Astron. Astrophys. 351, 97–102 (1999)

ASTRONOMY
AND
ASTROPHYSICS

The light curve and evolutionary status of the carbon star V Hya

G.R. Knapp[1], S.I. Dobrovolsky[1], Z. Ivezić[1], K. Young[2], M. Crosas[2], J.A. Mattei[3], and M.P. Rupen[4]

[1] Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA (gk, sid, ivezic@astro.princeton.edu)
[2] Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA (rtm, mcrosas@dolson.harvard.edu)
[3] American Association of Variable Star Observers, 25 Birch St., Cambridge, MA 02128-1205, USA (jmattei@aavso.org)
[4] National Radio Astronomy Observatory, P.O. Box 0, 1003 Lopezville Rd., Socorro, NM 87801, USA (mrupen@nrao.edu)

Received 15 December 1998 / Accepted 1 July 1999

Abstract. V Hya, an evolved carbon star with a complex circumstellar envelope, has two variability periods, $530^{\rm d}$ and $6000^{\rm d}$ (17 years). We analyze recent light curve data and show that both variations have been present for at least 100 years and have been regular over this time. The $530^{\rm d}$ period and its $1.5^{\rm m}$–$2^{\rm m}$ amplitude show that V Hya is a Mira variable. We suggest that the star is in a binary system (as also suspected from the structure of the circumstellar envelope) and that the 17-year variation is due to extinction by circumstellar dust orbiting with the companion. The properties of the envelope found from molecular line observations: the fast molecular wind, the relatively small size of the dense circumstellar envelope, and the high mass loss rate, all suggest that V Hya has entered its 'superwind' phase. However, its spectral type, period, colors, and lack of ionizing radiation show that the star is still on the AGB. These properties add to the evidence that the complex structures of many planetary nebulae, including fast stellar winds, originate during the final phases of mass loss on the AGB.

Key words: stars: mass-loss – stars: AGB and post-AGB – radio lines: stars

1. Introduction

V Hya is a cool evolved N type carbon star with several unusual properties, including: (1) two variability periods, of about 530 and 6000 days (Mayall 1965); (2) possible shock-excited forbidden-line emission similar to that seen from Herbig-Haro objects (Lloyd Evans 1991); (3) continuum emission at radio wavelengths far in excess of the expected photospheric flux (Luttermoser & Brown 1992); (4) a circumstellar envelope which has a flattened or disk-like shape (Tsuji et al. 1988; Kahane et al. 1988; Kahane et al. 1996); and (5) a 200 $\rm km\ s^{-1}$, possibly bipolar, wind seen in CO(v = 0–1) absorption (Sahai & Wannier 1988), in KI absorption and emission (Plez & Lambert 1994), in optical forbidden-line emission (Lloyd Evans 1991) and in CO millimeter-wavelength spectral line emission (Knapp et al. 1997, hereafter Paper I). Because V Hya is one of only two known evolved stars with a fast molecular wind which still has the infrared colors of an AGB star (the other being Π^1 Gru), it may be in the very earliest stages of evolution away from the AGB.

Send offprint requests to: G.R. Knapp

Table 1. Basic properties of V Hya

Spectral Type	N:C7,5
Variable Type	Mira
Distance	500 pc
$\rm T_{eff}$	2650 K
$\rm L_{bol}$	$1.4 \times 10^4\ \rm L_\odot$
$\rm R_\star$	3.8×10^{13} cm
$\rm P_1$: period	$6160^{\rm d} \pm 400^{\rm d}$
$\rm P_1$: amplitude	$3.5^{\rm m}$
$\rm P_1$: maximum	JD2446937
$\rm P_1$: minimum	JD2450017
$\rm P_2$: period	$529.4^{\rm d} \pm 30^{\rm d}$
$\rm P_2$: amplitude	$1.5^{\rm m}$
$\rm P_2$: maximum	JD2450017
$\rm P_2$: minimum	JD2449617

The present paper discusses several new observations of V Hya and its envelope, which we integrate with previous observational results to learn about the evolutionary status of V Hya and the behavior of stars as they evolve away from the AGB. The main part of the paper (Sect. 2) is an analysis of archival observations of the star's light curve made between October 1961 and July 1996. Appendix A summarizes new observations of the star's radio frequency emission and of the molecular circumstellar envelope. Sect. 3 discusses the implications of these and previous data for the evolutionary status of V Hya, and gives the conclusions.

Basic data for V Hya, including properties derived in this paper, are summarized in Table 1. Recently, Hipparcos (Perryman et al. 1997) has provided accurate astrometric data for V Hya. The parallax of the star is too small to measure ($\pi = 0.16 \pm 1.29$ milliarcseconds) giving a 2σ lower limit to the distance of 400 pc. Bergeat et al. (1998) discuss the period-luminosity relationship of carbon variables using Hipparcos data, and suggest an absolute K magnitude of $-9.05^{\rm m}$ for V Hya based on its variability period of 530 days, giving a distance of 550 pc. We assume a round-number distance of 500 pc in this paper.

2. The light curve of V Hya

Mayall (1965) analyzed data compiled by the American Association of Variable Star Observers (AAVSO) between 1884 and 1965. These data show a more or less regular variability with a period of 533 days and a peak-to-peak variation of $\sim 2^{\rm m}$ at V, plus a longer-term variation every 6500 days (17–18 years) with deep minima ($\sim 5^{\rm m}$–$6^{\rm m}$). Mayall's data also show some evidence for a third, much shorter, period, $30^{\rm d}$. Kholopov et al. (1985), in the notes to Volume 2 of the 'Catalogue of Variable Stars' note that V Hya has two superposed variations, a long-period variation with P = $6670^{\rm d}$ and amplitude $3.5^{\rm m}$, and a $531^{\rm d}$ period with amplitude $1.1^{\rm m}$ to $2^{\rm m}$. The $530^{\rm d}$ period is typical for stars at the tip of the AGB, but the 17 year period, and the depth of the minimum, is very unusual, not exhibited by any other AGB star (some supergiants, e.g. α Ori and μ Cep, have both long and short periods, though with much smaller amplitudes). V Hya is classified as a semi-regular (SRa) variable (Kholopov et al. 1985), but as shown, for example, by Kerschbaum (1993), the SRa class contains a mixture of Miras and "true" SR (SRb) variables. We suggest below that V Hya is a $530^{\rm d}$ Mira variable, and that the $6000^{\rm d}$ period is unrelated to pulsation.

We obtained the more recent light curve data for V Hya from the AAVSO archives. These data run from JD 2437602 (October 29, 1961), with a small overlap with the data discussed by Mayall (1965) to JD 2450268 (July 3 1996). They are plotted in Fig. 1, and the light curve shows a continuation of the behavior observed by Mayall (1965); periodic variability at $530^{\rm d}$, and three deep minima.

The total time interval covered by these observation is 12666 days, and there are 3260 data points. Were the sampling regular, the interval would be about 3.9 days, and the shortest period that could be found, corresponding to the Nyquist frequency, would be 7.8 days.

The irregular sampling of the light curve data precludes the application of conventional Fourier methods, and we used the algorithm developed by Lomb (1976) following the description by Press et al. (1992). This algorithm works with data $\rm y_i(t_i)$ sampled at irregular times $\rm t_i$ and normalized by the mean $\rm \bar{y}$ and gaussian variance σ. We calculated these quantities as the arithmetic mean and variance of the V magnitudes. The algorithm then compares the normalized data with periodic functions of angular frequency ω, modeling the data by

$$\rm y_i(t_i) \ = \ A\cos\omega t_i \ + \ B\sin\omega t_i \tag{1}$$

where the $\rm t_i$ are the times at which the observations were made. The Lomb periodogram is then

$$\rm P_N(\omega) \ = \ \frac{1}{2\sigma^2}\left(\frac{[\sum_i(y_i \ - \ \bar{y})\cos\omega(t_i-\tau)]^2}{\sum_i \cos^2\omega(t_i-\tau)} + \frac{[\sum_i(y_i-\bar{y})\sin\omega(t_i-\tau)]^2}{\sum_i \sin^2\omega(t_i-\tau)}\right) \tag{2}$$

where τ, the normalized phase, is given by

$$\rm \tan 2\omega\tau \ = \ \frac{\sum_i \sin 2\omega t_i}{\sum_i \cos 2\omega t_i} \tag{3}$$

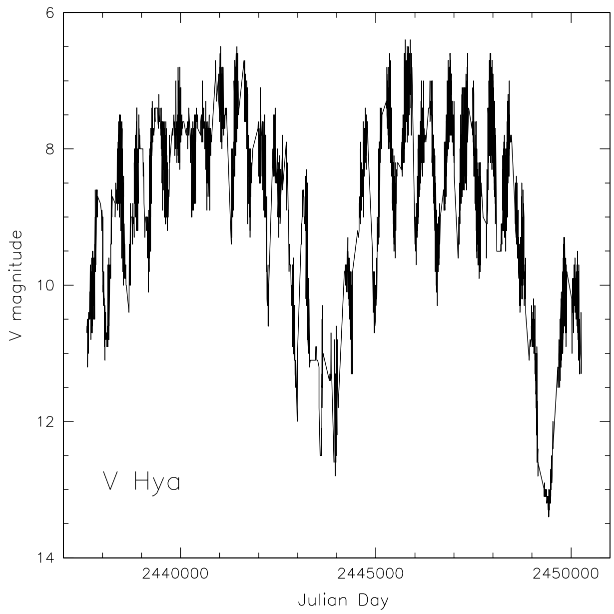

Fig. 1. V band light curve of V Hya between October 1961 and July 1996 from the AAVSO archives.

The periodogram is computed over a wide range of ω, with periodicities showing up as peaks in $\rm P_N(\omega)$.

Fig. 2 shows the periodogram for the 35 years of data for V Hya, plotted as power versus frequency f measured in $\rm days^{-1}$. The upper panel shows the periodogram calculated to the Nyquist frequency, 0.13 $\rm days^{-1}$, and the lower panel the structure of the low-frequency part of the curve, from periods of infinity to 250 days. Also plotted in Fig. 2 are the approximate 50%, 99% and 99.9% significance levels, calculated as described by Scargle (1982) and Press et al. (1992):

$$\rm P(> P_N) \ \simeq \ Me^{-P_n} \tag{4}$$

where M is taken as twice the number of data points.

The entire periodogram (Fig. 2, upper panel) shows highly significant peaks at $> 300^{\rm d}$ and approximately $195^{\rm d}$, $29^{\rm d}$ (this feature is split into two peaks at about $28^{\rm d}$ and $29^{\rm d}$), and $15^{\rm d}$. The two peaks at $28^{\rm d}$ and $29^{\rm d}$ are split by one day, and the two low-significance peaks on either side of the $15^{\rm d}$ peak also correspond to ± 1 day.

The lower-frequency region of the periodogram (Fig. 2, lower panel) shows three significant peaks (considering the peaks around f = 0.0028 $\rm days^{-1}$ to be part of the same feature). All three features are broadened, and give $\rm P_1 \ = \ 6600^d \pm 1400^d$, $\rm P_2 \ = \ 520^d \pm 30^d$, and $\rm P_3 \ = \ 360^d \pm 30^d$. The approximate separation of the peaks near f = 0.0028 $\rm days^{-1}$ corresponds to about 35 days. The estimated uncertainties of $\rm P_2$ and $\rm P_3$, and the substructure in $\rm P_3$, are all about 1 month.

Thus, the data show signatures of all the periods present in the data-taking process: one year, six months, one month, two weeks and one day. Even though the last is outside the frequency range sampled by the data, the irregular sampling ensures partial sampling of this and even shorter periods. We conclude that none of these periods is intrinsic to V Hya, and that the data support

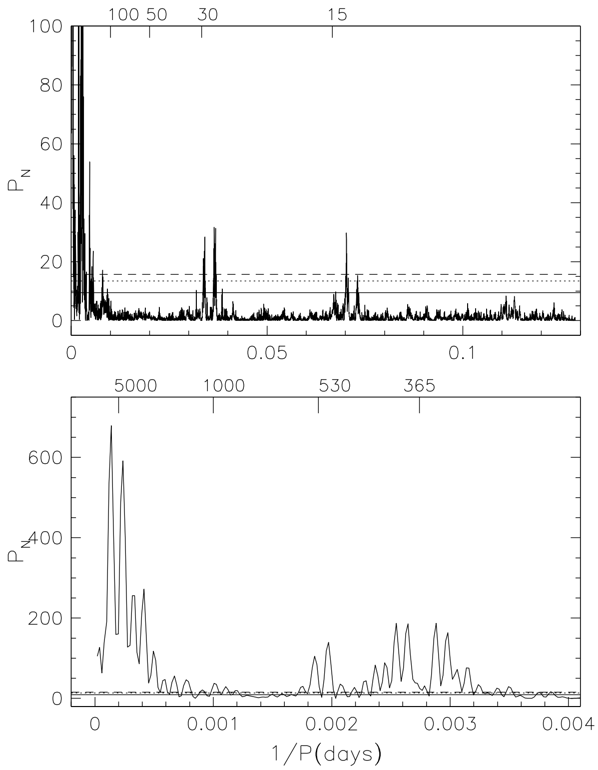

Fig. 2a and b. Lomb (1976) periodogram of the optical data for V Hya. **a** Upper panel: entire observed frequency range. **b** Lower panel: low frequency range (to periods of about $250^{\rm d}$). The ordinate is correlation power $\rm P_N$ (see text), the abscissa is frequency in $\rm days^{-1}$. The period in days is indicated on the upper x-axis. The horizontal lines correspond to confidence intervals of 50% (solid), 99% (dotted) and 99.9% (dashed).

only two stellar periods: $\rm P_1 = 6600^d$ and $\rm P_2 = 530^d$. The large uncertainty in the longer period is due both to the small number of cycles which have been sampled in the data and to the presence of the shorter-period variations, both intrinsic and observational.

To investigate this further, we analyzed the time series directly, using the data-folding technique of Schwarzenberg-Czerny (1989) who describes the use of one-way analysis of variance for searching for and measuring the periods of variable stars. The basis of this method is to fold the observed light curve $\rm y_i(t_i)$ with some trial period P, i.e. to cut the data sequence into portions P long and examine the normalized point-to-point variance of the folded data. The scatter around the average value of the data $\rm \bar{y}$ will be close to random regardless of the value of P unless the data stream has some periodicity close to P. The scatter of the folded data about $\rm \bar{y}$ is then computed for each value of P and compared with random scatter.

If N is the number of observations $\rm y_i(t_i)$,

$$\rm \bar{y} = \frac{\sum_{i=1}^{N} y_i(t_i)}{N} \tag{5}$$

The data are now folded and binned into M subsets with $\rm N_k$ points in the *kth* bin. Define $\rm y_{ij}$ as the *jth* point in the *ith* bin, and

$$\theta = \rm \frac{S_1^2}{S_2^2} \tag{6}$$

where

$$\rm S_1^2 = \frac{\sum_{i=1}^{N} N_i(\bar{y}_i - \bar{y})^2}{M-1} \tag{7}$$

and

$$\rm S_2^2 = \frac{\sum_{i=1}^{M}\sum_{j=1}^{N_i}(y_{ij} - \bar{y})^2}{N-M} \tag{8}$$

θ, the test statistic for the analysis of variance method, equals 1 for pure gaussian noise and is greater than 1 if there is any non- random component in the data. The stellar period is found by plotting θ–1 versus P; values of P for which θ–1 is larger than some threshold, corresponding to some confidence level, are considered to be periods of the star.

The analysis of variance code written by A. Udalski (Udalski et al. 1994) was used to analyze the light curve of V Hya shown in Fig. 1. Two periods at $>$ 99% significance are found: $\rm P_1 = 6160^d \pm 400^d$, and $\rm P_2 = 529.4^d \pm 30^d$ (these are final values – see below). Several spurious periods, at a significance level below 80%, were found: $\rm P_3 = 2P_2$; $\rm P_4 = 2/3P_2 = 344^d$; and $\rm P_5 = 2P_4$.

The data for V Hya have several properties which cause problems for this analysis. The time interval spanned by the data is only 2.4 $\rm P_1$, and the magnitude estimates in the deep stellar minimum are often poorly determined and/or lower limits. The third problem is that the amplitudes of the variations are different, which increases the range of the data and hence the "noise" for individual period determinations. We therefore refined our estimates of the periods of V Hya as follows. First, initial estimates of the amplitude, period and phase for the long-term variation (6160^d) were determined from the folded data. This variation was approximated by a sine wave and subtracted. The residual data were then folded to redetermine the periods. The light curve for $\rm P_2$ was determined, and subtracted. No significant further periods were found in the residual data. The amplitude, period and phase of maximum light for $\rm P_1$ and $\rm P_2$ are given in Table 1.

The resulting folded light curves, for $\rm P_1 = 6160^d$ with the $\rm 529.4^d$ variation subtracted and for $\rm P_2 = 529.4^d$ with the $\rm 6160^d$ variation subtracted, are shown in Figs. 3 and 4. The plotted light curves are averaged into 50 bins per cycle and the cycle repeated several times. As discussed above, the minima are not well determined. Fig. 4 shows a fairly typical Mira-type light curve, to first order a sine-wave variation but with a slow rise and more rapid decline. The long-period variation (Fig. 3) is not approximately sinusoidal however; it resembles the light curve of an eclipsing binary star, but with a far longer period and duration. The data of Mayall (1965) show a similar light curve shape, and cover five previous long-period cycles, with $\rm P_1 = 6200^d \pm 400^d$, in good agreement with the more recent data. The long-period variation in V Hya thus appears to be very regular.

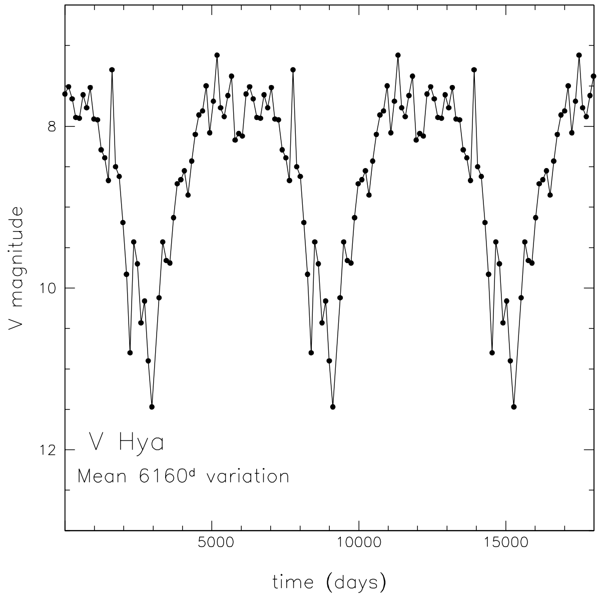

Fig. 3. Mean light curve for the $6160^{\rm d}$ period of V Hya. The short-period variation has been approximately subtracted from the data, which were then folded to the $6160^{\rm d}$ period. The data are binned to give 6160 points per cycle, and the mean cycle is repeated several times.

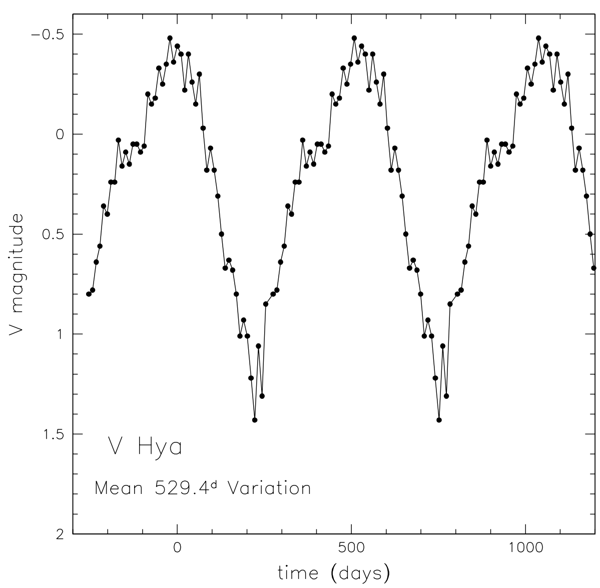

Fig. 4. Mean light curve for the $529^{\rm d}$ variation of V Hya. The longer-period variation has been approximately subtracted from the data, which were then folded to the $529^{\rm d}$ period. The data are binned to give 50 points per cycle, and the mean cycle is repeated several times.

Finally, we note that the amplitude of the 17-year variation, $3.5^{\rm m}$, agrees with that given by Kholopov et al. (1985) and is smaller than the amplitude of $5^{\rm m}$–$6^{\rm m}$ suggested by Mayall, which is actually the total range of variation due to both periodicities.

What is the origin of the $6000^{\rm d}$ variation of V Hya? The great depth of the minimum, and V Hya's large mass loss rate (Paper I), suggest obscuration by dust, analogous to the ejection of obscuring material by R CrB stars; however, the dimming of R CrB stars is irregular. The regularity of V Hya's $6000^{\rm d}$ variation support, rather, a dynamical origin for the variation. We suggest that V Hya is an eclipsing binary, but that the eclipse is caused not by a stellar companion but by circumstellar dust. Similar phenomena are seen in a small number of stars of widely different spectral types and at very different evolutionary stages. One such star is the F0 supergiant ϵ Aur, which undergoes an eclipse every 27.1 years. There is no secondary eclipse, and the primary eclipse is of long duration, (22 months) showing that the secondary cannot be a star but must be a large (5–10 A.U.) dark body, which observations strongly suggest is a dust disk orbiting with a companion (Huang 1965; McRobert 1985, 1988; Lissauer et al. 1996). Eclipses best explained by dust clouds attached to a binary companion are also seen in a small number of planetary nebula nuclei, e.g. in NGC 2346 (Costero et al. 1993). The shape of V Hya's light curve (Fig. 3) suggests that it may be a similar case. V Hya's period of $6160^{\rm d}$, if it is identified as an orbital period, corresponds to a distance from the star of $\sim 3.5 \times 10^{14}$ cm (about 10 $R_\star$) and a circular velocity of $2\,{\rm km\,s^{-1}}$ (assuming the mass of the system is $1\,M_\odot$). The transit time for an orbiting body is then about $2200^{\rm d}$ and its diameter at least several $\times 10^{13}$ cm. V Hya is a very evolved AGB star losing mass at a high rate, and the circumstellar envelope is flattened (Kahane et al. 1996); this could be caused by a companion orbiting in the inner parts of the circumstellar dust shell (e.g. Mastrodemos & Morris 1998). If this is taking place in V Hya's envelope, the eclipses of the star may be caused by a flattened density enhancement or wake in the envelope due to an orbiting companion.

3. Discussion and conclusions

3.1. The evolutionary state of V Hya

V Hya is a very unusual star; its $530^{\rm d}$ and $6000^{\rm d}$ periods are unique among evolved stars, its mass loss rate is high, and it is ejecting a very fast molecular wind (Paper I, Appendix A). Its molecular line envelope shows kinematic structure which has been interpreted as a bipolar outflow (Tsuji et al. 1988, Kahane et al. 1988, 1996) or as a tilted, expanding disk (Paper I). The optical spectrum shows unusually broadened lines, suggesting that the star is rapidly rotating (Barnbaum et al. 1995, hereafter BMK). Although some of these properties suggest that the star may be evolving beyond the AGB phase, its spectral type, IRAS colors and lack of radio continuum emission (Paper I, Appendix A) are all consistent with its being an AGB star.

BMK show that V Hya's rotation velocity is period dependent, decreasing as the star expands, and suggest that the rapid rotation is due to the star having evolved to a common envelope binary; the companion may, also, be responsible for the enhanced C abundance in the envelope (V Hya does not show the presence of Tc). The inferred rotation velocity suggests a period about 10% longer than the pulsation period of the star, with a large uncertainty due to lack of knowledge of the inclination: BMK suggest that this similarity in the pulsation and rotation periods may be responsible for the $6000^{\rm d}$ variation, which is identified as a beat frequency of the system. Further, they suggest that the rapid rotation of the star can drive the fast outflow.

If the interpretation of V Hya's light curve given in the previous section of the present paper is correct, on the other hand, only the $530^{\rm d}$ variation is intrinsic to the star, and the amplitude and period of this variation suggest that V Hya is a normal Mira. The suggested eclipse period of 17 years implies an external companion, but one which is close enough to the star to shape its outflowing wind into a flattened configuration (cf. Mastrodemos & Morris 1998) and, perhaps, to cause the fast wind. Of particular interest for both of these scenarios is the high mass loss rate ($4\times10^{-5}{\rm M}_\odot\,{\rm yr}^{-1}$) and small envelope size inferred from low resolution CO mapping observations (Paper I, Appendix A). The latter shows that the duration of the very high mass loss rate phase has been quite short,$<$ 2000 years. The envelope mass, about 0.1 ${\rm M}_\odot$, is similar to that found for many planetary nebulae. The recent onset of copious mass loss could be due to the formation of a common-envelope binary, as suggested by BMK, or could be due to the formation of the superwind which signals the end of evolution on the AGB. Whatever the reason(s) for the peculiarities of V Hya, the observational data show that the complex structures seen in many planetary nebulae (axisymmetric structure, fast winds) are often present in the envelope of the precursor star before it evolves beyond the AGB.

3.2. Conclusions

This paper discusses several new observations of the evolved AGB carbon star V Hya. We find:

1. An analysis of optical variability data finds only two significant periods in V Hya, at $529.4^{\rm d}$ with peak-to-peak variation of $1.5^{\rm m}$, and $6160^{\rm d}$, with peak-to-peak variation of $3.5^{\rm m}$. Both of these periods are seen in data taken back to 1880, and both appear to be very regular.
2. The morphology of the $6160^{\rm d}$ variation resembles that of an eclipsing binary, but with an eclipse duration which is far longer than can be produced by a stellar companion and of an amplitude which shows that essentially the entire stellar photosphere is occulted. We suggest that the regular long-period dimming of V Hya is due to a thick dust cloud orbiting the star and attached to a binary companion.
3. The $529.4^{\rm d}$ period is typical of a luminous Mira variable, and we suggest that V Hya is a Mira, not a semiregular variable. The persistence of this variation to the present day is further evidence that V Hya is still on the AGB.
4. No radio frequency emission was detected from V Hya to a limit of S(8.4 GHz) $<$ 0.17 mJy. This shows that the star is not hot enough to cause ionization of the envelope and is thus not yet evolved away from the AGB towards the planetary nebula phase.
5. Emission from the fast molecular wind was observed in the submillimeter CO(4–3) and CO(6–5) lines. Together with the CO(2–1) and CO(3–2) observations of Paper I, the relative line intensities show that both the fast wind and the slower wind appear to be of recent origin, only $\sim$ 1500 years in the case of the slower wind, and that copious mass loss (at rates of several $\times10^{-5}$ ${\rm M}_\odot\,{\rm yr}^{-1}$) began only recently. The gas in the fast wind does not appear to be significantly hotter than that in the slow wind, arguing against formation of the molecules in dense hot postshock gas and in favor of the direct production of the fast wind by V Hya.
6. The presence of the fast molecular wind and the recent onset of rapid mass loss suggest that V Hya may be in the initial stages of its evolution beyond the AGB. The formation of fast winds seems often to accompany the post-AGB evolution of a star. These observations of V Hya show that fast molecular winds and complex envelope structure can form while the star is still on the AGB.

Acknowledgements. We wish to thank the referee for a most thorough and helpful report on the first draft of this paper. We are very grateful to the staff at the CSO and VLA for granting the observing time used for part of this work, and to Norbert Bartel for donating an hour of VLA time during a VLBI run. This research made use of the SIMBAD data base, operated at CDS, Strasbourg, France. We thank Bohdan Paczynski, Przemyslaw Wozniak and Andrzej Udalski for advice and for providing the analysis-of-variance code. Astronomical research at the CSO is supported by the National Science Foundation via grant AST96-15025. Partial support for this work from Princeton University and from the N.S.F. via grant AST96-18503 is gratefully acknowledged.

Appendix A: observations of V Hya and its circumstellar envelope

Luttermoser & Brown (1992) detected 0.22$\pm$0.02 mJy at 8.4 GHz from V Hya using the Very Large Array (VLA). This is far stronger than expected for either the circumstellar dust or the stellar photosphere, and Luttermoser and Brown postulate an extended, partly ionized atmosphere. Another possible source of thermal radio frequency emission from circumstellar envelopes is ionization produced as the star evolves away from the AGB. Since evolution is rapid at this stage, the increase in the strength of the continuum emission from the compact central HII region can be observed in only a few years, as is found for AFGL 618 (Kwok & Feldman 1981). Since V Hya may be in the initial stages of evolution away from the AGB, we re-observed the star with the VLA to investigate whether the radio continuum flux density has changed.

V Hya was observed at 3.6 cm (8.4 GHz) on Dec 13, 1996. The array was in its ‘A’ (largest spacing) configuration. Two short observations, totaling 20 minutes of observing time, were made. The phases were calibrated by short observations of the phase calibrator 1048-191 before and after each set of observations. The data were of excellent quality. The flux density scale was calibrated relative to 3C 48 ($S_{8.4}$ = 3.2424 Jy) and 3C 286 ($S_{8.4}$ = 5.2001 Jy) (Taylor & Perley 1996). No emission was seen at or near the position of V Hya, with a 3σ upper limit of 0.17 mJy. Thus, the star has not yet evolved away from the AGB to the point where it is hot enough to produce ionizing photons.

CO observations of V Hya's envelope were made on the nights of March 24–28 with the 10.4 m Robert B. Leighton tele-

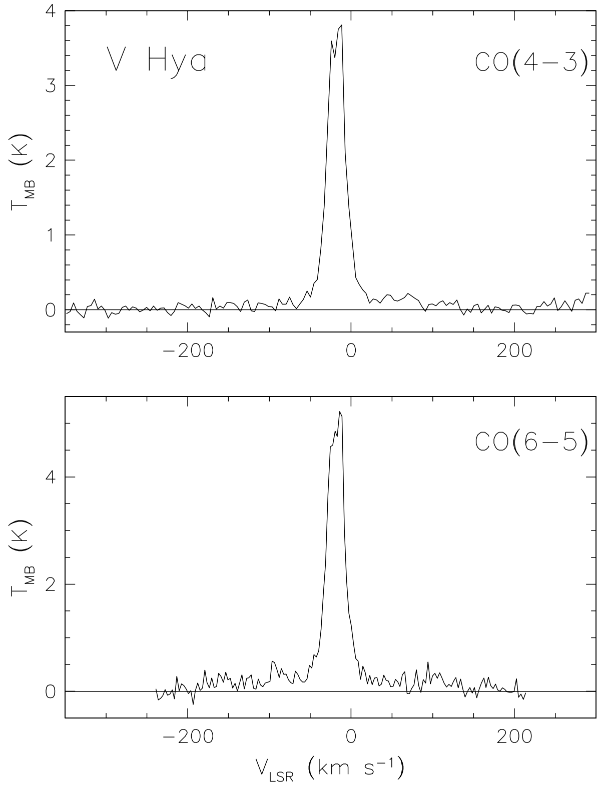

Fig. A1a and b. Submillimeter CO line emission from V Hya observed at the CSO. **a** Upper panel: CO(4–3) line at 650μm and **b** lower panel: CO(6–5) line at 440μm. The ordinate is main-beam brightness temperature and the abscissa velocity with respect to the Local Standard of Rest. Both line profiles have had a linear baseline removed. The fast wind is detected at the 2σ level in the CO(4–3) line and the 3σ level in the CO(6–5) line.

Table A1. CO Emission from V Hya's circumstellar envelope

line	T(wing) (K)	T(peak) (K)	T(wing)/T(peak)	θ ($''$)
CO(2-1)	0.044	1.75	0.025	30
CO(3-2)	0.104	3.30	0.032	20
CO(4-3)	0.127	3.80	0.034	15
CO(6-5)	0.188	5.21	0.036	10

scope of the Caltech Submillimeter Observatory on Mauna Kea, Hawaii. The weather was excellent, with a zenith opacity at 220 GHz of $\tau_\circ \le$ 0.03. The CO(4–3) line at 461.0408 GHz and the CO(6–5) line at 691.473 GHz were observed. The line profiles are shown in Fig. A1 – both the fast and normal winds are seen. Table A1 summarizes the CO line data obtained at the Caltech Submillimeter Observatory for V Hya, giving the brightness temperature of the fast wind (measured at +100 $\mathrm{km\ s^{-1}}$), the brightness temperature of the main component (measured at about $-10\,\mathrm{km\,s^{-1}}$), the ratio T(fast wind)/T(slow wind), and the half-power beamwidth of the CSO for each line. The CO(2–1) and CO(3–2) data are from Paper 1. These data show that the ratio of the CO(2–1) and CO(3–2) line intensities for both the fast and slow winds have about the value expected for an optically thick source which is roughly the same size as or smaller than the $20''$ beam for the CO(3–2) line. The ratios of the CO(6–5), CO(4–3) and CO(3–2) lines, however, show that the envelope is partly resolved at 460 and 691 GHz. The fast wind does not appear to be significantly hotter than the slow wind. These observations confirm the conclusions from Paper I: V Hya is ejecting a very fast molecular wind as well as slower winds, and the circumstellar envelopes formed by both the fast and slow winds have approximately the same diameter, $20''$. These data give a radius of $\sim 8 \times 10^{16}$ cm at a distance of 500 pc, a dynamical age for the slow wind of about 1600 years, and a total mass loss rate of about $4 \times 10^{-5}\ \mathrm{M_\odot\ yr^{-1}}$. This high mass loss rate, and the small dynamical age of the envelope, suggests that V Hya has entered its "superwind" phase.

References

Barnbaum C., Morris M., Kahane C., 1995, ApJ 450, 862 (BMK)
Bergeat J., Knapik A., Rutily B., 1998, A&A 332, L53
Costero R., Peña M., Schuster W.J., Tapia M., Echevarria J., 1993, Rev. Mex. Astron. Astrofis. 26, 108
Huang S.-S., 1965, ApJ 141, 976
Kahane C., Maizels C., Jura M., 1988, ApJ 328, L25
Kahane C., Audinos P., Barnbaum C., Morris M., 1996, A&A 314, 871
Kerschbaum F.J.H., 1993, PASP 105, 1496
Kholopov P.N., Samus N.N., Frolov M.S., et al., 1985, General Catalogue of Variable Stars. Vols. 1–4, Nauka Publishing House, Moscow
Knapp G.R., Jorissen A., Young K., 1997, A&A 326, 318 (Paper I)
Kwok S., Feldman P.A., 1981, ApJ 247, L67
Lissauer J.J., Wolk S.J., Griffith C.A., Backman D.A., 1996, ApJ 465, 371
Lloyd Evans T., 1991, MNRAS 248, 479
Lomb N.R., 1976, Ap&SS 39, 447
Luttermoser D., Brown A., 1992, ApJ 384, 634
Mayall M.W., 1965, J. R. Astron. Soc. Can. 59, 245
McRobert A., 1985, Sky & Telescope 70, 527
McRobert A., 1988, Sky & Telescope 75, 15
Mastrodemos N., Morris M., 1998, ApJ 497, 303
Perryman M.A.C., Lindegren L., Kovalevsky J., et al., 1997, A&A 323, L49
Plez B., Lambert D.L., 1994, ApJ 425, L101
Press W.H., Teukolsky S.A., Vetterling W.T., Flannery B.P., 1992, Numerical Recipes. Second Edition, Cambridge University Press
Sahai R., Wannier P.G., 1988, A&A 201, L9
Scargle J.D., 1982, ApJ 263, 835
Schwarzenberg-Czerny A., 1989, MNRAS 241, 153
Taylor G.B., Perley R.M., 1996, VLA Calibrators. NRAO
Tsuji T., Unno W., Kaifu N., et al., 1988, ApJ 327, L23
Udalski A., Kubiak M., Szymański M., et al., 1994, Acta Astron. 44, 317