A REMODEL OF THE ENVELOPE AROUND THE 21 μm PROTOPLANETARY NEBULA IRAS 07134+1005

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ABSTRACT

Recently, the CO J = 3–2 observational result of the envelope of the 21 μm protoplanetary nebula (PPN) IRAS 07134+1005 has been reported. Assuming that the CO J = 3–2 line was optically thin, the mass-loss rate of the superwind in this PPN was found to be at least 2 orders of magnitude lower than the typical range. In order to obtain a more accurate mass-loss rate, we reexamine these data and construct a radiative transfer model to compare with the data. Also, in order to better resolve the superwind, we adopt a different weighting on the data to obtain maps at a higher resolution. Our result shows that the CO J = 3–2 emission is located slightly further away from the central source than the mid-infrared emission, probably because the material is cooler on the outer part and is thus better traced by the CO emission. At a lower resolution, however, the CO emission appeared to be spatially coincident with the mid-IR emission. Our model has two components, an inner ellipsoidal shell-like superwind with an equatorial density enhancement and an outer spheroidal asymptotic giant branch wind. The thick torus in the previous model could be considered as the dense equatorial part of our ellipsoidal superwind. With radiative transfer, our model reproduces more observed features than the previous model, and it obtains an averaged superwind mass-loss rate of \( \sim 1.8 \times 10^{-5} M_\odot \text{yr}^{-1} \), which is typical for a superwind. The mass-loss rate in the equatorial plane is \( 3 \times 10^{-5} M_\odot \text{yr}^{-1} \), which is also the same as that derived before from modeling the CO J = 1–0 emission.

Key words: circumstellar matter – planetary nebulae: general – stars: AGB and post-AGB – stars: individual (IRAS 07134+1005) – stars: mass-loss

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1. INTRODUCTION

A protoplanetary nebula (PPN) is an object in a transient phase between an asymptotic giant branch (AGB) phase and a planetary nebula phase at the end stage of a low- to intermediate-mass (1–8 \( M_\odot \)) star. It consists of a post-AGB stellar core (star) and an extensive circumstellar envelope of dust and gas. It is bright at the infrared (IR) wavelength because of the dense and warm circumstellar dust. Recently, a large number of observations have revealed that PPNe are mostly bipolar, multipolar, or elliptical with a torus-like structure in the equator. Of observations have revealed that PPNe are mostly bipolar, multipolar, or elliptical with a torus-like structure in the equator. In the optical images, the elliptical shell was seen surrounded by a roughly round halo produced by the AGB wind in the past (Ueta et al. 2000). The CO J = 1–0 map (Meixner et al. 2004, hereafter M2004) also showed a torus-like structure similar to that seen in the mid-IR image. A radiative transfer model made by M2004 indicates that the envelope of I07134 has two components, an inner warm and dense superwind that corresponds to the elliptical shell and an outer cool and sparse AGB wind that corresponds to the round halo.

Nakashima et al. (2009, hereafter N2009) have reported the CO J = 3–2 observation of this PPN obtained with the Submillimeter Array (SMA; Ho et al. 2004). Unlike CO J = 1–0, CO J = 3–2 mainly traces the superwind component because it traces warmer and denser material than CO J = 1–0. N2009 have proposed a morpho-kinematics model to compare with the observation. They assumed the CO J = 3–2 line is optically thin and estimated a lower limit of the mass-loss rate, which is at least 2 orders of magnitude lower than the typical range (\( 10^{-7} \text{ to } 10^{-4} M_\odot \text{yr}^{-1} \); see, e.g., the review by Van Winckel 2003). For studying the shaping mechanism of I07134, we need to know the mass-loss rate, spatial structure, and kinematics of the superwind component as accurately as possible. Therefore, in this paper, we reexamine the CO data and construct a radiative transfer model to compare with the data. The details about our data reduction and mapping are described in Section 2. The observation results are presented in Section 3. Our model is described and compared with the observation in Section 4. We discuss and summarize our work in Sections 5 and 6, respectively.

2. OBSERVATION

The SMA CO J = 3–2 observation of I07134 in this paper has been reported by N2009; please refer to their paper for the details. In this section, we only summarize the parameters of this
observation in Table 1, and we describe the differences between their data reduction and mapping and ours.

Eight antennas were used in the observation. We adopted the data from seven (one more than N2009) of them in the data reduction and mapping because antenna 7 was excluded due to its weak fringes and amplitudes over the course of the whole observation. In addition, we removed the first half of the data from antenna 4 because of its scattering phase. In mapping, a “super-uniform” weighting is used to achieve the best compromise between the sensitivity and angular resolution. This results in an angular resolution of 1′.66 × 1′.46 with a position angle (P.A.) of 17°, which is 40% higher in beam area than what is described in N2009, thus showing a clearer compact structure. Our maps will show similar features to those of N2009 if we convolve our maps with their angular resolution.

The channel maps have a resolution of ~0.7 km s\(^{-1}\) per channel, with an rms noise (hereafter \(\sigma\)) of 0.27 Jy beam\(^{-1}\). They are used to produce an integrated intensity map, position velocity (PV) diagrams, and spectrum. The channel maps we include in this paper are binned to have a lower resolution of ~1.4 km s\(^{-1}\) per channel to show how the structure changes with the velocity. Although this velocity resolution is 40% lower than that of N2009, it is enough to show the main structure of I07134 in different velocities.

### 3. OBSERVATIONAL RESULTS

#### 3.1. Integrated Intensity Map

In Figure 1, we superposed our SMA CO J = 3–2 (integrated intensity) map on the near-IR (Ueta et al. 2005), the CO J = 1–0 (M2004), and the mid-IR (Kwok et al. 2002) maps as well as the CO J = 3–2 map of N2009 to analyze the structure of I07134. The near-IR emission mostly traces the light of the central star scattered by the surrounding dust, and the mid-IR emission mostly traces the thermal dust emission. The near-IR map shows a well-defined elliptical shell with a major axis at P.A. ~ 25° (Ueta et al. 2005), and the mid-IR map shows a roughly round envelope surrounding the central star. All of the maps show a double-peak structure around the minor axis (P.A. ~ 115°), indicating that the circumstellar envelope of I07134 has an equatorial density enhancement (i.e., a torus-like structure). At low resolution, the two peaks of the CO J = 3–2 emission appeared to be spatially coincident with those in the mid-IR (Nakashima et al. 2009). But here at higher resolution, the two peaks of the CO emission are located slightly further away from the source than those in the mid-IR, especially for the western peak. The two peaks are asymmetric around the central star, with the eastern peak closer to the central star than the western peak by about 20%. Note that both the CO J = 3–2 and the CO J = 1–0 emissions are weak in the north of the central star compared with those in the south, which is in contrast to what we have seen in the mid-IR.

#### 3.2. Channel Maps

Our channel maps (Figure 2) are similar to those of N2009 (their Figure 3), showing a similar variation of the morphology with the velocity. For example, the size of the emission gradually increases from high blue- and redshifted velocities toward the systemic velocity (72 km s\(^{-1}\), as found in our model described later), single peaks are seen at high blue- and redshifted velocities, an opening (less emission) toward the south (i.e., an inverted U-shape, “convex upward” in N2009) from 66.4 to 69.2 km s\(^{-1}\), an opening toward the north (i.e., a U-shape, “convex downward” in N2009) from 73.4 to 79 km s\(^{-1}\), and two elongated and clumpy peaks in the east and west near the...
The systemic velocity (from 70.6 to 72 km s\(^{-1}\)). Note that the high-velocity emission peaks are not exactly at the center of the map (central star position). The highest blueshifted peak is shifted slightly to the north, and the highest redshifted peak is shifted slightly to the southwest.

### 3.3. PV Diagrams

The PV diagrams cut along the major (the poles, P.A. = 15\(^\circ\), as found in our model described later) and the minor (the equator, P.A. = 105\(^\circ\)) axes of the ellipse are presented in Figure 3. Note that the major and minor axes here are different from those found in Ueta et al. (2005). These PV diagrams are similar to those of N2009 that cut along the similar P.A.s (0\(^\circ\) and 90\(^\circ\), their Figure 4). At a higher angular resolution, however, our PV diagrams show a clearer ring-like structure (as indicated by a white dashed ellipse on Figure 3(b)) in both cuts. The lack of emission inside the ring-like structure is consistent with a detached envelope around the central star. In the PV diagrams, there are two obvious asymmetric emission distributions: (1) the high redshifted emission is stronger than the high blueshifted emission toward the star position in both PV diagrams, and (2) in the PV diagram cut along the major axis, the southwestern emission in the redshifted part is much stronger than that in the blueshifted part, producing a gap (Gap 1) there. There is another gap near the highest blueshifted velocity (Gap 2) that separates the highest blueshifted emission from the main emission structure. Note that the emission at the highest blueshifted and redshifted emission are not at the source position in the PV diagram cut along the major axis. This is consistent with what we have seen in the channel maps as mentioned above.

From the observation, we suggest that the envelope of I07134 is a radially expanding ellipsoidal shell, with the redshifted emission stronger than the blueshifted emission. This envelope is inclined to the plane of the sky, producing the U-shape and the inverted U-shape structures in the channel maps. In the following section, we introduce our radiative transfer model and compare it with this observation in order to obtain a more accurate mass-loss rate, the morphology, and the kinematics of the envelope.

### 4. AN EXPANDING ELLIPSOIDAL MODEL

#### 4.1. Model

Here we construct a code with a model different from that of N2009 and include the radiative transfer to calculate the CO \(J = 3–2\) emission, rather than assuming an optically thin emission. As in M2004, the envelope has two components, an outer spherical AGB wind and an inner ellipsoidal shell-like superwind (Figure 4). In the superwind component, we do not adopt a spheroidal shell as was done in M2004 nor a thick torus as was done in N2009. This is because the near-IR image (Figure 1(a)) shows an elliptical shell-like morphology in the inner part of this envelope. Thus, the superwind is assumed to be an ellipsoidal shell elongated in the north–south direction that looks like a football. In the Cartesian coordinate system, the ellipsoidal shell can be described with the following equation:

\[
\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1, \tag{1}
\]

with the \(x-y\)-plane being the equatorial plane and the \(z\)-axis being the major axis in the north–south direction. Here, \(a\) and \(b\) are the one-half of the minor and major axes of the ellipsoidal shell with an constant ellipticity defined as \(\epsilon = 1 - \frac{b}{a}\). The ellipsoidal shell has an inner radius \(R_{\text{in}}\) and a thickness \(\Delta a\) in the minor axis, and thus \(a = R_{\text{in}} + \Delta a\) (which is the outer

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**Figure 2.** Observed channel maps in contours and gray scale. The contour levels are from 4.3\(\sigma\) to 39\(\sigma\) with a step of 4.3\(\sigma\), where \(\sigma\) is the 0.19 Jy beam\(^{-1}\). Top left corner of each channel map shows the local standard of rest velocity in km s\(^{-1}\). The systemic velocity is in the channel of 72 km s\(^{-1}\). The velocity width is \(\sim 1.4\) km s\(^{-1}\). The white cross symbol at the center of each channel map marks the position of the central star. The resolution is shown in the bottom left corner of the first channel map. The wedge shows the intensity scale in the Jy beam\(^{-1}\).

**Figure 3.** Observed PV diagrams cut along (a) the P.A. = 15\(^\circ\) and (b) the P.A. = 105\(^\circ\), respectively, in contours and gray scale. The contour levels are from 3\(\sigma\) to 23\(\sigma\) with a step of 3\(\sigma\), where \(\sigma\) is the 0.27 Jy beam\(^{-1}\). The capital NE, SW, SE, and NW indicate the northeast, southwest, southeast and northwest directions on the observed integrated intensity map. The wedge shows the intensity scale in the Jy beam\(^{-1}\).
radius). On the other hand, the spherical AGB wind has an outer radius of $R_{\text{out}}$, and its inner boundary is the outer boundary of the superwind.

We assume that the envelope is expanding radially, and the expansion velocity of the superwind follows the same equation as the ellipsoidal shell for self-consistency,

$$V_x^2 + V_y^2 + V_z^2 = 1,$$

with $V_x$ and $V_y$ being the expansion velocities in the minor (equator) and major (pole) axes, respectively. As can be seen from the equation, the expansion velocity increases from the equator to the poles, which is qualitatively similar to that expected in some of the interacting stellar winds wave simulations (e.g., Dwarkadas et al. 1996). As for the AGB wind, it expands radially with a constant velocity of $V_a$.

Below are our density and temperature profiles of the molecular gas (molecular hydrogen) in the envelope (in the spherical coordinate system).

$$\rho_{H_2}(R, \theta) = \begin{cases} \frac{\dot{M}_{\text{sw}}}{4\pi R^2 V_a} f(\theta) & \text{superwind component,} \\ F \frac{\dot{M}_{\text{sw}}}{4\pi R^2 V_a} & \text{AGB wind component,} \end{cases}$$

$$T_{\text{gas}}(R) = \begin{cases} T_{\text{in}} \left( \frac{R}{R_{\text{sw}}} \right)^{\gamma} & \text{superwind component,} \\ T_{\text{in}} F_T \left( \frac{R}{R_{\text{sw}}} \right)^{\gamma} & \text{AGB wind component,} \end{cases}$$

where $\dot{M}_{\text{eq}}$ is the mass-loss rate of the superwind component in the equator. The density decreases with radius $R$ with a power-law index of $-2$, in both the superwind and AGB wind components, and it has a sudden drop with a factor $F$ at the superwind–AGB wind boundary. In order to reproduce the observed equatorial density enhancement, the density of the superwind component is multiplied by a simple torus function

$$f(\theta) = 1 - \alpha \cos \theta,$$

where $\theta$ is the angle from the $z$-axis, and the value of $\alpha$ is between 0 and 1. Here $f(\theta)$ equals to 1 at the equator and $1-\alpha$ at the poles. $T_{\text{in}}$ is the temperature at $R_{\text{in}}$. The temperature is assumed to decrease with $R$ with a power-law index of $\beta$ in the superwind and $\gamma$ in the AGB wind. It also has a sudden drop with a factor $F_T$ in the superwind–AGB wind boundary. In the AGB wind, the temperature is set to 5 K when it decreases to below 5 K. The density and temperature profiles along the minor axis of the two components are shown in Figure 5.

Radiative transfer is used to derive the CO $J = 3–2$ emission in our model. The thermal line width $V_{\text{th}}$ and the line width due to the turbulence velocity $V_{\text{turb}}$ are also included. The systemic velocity $V_{\text{sys}}$ is assumed to be a free parameter. Also, we rotate our model counterclockwise by a P.A. from the $z$-axis and tilt it with an inclination angle $i$; the north part is tilted away from us.

To properly compare the model results with the observation, we use MIRIAD (Sault et al. 1995) to derive the model visibility from the model data cubes with the observed $uv$-coverage, and then we use the same imaging procedure as we did for the observed channel maps to derive the model channel maps. As a result, the model and the observed channel maps have the same spatial and velocity resolutions. With the channel maps, we can obtain the integrated map, the PV diagrams, and the spectrum of our model.

4.2. Model Results

The best-fit parameters are listed in Table 2. There are 18 parameters in our model; 3 are constant and 15 are free. The three constant parameters are the distance of the source, the
Figure 5. Equatorial density (upper panel) and temperature (lower panel) of the molecular gas as a function of the radius for the superwind and the AGB wind components in our model. Please note that we do not show the entire AGB wind region, which has an outer radius of $\sim 3 \times 10^{17}$ cm.

Table 2

| Parameter | Value                                      | Reference |
|-----------|--------------------------------------------|-----------|
| Distance  | 2.4 kpc                                    | 1         |
| $\text{CO}/\text{H}_2$ | $9.2 \times 10^{-4}$                         | 2         |
| $R_{\text{out}}$ | $8''$ ($\sim 19300$ AU)                     | 2         |

Free parameters

| Parameter | Value                                      |
|-----------|--------------------------------------------|
| $R_{\text{in}}$ | $173 \pm 0.1$ ($\sim 3100$ AU)               |
| $\Delta a$ | $0.9 \pm 0.1$ ($\sim 2160$ AU)               |
| $\epsilon$ | $0.2 \pm 0.05$                               |
| P.A.      | $15^\circ \pm 5^\circ$                      |
| $i$       | $25^\circ \pm 5^\circ$                      |
| $V_{\text{sys}}$ | $72 \pm 0.35$ km s$^{-1}$                    |
| $V_a$     | $9.3 \pm 0.35$ km s$^{-1}$                   |
| $V_{\text{turb}}$ | $1$ km s$^{-1}$                              |
| $T_{\text{in}}$ | $70 \pm 5$ K                                 |
| $F_T$     | $0.25 \pm 0.1$                               |
| $\beta$  | $-0.8 \pm 0.2$                               |
| $\gamma$ | $-1.5 \pm 0.5$                               |
| $F$       | $0.12 \pm 0.05$                              |
| $\dot{M}_{\text{eq}}$ | $3 (\pm 1) \times 10^{-5}$ M$_\odot$ yr$^{-1}$ |
| $\alpha$ | $0.8 \pm 0.1$                                |

Output

| Parameter | Value                                      |
|-----------|--------------------------------------------|
| $t_{\text{dyn}}$ | $\sim 1590$ yr                              |
| $t_{\text{SW}}$ | $\sim 1100$ yr                              |
| $t_{\text{AGB}}$ | $\sim 6760$ yr                              |
| Averaged $\dot{M}_{\text{SW}}$ | $1.8 (\pm 0.6) \times 10^{-5}$ M$_\odot$ yr$^{-1}$ |
| $M_{\text{AGB}}$ | $3.6 (\pm 1.0) \times 10^{-6}$ M$_\odot$ yr$^{-1}$ |

References. (1) Knapp et al. 2000; (2) Meixner et al. 2004.

CO abundance ($\text{CO}/\text{H}_2$ in number density), and $R_{\text{out}}$. For the CO abundance, we adopt the value of $9.2 \times 10^{-4}$ from M2004. If we adopt the value of $7.4 \times 10^{-4}$ as in N2009, which is $\sim 20\%$ lower than that in M2004, our mass-loss rate will increase only by $\sim 20\%$. The 15 free parameters are $R_{\text{in}}$, $\Delta a$, $\epsilon$, P.A., $i$, $V_{\text{sys}}$, $V_a$, $V_{\text{turb}}$, $T_{\text{in}}$, $F_T$, $\beta$, $\gamma$, $F$, $\dot{M}_{\text{eq}}$, and $\alpha$. We compare the results of our model with the observation, and we determine the best-fit parameters and their error bars based on the following five criteria: (1) The total flux of our model cannot be more or less than 10% that of the observation. Here the total flux is derived from within a 4$''$-wide box centered at the central star, where the emission mainly comes from the superwind region. (2) The blueshifted peak of the spectrum of our model cannot be more or less than 10% that of the observation. (3) The highest contour in the moment map of our model cannot be more or less than one contour level that of the observation. (4) The lowest contour in the moment map of our model should be in between the lowest and penultimate-low contours in the moment map of the observation. (5) The morphology trend in the channel maps and PV diagrams in our model should be similar to that in the observation as mentioned in Section 3.

As shown in Figures 6 and 7, our model can reproduce most of the observed structures and kinematics of the CO envelope,
for example, how the morphology and intensity of the emission change with the velocity in the channel maps, the equatorial-enhanced emission in the integrated intensity map, the intensity ratio of the high redshifted to high blueshifted peaks in the PV diagrams, and the emission gaps in the blueshifted part of the PV diagrams. The mean optical depth of the CO $J = 3–2$ emission estimated from the intensity ratio of the two peaks in our model spectrum toward the source position is $\sim 1$.

In our models, the values of $R_{\text{in}}$ and $\Delta a$ are very similar to those estimated by Ueta et al. (2005) from the near-IR image, which are 1\'4 and 0\'8, respectively. Also, $\epsilon \sim 0.2$ is almost the same value as 0.21, which was estimated from the optical image with a filter of F547M (Ueta et al. 2000). The mean expansion velocity of the superwind is also the same as the expansion velocity estimated by M2004 (10.5 km s$^{-1}$). In our model, $V_{\text{mb}} \sim 1$ km s$^{-1}$, and it is much more important than $V_{\text{th}}$, which has a maximum value of $\sim 0.2$ km s$^{-1}$. Our P.A. is $\sim 15^\circ \pm 5^\circ$, which falls between those of Ueta et al. (2005) and N2009. The inclination angle is estimated to be $\sim 25^\circ \pm 5^\circ$, which falls between those estimated by Ueta et al. (2005) and N2009. The $M_{\text{eq}}$ obtained from our model is the same as that in M2004. In our model for CO $J = 3–2$, the superwind has a $\beta$ of $-0.8$, which is shallower than the $-2.0$ found in CO $J = 1–0$ (M2004), but is steeper than the $-0.4$ found in the IR dust emission (Collison & Fix 1991; Meixner et al. 1997).

On the other hand, the AGB wind has a $\gamma$ of $-1.5$ in our model for CO $J = 3–2$, which is much steeper than the $-0.25$ found in CO $J = 1–0$ (M2004). We will discuss the differences in Section 5.

We can then derive five other quantities from our model: (1) the dynamical time at the inner boundary of the superwind $t_{\text{dyn}}$, (2) the duration of the superwind $t_{\text{sw}}$, (3) the averaged mass-loss rate of the superwind $M_{\text{SW}}$ averaged over $\theta$, (4) the duration $t_{\text{agb}}$, and (5) the mass-loss rate $M_{\text{AGB}}$ of the AGB wind. We divide $R_{\text{in}}$ by $V_{\text{a}}$ to obtain $t_{\text{dyn}}$ of $\sim 1590$ years, and we divide $\Delta a$ by $V_{\text{a}}$ to obtain $t_{\text{sw}}$ of $\sim 1100$ years. Our $M_{\text{SW}}$ is $1.8 \times 10^{-3} M_{\odot} \text{yr}^{-1}$, which is 40% lower than that of M2004. We divide the thickness of the AGB wind ($\sim 5\'5$) by $V_{\text{a}}$ to obtain $t_{\text{agb}}$ of $\sim 6760$ years. Our $t_{\text{agb}}$ is slightly larger than that obtained by M2004 (1240 years), because it has a larger inner radius. Our $t_{\text{sw}}$ and $t_{\text{agb}}$ are similar to those estimated by M2004, which are 840 and 6570 years, respectively. We multiply $M_{\text{eq}}$ by $F$ to obtain $M_{\text{AGB}}$ of $3.6 (\pm 1.5) \times 10^{-6} M_{\odot} \text{yr}^{-1}$. $M_{\text{AGB}}$ derived by M2004 is $5.1 \times 10^{-6} M_{\odot} \text{yr}^{-1}$ and it equals our upper limit. In our model, the CO emission of the AGB wind is rather weak, with less than $3\sigma$ even without having applied the observed $uv$-coverage. Thus, it will not be detected in our observation.

On the other hand, our model cannot reproduce the following observed features.

1. Our model is symmetric, so it cannot reproduce the different radii between the eastern and western peaks in the observed integrated intensity map. The reason for this asymmetry is unclear and will be discussed later.

2. The intensity excess at the low redshifted velocity in the observed spectrum (Figure 7(b)). The spectrum is obtained by averaging over a circular region of 1\' in diameter around the center, mainly showing the emission from the front and back walls of the envelope. Thus, the intensity excess indicates that there could be an additional material with a low expansion velocity in the back wall (redshifted part) of this envelope.

Figure 7. Comparison of our model and the observation in the integrated intensity map, the spectrum, and the PV diagrams. Gray contours and spectrum are from the observation. Dark contours (orange in the online version) and spectrum are from our model. Panel (a) shows the integrated intensity maps. The contour levels are the same as those in Figure 1. Note that, however, we do not include here the last contour of Figure 1. Panel (b) shows the spectra toward the central star position averaged over a circular region with a diameter of 1\'. Panels (c) and (d) show the PV diagrams cut along P.A. = 15\' and P.A. = 105\', respectively. The contour levels are the same as those in Figure 3.
3. In our model, the highest blueshifted emission is in the southwest, and the highest redshifted emission is in the northeast of the center (Figure 6), which is in contrast to what is seen in the observation. The superwind could have a non-radial velocity component, e.g., a poloidal velocity (directed from the equator to the poles). In the front wall of the superwind envelope, a poloidal velocity could increase the projected velocity of the northeastern gas and decrease the projected velocity of the southwestern gas near the center of the map. The opposite is true for the back wall of the superwind envelope. Alternatively, there could be an additional high-velocity component not included in our model.

5. DISCUSSION

5.1. Superwind Material in IR and CO Observations

As compared with N2009, the superwind is better resolved in our map optimized at a higher angular resolution. As a result, we can now study the superwind in more detail. At a higher rotational transition, CO $J = 3\rightarrow 2$ can trace warmer and denser material than CO $J = 1\rightarrow 0$. Therefore, our CO $J = 3\rightarrow 2$ map can reveal the superwind material better than the CO $J = 1\rightarrow 0$ map (Meixner et al. 2004), which shows both the superwind and AGB wind materials. Moreover, as mentioned in Section 3, the two emission peaks in the equator in our CO $J = 3\rightarrow 2$ map are located slightly further away from the source than those in the mid-IR map. This is likely because the mid-IR emission mainly traces the warmest material in the innermost part of the superwind, CO $J = 3\rightarrow 2$ emission mainly traces the warm material in middle part of the superwind, and CO $J = 1\rightarrow 0$ emission traces the cool material further out in the superwind and the AGB wind. Thus, in the superwind, the different temperature power-law index $\beta$ in different tracers and transitions may suggest that the power-law index becomes steeper with the change in distance from the source. On the other hand, the temperature power-law index of our AGB wind ($\gamma = -1.5$) in CO $J = 3\rightarrow 2$ is in between those of the superwind ($-2.0$) and the AGB wind ($-0.25$) in CO $J = 1\rightarrow 0$ (Meixner et al. 2004). This is probably because the superwind and the AGB wind in the CO $J = 1\rightarrow 0$ observation cannot be clearly separated at such a low resolution. It is also possible that our observation is not sensitive to the AGB wind.

5.2. Comparison with N2009 Results

N2009 has proposed a model to compare with this observation. Their model contains an inner toroidal superwind and an outer spheroidal AGB wind. Figure 4 (right) shows their model on top of our model. It is clear from the figure that their torus could actually be considered a dense equatorial part of our ellipsoidal superwind. Note that the radial extent of their torus is actually about one times larger than our superwind, and the P.A. derived by our model is between that derived by N2009 and that estimated by Ueta et al. (2005). In their model (N2009), there was no radiative transfer and they convolved their channel maps with a circular beam rather than the observed ellipsoidal beam. Their model reproduced the U-shaped and inverted U-shaped morphologies in the channel maps and the ring-like PV structure in the PV diagram. However, in order to reproduce the two elongated and clumpy structures in the equator around the systemic velocity, their model needed a distorted torus. Moreover, unlike that seen in the observation, the emission intensity in their channel maps did not gradually increase from the blueshifted to redshifted channels; instead, they had a sudden increase in some blueshifted channels. In their PV diagrams, Gap 2 was not seen on the high blueshifted velocity side. On the other hand, our model can reproduce all the above observed features reasonably well. Furthermore, the $M_{eq}$ estimated from our model is the same as that in M2004, and it is in the typical range for an AGB star. In contrast, by assuming that the CO $J = 3\rightarrow 2$ line is optically thin, N2009 estimated a lower-limit mass-loss rate of $\sim 10^{-9} M_\odot \text{yr}^{-1}$, which is 4 orders of magnitude lower than our $M_{eq}$, which is derived from our radiative transfer model. Therefore, radiative transfer is really needed to properly estimate the mass-loss rate. However, it is worth noting that it is unclear how N2009 obtained such a low mass-loss rate since the optical depth toward the central position in our model is only $\sim 1$.

5.3. Shaping Mechanism of Elliptical PPN

As mentioned in Section 1, most of the low- to intermediate-mass stars experience a structural change from a spherical to an elliptical or to a bipolar structure when they evolve from the AGB to the PPN phase (Ueta et al. 2000; Sahai et al. 2007). It is still uncertain what mechanism may cause this structural change. Moreover, most of PPNe contain an additional density enhancement (torus-like) structure that is perpendicular to their elliptical or bipolar structure. I07134 is one of the typical elliptical PPNe. It has an elliptical shell with an equatorial density enhancement embedded in a round halo, indicating that it also experiences the structural change mentioned above. Presently, a popular model to explain the forming mechanism of the density enhancement is a model with a binary system. In such a model, if the separation of the binary, the ejection velocity of the wind from the primary star, and the mass of the companion are in an appropriate range, the ejected material from the primary star can accumulate around the equator with a higher expansion velocity than the poles, thereby forming an asymmetric density enhancement in the equator as seen in the observation (Mastrodemos & Morris 1999). However, in this scenario, the elliptical shell will appear oblate with the long axes lying in the orbit plane, which is in contrast to what was seen in I07134. The elliptical structure of I07134 suggests that the poles of the superwind have a higher expansion velocity than the equator. Thus, if the binary system is to work, an additional element is needed to increase the expansion velocity at the poles. A bipolar jet launched by an accretion effect of the companion (Mastrodemos & Morris 1998; Frank & Blackman 2004) is a candidate that can produce a high expansion velocity at the poles, and it has been used to explain the shaping mechanism of bipolar PPNe (see, e.g., Lee & Sahai 2003). However, the observations toward I07134 do not show any such high-velocity emission. It is possible that the jet could be an atomic jet and, thus, could not be detected in the CO observation. Alternatively, a tenuous (and thus unseen) isotropic post-AGB wind with a higher expansion velocity than the superwind could have been launched and interacted with the superwind, thus producing the elliptical structure (Dwarkadas et al. 1996) of I07134. In either case, I07134 could be in the transient phase and is changing from a round to a bipolar structure.

However, the long-term (i.e., 20 years) radial velocity observation of Hrivnak et al. (2011) does not seem to support the binary scenario in I07134. If this is the case, the structural change of I07134 could be caused by some other mechanism due to a single star. Dorfi & Hoeftner (1996) proposed that a low rotation of a single AGB star would induce a preferential mass loss with higher velocities in the equatorial plane.
However, in this scenario, the envelope would form an oblate shape, which is inconsistent with what was seen in I07134. Matt et al. (2000) proposed that the dipole magnetic field in an AGB star could lead the mass loss along the equator. But, Soker (2006) argued that the magnetic field would carry the angular momentum away from the stellar envelope faster than the mass lost by the wind, which would cause the star to spin down on a short timescale. In this case, the lifetime of the magnetic field might not be long enough to produce the equatorial density enhancement structure. Soker (1998, 2000) proposed that the concentration of cool magnetic spots toward the equator on the surface of an AGB star would lead to the equatorial density enhancement, because dust would form above the cool spots more than any other area. Moreover, the mass-loss velocity above the cool spots is lower than other directions because of the weak radiation from the cool spots, which has the potential to form an elliptical envelope like I07134. However, it is unclear how these models can explain the asymmetric density distribution in the envelope of I07134.

6. CONCLUSION

We have reexamined and remodeled the SMA CO $J = 3–2$ observational result of I07134. Our main results are the following.

1. The CO map is consistent with the IR maps and shows an equatorial density enhancement. Compared with the mid-IR emission, the CO emission is located slightly further away from the central source. This is probably because the material is cooler in the outer part and, thus, is better traced by the CO emission.

2. Our model has two components, an inner ellipsoidal shell-like superwind with an equatorial density enhancement and an outer spheroidal AGB wind. The thick torus proposed by N2009 could actually be considered the dense equatorial part of our ellipsoidal superwind.

3. Our model can reproduce the observation reasonably well, better than the model proposed in N2009. The superwind mass-loss rate in the equator is estimated to be $\sim 3 \times 10^{-5} M_\odot$ yr$^{-1}$, which is the same rate derived by M2004, and the rate is in the typical range for an AGB star. The mean expansion velocities of the superwind and the AGB wind are 10.5 and 9.3 km s$^{-1}$, respectively. The mass-loss durations of the superwind and AGB wind are 1100 and 6760 years, respectively, which are similar to those estimated in M2004. The superwind ended its ejection about 1590 years ago.

One of the popular models explaining the forming mechanism of the density enhancement is a model with a binary system. However, for this binary model to work with this PPN, an additional element, such as a bipolar jet or a tenuous post-AGB wind, may be needed to produce the prolate elliptical structure with the density enhancement in the equator. Alternatively, the forming mechanism of the density enhancement could be due to a single star.

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