

V HYDRAE: A CARBON STAR IN TRANSFORMATION TO A BIPOLAR NEBULA

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ABSTRACT

It is found that the profiles of CO $J = 1-0$ at 2.6 mm observed in the cool carbon star V Hydrae show marked asymmetry and noticeable spatial variations, while the profiles of HCN $J = 1-0$ observed at the same time show no marked asymmetry. The two strong-velocity components in CO profile could be spatially resolved, indicating that the strong CO emission in V Hya originates in a region of bipolar geometry. The CO profiles also show temporal variation with time scale less than 1 yr, both in intensity and in shape, and such a time variation may indicate the importance of radiative excitation which can be time-dependent due to variability of the central star. Also, optical observations of V Hya can consistently be understood by a bipolar-disk model. Thus, V Hya may represent an early stage of the development of a bipolar nebula.

Subject headings: molecular processes — stars: carbon — stars: circumstellar shells — stars: mass loss

I. INTRODUCTION

It is now well recognized that the molecular spectroscopy in the radio frequency domain could be an important tool for our understanding of outer envelopes and mass-loss in cool luminous stars. Especially the mass-loss rate can be determined with better accuracy than by other methods from CO thermal emission (for example, Morris 1980; Olofsson 1985), and the mass-loss rate has been determined for a large sample of red giant stars (e.g., Knapp and Morris 1985). However, details of the spatial and velocity structures of the molecular envelope are still obscure, and we have initiated a project to study the physical structure of the outer envelope of red giant stars by using the 45 m telescope of Nobeyama Radio Observatory (NRO).⁶ During this project, we noticed that a classical carbon star V Hydrae has a highly asymmetric CO profile whose shape showed marked spatial variations. It is to be remembered that V Hya is one of a few classical carbon stars for which CO radio emission has been detected at an early time (Zuckerman *et al.* 1977). Further, a narrow emission line of CO was observed by Zuckerman and Dyck (1986), who suggested it to be a weak CO maser. After we first noticed the peculiarity of V Hya in 1985, we have made detailed observations during 3 yr, and we now realize that the easily observable strong emission of CO from this star may be due to anomalous excitation in an inhomogeneous outer envelope having bipolar structure.

II. OBSERVATIONS

The observations have been made in four observing runs between 1985 April and 1987 March by using the NRO 45 m telescope. The telescope beam width (HPBW) was $17'' \pm 1''$ at 115.3 GHz (CO $J = 1-0$). The antenna beam efficiency at 115.3 GHz was 0.34 before the summer of 1985 (Hasegawa 1987) but

improved to 0.45 ± 0.05 afterward. In 1986 and 1987, HCN $J = 1-0$ at 88.6 GHz has also been observed simultaneously; the telescope beamwidth was $24'' \pm 1''$, and the beam efficiency was 0.68 ± 0.05 (Inoue *et al.* 1987). All the observations have been done by the Acousto-Optical-Spectrometer (AOS) of NRO; it was operated both in wide-band and high-resolution modes, which give spectral resolution of 250 kHz (0.65 km s^{-1} at 115.3 GHz; 0.85 km s^{-1} at 88.6 GHz) and 37 kHz (0.097 km s^{-1} at 115.3 GHz; 0.125 km s^{-1} at 88.6 GHz), respectively, and each has eight arrays with 2000 channels. The intensity calibration has been done by the chopper-wheel method that measures temperature difference between the sky and a laboratory source of 293 K (for details, see Ulich and Haas 1976). The accuracy of the calibration is within 10% under normal observing conditions, and the system noise temperature varies between 500 and 1500 K depending on the sky condition (Inoue *et al.* 1987).

In 1985 April, we found marked spatial variation of asymmetric CO profile by a five-point cross map with spatial separation of $10''$ in R.A. and decl. centered on V Hya. This result was confirmed by extended mapping observations with 15 grid points in 1985 May. We have done a more detailed mapping observation with 25 grid points at spatial mesh of $15''$ in 1986 April and the major part of the resulting map is reproduced in Figure 1 (there is almost no signal in the part not shown). At the same time, HCN $J = 1-0$ at 88.6 GHz was detected, for the first time in V Hya, in another array of the AOS; the peak of the main-beam brightness temperature of HCN is found to be $T_B \approx 0.55 \text{ K}$ in co-added spectrum at (0, 0) position, but the other mapping data are too weak to be reproduced here.

In 1987 March, we again returned to the five-point cross mapping, with roughly one beamwidth offsets ($15''$), to obtain a spectrum of high S/N ratio. Unusually fine sky conditions with almost no wind permitted us to follow this southern star for more than 3 hr, and the resulting CO data are shown in Figure 2a. The tracking accuracy during this time has been checked and proved to be excellent (better than a few arcsec) by inspection of each 40 minutes integration separately before the total integration has been done. We have also observed HCN $J = 1-0$ simultaneously with CO, and the result is shown in Figure 2b.

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⁶ Nobeyama Radio Observatory (NRO), a branch of the Tokyo Astronomical Observatory, the University of Tokyo, is a cosmic radio observing facility open for outside users. This work was carried out under the common use observation program at NRO.

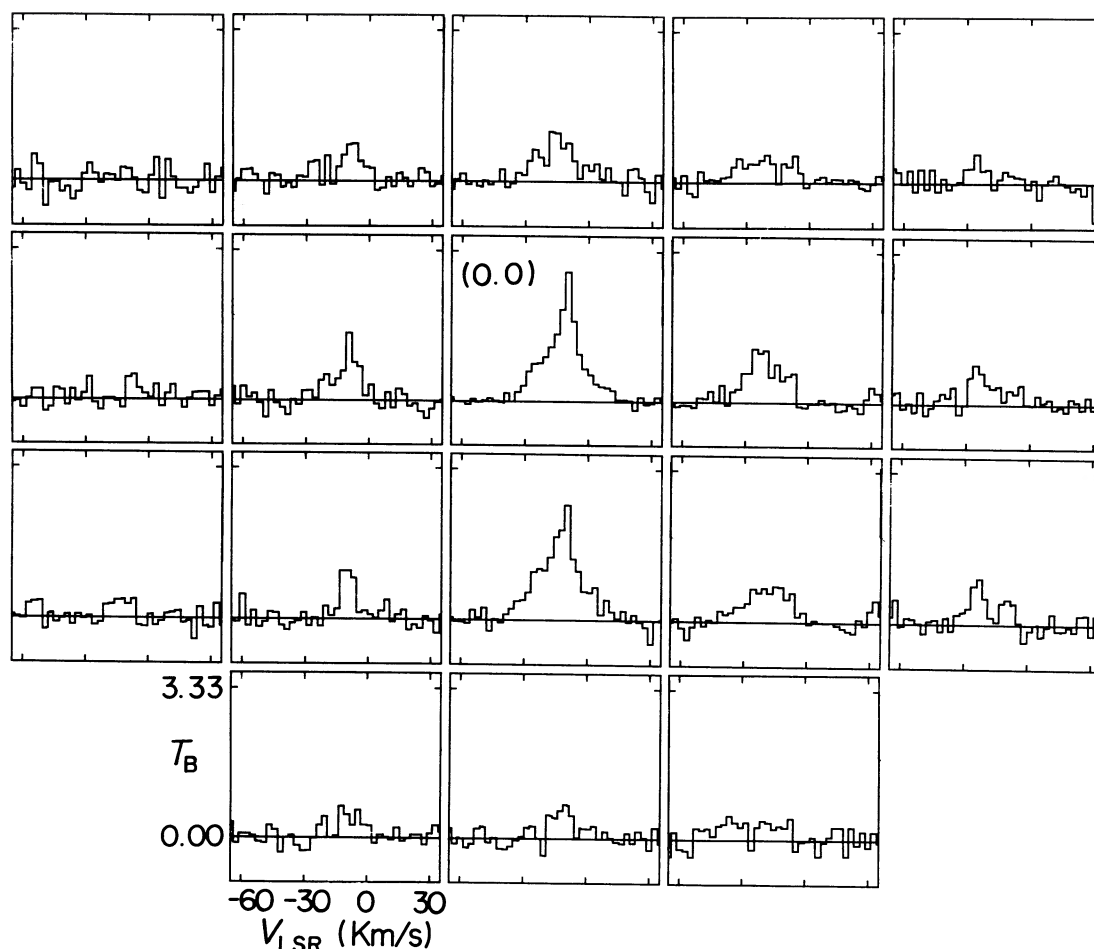


FIG. 1.—Mapping data of CO $J = 1-0$ (115271.204 MHz) toward V Hya observed on 1986 April 10–12: The mapping is based on five scannings with spatial mesh of $15''$ and each scan included at least one on-source position, which was used to confirm the pointing of each scan, in addition to five different points. The results gave a 25 point map on a diamond grid with E–W and S–N as diagonals. Here, the on-source data of all the scans are co-added and the spectrum at the (0, 0) position has a smaller noise level ($\sigma_{\text{rms}} \approx 0.09$ K) than those at other positions ($\sigma_{\text{rms}} \approx 0.21$ K). The center of each panel refers to the relative telescope offset position with respect to the source position, $\alpha = 10^{\text{h}}49^{\text{m}}11^{\text{s}}.3$; $\delta = -20^{\circ}59'4''.9$ (1950.0), which corresponds to the middle of the on-source spectrum marked by (0, 0), and CO profiles are reproduced for each $15''$ offset. The ordinate of each panel is the main beam brightness temperature T_B , and the abscissa is the radial velocity with respect to the local standard of rest, V_{LSR} , with scales shown in a lower left panel. The velocity resolution is reduced to 5.2 km s^{-1} by binning eight channels of an AOS wide-band array. The telescope pointing in this observation may be wrong and the true center may be to the south by several arcsec from the (0, 0) position in the figure. North is up, and east is left.

III. ANALYSIS

The repeated observations mentioned above revealed that the CO profiles of V Hya show marked spatial variation: For example, the profile observed at the east position shows narrow asymmetric emission peaked at $V_{\text{LSR}} = -9 \text{ km s}^{-1}$, while that at the west position is dominated by another component peaked at $V_{\text{LSR}} = -25 \text{ km s}^{-1}$ in 1987 (Fig. 2a). On the other hand, the profile at center consists of two emission components at $V_{\text{LSR}} = -9$ (red component) and -25 km s^{-1} (blue component) in 1987. Thus each of the two velocity components is spatially resolved by our observations. The profiles observed in 1986 shown in Figure 1 (and also of 1985 not shown here) show essentially the same spatial and velocity structures. However, the on-source spectrum of 1986 is apparently asymmetric with a single emission peak at $V_{\text{LSR}} = -9 \text{ km s}^{-1}$, and this change in intensity of the blue component relative to the red one between 1986 and 1987 is significantly larger than the rms noise levels of 0.09 K (on-source spectra of Figs. 1 and 2a). Also, observed maximum intensities, which always happen to

be the red component, are 3.95 K (1985 April 5), 2.88 K (1986 April 10–12), and 1.87 K (1987 March 30) with rms noise levels of 0.57 K, 0.21 K, and 0.09 K, respectively. Thus, the maximum brightness temperature has decreased during 3 yr, and this result is significant at twice the rms noise levels. Certainly, it is more difficult to discuss the variation of absolute intensity because we have not checked the intensity calibration by observing standard sources. Furthermore, small-scale structure in the source and possible pointing error may translate into apparent spectral variations. However, our five-point cross mapping could provide a check on pointing to some extent, and inspection of the mapping data suggests that the change of the profiles noted above cannot be due to pointing error alone. Thus, although further detailed examination should certainly be necessary, we tentatively conclude that the shape of CO profiles and possibly CO line intensity may have changed with time.

Despite the possible time variations in line shape as well as in line intensity, the basic space-velocity structure of the CO profile remains unchanged during 3 yr in that the two major

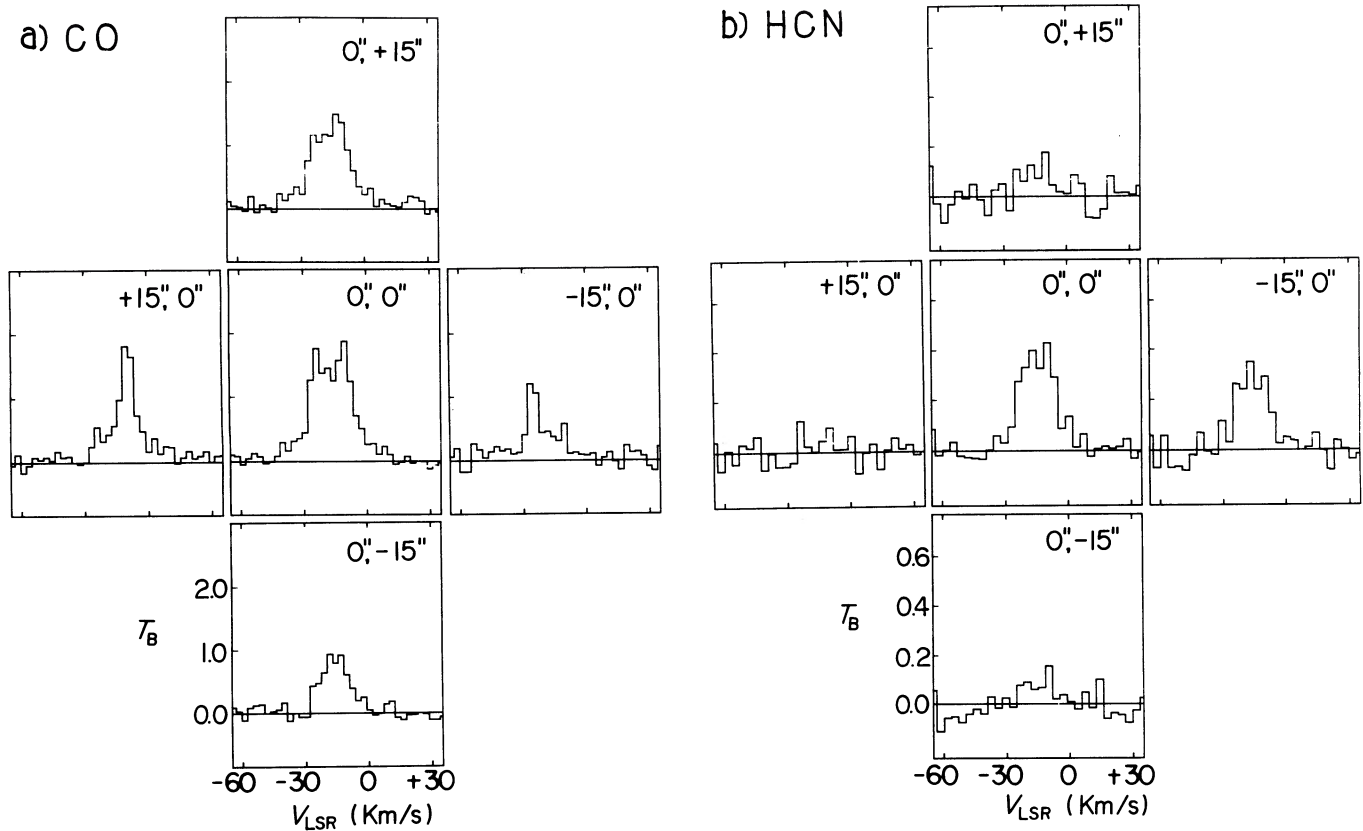


FIG. 2.—(a) Five-point cross map of CO $J = 1-0$ centered on V Hya with offsets of $15''$, observed on 1987 March 30 with total integration time of 190 minute ($\sigma_{\text{rms}} \approx 0.09$ K). The on-source spectrum is the sum of E-W and S-N scans. The velocity resolution is 5.2 km s^{-1} and see the legend to Fig. 1 for other details. (b) Same as (a), but for HCN $J = 1-0$ ($F = 1-1$; 88630.4157 MHz , $F = 2-1$; 88631.8473 MHz , $F = 0-1$; 88633.9360 MHz) observed simultaneously with CO. The velocity scale refers to the $F = 2-1$ component and the velocity resolution is 6.8 km s^{-1} ($\sigma_{\text{rms}} \approx 0.09$ K). Inspection of this result reveals that the true center of HCN envelope may be to the west by several arcsec from the center of the telescope pointing. This does not imply that the true center of the CO envelope is also shifted by the same amount, since different front ends see slightly different parts of the sky. It is confirmed that the center of the HCN envelope is shifted to the west by several arcsec relative to the center of CO envelope, by observing IRC +10216 just after V Hya by the same telescope setting. Thus, the telescope may have been correctly pointed to the true center of CO envelope of V Hya.

velocity components at $V_{\text{LSR}} = -9$ and -25 km s^{-1} dominate in the east and west portions, respectively. This fact may imply that the matter distribution and velocity structure did not change but only the excitation of CO gas may have changed with the time scale of less than 1 yr. This is what can be expected from the fact that the expansion time scale of the envelope is more than 3000 yr if we assume the distance of 1.4 kpc based on $M_V = -4.1$ for V Hya (Olson and Richer 1975), and 1 yr is too short to give any appreciable change in the basic structure of the gas flow. On the other hand, it is known that CO can be excited by the near-infrared photons (Morris 1980), which may be changing due to stellar variability.

Although the strong CO features show large asymmetry, it is to be noted that a weak but broad emission extends roughly from $V_{\text{LSR}} = -45 \text{ km s}^{-1}$ to $+15 \text{ km s}^{-1}$ (on-source spectra of Figs. 1 and 2a). This suggests that the stellar velocity is about $V_{\text{LSR}}^* = -15 \text{ km s}^{-1}$, and the CO envelope is expanding at a velocity of about 30 km s^{-1} . This CO flow velocity is unusually high for classical carbon stars, which generally show a CO expansion velocity of $10\text{--}15 \text{ km s}^{-1}$ (e.g., Knapp and Morris 1985; Zuckerman and Dyck 1986). Also, HCN emission is visible roughly between $V_{\text{LSR}} = -40 \text{ km s}^{-1}$ and $+10 \text{ km s}^{-1}$. Thus, HCN also indicates a stellar velocity of $V_{\text{LSR}}^* = -15 \text{ km s}^{-1}$, but the expansion velocity of the HCN envelope is only about 25 km s^{-1} . We assume a stellar velocity of $V_{\text{LSR}}^* = -15 \text{ km s}^{-1}$ (accuracy of about 1 km s^{-1}) in the following analysis.

Thus, if we assume the outflow velocity of CO envelope to be $V_{\text{exp}} = 30 \text{ km s}^{-1}$, the east lobe that gives rise to the emission at $V_{\text{LSR}} = -9 \text{ km s}^{-1}$ ($V_{\parallel} = +6 \text{ km s}^{-1}$, where $V_{\parallel}$ is the line-of-sight velocity with respect to the stellar velocity) should be expelled to the backside of the star with angle $\theta_1 = \sin^{-1}(6/30) = 12^\circ$ to the plane of the sky, while the west lobe with $V_{\text{LSR}} = -25 \text{ km s}^{-1}$ ($V_{\parallel} = -10 \text{ km s}^{-1}$) to the near side of the star with $\theta_2 = \sin^{-1}(10/30) = 20^\circ$. The cone angle $\Delta\theta$ (in the plane defined by the observer and the R.A. axis) may be estimated from the width of the emission component, whose FWHM measured above the background weak emission is typically 6 km s^{-1} . For example, $\Delta\theta_1 = 6/V_{\text{exp}} \sin(12^\circ) \approx 55^\circ$ for the east lobe, and this is a rough upper limit to the cone angle because of the possible internal motion (turbulence) in the expanding envelope.

IV. DISCUSSION

The result outlined above suggests that the strong CO emission from V Hya is originating from the regions of bipolar geometry. In this connection, it is to be noted that V Hya has a CO spectrum somewhat similar to that of the peculiar OH/IR star OH 231.8+4.2 (Morris *et al.* 1987), which is in fact a bipolar optical object (Reipurth 1987). Also, the polarization of the visible light for V Hya is as large as 3% in blue, and the position angle varies between $+2^\circ$ and $+7^\circ$ (Kruszewski, Gehrels, and Serkowski 1968). Then, the direction of polariz-

ation is nearly perpendicular to the axis of the bipolar lobes, and this is the same sense as found in other bipolar objects such as CRL 2688 (Ney *et al.* 1976). Thus, available observations are consistent with a bipolar-disk model.

In connection with the possible presence of a dust torus, it is interesting to remember that V Hya is a variable star with overlapping periods (Mayall 1965): In addition to a periodicity of 533 days with amplitude of about 1.5 mag in visual light, this semiregular variable star also shows a longer period of 6500 days with deep minimum. Furthermore, the presence of another superposed period of 20–30 days is suspected. The periodicity of several hundred days may be related to the intrinsic property of the envelope of the evolved stars, but that of several thousand days is more difficult to understand. One possibility is that the period of 6500 days may be related to the long secondary period known in red supergiant stars (for details, see Stothers and Leung 1971), and another possibility may be to assume a binarity, which is also thought to be an origin of bipolar flow (Morris 1981). A binary hypothesis may be consistent with the deep minima in the observed light curve over 80 yr (Mayall 1965), from which we can also infer that all of our radio observations have been done well outside of the deep minimum phase.

Now, it is interesting that Zuckerman and Dyck (1986) found a sharp emission of CO in V Hya at $V_{\text{LSR}} = -10 \text{ km s}^{-1}$ in 1985 June, and they suggested it to be a weak CO maser. Their peak antenna temperature of about 1 K observed by NRAO 12 m telescope may correspond to more than 10 K if observed by the NRO 45 m telescope, since the maser emission may be well localized. However, CO emissions observed by us may no longer be a maser since they are not so intense and also they originate from an extended region that can be spatially resolved by our observations as noted before. On the other hand, a possibility of a weak maser in CO has previously been predicted by Morris (1980), and it can be possible that the population inversion could be realized as an extreme case of an anomalous excitation in a restricted region of the bipolar flow. Anyhow, more detailed analysis on molecular excitation, on the basis of a realistic model of the outer envelope incorpo-

rating the bipolar-disk structure, should be needed before we could have better understanding on excitation of CO in V Hya.

Finally, it is to be remembered that HCN observed simultaneously with CO is much weaker than CO and shows little evidence of asymmetric flow. As can be inferred from Figures 2a and 2b, the HCN envelope should be more compact than the CO envelope: The radiation field may not be strong enough to excite HCN transition in the outer region, or HCN may already be dissociated in the outer part of the molecular envelope. Thus, HCN provides further constraints on the physical structure, radiation field, and chemistry of the molecular envelope around V Hya.

V. CONCLUDING REMARKS

Spatially resolved spectra of CO $J = 1-0$ at various times in the carbon star V Hya revealed that the outer envelope of this classical carbon star clearly shows bipolar structure. Thus, V Hya can now be added to the list of the bipolar nebulae at the late stage of stellar evolution (Morris 1981), and there is an interesting possibility that V Hya represents an early stage of the development of the bipolar nebula. It is to be noted that the CO spectrum observed in V Hya is quite rare among the known CO spectra of stellar sources, and it should be associated with an event of very short time scale during the rapid evolution in the asymptotic red giant branch phase. Such an episode, however, may play an important role in the latest stage of stellar evolution from red giants to planetary nebulae (e.g., Zuckerman *et al.* 1976, 1978; Lo and Bechis 1976). Thus there is no doubt that more detailed observations of V Hya, extended to the phase of deep minimum to be expected around 1995, should be necessary at all spectral regions.

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