

## $\eta$ CARINAE: BINARITY CONFIRMED

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### ABSTRACT

We report the recovery of a spectroscopic event in  $\eta$  Carinae in 1997/1998 after a prediction by Daminieli in 1996. A true periodicity with  $P = 2020 \pm 5$  days (0.2% uncertainty) is obtained. The line intensities and the radial velocity curve display a phase-locked behavior, implying that the energy and dynamics of the event repeat from cycle to cycle. This rules out S Doradus oscillation or multiple shell ejection by an unstable star as the explanation of the spectroscopic events. A colliding-wind binary scenario is supported by our spectroscopic data and by X-ray observations. Although deviations from a simple case exist around periastron, intensive monitoring during the next event (mid-2003) will be crucial to our understanding of the system.

*Subject headings:* binaries: general — stars: emission-line, Be — stars: individual ( $\eta$  Carinae) — stars: variables: other (luminous blue variables)

### 1. INTRODUCTION

The object  $\eta$  Carinae is key to understanding the evolution of massive stars. It is one of the most luminous stars known and underwent a great eruption that created the Homunculus 150 years ago. Since then, the nature of  $\eta$  Car has been the subject of an intense debate. However, the star does not fit any of the proposed models (see Davidson & Humphreys 1997 for a review). In the last three decades, the prevailing view was that  $\eta$  Car is a single luminous blue variable star. The spectroscopic events—fading of high excitation lines—occasionally observed were interpreted as being imprints of S Doradus oscillations (Damineli et al. 1998). The regularity of the 5.5 yr cycle, however, makes such a hypothesis unlikely (Damineli 1996). The binary system proposed by Damineli, Conti, & Lopes (1997, hereafter DCL) brought new insight to the problem. The solution to the radial velocity (RV) curve of the broad component in the  $\text{P}\gamma$  line resulted in two massive stars ( $M_1 \sim M_2 \sim 70 M_\odot$ ). The large mass-loss rates of the stars would imply strong wind-wind collision that produces thermal hard X-rays. The highly eccentric orbit would produce phase-locked X-ray variability. Those features are in accord with the observations (Corcoran et al. 1998), indicating that  $\eta$  Car is a colliding-wind binary (CWB). Davidson (1997) presented an alternative solution to the DCL data, leading to similar characteristics but larger eccentricity. The parameters of the binary system, however, were not trustworthy because they were derived from only one cycle and were based on a single emission line. The prediction of a spectroscopic event for late 1997 through early 1998 created an outstanding opportunity to test this model against the (at the time dominant) idea of recurrent shell ejection.

The expected event indeed occurred at the right time, as

shown by the spectroscopic data analyzed in § 2. The event was also detected at radio wavelengths (Abraham & Damineli 1999) and in X-rays, displaying dramatic variation (Ishibashi et al. 1999). A full two-dimensional hydrodynamic simulation (Stevens & Pittard 1999) and even a simple CWB model (Ishibashi et al. 1999) reproduce the overall behavior of  $\eta$  Car in X-rays. However, significant discrepancies remain around periastron. This is not unexpected, taking into account that near periastron the stars are close enough for deviations from spherical symmetry to be important. The wind is probably non-spherical, and an equatorial disk may surround the primary star.

The event observed in optical/near-infrared spectral lines and at radio wavelengths is due to a cause different from that in X-rays, despite their temporal coincidence. Following Damineli, Lopes, & Conti (1999a), the secondary star is the main source of hard photons, not the wind-wind colliding zone. The immersion of the secondary star into the companion's wind prevents hard photons from reaching the external regions of the wind of the primary and the circumstellar gas. The resulting effect is a temporary drop in the degree of ionization and, consequently, the fading of the high excitation lines.

Although preliminary results indicate that  $\eta$  Car is likely to be a binary, critical tests must be carried out to provide definitive proof. Such tests are provided in this Letter, based on the data collected in a spectroscopic campaign initiated in 1989 that covered the 5.5 yr cycle twice.

### 2. A TRUE PERIODICITY

Spectroscopic observations of  $\eta$  Car were carried out at the European Southern Observatory, Chile and at the National Astrophysical Laboratory, Brazil; see Wolf et al. (1999) and Damineli et al. (1999b) for details. The [S III] and [Ar III] spectral lines plummeted in 1997 November and disappeared a month later (Lopes & Damineli 1997). Around that time, the near-infrared light curve reached a local maximum (Whitelock &

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Laney 1999) and the spectroscopic lines a minimum, similar to those reported by Whitelock et al. (1994) and by Damineli (1996). Since we have detailed observations of the 1992 event, we folded them in with the 1998 event. The sawtooth structure in the RV curve provides an accurate measure of the elapsed time between the last two events. We plotted in Figure 1a the RV variations of the broad component in He I  $\lambda 6678$  for the 1998 event (*solid line*) superposed with the previous event shifted by 2020 days (*dotted line*). The match was obtained by shifting one relative to the other by  $2020 \pm 5$  days. The same recurrence time was derived from Pa $\gamma$ , although the uncertainty is larger for this line because of a smaller number of observations.

We should not expect, a priori, that line intensities would result in the same elapsed time as for RV. The narrow component in the [S III]  $\lambda 6312$  and He I  $\lambda 6678$  lines disappeared around 1997 December 12 (JD 2,450,794  $\pm$  2 days). The same was observed on 1992 June 2 (JD 2,448,775  $\pm$  5 days), resulting in a recurrence time 2019  $\pm$  7 days, which is compatible with that from RV curve. This timescale is also in agreement with  $P = 2014 \pm 50$  days proposed by DCL based on the 1948, 1965, 1981, 1987, and 1992 events. This is an indication that the previous events resembled closely the last two we have observed: deep and brief. If the events had lasted longer, no obvious strict periodicity would have been hinted from such a short list of occurrences. If line intensity fadings had not been so remarkable, they would have been mistaken as secondary fluctuations that are frequent in the  $\eta$  Car spectrum.

An additional way of checking whether the periodicity is true is by comparing our data with those of Gaviola (1953). The description of the spectrum collected by that author in 1948 is detailed enough to show that  $\eta$  Car was very close to the center of a spectroscopic event on April 19. He reported that [N II]  $\lambda 5755$  was fainter than [Fe II]  $\lambda 5748$ . Our spectra collected during the last two events show that such an inversion of intensities remains for less than 3 months around the center of an event. The nine cycles between the 1948 and the 1998 events constrain very well the uncertainty in the periodicity:  $P = 2019 \pm 10$  days. This figure is in excellent agreement with that described above, based on the last two events. We can conclude that the events in  $\eta$  Car are truly periodic with  $P = 2020 \pm 5$  days (or  $P = 5.53 \pm 0.01$  yr).

The equivalent widths of the spectral lines, especially He I and the high-excitation forbidden lines, are quite predictable from cycle to cycle. In Figure 1b we display the He I  $\lambda 6678$  line during the events of 1998 and 1992 (the latter one shifted by 2020 days). This figure implies that the emitting volume and the speed of gas display a phase-locked behavior. Since no luminous hot star has been observed pulsating in such a regular fashion and ejecting identical shells, we rule out stellar instability as the mechanism responsible for the spectroscopic events in  $\eta$  Car.

### 3. THE ORBITAL PARAMETERS

The orbital solution presented by DCL had been discussed by Davidson (1997, 1999). Some concerns have been raised about the reliability of the broad-line components for tracing the orbital motion. On the one hand, broad lines are formed inside the wind and should display Doppler shifts if the star were a binary. On the other hand, radiative transfer effects could mask Doppler motion. If the event is produced by the plunging of the secondary star into the primary star wind (Dam-

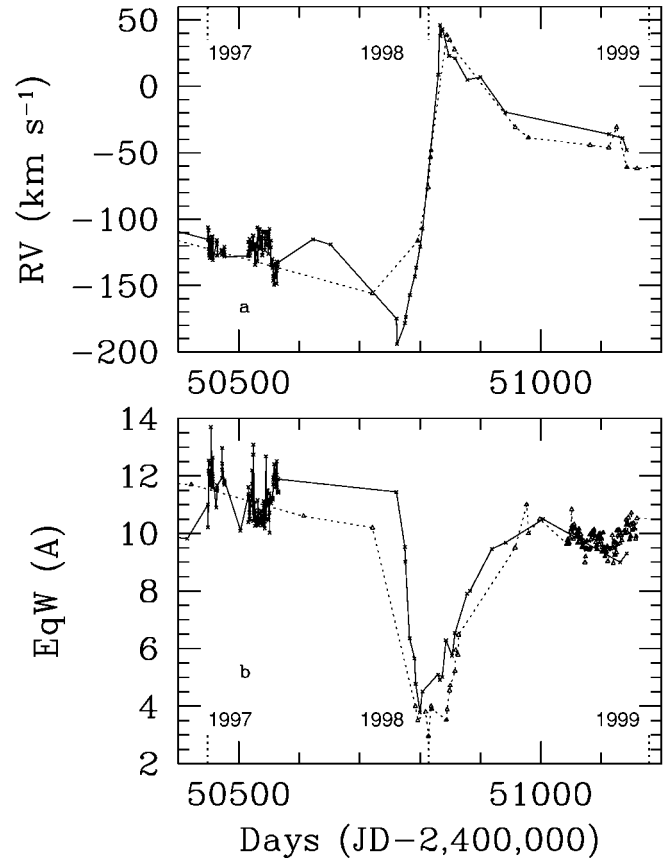


FIG. 1.—Variability during the present cycle (*solid line*) folded with the previous one displaced by 2020 days (*dotted line*): (a) radial velocity of the broad component in the He I  $\lambda 6678$  emission line and (b) equivalent width of the blend He I  $\lambda 6678$  + [Ni II]  $\lambda 6666$ . Dotted tick marks indicate the beginning of years.

ineli et al. 1999a), the ionization structure of the wind should change around periastron, mixing together Doppler and radiative transfer effects. Different lines would display different line-profile variations, making it difficult to predict which line tracks the orbital motion better. The best candidates are lines (broad components) displaying small changes in equivalent width and in line shape, with as faint as possible P Cygni absorption components. Some hydrogen Paschen lines are free of blends and look suitable for this purpose, as seen in DCL (their Fig. 1).

He I lines show strong variability in intensity and line profile. Deblending the broad components from the nebular and P Cyg contamination is not as straightforward as in hydrogen Paschen lines. The observed changes in He I lines reflect more the excitation effects in the wind than Doppler motion of the stars, and this is why we did not use them in the RV solution. The large number of observations we collected for the He I  $\lambda 6678$  line, however, still makes it the best tool for measuring the period length.

The RV curve containing all the available Pa $\gamma$  and Pa $\delta$  data results in the solution displayed in Figure 2. The best fit gives  $e = 0.75$ ,  $\omega_1 = 275^\circ$ ,  $T_{\text{periastron}} = \text{JD } 2,450,861$  (1998 February 17),  $K_1 = 50 \text{ km s}^{-1}$ , and  $fm_1 = 7.5 M_\odot$ . Conjunctions occur at phases 0.999 and 0.438. The standard deviation is  $\sigma = 11 \text{ km s}^{-1}$ . This result is in general agreement with those of Damineli et al. (1999a) and Davidson (1997). The main difference between present and previous results is the smaller mass func-

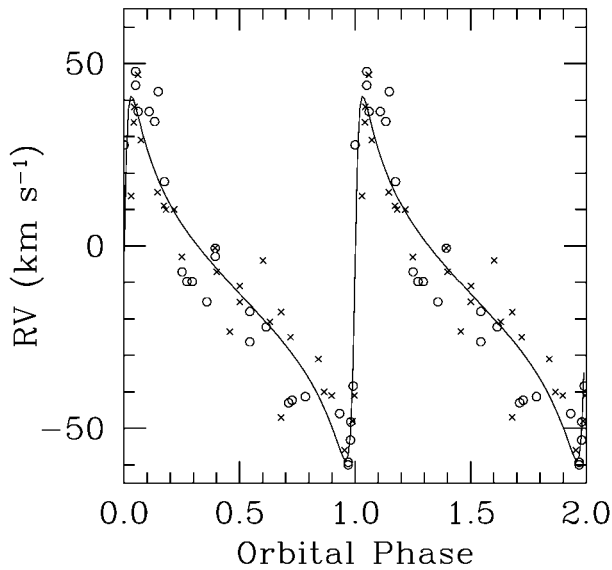


Fig. 2.—Radial velocity curve of Pa $\gamma$  and Pa $\delta$  broad-line components: previous cycle (circles), present cycle (crosses), and orbital solution (solid line).

tion ( $f m_1$ ) accommodating a smaller mass for the secondary star, which is desirable, since its spectrum is not visible in the optical or the UV. The mass of the unseen companion is difficult to constrain, since it depends on the mass of the primary star, the mass-loss rate, and the orbital inclination. Regarding the primary star, we adopt DCL's  $M_1 \sim 70 M_\odot$ , based on the total luminosity of the star, the age of the Tr16 cluster, and standard evolutionary models.

Figure 2 gives strong support in favor of binarity in  $\eta$  Car, but it does not necessarily guarantee that our orbital elements are accurate. There are two problems with our RV curve. First, Pa $\gamma$  shows changes in the shape of the broad-line component, indicating that the wind is not rigidly following the star. The effect in the RV curve seems to be small because the  $\gamma$  velocity ( $-12 \text{ km s}^{-1}$ ) derived from the RV curve agrees with  $V_{\text{rad}} = -7 \pm 9 \text{ km s}^{-1}$  obtained by Conti, Leep, & Lorre (1977) from seven O-type stars in the Carina Nebula. Second, data around the periastron are scarce, which is a problem for a system with such a high eccentricity. Acceptable eccentricities range from  $e \sim 0.65$  up to  $e \sim 0.85$ , displacing the time of periastron by several months (up to 0.05 in phase) around the center of the spectroscopic event. The other orbital elements are less sensitive to the details of the RV curve around periastron.

#### 4. DISCUSSION

The recovery of the 1998 spectroscopic event within less than 1% of the predicted time supports the hypothesis of true

periodicity. The strict repeatability in the RV curve and line intensities is unambiguously in favor of the binary model and against the idea of an unstable star as the explanation of the 5.5 yr cycle. Regardless of the particular value adopted for the orbital eccentricity ( $e > 0.65$ ), the primary star is a typical luminous blue variable star and the unseen companion a hotter and less evolved star. The orbital parameters must be regarded as very provisional, because data around periastron are scarce and based on broad emission lines and the physical parameters of very massive stars are uncertain. Nevertheless, the success of the CWB models in reproducing X-ray luminosity, temperature,  $N_{\text{H}}$ , and the dip in the light curve add credibility to the solution. Fitting the X-ray light curve by CWB models presents some problems around periastron, as shown by Ishibashi et al. (1999) and Stevens & Pittard (1999). However, nonspherical symmetry in the stellar wind or a circumstellar disk might remove the disagreement between observations and CWB models.

However, the  $\eta$  Car wind is not steady and probably not homogeneous, producing an RV curve that is not as simple as in classical cases. Significant profile variations have been seen in some spectral lines around periastron (Davidson 1999), indicating that gas blobs are thrown away from the stars, reminiscent of shell ejection suggested in previous works. This time, however, the mechanism is not advocated to explain the whole 5.5 yr cycle behavior, but minor perturbations.

Although the binary scenario accounts for the main observational characteristics of  $\eta$  Car, the nature of the spectroscopic events is not fully understood. Continuous monitoring of the system, with a better time sampling than that previously attained, is needed for the next event in 2003. An observational campaign starting in May should extend until late September to determine the RV curve, to late October to survey the dip in the X-ray light curve, and through December to follow the variability in different spectral lines. The star is not accessible during nighttime from August through October, which will preclude ground-based optical observations. High spatial resolution will be crucial to disentangle the stellar intrinsic variability from the associated light reflections through the surrounding nebula. Far-UV spectra are relevant, since the secondary (hotter) component of the system may be detectable; consequently, space-based facilities will be invaluable. From the ground, infrared and near-infrared will be required to perform daylight observations.

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