Bipolar jets growth and decline in Hen 3-1341: a direct link to fast wind and outburst evolution*

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ABSTRACT

The appearance and disappearance of collimated bipolar jets in the symbiotic star Hen 3-1341 is reported and investigated. From modeling of the emission line spectrum it turns out that the accreting white dwarf in quiescence has $T_{\text{WD}} \sim 1.210^5$ K and $R_{\text{WD}} \sim 0.14$ R$_\odot$, for a luminosity of $3.810^3$ L$_\odot$, and it is stably burning hydrogen on the surface at a rate of $M_{\text{H}} \sim 510^{-8}$ M$_\odot$ yr$^{-1}$, feeding ionizing photons to a radiation bounded circumstellar nebula extending for $\sim 17$ AU. The WD underwent a multi-maxima outburst lasting from 1998 to 2004 during which its H-burning envelope reacted to a probable small increase in the mass accretion by expanding and cooling to $T_{\text{eff}} \sim 110^4$ K and $R \sim 20$ R$_\odot$, mimicking an A-type giant that radiated a total of $\sim 610^{44}$ erg, at an average rate of $\sim 10^3$ L$_\odot$. Bipolar jets developed at the time of outburst maximum and their strength declined in parallel with the demise of the fast wind from the inflated WD, finally disappearing when the wind stopped halfway to quiescence, marking a 1:1 correspondence between jets presence and feeding action of the fast wind. The total mass in the jets was $M_{\text{jet}} \sim 2.510^{-7}$ M$_\odot$ for a kinetic energy of $E_{\text{kin}}^{\text{jet}} \sim 1.710^{42}$ (sin $i$)$^{-1}$ erg, corresponding to $\sim 0.3$ (sin $i$)$^{-1}$% of the energy radiated during the whole outburst.

Key words: Stars: binaries: symbiotic - Stars: mass-loss - Stars: winds, outflows - ISM: jets and outflows

1 INTRODUCTION

Tomov et al. (2000), hereafter TMM, discovered spectroscopically in Hen 3-1341 (= V2523 Oph) one of the finest examples of highly collimated bipolar jets seen in a symbiotic binary. The jets, with a projected velocity of $|\Delta V| \sim 820$ km sec$^{-1}$, were observed when the system was in outburst at $V \sim 10.5$ mag. No follow-up study monitored the jet or outburst evolution.

Some symbiotic binaries are already known to present or have presented jets, in the optical and/or radio: R Aqr (Burgarella & Paresce 1992; Dougherty et al. 1993), CH Cyg (Taylor et al. 1986; Sol 1987), MWC 560 (Tomov et al. 1990; Shore et al. 1994; Schmid et al. 2001), RS Oph (Taylor et al. 1989), Hen 2-104 (Corradi et al. 2001) and Hen 3-1341 (TMM). Other possible examples of jets or collimated mass outflows from symbiotic binaries and related systems are StH 190 (Munari et al. 2001).

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ing of ionizing photons. Direct evidences for accretion disks are missing, given their low luminosity compared with the glare of the circumstellar nebular material and the brightness of the central star (especially if burning hydrogen at the surface). Indirect suggestions for the presence of disks are generally based on the interpretation of the flickering so far detected in ∼20% of surveyed symbiotic stars (e.g. CH Cyg; Sokoloski & Kenyon 2003; T CrB: Zamanov et al. 2004; MWC 560: Tomov et al. 1995; Dobrzycka et al. 1996; RS Oph and Mira A+B: Sokoloski et al. 2001).

In this paper we present direct evidences that, at least in the symbiotic binary Hen 3-1341, the appearance of bipolar jets is limited to the early and brightest outburst phases, and that the jets are fed by the wind from the outbursting component. When the wind quenches during the decline from outburst maximum, the jets also vanish, in a 1:1 correspondence.

2 CONDITIONS IN QUIESCENCE AND OUTBURST

When TMM discovered the jets in the summer of 1999 they found Hen 3-1341 at V=10.5, much brighter than on the Palomar charts (B=14.0), and concluded the system was undergoing an outburst. Not much else is known about the photometric and spectroscopic history of Hen 3-1341 or the reality and characteristics of the outburst itself. A proper investigation is mandatory for the obvious implications on the nature and evolution of the jets.

With the aim of recovering the photometric history of Hen 3-1341, we have (a) obtained $UBV(RI)\_C$ and JHK photometry of Hen 3-1341 with the USNO 1.0m and 1.5m telescopes, (b) measured the brightness on photographic plates found in the Asiago 67/92 Schmidt archive and on plates of the DSS-1, DSS-2, GSC and Vehrenberg’s photographic surveys, and (c) derived $UBV(RI)\_C$ magnitudes from published optical spectra calibrated into absolute fluxes. These data are given in Table 1 together with values from the 2MASS and DENIS survey, and $UBV(RI)\_C$ and JHK from the symbiotic star photometric catalogs of Allen (1982) and Munari et al. (1992). They are plotted in Figure 1, together with amateur estimates kindly provided by Albert Jones (New Zealand) and VSNET organization, to document the photometric evolution over the last 15 yr.

Figure 1 reveals that Hen 3-1341 has undergone a large outburst lasting from 1998 to 2004, characterized by a rapid rise to maximum and a complex pattern of minima and maxima during the decline phase. The outburst reached maximum $V$ brightness right at the time TMM discovered the jets and found the high ionization emission lines to have vanished and lower energy ones somewhat weakened while an A-type continuum dominated the spectrum, like in a typical symbiotic star outburst (cf. Ciatti 1984). The end of the outburst and return to quiescence by summer 2004 is confirmed by the spectrum in Figure 2, that we obtained on July 17, 2004 with the B&K+C+CCD spectrophotograph of the 1.22m telescope operated in Asiago by the Department of Astronomy of the University of Padova. The spectrum is characterized by strong emission lines of [FeVII], [NeV], HeII and OVI (Raman scattered), identical to the 1993 pre-outburst quiescent spectrum by Munari & Zwitter (2002).

The emission line spectrum of Hen 3-1341 in quiescence both in the optical (from Figure 2) and in the ultraviolet (the IUE spectrum of Gutiérrez-Moreno et al. (1997) has been modeled with the CLOUDY software package (see http://www.nublado.org/) to get round estimates of basic physical parameters, assuming a simple spherical symmetric gas distribution originating from the $\rho(r) \propto r^{-2}$ wind of the cool giant ionized by the radiation from the WD companion. We found the nebular material to be radiation bounded and to extend for ∼17 AU, for a total mass of ∼7×10^{-6} M\_\odot contained within. The gas electronic temperature and density are $T_e$∼10^{5} K and $N_e$∼10^{8} cm^{-3} close to the ionizing source, decreasing to $T_e$∼10^{4} K and $N_e$∼10^{5} cm^{-3} at the ionization boundary. The modeling supports solar metallicity and chemical partition, although with Ne and N apparently enhanced by ∼10× (which is what is expected when ejecta or wind from the outbursting WD are mixed with the circumstellar material originating from the M giant, cf. Nussbaumer et al. (1988) and N. The central star has $T_{WD}$∼1.2×10^{5} K and $R_{WD}$∼0.14 R\_\odot for a luminosity of 3.8×10^{3} L\_\odot, which are consistent with those previously found by Gutiérrez-Moreno et al. (1997). Such a quiescent luminosity cannot be sustained by pure accretion since that would require an implausibly large accretion rate of 10^{-6} M\_\odot yr^{-1} on a 0.5 M\_\odot WD.

The quiescent luminosity is instead well explained by stable H-burning conditions of accreted matter on the surface of the white dwarf. Because the stably burning WD in Hen 3-1341 does not expand to large dimensions during quiescence, the accretion rate must match the burning rate, or $M_{\dot{M}}$∼5×10^{-8} M\_\odot yr^{-1} which is in line with the expected accretion rate for symbiotic stars (cf. Kenyon & Webbink 1984). From Iben & Tutukov (1999) numerical simulations, $T_{WD}$∼10^{5} K and $R_{WD}$∼0.1 R\_\odot correspond to a stable H-burning 0.4 M\_\odot white dwarf. From Table 1 it is evident that the white dwarf in Hen 3-1341 has been in that state since at least the time of the first Palomar survey, 50 yr ago. This is in line with the theoretical expectations for a 0.4 M\_\odot H-burning white dwarf, that predicts an “on” period of ∼5000 yr, or ten times shorter if the mass of the envelope is reduced by a wind (Iben 2003).
To gain physical insight on the optical 1998-2004 outburst we have integrated the energy between the outburst light-curve in Figure 1 and the $V \sim 13.1$ reference value for quiescence, to derive the total radiated energy. The color evolution of the outbursting component is missing for lack of multi-band simultaneous observations. Color information is available (cf. Table 1) only for the three observations in 2000, when the outbursting component was roughly midway between outburst maximum and quiescence. For sake of discussion, the corresponding $B - V = 0.52$ is taken to represent the average color of the outbursting component. To estimate the reddening we have measured the equivalent width of interstellar NaI and KI absorption lines in high resolution spectra of Hen 3-1341 that we have secured with ELODIE spectrograph at the Observatoire de Haute-Provence (OHP) and the Echelle spectrograph at the 1.82m telescope operated in Asiago by the Italian National Institute of Astrophysics (INAF). Following the calibration of Munari & Zwitter (1997), the reddening is found to be $E_{B-V} = 0.47$ and therefore the intrinsic average color for the outbursting component is $(B-V)_c = 0.05$. The corresponding bolometric correction is $-0.10$ according to Bessell et al. (1998) and the spectral type is A2 following Fitzgerald (1970). Adopting the distance of 3.1 kpc derived by Gutiérrez-Moreno et al. (1997), the total energy radiated by the outburst turns out to be $\sim 10^{44}$ erg. It would corre-
respond to the potential energy released by the accretion onto a 0.5 M⊙ white dwarf of ~4 × 10⁻⁶ M⊙ (at a mean rate of ~1 × 10⁻⁶ M⊙yr⁻¹) which is implausibly large. In fact, it is orders of magnitude larger than the typical mass dumped through an accretion disk during outbursts in cataclysmic variables (Warner 1995), and the required mass loss from the donor star would be orders of magnitude larger than expected for the M2 III non-variable companion, which did not experience any major instability at the time of outburst.

The reprocessing took place in the envelope of the WD that expanded and cooled to T_eff ~ 10⁴ K and R ~ 20 R⊙. The width of the stable H-burning strip in the MWD, M_acc,WD plane is a narrow one, and minimal increases in M_acc,WD triggers an expansion and consequent cooling of the WD envelope (cf. Iben 2003). We are therefore led to interpret the 1998-2004 “outburst” as having been caused by a temporary (and marginal) increase in the mass loss from the M2III that gave no appreciable signal in the IR photometry of Table 1 but caused M_acc,WD to rise above the narrow equilibrium strip. The surplus accreted material was partially burned and partially carried away by the fast wind traced by the P-Cyg profiles of HeI lines in Figure 3. When the WD envelope mass returned to equilibrium value, the envelope retraced to small radius and high temperature and Hen 3-1341 resumed the photometric and spectroscopic “quiescent” appearance.

### Table 1

The table collects existing and new multi-band information on the photometric history of Hen 3-1341. Sources: a = DSS-1, DSS-2, GSC, Vehrenberg’s photographic surveys remeasured by us, b = Asiago 67/92 cm Schmidt telescope archival plates, c = Allen (1982), d = Munari & Buson (1994), e = derived from evolution with band transmission profiles of the fluxed spectra in Gutierrez-Moreno et al. (1997), f = similarly for Munari & Zwitter (2002), g = 2MASS, h = Tomov et al. (2004), i = photometry with the USNO 1m telescope, j = DENIS survey.

| Date       | U  | B  | V  | R_C | I_C | J-H | H-K | ref |
|------------|----|----|----|-----|-----|-----|-----|-----|
| 26-04-1954 | 10.8 |   |    |  a  |     |     |     |     |
| 01-07-1954 | 14.0 |   |    |  a  |     |     |     |     |
| 14-07-1969 | 13.3 |   |    |  b  |     |     |     |     |
| 16-07-1969 | 13.2 |   |    |  b  |     |     |     |     |
| 06-04-1970 | 14.0 |   |    |  a  |     |     |     |     |
| 02-06-1970 | 14.4 |   | 11.0|  b  |     |     |     |     |
| 01-07-1970 | 13.8 |   | 10.9|  b  |     |     |     |     |
| ~1981      |     |    | 7.58| 0.98| 0.34|  c  |     |     |
| 22-03-1982 | 13.0 |   |    |  a  |     |     |     |     |
| 29-06-1987 |     | 12.5|    |  a  |     |     |     |     |
| 24-06-1990 | 12.72| 13.73| 12.94| 11.82| 10.82|  d  |     |     |
| 16-03-1990 | 12.6 | 13.7 | 12.9 | 11.6 | 10.8  |  e  |     |     |
| 01-07-1991 | 7.66 | 1.06| 0.31|  d  |     |     |     |     |
| 09-03-1992 |     | 11.7 |    |  a  |     |     |     |     |
| 27-07-1993 | 14.1 | 13.1 | 12.0 |     |  f  |     |     |     |
| 16-06-1996 | 12.7 |     |    |  a  |     |     |     |     |
| 23-04-1998 |     | 7.48| 0.87| 0.41|  g  |     |     |     |
| 08-06-1999 | 10.5 |     |    |  h  |     |     |     |     |
| 30-04-2000 | 10.97| 11.82| 11.32| 10.65| 10.03|  i  |     |     |
| 02-05-2000 | 11.00| 11.91| 11.36| 10.74| 10.07|  i  |     |     |
| 28-05-2000 | 11.08| 11.90| 11.38| 10.70| 10.09|  i  |     |     |
| 10-10-2000 |     | 10.11| 7.50 |     |  l  |     |     |     |
| 16-07-2004 | 13.15| 13.84| 13.09| 11.72| 10.72|  i  |     |     |
| 04-08-2004 | 13.22| 13.91| 13.14| 11.74| 10.74| 7.56| 0.94| 0.36|     |     |

3 EVOLUTION OF THE JETS AND THEIR FEEDING MECHANISM

Following the discovery of bipolar jets by TMM in June 1999, we re-observed Hen 3-1341 in high resolution at later dates. The results for Hα and HeI 5876 Å profiles are shown in Figure 3 together with the original TMM discovery spectrum and a pre-outburst spectrum obtained at ESO by van Winckel et al. (1992). From Figure 3 it is evident how the bipolar jets were absent in the quiescence before as well as after the outburst, and were strongest at peak outburst optical brightness, declining in strength with the outburst retraction from maximum. It is worth noticing the similarity
between the terminal wind velocity ($\sim 770$ km sec$^{-1}$) and jet projected velocity ($|\Delta RV| \sim 820$ km sec$^{-1}$) at the time of onset of the jets (June 1999), which is best appreciated in the left insert of the bottom panel of Figure 1 of TMM. A most interesting comparison is between jet strength and amount of mass loss by wind from the WD as traced by the P-Cyg profiles of HeI lines in Figure 3. The correlation is a very tight one. The jets were most prominent when the wind was strongest, and declined in parallel with the decrease of wind intensity. To our knowledge, these evidences are among the most direct and convincing proofs of the 'energy/wind source associated with the central accreting object' postulated by Livio (1997) mechanism of jet production. We suggest that the search for jets in symbiotic stars should be focused on the outburst phases characterized by maximum wind intensity.

From the integrated flux of the jet features in the H$\alpha$ spectrum at outburst maximum in Figure 3 (Jun 8, 1999), and assuming that all the hydrogen within the jets is ionized and that the jets are optical thin in H$\alpha$, a total mass in the jets of $M_{\text{jet}} \sim 2.5 \times 10^{-7} M_\odot$ is derived. The kinetic energy deposited in the jets corresponding to $\sim 820$ km sec$^{-1}$ jet velocity is therefore $E_{\text{kin}} \sim 1.7 \times 10^{32} (\sin i)^{-1}$ erg, where $i$ is the unknown orbital inclination. This corresponds to $\sim 0.3(\sin i)^{-1}\%$ of the total energy radiated during the outburst.

Figure 3 suggests a small increase with time in the observed velocity separation of the jets, amounting to $|\Delta RV| \sim 820$ km sec$^{-1}$ on June 1999, 910 km sec$^{-1}$ on Sept. 1999, and 1000 km sec$^{-1}$ on Sept. 2001. Different explanations could be invoked - including a variable projection angle of the jet axis on the line of sight as caused by a precession motion - but there are not enough data to decide in favor of any of them.

Finally, we have also searched for a signature of rotation of a magnetic WD in Hen 3-1341 by looking for coherent modulation in time resolved $B$-band photometry that we secured in 2004 with the USNO 1.0m telescope (see Figure 4). None was found, but this was an expected result, because with the system in quiescence the circumstellar nebular emission is enormously brighter that the WD in $B$ band. A more profitable search will have to wait for the next outburst state of Hen 3-1341.

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