PECULIAR MOLECULAR ENVELOPE AROUND THE POST-AGB STAR IRAS 08544−4431

Dinh-V-Trung

Institute of Astronomy and Astrophysics, Academia Sinica, P.O. Box 23-141, Taipei 106, Taiwan; trung@asiaa.sinica.edu.tw

Received 2008 March 18; accepted 2008 October 30; published 2009 February 24

ABSTRACT

Circumbinary disks have been hypothesized to exist around a number of binary post-asymptotic giant branch (AGB) stars. Although most of the circumbinary disks have been inferred through the near-infrared (IR) excess, a few of them are strong emitters of molecular emission. Here we present high-angular resolution observations of the emission of $^{12}$CO and its isotopomer $^{13}$CO $J = 2–1$ line from the circumstellar envelope around the binary post-AGB star IRAS 08544−4431, which is one of the most prominent members of this class of objects. We find that the envelope is resolved in our observations and two separate components can be identified: (a) a central extended and strong component with very narrow linewidth between 2 and 6 km s$^{-1}$; (b) a weak bipolar outflow with expansion velocity up to 8 km s$^{-1}$. The central compact component possesses low and variable $^{12}$CO/$^{13}$CO $J = 2–1$ line ratio, indicating optically thick emission of the main isotope. We estimate a molecular gas mass of 0.0047 $M_\odot$ for this component based on the optically thinner $^{13}$CO $J = 2–1$ line. We discuss the relation of the molecular envelope and the circumbinary disk inferred from near-IR excess and compare with other known cases where the distribution of molecular gas has been imaged at high angular resolution.

Key words: circumstellar matter – ISM: molecules – stars: AGB and post-AGB – stars: individual (IRAS 08544−4431) – stars: mass loss

1. INTRODUCTION

The rapid evolution of low- and intermediate-mass stars (0.5–8 $M_\odot$) after the end of the asymptotic giant branch (AGB) phase is accompanied by a radical change in morphology of the circumstellar envelope around them. The circumstellar envelope created by the slow and dusty stellar wind during the AGB phase is known to be roughly spherically symmetric as the radiation pressure on dust grains is expected to be isotropic. However, a variety of morphologies ranging from spherical to multipolar shapes have been observed in post-AGB envelopes and planetary nebulae (Sahai et al. 2007). This morphological change has also been seen together with the appearance of collimated high-velocity outflows such as the Egg nebula (Cox et al. 2000) or CRL 618 (Sánchez-Contreras et al. 2004). The origin of the morphology and the mechanism to generate the high-velocity outflow are still under active study. One commonly suggested mechanism is the presence of a binary companion (Balick & Frank 2002). The companion can capture wind material into a rotating disk around it. Consequently, high-velocity jets could be launched from the disk through magneto-centrifugal effect (Soker 2006, Nordhaus & Blackman 2006, Nordhaus et al. 2007). Alternatively, the gravitational force of the companion may also attract the wind material toward the equatorial, thus forming a circumbinary disk-like structure or torus. Numerical simulations by Mastrodemos & Morris (1999) and more recently by Edgar et al. (2008) suggest that the torus is likely to be in expansion and not in rotation around the central star. However, when the torus is dense enough, it could serve to confine and channel the wind from the central star into bipolar directions.

The presence of rotating disks around a large number of post-AGB stars has been inferred from the infrared (IR) excess (De Ruyter et al. 2006). The excess suggests that hot dust exists close to the hot post-AGB stars, even though the mass loss due to dusty slow wind is expected to have ceased long ago. However, until recently only the rotating disk around post-AGB star Red Rectangle has been imaged at high-angular resolution (Bujarrabal et al. 2005).

IRAS 08544−4431 is an F-type post-AGB star and is among the first post-AGB stars discovered to have near-IR excess (Maas et al. 2003). From radial velocity measurements, Maas et al. (2003) inferred that the star is a binary system with an orbital period of 499 days and a mass function, which is a measure of the ratio between the companion mass to the primary mass in a single-line spectroscopic binary system, of 0.02 $M_\odot$. Using a typical luminosity for post-AGB stars, de Ruyter et al. (2006) suggested a distance close to 1 kpc for IRAS 08544−4431. Spectroscopic observations by Maas et al. (2003) show that the star is an O-rich post-AGB star. More interesting, the abundance of metals with high condensation temperature is strongly depleted. Such an anomaly could be explained as gas and dust separation and reaccretion from a long-lived reservoir of material around the star, i.e., a rotating disk. CO emission lines have also been detected from IRAS 08544−4431 (Maas et al. 2003). Unlike the parabolic shape seen in the envelope around AGB stars, the line profiles of CO lines of IRAS 08544−4431 are very peculiar with a strong central peak and extended wings, suggesting unusual kinematics of the molecular gas in the envelope. Using optical interferometry techniques, Deroo et al. (2007) resolved the near-IR continuum emission into an elongated structure. They found that both the spectral energy distribution (SED) and the interferometric data could be well fitted using the irradiated dust disk model. However, information on the kinematics of the molecular gas around IRAS 08544−4431 is really needed to settle the question concerning the existence of a rotating disk around this star.

In this paper, we present high angular resolution observations of CO $J = 2–1$ transition and its isotopes from the envelope around IRAS 08544−4431 using the submillimeter array (SMA). We resolve the envelope and probe its morphology and kinematics. In Section 4, we will discuss the implication of our new results.
2. OBSERVATION

We use the SMA, which consists of eight antennas of 6 m diameter, to observe IRAS 08544–4431. The observation was carried out during the night of 2007 April 9 under excellent weather conditions. The zenith opacity of the atmosphere at 230 GHz was around 0.1, resulting in antenna temperatures (single sideband) in the range of 300–400 K. In our observation, the SMA provides projected baselines in the range between 6 m and 78 m. The total on-source integration time of our observation is slightly less than 0 hours. The coordinates of IRAS 08544–4431 taken from Maas et al. (2005), α2000 = 08:56:14.18, δ2000 = -44:44:10.7, were used as phase center in our observation. The nearby and relatively strong quasar 0826–225 was monitored frequently to correct for gain variation due to atmospheric fluctuations. Saturn and its moon Titan were used as bandpass and flux calibrator, respectively. The large bandwidth (~2 GHz) of the SMA correlator allows us to cover simultaneously the 12CO J = 2–1 line in the upper sideband and the 13CO J = 2–1 and C18O J = 2–1 lines in the lower sideband. In our observation the SMA correlator was setup in normal mode, providing a frequency resolution of 0.825 MHz or ~1 km s⁻¹ in velocity resolution. The visibilities are edited and calibrated using the MIR/IDL package (Scoville et al. 1993), which is developed specifically for SMA data reduction. The calibrated data are then exported for further processing with the MIRIAD package (Sault et al. 1995). The line data are then Fourier transformed to form dirty images. Deconvolution of the dirty images is done using the task clean. The resulting synthesized beam for 12CO J = 2–1 channel maps is 5.9′ × 2.2′ at position angle P.A. = 17.5. The corresponding conversion factor between flux and brightness temperature is 1.76 K Jy⁻¹. The rms noise level for each channel of 1 km s⁻¹ is 110 mJy beam⁻¹. 13CO J = 2–1 emission has been also detected and imaged. The synthesized beam for the 13CO J = 2–1 emission is 5.8′ × 2.4′. The C18O J = 2–1 line is not detected in our observations and, therefore, we will not discuss this line any further in this paper.

We also form the continuum image by averaging line free channels in the upper sideband. No 230 GHz continuum emission from IRAS 08544–4431 is detected in our observations with rms noise level of 3 mJy beam⁻¹.

3. RESULTS

In Figure 1, we show the channel maps of 12CO J = 2–1 emission. Because of the very low declination of the source, resulting in an elongated synthesized beam, the emission in the channel maps near the systemic velocity appears extended and resolved. The deconvolved size of the emission at velocity \(V_{\text{LSR}} = 44 \pm 4 \text{ km s}^{-1}\) is 4.3′ × 4.5′. The 12CO J = 2–1 emission also reveals more asymmetry to the northeast of the envelope, namely in channels at velocity \(V_{\text{LSR}} = 45–46 \text{ km s}^{-1}\). In Figure 3 we compare the total flux of the 12CO J = 2–1 line detected with the SMA with that obtained previously with the SEST telescope (Maas et al. 2003). The line shape is very similar between interferometric and single-dish observations, although the line intensity seen by the SMA is slightly higher, probably related to the difficulty of calibrating the absolute flux for this very low declination source. Therefore, we conclude that the SMA detects all the flux of the 12CO J = 2–1 line.

In Figure 2 we show the channel maps of 13CO J = 2–1. This line is significantly weaker than the J = 2–1 line of the main isotope and its emission appears spatially less extended. We note that the 13CO J = 2–1 line is also noticeably narrower, covering a velocity range between 42 and 48 km s⁻¹, as can be seen in the total intensity profiles shown in Figure 3. Only central velocity channels between 44 and 46 km s⁻¹ contain significant amount of emission. The higher velocity component seen in the main isotope line is not detected in 13CO J = 2–1 emission. That suggests a strong variation in the 12CO/13CO line ratio within the envelope of IRAS 08544–4431. We will discuss the implication of the variation of this ratio in the following section.

4. MOLECULAR GAS IN IRAS 08544–4431

4.1. CO Line Opacity

In IRAS 08544–4431 the 12CO J = 2–1 transition is very likely optically thick. This is supported by two observational results: the relatively intense J = 1–0 line and the relatively high and variable 12CO/13CO J = 2–1 intensity ratio.

The 12CO J = 1–0 transition was observed by Maas et al. (2003) using the same SEST telescope. The peak main beam temperature is ~ 0.15 K. Because the emission region as seen in our SMA channel maps is small in comparison to the telescope beams, when converted to the same telescope beam, the intensity ratio of 12CO J = 2–1 and J = 1–0 is almost exactly 1. When these lines are optically thin and for the high excitation temperatures deduced in the previous subsection, such an intensity ratio should approach 4 (the ratio of the squares of the upper level J-value for each transition), which is the opacity ratio in the high-excitation limit. The measured line ratio of 1 is clearly incompatible with optically thin emission. We conclude that both 12CO J = 1–0 and J = 2–1 lines are optically thick.

In our observations the J = 2–1 line of the isotope 13CO is significantly weaker than the line of the main isotope. The emission of this line concentrates in a few channels around the systemic velocity, between \(V_{\text{LSR}} = 44\) and 46 km s⁻¹. By comparing the channel maps of the two lines we conclude that the 12CO/13CO J = 2–1 intensity ratio significantly varies for the different parts of the nebula. This strong variation can be readily seen from the total spectra in main-beam brightness units. Values as low as 2.5 are reached around the peak of emissions at the systemic velocity of the nebula. In the wings where the emission of the isotope line is much weaker, the ratio
increases rapidly. Such a trend of the line ratio, depending on
the intensity, is expected if the emission of the main isotope is
optically thick. The low values of the $^{12}$CO/$^{13}$CO intensity ratio
near the systemic velocity are, on the other hand, too low to
represent the abundance ratio, as would be the case if both lines
are optically thin. For instance, the $^{12}$CO/$^{13}$CO line intensity
ratios for circumstellar envelopes around AGB and post-AGB
stars are usually much larger (Bujarrabal et al. 2001), about
10 or higher. We note that similar behavior of the $^{12}$CO/$^{13}$CO
$J = 2–1$ intensity ratio has been seen in a few other cases such
as in the molecular envelope around young planetary nebula
NGC 6302 (Dinh-V-Trung et al. 2008).

### 4.2. Estimate of Gas Temperature

The kinetic temperature ($T_k$) of the molecular gas detected
in our maps can be estimated from the brightness temperature
distribution ($T_{mb}$), particularly for the $J = 2–1$ transition. We
can see that values as high as $T_{mb} \sim 8$ K are found at the peak of
the emission in the velocity channel maps around the systemic
velocity. $T_{mb}$ is approximately equal to $T_k - T_{bg}$ (the cosmic
background temperature, 3 K), in the limit of thermalized level
populations, high opacities, and resolved spatial distribution.
Otherwise, $T_k$ must be larger than $T_{mb} + T_{bg}$, except for very
peculiar excitation states. The envelope is also clearly resolved
in our observations. As we argue in the previous section, $^{12}$CO
$J = 2–1$ line is likely optically thick and the gas densities are
high enough to thermalize the CO low-$J$ lines. Therefore, we
conclude that the kinetic temperature in the molecular gas in
IRAS 08544−4431 is typically $\sim 10$ K.

### 4.3. Mass of Molecular Gas in the Nebula

We use the formula of Olofsson & Nyman (1999) and Chiu
et al. (2006) to estimate the mass of molecular gas in IRAS
08544−4431. We have used the $^{13}$CO $J = 2–1$ line, assuming
optically thin emission, a typical excitation temperature $T_{ex}$ of
10 K, and a $^{13}$CO relative abundance of $f^{13}$CO = $2 \times 10^{-5}$ with
respect to H$_2$ (Bujarrabal et al. 2001). Because the distance to
IRAS 08544−4431 is still very uncertain, we adopt a distance
$D = 1$ kpc.

$$M = \frac{16\pi km_H}{hc\gamma a} \frac{D^2}{I^{13}\text{CO} Q(T_{ex}) e^{E_s/kT_{ex}}},$$

(1)
As shown in the above equation, the estimated gas mass scales with square of the distance to the star, which is currently not known. Thus the gas mass in the envelope will be lower if the star is located at a smaller distance. If we adopt higher excitation temperature of 250 K as in Maas et al. (2003), the molecular gas mass is $\sim 0.03 M_\odot$. The molecular gas mass estimate from Maas et al. (2003) is $\sim 0.02 M_\odot$ (the larger value quoted in their paper is probably a typographic error), which is a factor of four higher than our estimate here, mainly due to the difference in the assumed excitation temperature of the gas.

5. IMPLICATIONS OF OUR OBSERVATIONS

As seen in Section 3, the nebula around IRAS 08544−4431 consists of a central component with strong CO emission but with very low expansion velocity traced mainly by the $^{13}$CO $J = 2$−1 emission, and a weak bipolar outflow oriented roughly in the east–west direction. The very narrow linewidth of the emission from the central component implies an expansion velocity of only $\sim 1–3$ km s$^{-1}$. Such low expansion velocity is rarely seen in normal AGB or post-AGB stars where the expansion velocity is usually in the range of 10–20 km s$^{-1}$. An alternative interpretation commonly put forward in the literature (Maas et al. 2003) is that the gas is not in expansion but is...
distributed in the form of a stable rotating disk around the central star. At large radial distance from the star, say a few thousands AU, the rotation velocity is expected to be quite small, approximately 1 km s\(^{-1}\) or less for a 1 \(M_\odot\) central post-AGB star. In addition, the spatially extended emitting region suggests that such a disk is seen at moderate inclination angle, i.e., close to face-on. Thus the apparent narrow linewidth is consistent with the hypothesis of a rotating disk around the central post-AGB star. However, to date only the disk around Red Rectangle has been imaged and clearly resolved using radio interferometry (Bujarrabal et al. 2005). In this case, the kinematics of the disk is found to be quite complex with the inner part in Keplerian rotation and some slow expansion in the outer part.

Currently, the formation mechanism of the rotating disk around these post-AGB stars is not well understood. The source that provides the large amount of angular momentum of the gas and dust in the rotating disk has not been identified. It has commonly been thought that the gas and dust acquire the necessary angular momentum through gravitational interaction with a binary companion, although how that process happens has not been demonstrated clearly in detail. Recently, Akashi & Soker (2007) propose a different scenario for the formation of these circumbinary rotating disk. They argue that the interaction between a wide angle jet and the slowly expanding envelope pushes back the wind material toward the center of the nebula. The back-flowing material will then form a rotating disk with diameter up to 10\(^3\) AU around the central post-AGB star. This model, however, is still rather speculative and has not been tested in any real three-dimensional hydrodynamic simulation.

In the near future, high-angular resolution observations with ALMA will allow us to resolve the central component and to study its spatial kinematics in much greater detail.

We are grateful to an anonymous referee for constructive comments which helped improve the presentation of the paper. We thank the SMA staff for their help with the observations. This research has made use of NASA’s Astrophysics Data System Bibliographic Services and the SIMBAD database, operated at CDS, Strasbourg, France.

REFERENCES

Akashi, M., & Soker, N. 2007, NewA, 13, 157
Balick, B., & Frank, A. 2002, ARA&A, 40, 439
Bujarrabal, V., Castro-Carrizo, A., Alcolea, J., & Neri, R. 2005, A&A, 441, 1031
Bujarrabal, V., Castro-Carrizo, A., Alcolea, J., & Sánchez-Conteras, C. 2001, A&A, 377, 868
Bujarrabal, V., Van Winckel, H., Alcolea, J., Castro-Carrizo, A., & Deroo, P. 2007, A&A, 468, L45
Chiu, P.-J., Hoang, C.-T., Dinh-V-Trung, Lim, J., Kwok, S., Hirano, N., & Muthu, C. 2006, ApJ, 645, 605
Cox, P., et al. 2000, A&A, 353, L25
Deroo, P., Acke, B., Verhoeest, T., Dominik, C., Tatulli, E., & Van Winckel, H. 2007, A&A, 474, L45
De Ruyter, S., Van Winckel, H., Maas, T., Lloyd Evans, T., Waters, L. B. F. M., & Mastrodemos, N. 2006, A&A, 448, 641
Dinh-V-Trung, Bujarrabal, V., Castro-Carrizo, A., Lim, J., & Kwok, S. 2008, ApJ, 673, 934
Edgar, R. G., Nordhaus, J., & Frank, A. 2008, ApJ, 675, L101
Maas, T., Van Winckel, H., & Lloyd Evans, T. 2005, A&A, 429, 297
Maas, T., Van Winckel, H., Lloyd Evans, T., Nyman, L. Å, Kilkenny, D., Martinez, P., Marang, F., & Van Wyk, F. 2003, A&A, 405, 271
Mastrodemos, N., & Morris, M. 1999, ApJ, 523, 357
Nordhaus, J., & Blackman, E. G. 2006, MNRAS, 370, 2004
Nordhaus, J., Blackman, E. G., & Frank, A. 2007, MNRAS, 367, 599
Olofsson, H., & Nyman, L.-A. 1999, A&A, 347, 194
Sahai, R., Morris, M., Sánchez-Contreras, C., & Claussen, M. 2007, AJ, 134, 2200
Sánchez-Contreras, C., Bujarrabal, V., Castro-Carrizo, A., Alcolea, J., & Sargent, A. 2004, ApJ, 617, 1142
Sault, R. J., Teuben, P. J., & Wright, M. C. H. 1995, in ASP Conf. Ser. 77, Astronomical Data Analysis Software and System IV, ed. R. A. Shaw, H. E. Payne, & J. J. E. Hayes (San Francisco, CA: ASP), 433
Scoville, N. Z., Carlstrom, J. E., Chandler, C. J., Phillips, J. A., Scott, S. L., Tilanus, R. P. J., & Wong, Z. 1993, PASP, 105, 1482
Soker, N. 2006, PASP, 118, 260