  |
| 354580.9970      | HCC3C13N (0001)                 | J = 39–38                  |
| 354650.5747      | H13CCCN (0002)                  | J = 40–39                  |
| 354697.4631      | HC3CN (0002)                    | J = 39–38                  |
| 354721.1070      | HC3N (0100)/(0001)              | J = 39–38                  |
| 354780.4494      | H13CCCN (0002)                  | J = 40–39                  |
| 354913.0924      | H13CCCN (0002)                  | J = 39–38                  |
| 354918.6770      | HC3N (0100)/(0001)              | J = 39–38                  |
| 354957.7936      | HC3N (0102)/(0200)              | J = 39–38                  |
| 355108.4000      | HC3N (0001)                     | J = 39–38                  |
| 355215.8330      | HCC3C13N (0002)                 | J = 39–38                  |
| 355277.5940      | HC3N (0010)                     | J = 39–38                  |
| 355281.4277      | HCC3C13N (0002)                 | J = 39–38                  |
| 355317.9566      | CH3CHCN                         | J = 38(2,37)–37(2,36)     |
| 355365.4210      | HCC3C13N (0002)                 | J = 39–38                  |
| 355424.7668      | HCC3C13N (0002)                 | J = 39–38                  |
| 355463.0140      | HC3N (0110)                     | J = 39–38                  |
| 355520.9620      | HCC3C13N (0002)                 | J = 39–38                  |
| 355533.6650      | HC3N (0110)                     | J = 39–38                  |
| 355544.9810      | HC3N (0110)                     | J = 39–38                  |

Notes. a For HC3N and its isotopologues, the vibrational states are (v1,v2,v3). A “?” in the vibrational state indicates a Fermi resonance transition. The rest frequencies of the HC3N lines are mostly obtained from Mbosei et al. (2000) and their 13C isotopologue lines from the Cologne Database for Molecular Spectroscopy (CDMS; Müller et al. 2005; Thorwirth et al. 2001). A “?” indicates a possible detection.

d to absorption on the blueshifted side (Figures 8(c) and (d)). This ring-like PV structure indicates that for a given position offset from the central star, the blueshifted and redshifted emission are seen. This is expected because the dense core has a small inclination angle and it is thick enough for the cut to pass through both the far side and near side of the dense core.

As mentioned above, the expansion velocity is found to increase with distance from the central star. Here we can study
quantitatively how fast the increase is using the linewidth and the angular radius of the dense core seen in the lines of HC$_3$N and its isotopologues. We first measure the angular diameter and then divide it by 2 to obtain the angular radius. The angular diameter of the dense core in different line emission can be defined as the full extent in the major axis at the half maximum of the emission peak. It can be measured from those integrated maps (Figures 4 and 5) that have enough S/N, as listed in Table 2. Figure 9 shows the FWHM linewidth, $\Delta v$, versus the angular radius $r$ of the dense core. It shows that the linewidth and thus the expansion velocity increase roughly linearly with the angular radius. In this figure, we exclude the lines with the highest upper energy level, due to their low S/N. Also, we exclude the zero vibrational line of HC$_3$N, which could be affected by the outflow lobes.

### 3.2.4. Physical Properties

A population diagram can be used to estimate the mean excitation temperature and the column density of HC$_3$N toward the inner part of the dense core. It is a diagram that plots the column density per statistical weight in the upper energy state in the

---

| Molecule and Vibrational State | Transition | Frequency (MHz) | $E_u$ (K) | $T_{MB}$ (K) | $\Delta v$ (km s$^{-1}$) | Diameter (°) |
|--------------------------------|------------|----------------|-----------|-------------|----------------|-------------|
| HC$_3$N                        | (0000)     | $J = 38-37$   | 1590.042  | 25.0        | 8.0            | 0.59        |
|                                | (0000)i    | $J = 38-37$   | 323.493   | 77.0        | 17.0           | 1.12        |
|                                | (0010)     | $J = 38-37$   | 1907.628  | 7.0         | 6.5            | ...         |
|                                | (0000)i    | $J = 39-38$   | 1607.041  | 22.0        | 8.0            | 0.57        |
|                                | (0100)/(0001) | $J = 39-38$ | 1294.737  | 40.0        | 10.0           | 0.60        |
|                                | (0100)     | $J = 39-38$   | 1924.670  | 7.0         | 7.0            | 0.50        |
|                                | (0010)     | $J = 39-38$   | 1058.752  | 50.0        | 10.5           | 0.65        |
|                                | (0101)     | $J = 39-38$   | 1597.035  | 21.0        | 8.0            | 0.53        |
|                                | (0020)     | $J = 39-38$   | 1766.135  | 14.0        | 7.0            | 0.61        |
|                                | (0101)     | $J = 39-38$   | 1759.035  | 17.0        | 8.0            | 0.54        |
|                                | (0101)     | $J = 39-38$   | 1597.035  | 19.0        | 8.5            | 0.54        |
|                                | (0001)i    | $J = 39-38$   | 662.686   | 73.0        | 13.0           | 0.86        |
|                                | (011)      | $J = 39-38$   | 1378.505  | 38.0        | 8.5            | 0.53        |
|                                | (011)      | $J = 39-38$   | 1379.687  | 31.0        | 9.0            | 0.60        |
|                                | (0102)/(0200) | $J = 39-38$ | 2246.276  | 3.5         | 8.0            | ...         |
|                                | (0102)/(0200) | $J = 39-38$ | 2246.276  | 3.5         | 8.0            | ...         |
|                                | (0011)     | $J = 39-38$   | 1379.991  | 33.0        | 9.5            | 0.54        |
|                                | (0002)i    | $J = 39-38$   | 987.708   | 51.0        | 11.0           | 0.65        |
|                                | (0112)     | $J = 39-38$   | 1683.361  | 15.0        | 6.0            | ...         |
|                                | (0112)/(0001) | $J = 39-38$ | 1298.070  | 38.0        | 8.5            | 0.58        |
|                                | (0112)     | $J = 39-38$   | 1683.361  | 15.5        | 9.0            | 0.48        |
|                                | (0112)     | $J = 39-38$   | 1683.361  | 13.0        | 9.0            | 0.60        |
|                                | (0112)     | $J = 39-38$   | 1683.361  | 13.5        | 8.0            | 0.60        |
|                                | (0112)     | $J = 39-38$   | 1683.361  | 12.5        | 8.5            | 0.54        |
|                                | (0112)     | $J = 39-38$   | 1683.361  | 15.0        | 6.5            | ...         |
| H$^{13}$CCCN                   | (0000)     | $J = 38-37$   | 329.992   | 55.0        | 11.0           | 0.76        |
|                                | (0010)     | $J = 38-37$   | 1047.903  | 8.5         | 7.5            | 0.52        |
|                                | (001)      | $J = 38-37$   | 648.992   | 28.0        | 9.0            | 0.60        |
|                                | (001)      | $J = 38-37$   | 649.453   | 28.0        | 8.0            | 0.61        |
|                                | (002)      | $J = 38-37$   | 971.520   | 8.5         | 7.5            | 0.58        |
| H$^{13}$CCCN                   | (0000)     | $J = 38-37$   | 322.121   | 54.0        | 11.0           | 0.74        |
|                                | (0010)i    | $J = 38-37$   | 1030.321  | 5.0         | 7.5            | ...         |
|                                | (0001)     | $J = 38-37$   | 638.768   | 23.0        | 10.0           | 0.60        |
|                                | (0010)i    | $J = 38-37$   | 1030.577  | 6.0         | 5.0            | ...         |
|                                | (0001)     | $J = 38-37$   | 639.234   | 24.0        | 8.5            | 0.57        |
|                                | (0002)     | $J = 38-37$   | 972.521   | 13.0        | 8.5            | 0.58        |
|                                | (0002)     | $J = 38-37$   | 975.606   | 8.0         | 9.0            | 0.57        |
|                                | (0002)     | $J = 38-37$   | 975.684   | 10.0        | 7.5            | 0.46        |
| H$^{13}$CN                     | (0000)     | $J = 38-37$   | 322.152   | 51.0        | 11.5           | 0.74        |
|                                | (0010)     | $J = 38-37$   | 1025.870  | 8.0         | 7.0            | ...         |
|                                | (0001)     | $J = 38-37$   | 641.726   | 25.0        | 8.5            | 0.58        |
|                                | (0002)     | $J = 38-37$   | 799.687   | 8.5         | 6.0            | ...         |

Note. i denotes the data that will not be used for the population diagram fitting.
4. MODEL

In order to derive the properties of the dense core more accurately, we construct a radiative transfer model to calculate the free–free emission of the H ii region and the thermal dust emission and molecular line emission of the dense core to compare with the observations.

Figure 11 shows a schematic diagram for our model. As discussed in Section 3.1, the H ii region is a filled region at the center elongated in the east–west direction. The radius of the H ii region in the equatorial plane is uncertain and it might have grown to ~0′′14 as discussed. Thus, the H ii region is assumed to be an ellipsoid with a size of 0′′6 × 0′′28 × 0′′28 elongated in the east–west direction, which is an approximate representation of the size and morphology of the 23 GHz continuum map (Figure 1). The inner radius of this H ii region is unresolved and set to a small value of 0′′01 (9 AU), which is more than 20 times smaller than our resolution and thus should not affect our model comparison. In order to produce the bright compact emission peak at the center, the electron density in the H ii region is assumed to decrease with the radial distance from the central star, r, as follows:

\[ n_e = n_{e0} \left( \frac{r}{0.05} \right)^{-2} \text{ cm}^{-3}. \] (1)

The electron temperature of the H ii region is assumed to be constant at 15,000 K, in between that derived by Martin-Pintado et al. (1993) and Wyrowski et al. (2003). Note that the H ii shell detected at 23 GHz could suggest an increase in electron temperature (Martin-Pintado et al. 1993) or density (Kwok & Bignell 1984) in the outer part of the H ii region. However, at 350 GHz, the shell is optically thin and it is not detected here because of its low column density. Therefore, its flux can be ignored as compared to that of the dense H ii core at the center. As a result, the possible increase in the electron temperature or density is not included in our model.

The dense core is assumed to be originally spherical, with the inner radius set by the outer boundary of the H ii region and the outer radius set to 1″, as found in Setal04. The dense core is evacuated by the outflow lobes. For simplicity, we assume two outflow cavities, one in the east and one in the west, both with a half opening angle of 25° (Figure 11), as judged from the HC3N map in Figure 6(a), which shows emission extending to the northeast, northwest, southeast, and southwest.

The dense core is dusty and molecular, producing both thermal dust emission and molecular emission. For simplicity, the dust and molecular gas are assumed to have the same temperature. This temperature was first assumed to have a single power-law distribution as follows:

\[ T \propto r^{-p} \text{ K}. \] (2)

We found that when \( p = 1.8 \), this temperature distribution can roughly reproduce the low excitation lines in the outer part. However, it cannot produce enough emission for the high excitation lines in the inner core, because the temperature there was too high. Therefore, the temperature is assumed to have the following two power-law distributions with a turning point at \( r_0 \):

\[ T(r) = \begin{cases} \frac{T_0}{r}^{-p} & \text{if } r < r_0, \\ \frac{T_0}{r_0}^{-p} & \text{if } r \geq r_0 \end{cases} \] (3)
Figure 8. PV diagrams for the HC$_3$N (0000) and H$^{13}$CCCN (0000) lines. Panels (a) and (b) are the axial PV diagrams cut perpendicular to the dense core. Panels (c) and (d) are the equatorial PV diagrams cut along the major axis of the dense core. The angular and velocity resolutions are shown in the lower left corner. The positive (negative) contours start from 16 (−16) K with a step of 16 (−16) K.

Figure 9. Plot of the FWHM linewidth vs. the half width of the emitting size (or angular radius) of the dense core for the lines of HC$_3$N and its singly $^{13}$C substituted isotopologues. The solid line is a linear fit to the data.

with the power-law index $p_i < p_0$. In our model, the expansion velocity is assumed to increase linearly with the radius,

$$v_{\text{exp}} = v_0 \left( \frac{r}{r_0} \right) \text{ km s}^{-1} \quad (4)$$

as we discussed earlier. However, note that the dense core will have a maximum (i.e., terminal) expansion velocity, which is assumed to be equal to the expansion velocity of the extended halo or $\sim$16 km s$^{-1}$, as found earlier. The mass-loss rate in the dense core is assumed to be constant for simplicity, as in Fonfría et al. (2011). Thus, the number density of molecular hydrogen in the dense core becomes

$$n = n_0 \left( \frac{r}{r_0} \right)^{-3} \text{ cm}^{-3}. \quad (5)$$

For the thermal dust emission in the dense core, the dust opacity per unit gas mass, $\kappa_\nu$, is assumed to be a free parameter on the order of $10^{-2}$ cm$^2$ g$^{-1}$ at 350 GHz (Sahai et al. 2011). In the model, the molecules that trace the dense core are included. The outflow lines, e.g., CO, CS, HCO$^+$, and HCN $v = 0$, are excluded. The abundance of HC$_3$N is assumed to be $2 \times 10^{-7}$ as found in Setal04. The abundances of other molecular species
Figure 10. Population diagram for HC$_3$N and its singly $^{13}$C substituted isotopologues. The line intensity of the isotopologues has been multiplied by a factor of 10. The solid line is a linear fit to the data. The HC$_3$N data points with an upper arrow are not optically thin and thus excluded from the fitting.

Figure 11. Schematic diagram for our simple model in the $yz$-plane, with $y$ to the west and $z$ to the north. The H$^\text{II}$ region (dark gray region) is ellipsoidal with a size of $0.6\arcsec \times 0.28\arcsec \times 0.28\arcsec$, and thus it has a radius of $0.14\arcsec$ in the $z$-axis and a radius of $0.31\arcsec$ in the $y$-axis. The dense core (light gray region) is spherical, with its outer radius set to $1.2\arcsec$ and its inner boundary set by the outer boundary of the ellipsoidal H$^\text{II}$ region. There are two outflow cavities, one in the east and one in the west, both with an half opening angle of $25^\circ$. In our model, the free–free emission is from the H$^\text{II}$ region, and both the dust and molecular emissions are from the dense core.

are derived from our model by fitting the line profiles of each of these species.

Radiative transfer is used to calculate all the emissions with an assumption of LTE. The thermal linewidth and the linewidth due to a turbulence velocity of 2 km s$^{-1}$ are included. The systemic velocity is assumed to be $-21.5$ km s$^{-1}$. Also, we rotate our model counterclockwise by a P.A. of $3\degree$ and tilt it with an inclination of $30\degree$ to match the observations. The distance of the source is assumed to be 900 pc.

4.1. Model Results

Figure 12 shows the fit of the spectra with our simple model. The parameters are listed in Table 3, and the profiles of the temperature, density, and velocity in the dense core are shown in Figure 13. In order to produce the observed flux density for the H$^\text{II}$ region, we obtain $n_0^\text{v0} = 6.4 \times 10^5$ cm$^{-3}$. For the inner, denser part of the H$^\text{II}$ region, the emission measure averaged over a radius of $0.14\arcsec$ is $\sim 4.2 \times 10^{10}$ cm$^{-6}$ pc, in agreement with the emission measure derived by Wyrowski et al. (2003), who assumed a radius of $\sim 0.14\arcsec$ for the H$^\text{II}$ region.

With the assumed abundance of HC$_3$N, we obtain the temperature, density, and velocity distributions of the dense core by fitting all the HC$_3$N lines that trace the dense core, including both the optically thin and optically thick lines. Then we derive the abundance of other molecular species by fitting their lines. The HC$_3$N isotopologues are much less abundant than HC$_3$N and their lines are mostly optically thin. The lines for CH$_2$CHCN and HC$^{15}$N are optically thin. For H$^{13}$CN, the abundance is strongly constrained by the $v2 = 1 J = 4-3$ line (at 345238.7103 MHz see Table 1) since it is optically thin ($\tau \sim 0.06$) in the region where the bulk of its emission arises (radii <0.5). For HCN, the abundance is strongly constrained
Figure 12. Fit of our model to the spectra. The black spectra are the same as those in Figure 3. Red spectra are derived from our model. The green spectrum shows the possible HCCC\(^{15}\)N (0000) line at 344.3853481 GHz predicted from our model assuming an abundance ratio of [HC\(_3\)N]/[HCCC\(^{15}\)N] = 150.

Table 3
Model Parameters

| Species         | Abundance          |
|-----------------|--------------------|
| HC\(_3\)N       | 2 ± 0.4 × 10\(^{-7}\) |
| H\(^{13}\)CCCN  |                    |
| H\(^{13}\)CCN   | 2 ± 0.4 × 10\(^{-8}\) |
| HCC\(^{13}\)CN  |                    |
| H\(^{13}\)C\(^{15}\)CN | 2 ± 0.4 × 10\(^{-9}\) |
| HCC\(^{13}\)C\(^{13}\)N |                |
| CH\(_2\)CHCN    | 3 ± 0.6 × 10\(^{-8}\) |
| HCN             | 1.4 ± 0.3 × 10\(^{-7}\) |
| H\(^{13}\)CN    | 1.8 ± 0.4 × 10\(^{-8}\) |
| HC\(^{15}\)N    | 1.1 ± 0.3 × 10\(^{-9}\) |

| Parameter | Value                   |
|-----------|-------------------------|
| n\(_e\)   | 6.4 ± 1.3 × 10\(^6\) cm\(^{-3}\) |
| r\(_0\)   | 0\(^\prime\)\, 0\(^\prime\) 0\, 0.04 |
| T\(_0\)   | 440 ± 90 K              |
| p\(_1\)   | 0.8 ± 0.2               |
| p\(_2\)   | 1.8 ± 0.4               |
| n\(_0\)   | 4.0 ± 0.8 × 10\(^8\) cm\(^{-3}\) |
| v\(_0\)   | 4.9 ± 0.5 km s\(^{-1}\) |
| \(\kappa\) | 0.022 ± 0.004 cm\(^2\) g\(^{-1}\) |

Note. The uncertainties are assumed to be 20% for all parameters.

by the \(v_2 = 2\), \(J = 4\text{--}3\) (at 356301.1780 MHz) and \(v_2 = 1\), \(J = 4\text{--}3\) (at 354460.4346 and 356255.5682 MHz) lines (see Table 1), as these have optical depths less than unity (\(\tau \sim 0.08\) and 0.70, respectively) in the region where the bulk of their emission arises (radii <0\(^\prime\)3). Nonetheless, since our model assumes LTE, there could be uncertainty in our calculation of the abundances because of non-LTE effects.

It is clear from Figure 12 that our model can roughly reproduce the line peak and linewidth for most of the lines that trace the dense core. As mentioned early, the outflow lines are excluded in the fitting. Since they are strong and broad, the lines that are close to them are significantly affected and thus cannot be fitted well. In order to further check the reliability of our model, we also present the comparison of the synthetic and observed 350 GHz continuum maps as well as the maps for three emission lines. Since H\(^{13}\)CCCN is mostly optically thin and bright, we choose three of its isolated lines at different vibrational states to trace the different parts of the dense core. As can be seen from Figures 14 and 15, our model can also roughly reproduce the structures and the kinematics of the dense core in these emissions. Our model is symmetric and thus will not account for the asymmetric structure.

Nonetheless, there are still some minor discrepancies between our model and the observations. Although our model can roughly fit the line peaks for the two bright HCN \(v_2 = 1\) lines,
it produces a linewidth smaller than what was observed. This is probably because these two lines might have been affected by outflows, as found in the line in the ground vibrational state of HCN. Also, for the three HC₃N isotopologues with double substitutions of ¹³C, we expect to see one line for each of them in our frequency ranges. However, the H¹³C₁³CCN line at 342467.9204 MHz is not observed. Moreover, although we can roughly reproduce the peak of the lines for the other two isotopologues, H₁³CC₁³CN and HC₁³C₁³CN, the lines in our model are too broad. Since these lines are very weak, future observations at a higher sensitivity will be needed to confirm our result.

In our model, since the density and temperature both decrease rapidly with increasing radius, the line emissions mainly arise from the inner part of the dense core within ~0.7 from the central star, as seen in the observations. In this part of the dense core, the expansion velocity increases from ~3 km s⁻¹ to the maximum velocity of ~16 km s⁻¹ at r ~ 0.7 (630 AU). The outer part of the dense core does not change the spectra a lot; it only produces a deep absorption dip at ~−16 km s⁻¹ for the v = 0 lines of HC¹⁵N, H¹³CN, and even HC₃N. This is because the expansion velocity there reaches and stays at the maximum velocity of ~16 km s⁻¹.

The parameters in our model are consistent with what we estimated earlier. For instance, the mean column density of HC₃N averaged over a radius of 0.5 is ~2 × 10¹⁷ cm⁻², only about two times the lower limit derived from the population diagram. The temperature averaged over a radius of 0.5 is ~340 K and is similar to the mean excitation temperature derived from the population diagram. The temperature power-law index in the outer part of the dense core is similar to that found in Setal04 by fitting a low excitation line of HC₃N. The temperature power-law index in the inner part of the dense core is the same as that found in Wyrowski et al. (2003). The temperature within r₀ (i.e., 0.22) is also consistent with that found by Fonfría et al. (2011). By fitting the infrared spectra of C₂H₂ and C₄H₂, they found that the temperature decreases from ~600 K to 400 K from the innermost part of the dense core to r₀, similar to our model.

A sophisticated model was previously proposed by Pardo et al. (Pardo et al. 2004, 2005, 2007; Pardo & Cernicharo 2007) to explain various molecular emissions of CRL 618 observed with the IRAM 30 m telescope in the frequency range from 80 to 276 GHz. The dense core here can be considered as a refined version of the slowly expanding envelope (SEE) in their model. In their model, the SEE has an outer radius of 1.5, which is slightly larger than that of the dense core. It has a temperature of 250–275 K, which is slightly lower than the mean temperature in the dense core. The expansion velocity field has a radial component ranging from 5 to 12 km s⁻¹ with a possible extra azimuthal component reaching 6 km s⁻¹ at 1.5 and is thus not much different from that in the dense core. The column density of HC₃N is (2.0–3.5) × 10¹⁷ cm⁻², also similar to that found in the dense core. In their model, the SEE is surrounded by a colder (~60 K) and outer (a radius from 1.5 to 2.25) circumstellar shell (CSS) created during the AGB phase and is responsible for most
Figure 14. Comparison of the emission structure in the 350 GHz continuum and three $^{13}$CCCN lines at different vibrational states. The images with gray contours are from the observations, and the black contours are from our model. Panel (a) has the same contour levels as in Figure 1(a). The lowest contour is affected by the outflow and thus excluded. Panel (b) has the same contour levels as in Figure 6(b). Panels (c) and (d) have the same contour levels as in Figure 5.

Figure 15. Comparison of the PV structure in the three $^{13}$CCCN lines at different vibrational states. The images with gray contours are from the observations, and the black contours are from our model. Panels (a) and (b) have the same contour levels as in Figure 8(b). In panels (c)–(f), the positive (negative) contours start from 6 ($-6$) K with a step of 6 ($-6$) K.
of the rotational emission from HC$_3$N $\nu_7$ and $\nu = 0$ and HC$_3$N $\nu = 0$ (Pardo et al. 2005). In our model, there is no need for such an extended shell because our observations mostly probe the central region within $\sim 0''7$ from the central star.

5. DISCUSSION

Our model is very simple. Nonetheless, it can already produce a reasonable fit to the observations of the dense core. The abundance for each species is assumed to be constant, and no chemical effect is included. The dense core is assumed to be in LTE, which may not be the case near the central star because of possible infrared pumping there. The different power-law indices for the temperature in the inner part of the dense core could be related to this. The dense core is assumed to be spherical with two conical cavities. The actual dense core could have a density enhancement in the equatorial plane, as hinted in the two conical cavities. The actual dense core could have a density enhancement in the equatorial plane, as hinted in the Figure 2) and 23 $\pm$ 4 Jy at 850 GHz (350 $\mu$m) (Knapp et al. 1993). As argued by the authors, the continuum emission at those two frequencies is highly dominated by the dust emission of the circumstellar envelope and thus the fluxes there can be considered as the upper limits for the dust emission in the dense core. Fitting the fluxes at the three frequencies, we find that the flux of the dense core $\propto v^{-2.94 \pm 0.2}$, which results in a dust emissivity index of $\beta = 0.8 \pm 0.2$, to be an upper limit. This value of $\beta$ is in good agreement with that derived by Knapp et al. (1993) for the circumstellar envelopes around five highly evolved stars, including CRL 618. A value of $\beta \lesssim 1$ has been used to imply the presence of large (millimeter-sized) grains in protoplanetary disks (Draine 2006), as well as in tori and disks around post-AGB stars (Sahai et al. 2011). Thus, there could be large (millimeter-sized) grains in the dense core of CRL 618, as well down to $\sim 126$ AU ($0''14$) from the source.

In the dense core, the dust opacity per gas mass is found to be $\sim 0.022 \pm 0.004$ cm$^2$ g$^{-1}$ in our model. The gas-to-dust ratio is uncertain. It was found to be $\sim 63$ by single-dish observations averaged over both the extended halo and the dense core (Knapp et al. 1993). If we assume this ratio for the dense core, then the dust opacity per dust mass will be $\sim 1.4 \pm 0.3$ cm$^2$ g$^{-1}$, the same as that adopted to derive the mass of the disks and tori around the post-AGB stars (Sahai et al. 2011). Note that the gas-to-dust ratio and dust opacity could be a factor of two larger in the dense core compared to that in the extended halo (Meixner et al. 2004).

As discussed above, the dense core could result from a heavy mass loss at the end of the AGB phase. The mass loss (or wind) could be driven by radiation pressure of the stellar light on dust grains. For radiation-driven wind, most of the acceleration is believed to take place in the very thin innermost part where the dust grains have sizes of up to a micrometer. Here in CRL 618, however, we see that the acceleration continues out to $0''7$ (630 AU) even though the dust grains could have grown to millimeter sizes. Thus, further observations are needed to study the cause of this acceleration in the dense core.

5.2. Dust Properties

As discussed in Section 3.1, at 350 GHz, the extended continuum emission traces the dust emission from the dense core, and it has a flux density of $\sim 1.9 \pm 0.4$ Jy. Previously in single-dish observations, continuum emission was detected with a flux of $\sim 12 \pm 2.5$ Jy at 670 GHz (450 $\mu$m, see also Figure 2) and 23 $\pm$ 4 Jy at 850 GHz (350 $\mu$m) (Knapp et al. 1993). As argued by the authors, the continuum emission at those two frequencies is highly dominated by the dust emission of the circumstellar envelope and thus the fluxes there can be considered as the upper limits for the dust emission in the dense core. Fitting the fluxes at the three frequencies, we find that the flux of the dense core $\propto v^{-2.94 \pm 0.2}$, which results in a dust emissivity index of $\beta = 0.8 \pm 0.2$, to be an upper limit. This value of $\beta$ is in good agreement with that derived by Knapp et al. (1993) for the circumstellar envelopes around five highly evolved stars, including CRL 618. A value of $\beta \lesssim 1$ has been used to imply the presence of large (millimeter-sized) grains in protoplanetary disks (Draine 2006), as well as in tori and disks around post-AGB stars (Sahai et al. 2011). Thus, there could be large (millimeter-sized) grains in the dense core of CRL 618, as well down to $\sim 126$ AU ($0''14$) from the source.

In the dense core, the dust opacity per gas mass is found to be $\sim 0.022 \pm 0.004$ cm$^2$ g$^{-1}$ in our model. The gas-to-dust ratio is uncertain. It was found to be $\sim 63$ by single-dish observations averaged over both the extended halo and the dense core (Knapp et al. 1993). If we assume this ratio for the dense core, then the dust opacity per dust mass will be $\sim 1.4 \pm 0.3$ cm$^2$ g$^{-1}$, the same as that adopted to derive the mass of the disks and tori around the post-AGB stars (Sahai et al. 2011). Note that the gas-to-dust ratio and dust opacity could be a factor of two larger in the dense core compared to that in the extended halo (Meixner et al. 2004).

As discussed above, the dense core could result from a heavy mass loss at the end of the AGB phase. The mass loss (or wind) could be driven by radiation pressure of the stellar light on dust grains. For radiation-driven wind, most of the acceleration is believed to take place in the very thin innermost part where the dust grains have sizes of up to a micrometer. Here in CRL 618, however, we see that the acceleration continues out to $0''7$ (630 AU) even though the dust grains could have grown to millimeter sizes. Thus, further observations are needed to study the cause of this acceleration in the dense core.

5.3. Isotope Ratios

5.3.1. Carbon

Isotopic ratios can be used to constrain current nucleosynthesis models in evolved stars. Previously, with the IRAM 30 m single-dish observations, Pardo & Cernicharo (2007) found that the isotopic ratio of $^{12}$C/$^{13}$C is 15 in the dense core (or SEE in their model) and $\geq 40$ in the extended halo (or CSS in their model), using, e.g., HC$_3$N, HCN, HNC, and their isotopologues in lower transition lines. Here, with the observations at higher angular resolutions in higher transition lines, the isotopic ratio of $^{12}$C/$^{13}$C is found to be $\sim 10 \pm 3$, using HC$_3$N and its isotopologues. This value is the same as that found by Wyrowski...
et al. (2003) and similar to that found by Pardo & Cernicharo (2007) using the same species in lower transition lines. This is expected because this species is mainly present in the dense core. The ratio is found to be $\sim 8 \pm 3$, using HCN and its isotopologues. Thus, the mean value of the ratio is $\sim 9 \pm 4$, similar to that found by Pardo & Cernicharo (2007) in the dense core using various molecules. Note that lower $^{12}\text{C}/^{13}\text{C}$ ratios have been seen before in C-rich PPN/PPN, for instance a value of $\sim 5$ in the Boomerang Nebula (PPN; Sahai & Nyman 1997) and a value of $\sim 3$ in M1-16 (which is a very young multipolar PN with a dense core (so very similar to CRL 618) and compact H II region; Sahai et al. 1994).

Compared to a recent extensive study by Milam et al. (2009) with Arizona Radio Observatory single-dish observations in CN, CO, and their isotopologues, we find that our value is smaller than those found in the circumstellar envelopes around C-rich stars, which are $\sim 25$–90, but the value is in the lower limit of those found in the circumstellar envelopes around O-rich stars, which are $\sim 10$–35. Note that in their study, the ratios are the values averaged over a large extent of the circumstellar envelopes including both the extended halos and dense cores. For CRL 618, they found a ratio of $\gtrsim 32$, which is much larger than our value and probably due to the high ratio of $\gtrsim 40$ found in the extended halo (Pardo & Cernicharo 2007). In this case, high-resolution observations are really needed to derive the ratio in the dense core.

More recently, by modeling Herschel data of CO/$^{13}\text{C}$ and HCN/$^{13}\text{C}$ lines in CRL 618, Wesson et al. (2010) found a $^{12}\text{C}/^{13}\text{C}$ ratio of 21, which is intermediate between the high value of $\gtrsim 40$ and our low value of 9. The region they probed has a temperature of 70–230 K, and thus corresponds to our dense core in the middle part from $\sim 0''$3 to 0''6. As a result, the $^{12}\text{C}/^{13}\text{C}$ ratio indeed appears to decrease (perhaps in a continuous manner) from $\gtrsim 40$ in the extended halo to 9 in the inner part of the dense core, as argued by Pardo & Cernicharo (2007). The timescale for this change is short. In Pardo & Cernicharo (2007), the ratio of $\gtrsim 40$ was obtained at a radius of $\sim 2''$. Our value is mostly from the inner part and can be assumed to be at a radius of $\sim 0''3$. Assuming an expansion velocity of $\sim 16$ km s$^{-1}$, then the timescale is only $\sim 450$ yr.

Our $^{12}\text{C}/^{13}\text{C}$ ratio in the dense core is much smaller than the solar value, which is $\sim 89$. For an AGB star, the $^{12}\text{C}/^{13}\text{C}$ ratio is first expected to go down from the solar value due to the first dredge-up. This is because $^{13}\text{C}$, which is produced in a CNO cycle during the RGB phase, is transported out to the envelope by the first dredge-up. Then when the third dredge-up occurs and adds fresh $^{12}\text{C}$ to the envelope, the $^{12}\text{C}/^{13}\text{C}$ ratio starts going up again. When the envelope becomes C-rich, this ratio is expected to be $\gtrsim 35$, which is what is seen in the extended halo in CRL 618. However, it is unclear how the ratio can decrease again after the envelope has become C-rich. As suggested by Pardo & Cernicharo (2007), one possibility is to have a late CNO cycling phase that follows the He-burning phase, as in Sakurai’s object (Asplund et al. 1999). Note that the $^{12}\text{C}/^{13}\text{C}$ equilibrium value from CNO cycling is $\sim 3.5$ (Asplund et al. 1999).

5.3.2. Nitrogen

$^{15}\text{N}$ is clearly detected here in the dense core in the $J = 4$–3 line. It was also detected in the $J = 1$–0, 2–1, and 3–2 lines by Pardo et al. (2007), see the electronic version of the Figure 5), although it was not listed in their Table 2. The isotopic ratio of $^{14}\text{N}/^{15}\text{N}$ in the dense core can thus be derived by dividing the abundance of HCN by that of $^{15}\text{N}$ and is found to be $\sim 130 \pm 40$. As will be discussed later, this value is low compared to those found in AGB stars (Wannier et al. 1991). It could be due to a possible underestimate of the HCN abundance in our model considering that Thorwirth et al. (2003) has detected direct $l$-doubling transition lines of HCN (for which the line strengths are very low). We also derive an independent estimate of the $^{14}\text{N}/^{15}\text{N}$ ratio, $\sim 160 \pm 40$, by multiplying the $[^{13}\text{C}]/[^{15}\text{N}]$ ratio (16 ± 4) by the $^{12}\text{C}/^{13}\text{C}$ ratio ($\sim 10$, derived earlier from HC3N and its isotopologues). Therefore, the mean ratio of $^{14}\text{N}/^{15}\text{N}$ can be $150 \pm 50$. With this ratio, our model predicts a weak HCCC$^{15}\text{N}$ (0000) $J = 39$–38 line at 344385.3481 MHz (see the green spectrum in Figure 12), roughly consistent with the line emission feature tentatively detected there. However, such a feature could be alternatively identified with weak emission from the HCC$^{13}\text{CN}$ (0100)/(0003) $J = 38$–37 ($f$ component) transition (see the red spectrum in Figure 12). Further work is needed to check this possible detection of the HCCC$^{15}\text{N}$ (0000) line.

In Pardo et al. (2007), CN and C$_{3}$N were not detected in the dense core (or their SEE), and neither were their $^{15}\text{N}$-isotopologues. Although HNC and HC$_{3}$N were also detected in the dense core, their $^{15}\text{N}$-isotopologues were not detected likely because of not enough sensitivity in their observations as discussed below. Since HNC lines are likely optically thick, we use HC$_{15}$N lines in their observations to estimate the expected peak intensities for the H$^{15}$NC lines. Assuming the abundance ratio of $[^{13}\text{C}]^{15}\text{N}/[^{15}\text{C}]^{15}\text{N} = [\text{HCN}]/[\text{HNC}] = 10$ (as found in the SEE by Pardo et al. 2007) and that the lines are optically thin, then the H$^{15}$NC lines are expected to have a peak of $\sim 1$ mK, 10 mK, and 12 mK, respectively, for the $J = 1$–0 (89 GHz), $J = 2$–1 (178 GHz), and $J = 3$–2 (267 GHz) lines. In their observations, the noise was $\sim 4$ mK at 3 mm (100 GHz), 8 mK at 2 mm (150 GHz), 11 mK from 204 to 240 GHz, and 14 mK above 240 GHz, and thus those lines were lost in the noise. As for HCCC$^{15}\text{N}$, here we only check if its $(0000)$ lines can be detected because its higher vibrational lines are much weaker. In Pardo et al. (2007), the HC$^{3}$N (0000) lines have a peak of 0.4–0.6 K for those below 100 GHz and $\sim 1$ K for those above 140 GHz. Assuming $^{14}\text{N}/^{15}\text{N} = 150$ (as derived above) and the lines are optically thin, then HCCC$^{15}\text{N}$ (0000) lines are expected to have a peak of $\sim 3$ mK below 100 GHz and 7 mK above 140 GHz, and thus were also lost in the noise. More sensitive observations are needed.

Previously, using single-dish observations in HC$_{3}$N lines at lower frequencies, Wannier et al. (1991) derived a $^{15}\text{N}^{12}\text{C}/^{14}\text{N}^{13}\text{C}$ ratio of $< 0.12$. Assuming a $^{12}\text{C}/^{13}\text{C}$ ratio of $\gtrsim 30$, they estimated a $^{14}\text{N}/^{15}\text{N}$ ratio of $> 250$. However, since the $^{12}\text{C}/^{13}\text{C}$ ratio in CRL618 decreases from $\gtrsim 40$ in the extended halo to $\sim 9$ in the dense core, the Wannier et al. lower limit on the $^{14}\text{N}/^{15}\text{N}$ ratio is $> 75$ in the dense core, consistent with our derived value. Wannier et al. (1991) found the $^{14}\text{N}/^{15}\text{N}$ ratio to be $> 500$ for their small sample of a few carbon-rich AGB stars and one PN; Zhang et al. (2009) confirm this for AGFL 3068, finding $^{14}\text{N}/^{15}\text{N} = 1099$. CRL 618 appears to be different from these with its lower $^{14}\text{N}/^{15}\text{N}$ ratio. However, these studies use single-dish observations and their derived ratios are likely characteristic of the extended circumstellar envelopes in these objects and not their dense central regions. High-resolution studies of these objects, like the one presented here, should be carried out to probe the latter.

Our value of $^{14}\text{N}/^{15}\text{N}$ is smaller than the solar value, which is $\sim 272$. In current models of nucleosynthesis in the evolved stars,
however, the CNO cycle is a cold CNO cycle that destroys $^{15}\text{N}$, resulting in a $^{14}\text{N}/^{15}\text{N}$ ratio always $\gtrsim 2000$ (see, e.g., Palmerini et al. 2011). The only known way to produce abundant $^{15}\text{Ni}$ is through a hot CNO cycle as in novae (Wiescher et al. 2010). However, it is unclear if the hot CNO cycle can really take place in the AGB stars at the end of the AGB phase. Also, chemical fractionation that can enhance the abundance of the isotopically substituted species is unlikely to be an effect at the high temperatures of the dense core, because it is important only at low temperatures (Terzieva & Herbst 2000).

6. CONCLUSIONS

With the SMA, we have mapped the central region of CRL 618 in continuum and molecular lines at 350 GHz at $0.3-0.5'$ resolution. Most of the emission detected in our observations arises within a radius of $\sim 630$ AU ($0.7'$) from the source. The main conclusions are as follows.

1. In the continuum, there are two components, (1) a compact emission at the center tracing the dense inner part of the $\text{H}\text{ii}$ region previously detected in a 23 GHz continuum and it may trace a fast ionized wind at the base, and (2) an extended emission tracing the thermal dust emission from the dense core around the $\text{H}\text{ii}$ region. The dense core seems to have a density enhancement in the equatorial plane that can confine the $\text{H}\text{ii}$ region to a bipolar morphology. The dust emissivity index is estimated to be 0.8 $\pm$ 0.2, suggesting that the dust grains in the dense core may have grown to become millimeter-sized.

2. The dense core is also detected in $\text{HC}_3\text{N}$, $\text{HCN}$, and their isotopologues, with higher excitation lines tracing closer to the source. It is also detected in $\text{CH}_2\text{CHCN}$ toward the innermost part. The dense core detected here is the inner part of that seen before in a lower excitation line of $\text{HC}_3\text{N}$, and it could also have a density enhancement in the equatorial plane. The dense core is probably also excavated by the outflow lobes.

We have fitted a simple radiative transfer model to our observations in order to derive the kinematics, physical conditions, and the chemical abundances in the dense core. In this model, the $\text{H}\text{ii}$ region is ellipsoidal at the center. The dense core is spherical with the inner boundary set by the outer boundary of the $\text{H}\text{ii}$ region and the outer radius set to $1^\prime.2$. It is dusty and molecular, producing both the thermal dust emission and molecular emission. Two outflow cavities are also included. This simple model can roughly fit the observations. The model results are the following:

1. The dense core is expanding, with the velocity increasing roughly linearly from $\sim 3$ km s$^{-1}$ in the innermost part to $\sim 16$ km s$^{-1}$ at 630 AU. The mass-loss rate in the dense core is extremely high with a value of $\sim 1.15 \times 10^{-3} M_{\odot}$ yr$^{-1}$. The dense core has a mass of $\sim 0.47 M_{\odot}$ and a dynamical age of $\sim 400$ yr. It could result from a recent enhanced heavy mass-loss episode that ends the AGB phase.

2. The isotopic ratios of $^{12}\text{C}$/^{13}\text{C}$ and $^{14}\text{N}$/^{15}\text{N}$ are $\sim 9 \pm 4$ and $150 \pm 50$, respectively, both smaller than the solar values. The $^{12}\text{C}$/^{13}\text{C}$ ratio is also much smaller than that found in the extended halo, indicating that this ratio decreases toward the center, as argued before. It is not clear if current models of nucleosynthesis in evolved stars can produce our isotopic ratios in a C-rich star like that in CRL 618.

We thank the anonymous referee for valuable and insightful comments. We thank the SMA staff for their efforts in running and maintaining the array. C.-F. Lee and C.-H. Yang acknowledge grants from the National Science Council of Taiwan (NSC 99-2112-M-001-007-MY2 and NSC 101-2119-M-001-002-MY3). CSC has been partially supported by the Spanish MICINN/MINECO through grants AYA2009-07304, AYA2012-32032, and CONSOLIDER INGENIO 2010 for the team “Molecular Astrophysics: The Herschel and ALMA Era—ASTROMOL” (ref.: CSD2009-00038).

REFERENCES

Asplund, M., Lambert, D. L., Kipper, T., Pollacco, D., & Shetrone, M. D. 1999, A&A, 343, 507

Balick, B., & Frank, A. 2002, ARA&A, 40, 439

Cernicharo, J. 2004, ApJL, 608, L41

Cernicharo, J., Heras, A. M., Pardo, J. R., et al. 2001, ApJL, 546, L127

Cernicharo, J., Heras, A. M., Tielens, A. G. G. M., et al. 2001, ApJL, 546, L123

Draine, B. T. 2006, ApJ, 636, 1114

Fonfria, J. P., Cernicharo, J., Richter, M. J., & Lacy, J. H. 2011, ApJ, 728, 43

Ho, P. T. P., Moran, J. M., & Lo, K. Y. 2004, ApJL, 616, L11

Huggins, P. J. 2007, ApJ, 663, 342

Knapp, G. R., Sandell, G., & Robson, E. I. 1993, ApJS, 88, 173

Kwok, S., & Bignell, R. C. 1984, ApJ, 276, 544

Lee, C.-F., Hsu, M.-C., & Sahai, R. 2009, ApJ, 696, 1630

Lee, C.-F., & Sahai, R. 2003, ApJ, 586, 319

Martin-Pintado, J., Bujarrabal, V., Bachiller, R., Gomez-Gonzalez, J., & Planesas, P. 1998, A&A, 197, L15

Martin-Pintado, J., Gaume, R., Bachiller, R., & Johnson, K. 1993, ApJ, 419, 725

Mboise, L., Fayet, A., Dréan, P., & Cosléou, J. 2000, JMoSt, 517, 271

Meixner, M., Zalucha, A., Ueta, T., Fong, D., & Justtanont, K. 2004, ApJ, 614, 371

Milam, S. N., Woolf, N. J., & Ziurys, L. M. 2009, ApJ, 690, 837

Müller, H. S. P., Schöder, F., Stutzki, J., & Winnewisser, G. 2005, JMoSt, 742, 215

Palmerini, S., La Cognata, M., Cristallo, S., & Busso, M. 2011, ApJ, 729, 3

Pardo, J. R., & Cernicharo, J. 2007, ApJ, 654, 978

Pardo, J. R., Cernicharo, J., & Goicoechea, J. R. 2005, ApJ, 628, 275

Pardo, J. R., Cernicharo, J., Goicoechea, J. R., Güelman, M., & Asensio Ramos, A. 2007, ApJ, 661, 250

Pardo, J. R., Cernicharo, J., Goicoechea, J. R., & Philips, T. G. 2004, ApJ, 615, 495

Sahai, R., Claussen, M. J., Schnee, S., Morris, M. R., & Sánchez Contreras, C. 2007, ApJL, 739, L3

Sahai, R., Morris, M., Sánchez Contreras, C., & Claussen, M. 2007, AJ, 134, 2200

Sahai, R., & Nyman, L.-Å. 1997, ApJL, 487, L155

Sahai, R., Wootten, A., Schwarz, H. E., & Wild, W. 1994, ApJ, 428, 237

Sánchez Contreras, C., Bujarrabal, V., Castro-Carrizo, A., Alcolea, J., & Sargent, A. 2004, ApJL, 617, 1142

Sánchez Contreras, C., & Sahai, R. 2004, ApJ, 602, 960

Sánchez Contreras, C., Sahai, R., & Gil de Paz, A. 2002, ApJ, 578, 269

Terzieva, R., & Herbst, E. 2000, MNRAS, 317, 563

Thorwirth, S., Müller, H. S. P., & Winnewisser, G. 2001, PCCP, 3, 1326

Thorwirth, S., Wyrwoski, F., Schilke, P., et al. 2003, ApJ, 586, 338

Trammell, S. R., & Goodrich, R. W. 2002, ApJ, 579, 688

Wannier, P. G., Andersson, B.-G., Olofsson, H., Ukita, N., & Young, K. 1991, ApJ, 394, 593

Wesson, R., Cernicharo, J., Barlow, M. J., et al. 2010, A&A, 518, L144

Wiescher, M., Görres, J., Uberseder, E., Imbriani, G., & Pignatari, M. 2010, ARNPS, 60, 381

Wyrwoski, F., Schilke, P., Thorwirth, S., Menten, K. M., & Winnewisser, G. 2003, ApJ, 586, 344

Zhang, Y., Kwok, S., & Nakashima, J.-i. 2009, ApJ, 700, 1262