JOURNAL OF THE KOREAN ASTRONOMICAL SOCIETY
38: 219 ~ 222, 2005

IMAGING THE CIRCUMSTELLAR ENVELOPES AROUND EVOLVED STARS WITH THE SMA

NAOMI HIRANO, PO-JIAN CHIU, SEBASTIEN MULLER, AND DINH-V-TRUNG
Academia Sinica, Institute of Astronomy and Astrophysics, P.O.Box 23-141, Taipei, 106, Taiwan
E-mail: hirano@asiaa.sinica.edu.tw
(Received February 1, 2005; Accepted March 15, 2005)

ABSTRACT

We present the high-resolution (2″–4″) images of the molecular envelopes surrounding the evolved stars, V Hya, VY CMa, and π^1 Gru observed with the Submillimeter Array. The CO J=2–1 and 3–2 images of the carbon star V Hya show that the circumstellar structure of this star consists of three kinematic components; there is a flattened disk-like envelope that is expanding with a velocity of ~16 km s^{-1}, the second component is the medium-velocity wind having a deprojected velocity of 40–120 km s^{-1} moving along the disk plane, and the third one is the bipolar molecular jet having an extreme velocity of 70–185 km s^{-1}. The axis of this high velocity jet is perpendicular to the plane of the disk-like envelope. We found that the circumstellar structure of the S-star π^1 Gru traced by the CO J=2–1 resembles that of V Hya quite closely; the star is surrounded by the expanding disk-like envelope and is driving the medium-velocity wind along the disk plane. We also obtained the excellent images of VY CMa with the CO and ^{13}CO J=2–1 and SO 6_5–5_4 lines. The maps of three molecular lines show that the envelope has a significant velocity gradient in the east-west direction, suggesting that the envelope surrounding VY CMa is also flattened and expanding along its radial direction. The high-resolution images obtained with the SMA show that some AGB stars are associated with the asymmetric mass loss including the equatorial wind and bipolar jet.

Key words : ISM: individual (V Hya, VY CMa, π^1 Gru) — ISM: jets and outflows — ISM: molecules — stars: AGB and post-AGB

I. INTRODUCTION

One of the most spectacular phenomena in the final stage of low to intermediate mass stars is the metamorphosis of a spherically symmetric asymptotic giant branch (AGB) star into a planetary nebula (PN) with highly asymmetric shape. It is known that most of the AGB stars are surrounded by the spherically symmetric envelope, while more than half of the PNe and proto-PNe show the ring-like, bipolar, or butterfly shapes (e.g., Su, Hrivnak, & Kwok 2001); it is still an open question as to when and how the asymmetry appears and develops. Knapp et al. (1998) surveyed the CO J=2–1 and 3–2 from 45 nearby AGB stars with the single-dish telescope and found that at least one third of their sample showed the lines that are strongly non-parabolic shape. This suggests that the mass loss from the AGB stars is more complex than the spherically symmetric wind expanding at uniform velocity. It is therefore important to study the spatial and velocity structure of the circumstellar envelope around the AGB stars with high angular resolution and examine how the asymmetric structure forms. We have selected the AGB stars which show the non-parabolic CO line profiles and imaged them with high angular resolution using the Submillimeter Array (SMA; Ho et al. 2004)[1]. Here we present the results of V Hya, VY CMa, and π^1 Gru.

II. BIPOLAR OUTFLOW AND DISK-LIKE ENVELOPE AROUND V HYA

V Hya, an evolved star located at 380 pc away from the sun (Knapp, Jorissen, & Young 1997) is a carbon star with a high mass loss. Although the optical properties of V Hya are those of the normal N type carbon star, the envelope surrounding this star shows several peculiar properties. Single-dish molecular line observations have shown that the envelope of V Hya is elongated along the north-south direction with a velocity gradient along its minor axis (e.g. Kahane et al. 1996). Such morphological and kinematic properties are different from those of the typical AGB envelope, which has spherically symmetric shape and uniform expansion. In addition, V Hya is associated with a very fast (> 100 km s^{-1}) outflow that was observed in the optical and infrared spectra (e.g. Sahai & Wannier 1988; Lloyd Evans 1991) and in the CO J=2–1 and 3–2 spectra

---

Proceedings of *the 6th East Asian Meeting of Astronomy*, held at Seoul National University, Korea, from October 18-22, 2004.

[*] The Submillimeter Array is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics, and is funded by the Smithsonian Institution and the Academia Sinica.

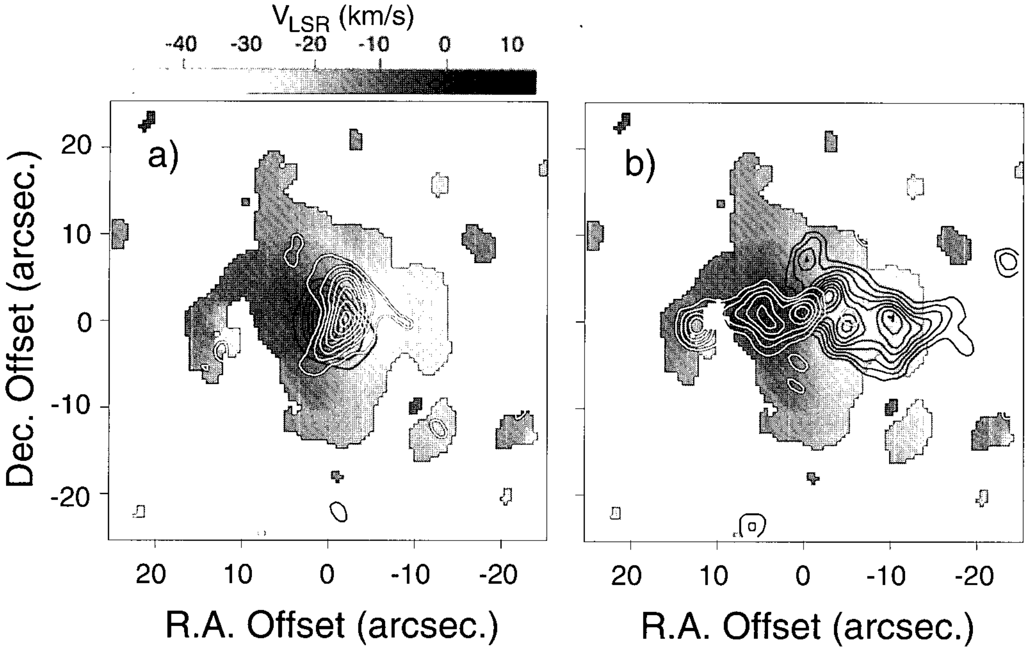

Fig. 2.— Velocity structure of V Hya. Contours of the (a) medium-velocity (±30.0 to 60.0 km s^{-1}) and (b) high-velocity (±60.0 to 162.2 km s^{-1}) redshifted (black contours) and blueshifted (white contours) components of the CO J=2–1 superposed on the intensity-weighted mean velocity map (the 1st moment map) of the low-velocity component (grey scale).

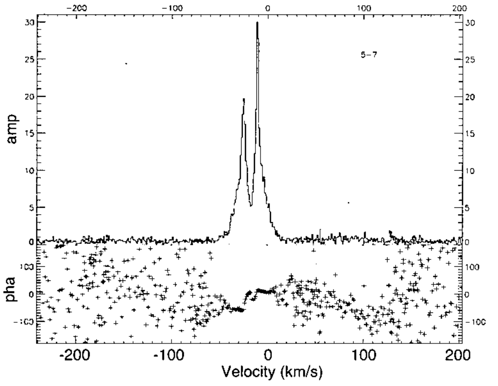

Fig. 1.— The CO J=2–1 spectrum of V Hya observed with one of the SMA baselines.

(Knapp et al. 1997). Knapp et al. (1997) also found that the high-velocity CO gas is bipolar, and proposed that the fast-moving gas is expanding along the east-west direction, which is perpendicular to the major axis of the envelope. However, previous observations did not bring us the detailed structure of the high-velocity outflow and the relation between the high-velocity flow and the slowly expanding envelope.

We have mapped the envelope surrounding V Hya in the CO J=2–1 and 3–2 lines using the five antennas of the SMA during the period from February to May in 2003. The primary-beam size (HPBW) of the 6 m antennas at 230 and 345 GHz were measured to be ~54″ and ~36″, respectively. The synthesized beam had a size of 4.4″×3.1″ at 230 GHz and 2.1″×1.9″ at 345 GHz. Fig. 1 shows the CO J=2–1 spectrum observed with one of the SMA baselines. It is shown that the circumstellar structure of V Hya consists of three kinematic components (Hirano et al. 2004). The CO line profile shows the two spikes having the radial velocity offsets of $\Delta V = \pm 8$ km s^{-1} from $V_{\rm sys} = -17.5$ km s^{-1}. The spatial distribution of this component is elongated along the north-south direction with its approaching part to the west and the receding part to the east of the star (grey scale of Fig. 2), which is consistent with the previous single-dish CO J=2–1 results of Kahane et al. (1996). Such a spatial-kinematic structure can be explained if the CO emission arises from an inclined disk-like envelope expanding along its radial direction. A flattened disk-like structure was also identified by Sahai et al. (2003) based on their interferometric CO J=1–0 observations. Hereafter, we refer to this component as the low-velocity disk. The CO line profile shows strong wings that extends to $\Delta V < \pm 60$ km s^{-1} from the systemic velocity (hereafter referred to as the medium-velocity wind). The medium-velocity wind (black and white contours in Fig. 2a) is spatially compact (~5″–8″) and has a clear bipolarity with the same orientation as that of the low-velocity disk. In addition, the CO emission from V Hya is associated with the extremely high-velocity component with ΔV = ±60–160 km s^{-1}. The detection of these wing components is

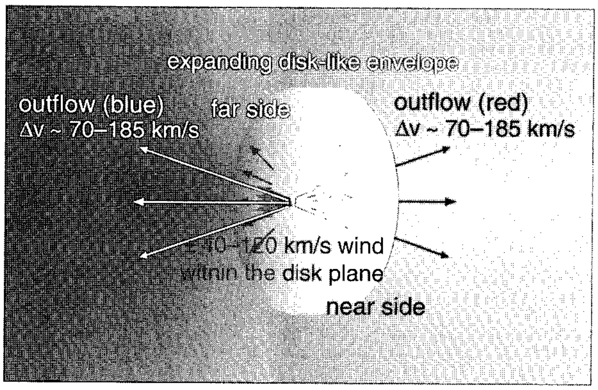

Fig. 3.— Schematic picture of the circumstellar structure of V Hya.

confident because the phases of the visibilities show coherent behavior across the velocity range of ±160 km s^{-1} (see Fig. 1). The high-velocity component (black and white contours in Fig. 2b) is well collimated bipolar with its approaching part in the east and receding part in the west of the star. This orientation is opposite with respect to those of the low- and medium-velocity components, and can be explained if the direction of the high velocity component is perpendicular to the disk plane. Hereafter, we refer to this component as the high-velocity jet.

If we assume that the low-velocity disk is thin, the ratio between the major and minor axes suggests that the disk plane is inclined by ~60° from the line of sight, which is consistent with the the previous estimation of ~70° by Sahai et al. (2003). We find that the gas in the low-velocity disk is moving at almost constant deprojected velocity of 16 km s^{-1}, which is similar to the typical AGB wind velocity. The north-south extent in the CO J=2–1 map suggests that the low-velocity disk has a radius of 5700 AU and a dynamical time scale of 1700 yr. If we assume that the axis of the high velocity jet is perpendicular to the disk plane, the deprojected velocity and the dynamical time scale of the jet are estimated to be 70–185 km s^{-1} and 100–250 yr, respectively.

The nature of the medium-velocity wind is puzzling. Here we present three possible scenarios; 1) the interaction between the low-velocity disk and the high-velocity wind, 2) equatorial mass outflow with higher velocity, or 3) a second bipolar outflow with different axis. In the first and the second scenarios, the direction of the medium-velocity wind is close to the disk plane, and the deprojected velocity of the wind is estimated to be 40–120 km s^{-1}. The dynamical time scale of this medium-velocity wind estimated from the spatial extent of ~5–8″, inclination angle, and the deprojected velocity is 100–400 yr, which is close to the time scale of the high-velocity jet. The third scenario is the interpretation proposed by Kahane et al. (1996), in which the medium-velocity wind came from a bipolar outflow with large opening angle. However, the orientation of the approaching and receding parts of the medium-velocity wind suggests that the axis of this bipolar flow should be close to the plane of the disk. If we take into account the geometry of the low-velocity disk and the high-velocity jet, the third scenario is less likely, although we cannot rule out the possibility that V Hya ejects two orthogonal outflows as in the case of CRL 2688 (Cox et al. 2000). In Figure 3, we show a schematic picture of these three kinematic components based on the scenarios of case 1 or 2.

III. ENVELOPES SURROUNDING THE RED SUPERGIANT VY CMa

VY CMa is known as the most luminous red supergiant (~5×10^5 $L_\odot$) at a distance of 1.5 kpc (Richards et al. 1998). The very high mass loss rate of ~3.5×10^{-4} $M_\odot$ yr^{-1} (Stanek et al. 1995) produces a very thick circumstellar envelope, which completely obscures the central star. We have mapped the envelope of VY CMa using the eight antennas of the SMA. The angular resolution was 4.2″×2.8″. Thanks to the wide coverage of the correlator, strong emission lines of CO J=2–1, ^{13}CO J=2–1 and SO 6_5–5_4 were observed simultaneously. The CO and SO maps show that the envelope has a circular shape with its radius of ~6000 AU. In the CO J=2–1, there is a diffuse component that extends to the NE direction. Although the projected shape of the envelope is close to circular, the velocity structure is different from that of the spherically expanding envelope. There is a significant velocity gradient in the east-west direction, suggesting that the envelope surrounding VY CMa is also flattened and expanding along its radial direction. Recent optical images of VY CMa obtained with Hubble Space Telescope show a one-sided reflection nebula of the size ~5″ (Smith et al. 2001). The spatial-kinematic structure of the molecular envelope and the one-sided reflection nebula suggest that VY CMa has a disk-like component that is slightly inclined from the plane of the sky and a bipolar outflow perpendicular to the disk plane.

IV. FLATTENED ENVELOPE AROUND PI(1) GRU

π^1 Gru is a nearby mass-losing S star at a distance of 153 pc (Perryman et al. 1997). This star is known to be accompanied by a faint main-sequence (G0V) companion separated by 2.7″ (e.g., Proust et al. 1981; Sahai 1992). Previous single-dish CO J=2–1 and 1–0 observations by Sahai (1992) and Knapp, Young, & Crosas (1999) revealed that the circumstellar structure of π^1 Gru traced by the CO emission resembles that of V Hya quite closely. The CO line profiles are double-horned shapes with strong line wings. There is a significant velocity gradient along the north-south direction, which corresponds to the minor axis of the elongated envelope. Furthermore, Knapp et al. (1999) found a fast molecular wind with a projected outflow speed of at least 70 km s^{-1}.

We have observed the CO J=2–1 emission lines from π^1 Gru using the eight antennas of the SMA. Since the declination of this source is -46°, the SMA is the only interferometer that can observe the CO J=2–1 line from this source. The CO J=2–1 map with an angular resolution of 4.0″×2.2″ shows that the molecular envelope of π^1 Gru is elongated along the east-west direction. The size of the envelope is 20″×12″, that corresponds to 3000×1800 AU. The velocity structure seen in the high-resolution map of π^1 Gru is similar to that of V Hya. The low-velocity component that corresponds to the two horns in the line profile having the radial velocity offsets of $\Delta V = \pm 5$ km s^{-1} from $V_{\rm sys}$ = -11.8 km s^{-1} has its approaching part to the south and the receding part to the north of the star. This suggests that π^1 Gru is surrounded by the inclined disk-like envelope expanding along its radial direction. As in the case of V Hya, the higher velocity component ($\Delta V < \pm 25$ km s^{-1}) of π^1 Gru is spatially compact and shows a clear bipolarity with its approaching part to the south and the receding part to the north of the star, which is the same orientation as that of the low-velocity component. Unfortunately, we could not detect the extremely high-velocity component that extends to ±70 km s^{-1} because of the lack of sensitivity.

V. SUMMARY

The high-resolution (2″–4″) images of V Hya, VY CMa and π^1 Gru obtained with the SMA show that these three evolved stars are surrounded by the flattened disk-like envelopes. Although the origin of equatorial mass loss and the nature of the medium-velocity wind observed in V Hya and π^1 Gru are not understood well, it is certain that such an asymmetric mass loss at the late stage of AGB phase plays an important role in forming the PNe with highly asymmetric shapes.

ACKNOWLEDGEMENTS

We wish to thank all the SMA staff in Hawaii, Cambridge, and Taipei for their enthusiastic help during these observations.

REFERENCES

Cox, P., et al., 2000, A&A, 353, L25

Hirano, N., Shinnaga, H., Dinh-V-Trung, Fong, D., Keto, E, Patel, N., Qi, C., Young, K., Zhang, Q., & Zhao, J., 2004, ApJ, 616, L43

Ho, P. T. P., Moran, J. M., & Lo, K. Y., 2004, ApJ, 616, L1

Kahane, C., Audinos, P., Barnbaum, C., & Morris, M., 1996, A&A, 314, 871

Knapp, G. R., Jorissen, A., & Young, K., 1997, A&A, 326, 318

Knapp, G. R., Young, K., & Crosas, M., 1999, A&A, 346, 175

Knapp, G. R., Young, K., Lee, E., & Jorissen, A., 1998, ApJS, 117, 209

Lloyd Evans, T., 1991, MNRAS, 248, 479

Perryman, M. A. C., Lindegren, L., Kovalevsky, J., et al., 1997, A&A, 323, L49

Proust, D., Ochsenbein, F., & Petterson, B. R., 1981, A&AS, 44, 179

Richards, A. M. S, Yates, J. A., & Cohen, R. J., 1998, MNRAS299, 319

Sahai, R. 1992, A&A, 253, L33

Sahai, R., & Wannier, P. G., 1988, A&A, 201, L9

Sahai, R., Morris, M., Knapp, G.R., Young, K., & Barnbaum, C., 2003, Nature, 426, 261

Smith, N., Humphreys, R. M., Davidson, K., Gehrz, R. D., Schuster, M. T., & Krautter, J., 2001, AJ121, 1111

Stanek, K. Z., Knapp, G. R., Young, K., Phillips, T. G., 1995, ApJS100, 169

Su, K. Y. L., Hrivnak, B. J., & Kwok, S., 2001, AJ, 122, 1525