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THE BIPOLAR OUTFLOW FROM THE ROTATING CARBON STAR, V HYDRAE

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ABSTRACT

We have obtained a high-resolution optical spectrum of the mass-losing red giant carbon star, V Hya, and we have mapped the ^{12}CO ($J = 1$–0) millimeter emission in the circumstellar envelope around this star. We find that the CO emission is extended, clearly anisotropic and can be interpreted as the superposition of an isotropic emission with that of a bipolar flow. The optical spectrum of the photosphere suggests that this star is rotating with $v \sin i$ between 10 and 20 km s^{-1}. We interpret these data, together, to suggest that the bipolar nature of the outflow results from the flattening of the star induced by its rapid rotation.

Subject headings: stars: carbon — stars: circumstellar shells — stars: mass loss — stars: rotation

I. INTRODUCTION

Carbon stars typically are losing mass at $> 10^{-7}$ $M_{\odot}$ yr^{-1} (Claussen *et al.* 1987). In the best model to explain these outflows, pulsations levitate matter above the photosphere, the gas cools and grains form, and then matter is driven away from the star by radiation force (see Jura 1986). This picture, however, does not obviously explain anisotropies that are observed in many outflows (see, for example, Morris 1981, 1987). Here, we provide evidence that V Hya has a bipolar outflow that is probably induced by asymmetries in the mass-losing star caused by its rotation.

II. OPTICAL OBSERVATIONS

The optical observations were obtained on 1987 May 18 and 19 U.T. using the 120 inch (3 m) Shane telescope at Lick Observatory. We used the 800 × 800 CCD detector at coudé. The 40 inch (1 m) camera with a 900 lines mm^{-1} grating in second order yielded a dispersion of 0.073 Å $pixel^{-1}$ or 4.8 Å mm^{-1}. The spectral resolution was 0.16 Å. An OG 515 filter blocked unwanted orders, transmitting 1% blueward of 5000 Å. Our high S/N, high-dispersion spectra span 56 Å with the central wavelength at 7462 Å.

The spectrum of V Hya is striking in that it displays broadened absorption lines. A remarkable feature of carbon stars is the strong similarity of their optical spectra. We have exploited the similar nature of carbon star spectra to estimate the rotation velocity of V Hya by comparing it with other carbon stars.

We chose as "templates" the six other carbon stars observed during the same period as V Hya. Since the placement of the continuum is difficult to estimate, all the spectra were normalized so the area under each spectrum, from 7434 Å to 7492 Å, was the same for all stars. The templates were broadened by convolving the spectra with a rotation profile (Gray 1976) sequentially from $v \sin i = 1$–30 km s^{-1} (see Fig. 1), where i is the view angle of the rotation axis and v is the equatorial velocity. We estimated the best $v \sin i$ fit of each template to V Hya both visually and with a simple least-squares fit. The agreement between both estimates is of the order of 2 km s^{-1}. Table 1 lists the best fit of each template to V Hya: the span in rotation velocity is from 9 to 19 km s^{-1}.

The range in estimated $v \sin i$ might be due to a number of causes. Although the six template spectra demonstrate strong similarity to each other, there are differences in the ratios of line strengths which might affect the fit. Also, if the standard star is rotating or for some other reason has broadened lines, we would fit a smaller $v \sin i$ to V Hya than with unbroadened template. We estimate $v \sin i$ for V Hya to be 15 ± 5 km s^{-1}.

This rapid rotation is surprising. If we assume simple conservation of angular momentum from the main sequence to red giant expansion, then an observed $v \sin i$ greater than 2 km s^{-1} would exceed the break-up velocity for the star in its main-sequence phase. The most plausible explanation that we have for the rapid rotation of V Hya is that it was spun up by a close companion, one that is perhaps now incorporated into the envelope of this red giant, when V Hya expanded to or when it actually reached its current radius (see Webbink 1976; Morris 1981). This is then similar to the model for FK Comae stars proposed by Bopp and Stencel (1981). We cannot rule out that the observed line broadening in V Hya is due to macroturbulence. However, the combination of both unusual and distinctive optical and radio spectra, together, points toward a single interpretation. The most obvious and straightforward model is that the star is rotating rapidly and therefore losing mass in a bipolar rather than spherically symmetric flow.

III. RADIO OBSERVATIONS

V Hya is a classical N-type carbon star, first seen in ^{12}CO ($J = 1$–0) emission in 1976 June (Zuckerman *et al.* 1977). It was reobserved in 1985 June (Zuckerman and Dyck 1986), and it displayed a narrow emission feature superposed on a characteristic broad stellar profile. This spike was not present on the 1976 spectrum and was interpreted as a CO maser emission.

To check this interpretation, we observed V Hya in ^{12}CO (1–0) emission with the IRAM 30 m telescope on 1987 June 29 to 1987 July 3. The telescope equipment has been described in detail by Baars *et al.* (1987). The telescope was equipped with a Schottky receiver (DSB temperature of 300 K). The beam-

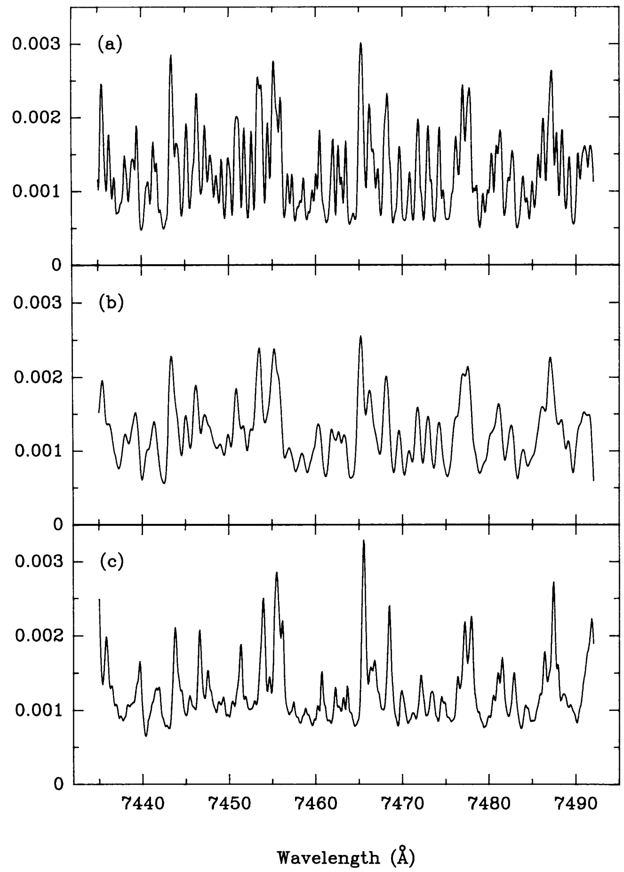

FIG. 1.—The normalized absorption-line spectrum of a template star, U Hya, in (*a*). The same spectrum broadened by a rotation velocity of 16 km s^{-1} (see text) in (*b*). The normalized absorption-line spectrum of V Hya in (*c*).

width was measured to be 21″ at 115 GHz, and the pointing was frequently checked and found to be accurate within 3″. The backend consisted of 256 channels, each 1 MHz wide. The observations were made in position-switching mode with a reference point 500″ east from the star position. The antenna temperature scale was calibrated every 20 minutes or so by successively observing a cold load, a room-temperature load, and the sky. The atmospheric opacity at the zenith was typically 0.25–0.35. The temperatures reported in Figure 2, denoted $T_A{}^*$, are single-sideband antenna temperatures reported above atmosphere. The brightness temperatures T_B are derived from the antenna temperatures by $T_B = T_A{}^*/\eta$, where the factor η is the ratio of the main beam to forward beam efficiencies and is measured to be 0.70.

We observed 14 positions with a spacing of 20″, i.e., 1.0×10^{17} cm for a distance to V Hya of 340 pc (Claussen *et al.* 1987). The $^{12}CO(1–0)$ emission extends at least 20″ in all four directions from the central position. A striking feature is the drastic change in line shapes from one beam to the other. The central spectrum presents a shape similar to that observed by Zuckerman and Dyck: a broad emission, typical of circumstellar envelopes, centered at a velocity of -17 km s^{-1} with a strong spike on the red side (at a velocity of -9 km s^{-1}) and a smaller one on the blue side (at -24.7 km s^{-1}). Furthermore, with the high signal-to-noise ratio of our spectrum, two wings are clearly detected. Along the declination axis, the lines are broad- and flat-topped, and wings (at least one of them) are also present. In contrast, 20″ west and east from the central position, the lines are much narrower. The western one peaks at the same velocity as the central blue spike, and the eastern one corresponds to the red spike velocity. Both lines present a weak wing. This extension of the red spike emission rules out its interpretation as due to maser emission. Its absence on the earliest spectrum (Zuckerman *et al.* 1977) might be explained by a slight difference in pointing and/or insufficient signal to noise ratio.

Three gas components can be defined: the circumstellar envelope (-24.7 km $s^{-1} < V_{LSR} < -9.1$ km s^{-1}), the red flow (-9.1 km $s^{-1} \leq V_{LSR} \leq 20$ km s^{-1}), and the blue flow (-40 km $s^{-1} \leq V_{LSR} \leq -24.7$ km s^{-1}). The velocity integrated emissions of these three components are plotted in Figures 3*a* and 3*b*. The envelope is roughly circular. The displacement between the blue and the red lobes' centers is about 15″. The blue lobe is somewhat elongated along the right ascension axis ($R_{max}/R_{min} = 1.3$), and the red lobe is more circular. Whether these low collimation factors are intrinsic or result from projection effects (bipolar flow seen almost face-on) is an open question, but it can be noticed that most bipolar flows observed in the molecular clouds present low collimation factors (Lada 1985). As both red and blue wings are present on the central profile, the opening angle θ of the bipolar flow must be larger than the view angle i of the flow axis. Furthermore, emission from the front cone is entirely blueshifted, while the far cone is entirely redshifted. This means that $\theta + i \leq \pi/2$. As the disruption limit for the equatorial velocity of the star is about 30 km s^{-1}, i cannot be much smaller than 30° and θ is the range 30°–60°.

Several authors have suggested that bipolarity in circumstellar envelopes could be due to the rotation of the progenitor (Phillips and Reay 1977; Mufson and Liszt 1975). Pascoli (1987) has argued that realistic stellar rotation velocities for evolved red giants are far too low to create an effective anisotropy of the outflow. Such an argument does not apply to V Hya if the observed optical line broadening is due to rotation. Other mechanisms cannot be ruled out, but the simplest and most straightforward interpretation of our observations is that we are witnessing an anisotropic mass outflow due to the star's rotation.

TABLE 1

LEAST-SQUARES FIT

Template	$v \sin i$ (km s^{-1})
U Hya	16
V CrB	12
X Cnc	13
V Oph	9
T Cnc	14
Y CVn	19

IV. CONCLUSIONS

With our data, we reach several important conclusions.

1. The optical spectrum of V Hya is broadened compared to other carbon stars, and this suggests that it is rotating with $v \sin i$ between 10 km s^{-1} and 20 km s^{-1}.

2. The radio map of the circumstellar envelope around

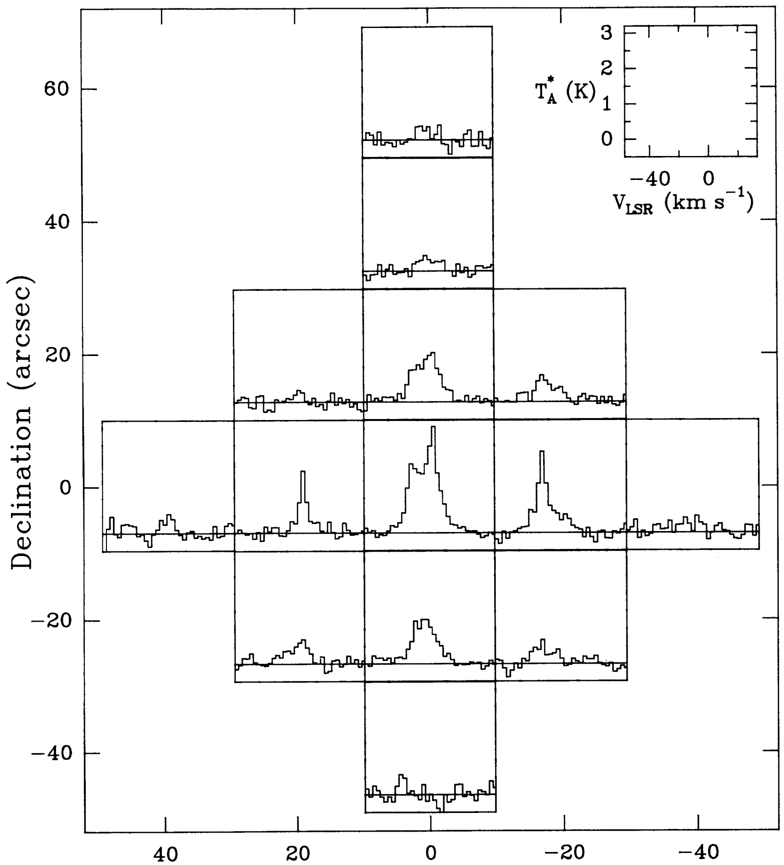

FIG. 2

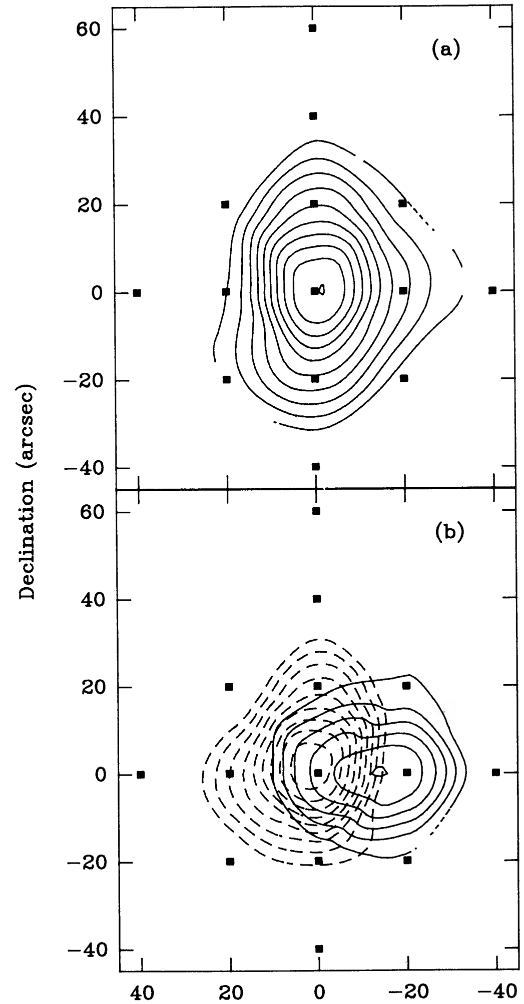

FIG. 3

FIG. 2.—The ^{12}CO (1–0) spectra observed toward V Hya. The coordinates of the (0, 0) position are those of the star: $\alpha(1950) = 10^h49^m11\overset{s}{.}3$ and $\delta(1950) = -20°59'05''$. The velocity resolution is 2.6 km s^{-1}. First-degree polynomials have been subtracted from the spectra.

FIG. 3.—Maps of the ^{12}CO(1–0) integrated brightness temperature over three velocity ranges. (*a*) shows the central velocity component ("envelope"): -24.7 km s^{-1} $< V_{LSR} < -9.1$ km s^{-1}. The first contour is 9.0 K km s^{-1}, and the contour interval is 4.0 K km s^{-1}. The black squares represent the observed positions. (*b*) shows the high-velocity component ("red wing") in dashed lines: -9.1 km s^{-1} $\leq V_{LSR} \leq 20$ km s^{-1} and the low-velocity component ("blue wing") in solid lines: -40 km s^{-1} $\leq V_{LSR} \leq -24.7$ km s^{-1}. In both cases the lowest contour is 7.0 K km s^{-1}. The observed positions are indicated by black squares.

V Hya clearly is anisotropic and presents a bipolar component.

3. It is plausible that the anisotropy in the outflow from V Hya results from the flattening produced by the rotation of the star.

4. The relatively rapid rotation of V Hya probably results from having been spun up by a close companion (which may now be inside V Hya) during the time the main-sequence progenitor was expanding to or at its current radius.

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