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THE 5.52 YEAR CYCLE OF ETA CARINAE[1]

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ABSTRACT

I have discovered spectroscopic variations correlated with the photometric near-infrared (NIR) light curve in η Carinae. The fading of the high-excitation lines is coincident with the peaks in the NIR light curve, strongly resembling an S Doradus type of variability. The cycle, however, is highly stable, and the 5.52 yr period fits well all the shell episodes reported in the last 50 years. This period also recovers the three historical bursts of the last century, in phase with the present low-amplitude oscillations, which suggests a connection between the S Doradus cycle and the giant bursts. The present data reveal that η Car is continuously varying in the He I λ10830 line by thousands of solar luminosities. The last spectra in this line show that the low-excitation phase is already in progress. A test for the strict periodicity will be the confirmation of the central phase epoch of the next shell event, predicted to occur in 1997 December. A very sensitive mapping technique is also proposed for this occasion, in order to prove Homunculus geometry.

Subject headings: stars: individual (η Carinae) — stars: variables: other (luminous blue variables) — stars: emission-line, Be

1. INTRODUCTION

η Carinae is one of the most luminous stellar objects of our Galaxy, with a luminosity of $5 \times 10^6 L_\odot$ (Andrisse, Donn, & Viotti 1978). If single, it is also one of the most massive stars known, having a mass of 120 $M_\odot$. It is believed to be in the luminous blue variable (LBV) stage, a short-lived strongly mass-losing phase, which causes a deep erosion in the outer layers of massive stars before they enter the Wolf-Rayet phase. η Car shares many features with other LBVs. In addition, this star underwent giant bursts in the last centuries. However, the S Dor–type variability, typical of LBV stars, is not clear in this object (van Genderen, de Groot, & Thé 1994). The main characteristic of the S Dor behavior is alternating states of quiescence, in which the star is fainter and hotter, and eruptive phases, in which it is cooler and brighter, in timescales of years to tens of years (van Genderen & Thé 1984; Humphreys & Davidson 1994; Lamers 1995). Occasional shell episodes were observed in η Car (see Damineli et al. 1995 for references). During those events, the high-excitation lines characteristic of the "normal spectrum" ([Ne III], [Fe III], [Ar III], and He I) faded out. This behavior has been suggested as being related to S Dor variability, although the associated photometric variations were not evident.

The last shell event of 1992 (Damineli et al. 1995; Baratta, Damineli, & Viotti 1993) was followed by an enhancement of flux in the radio wavelength range (Duncan et al. 1995) and by the reappearence of the stellar source in hard X-rays (Corcoran et al. 1995). A binary scenario was sometimes invoked to explain some features of the optical light curve (van Genderen et al. 1994), but this hypothesis is not supported by the observations.

The Homunculus is mainly a reflecting nebula (Humphreys & Davidson 1994; van Genderen & Thé 1984), which is apparently produced by a bipolar outflow (Warren-Smith et al. 1979; Hyland et al. 1979; Mitchell et al. 1983; Allen & Hillier 1993; Meaburn, Walsh, & Wolstencroft 1993; Frank, Balick, & Davidson 1995). Accurate maps of this nebula could shed some light on the mass ejection mechanism of this highly obscured star.

In this Letter, I propose a technique to map in detail the geometry of the Homunculus and to check the coherent periodicity of the central star, which been strongly suggested by recent data.

2. THE 5.52 YEAR SPECTRAL CYCLE

Spectroscopic observations of η Car were carried out with the 1.6 m telescope of the National Astrophysical Laboratory (LNA, Brazil) between 1989 and 1995 at the coudé focus with resolution of $R = 16{,}000$. During 1992 March through November, a shell episode was registered in great detail (Baratta et al. 1993; Damineli et al. 1995). The He I λ10830 line disappeared and was accompanied by a strong fading of other He I lines—λ5876, λ7065, and λ6678—and of [Ar III] λ7135. The lines of the Balmer and Paschen hydrogen series decreased moderately in intensity, as was also reported for past shell events. Table 1 shows the He I λ10830 line equivalent width (He I $W_{\rm eq}$) derived from the LNA data and from other authors (Allen, Jones, & Hyland 1985; McGregor, Hyland, & Hillier 1988).

Figure 1 displays the He I $W_{\rm eq}$ variations, superimposed on the light curve of Whitelock et al. (1994), that will be discussed in the next section. The plot shows a continuously varying line intensity, from He I $W_{\rm eq} = 806$ Å to He I $W_{\rm eq} = 6$ Å. It corresponds to a variation from ≈1500 to ≈15 $L_\odot$ in this single line. This behavior is different from that of a quiescent star perturbed by erratic shell episodes, as is frequently assumed in the literature. Those shell episodes correspond to phases of short duration around the minimum of cyclic high- and low-excitation states. I considered the epoch of the minimum to be the date of the lowest recorded He I $W_{\rm eq}$, which occurred on 1992 June 3 (1992.42). I cannot exclude, however, that even zero value could have been reached in the interval 1992 May 28–July 17. The rate of change in He I $W_{\rm eq} \approx 60$ Å per month is a typical value in the time interval 1992 March–November,

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[1] Based on data collected at CNPq/Laboratório Nacional de Astrofísica, Brazil.

TABLE 1

OBSERVATIONS OF He I λ10830

Julian Date (2,400,000+)	W_{eq} (Å)	References
44,955.5	298	1
45,109.5	806	1
46,176.5	463	2
46,864.9	45	3
47,614.6	643	4
47,917.7	487	4
48,022.5	427	4
48,062.6	412	4
48,257.8	360	4
48,286.6	349	4
48,405.5	359	4
48,700.6	216	4
48,769.6	30	4
48,777.6	6	4
48,821.8	24	4
48,938.8	205	4
48,959.8	249	4
49,058.7	347	4
49,106.7	315	4
49,134.5	464	4
49,162.5	367	4
49,192.5	373	4
49,317.8	323	4
49,414.7	354	4
49,562.5	397	4
49,646.8	428	4
49,761.6	426	4
49,797.7	424	4
49,849.5	426	4
49,852.5	432	4
50,051.8	375	4

REFERENCES.—(1) Allen et al. 1985; (2) McGregor et al. 1988; (3) Altamore et al. 1993; (4) this author.

characterizing a very sharp minimum, compared to the ≈10 Å per month scatter during the high-excitation phases.

The maximum value of the He I W_{eq} seems to be decreasing from cycle to cycle. The exact amount of fading, however, is difficult to derive, because of the coarseness of the time sampling. For the same reason, we cannot assume that the first point of the curve is the very minimum or that the second is the peak of that cycle. Their intensities are only an indication of how high or low is the state of the line excitation on that particular date.

There are five shell episodes documented in the literature since 1944, characterized by faint or absent high-excitation lines (Gaviola 1953; Rodgers & Searle 1967; Thackeray 1967; Viotti 1969; Melnick, Ruiz, & Maza 1982; Whitelock et al. 1983; Zanella, Wolf, & Stahl 1984; Allen et al. 1985; Bandiera, Focardi, & Altamore 1989; Baratta et al. 1993; Altamore, Maillard, & Viotti 1994). The shell episodes occurred in the years 1948, 1965, 1981, 1987, and 1992. The last three shell events indicate a cycle of about 5 years, suggested also by the near-infrared (NIR) data of Whitelock et al. (1994).

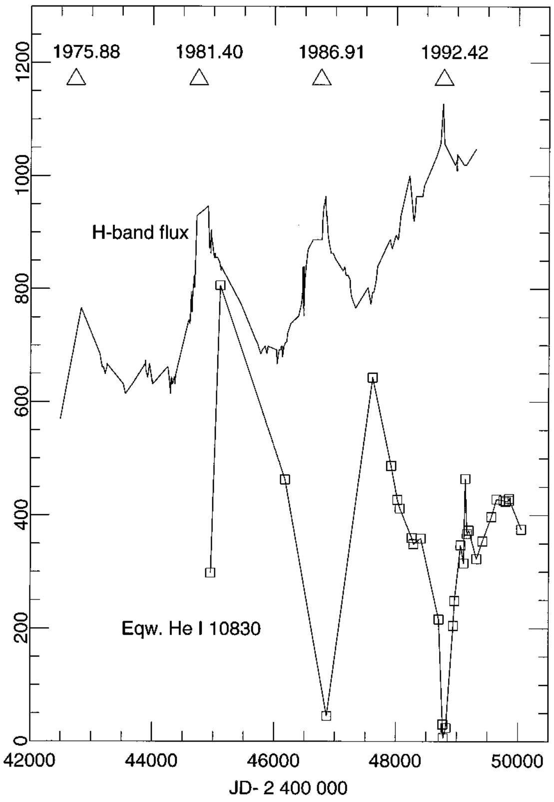

FIG. 1.—*Upper curve*: Flux in the H band, in units of 10^{-14} ergs cm^{-2} s^{-1} Å^{-1} data from Whitelock et al. (1994). *Lower curve*: He I W_{eq} = equivalent width of He I λ10830; triangles and dates at the top: predicted epochs of minimum excitation.

In order to search for a possible coherent variability, I chose as real minima the shell event of 1992 June 3 (1992.42) and that of 1948 April 19 (1948.30), reported by Gaviola (1953) on the basis of 70 plates, collected between 1944 and 1951. Eight complete cycles of 2014 days (5.52 yr) would have elapsed between them. The low-excitation episodes of 1965, 1981, and 1987 fit quite closely the epochs of predicted minima. $O - C$ values are summarized in Table 2 (col. [3]). The proposed period was successful not only in fitting all the registered shell episodes but also in assigning nonshell phases to all the time intervals in which the η Car spectrum exhibited the high-excitation lines (Gaviola 1953; Rodgers & Searle 1967; Thackeray 1953; Viotti 1968; Whitelock et al. 1983; Zanella et al. 1984; Ruiz, Melnick, & Ortiz 1984; Hillier & Allen 1992; Bidelman, Galen, & Wallerstein 1993; Damineli et al. 1995).

By adopting the last observed shell event as T_0, the epochs of the minima are given by

$$\text{JD} = 2{,}448{,}777 + 2014n, \qquad (1)$$

where JD is the Julian Day and n is any integer. The uncertainty in T_0 is assumed to be the time delay between the lowest recorded He I W_{eq} and the dates of the two contiguous measures, 6 days before and 48 days after. The next zero phase is predicted to occur on 1997 December 8, but, taking into account the uncertainty in T_0, it can occur as early as 1997 December 2 or as late as 1998 January 25. Other minima must have occurred around 1975 November, 1970 May, 1959 May, and 1953 November. A search in archival data, spread all over the world, could reveal some yet unnoticed shell event or perhaps refute the proposed periodicity.

3. PHOTOMETRIC OSCILLATIONS

The highly homogeneous NIR photometry of Whitelock et al. (1994) is an important piece of data to study the S Doradus behavior of η Car. The H-band data reported by these authors, transformed into flux units, are plotted in Figure 1, together with the epochs of minimum excitation, predicted by the spectroscopic period. There is a remarkable correlation be-

TABLE 2

EVENTS OF LOW EXCITATION OR PHOTOMETRIC PEAKS

Predicted (Year) (1)	Observed (Year) (2)	$O - C$ Phase (3)	Type of Event (4)	References (5)
1827.01	1827.1	0.02	mag = 1.0, marked peak	1
1838.03	1838.0	−0.01	mag = 0.2, marked peak	1
1843.55	1843.2	−0.06	mag = −1.0, highest peak	1
1948.30	1948.30	0.00	He I, [Ne III], [Fe III] disappeared	2,13
1964.85	1965.2	0.06	He I, [Ne III], [Fe III] faded out	3
1975.88	1976.1	0.04	Photometric local max, *H* band	4
1975.88	1976.3	⋯	Photometric local max, *V* band	5
1981.40	1981.49	0.02	[Fe III] disappeared; N III], Si III] faint	6,12
1981.40	1981.62	⋯	Photometric local max, *J*, *H*, *K*, *L*	4
1981.40	1981.89	⋯	Photometric local max, *V* band	5
1986.91	1987.09	⋯	Photometric local max, *J*, *H*, *K*	4
1986.91	1987.04	0.02	He I λλ10830, 5876 very faint	7, 8
1992.42	1992.42	⋯	[Ar III], [Fe III], He I disappeared	9
1992.42	1992.30	−0.02	Photometric local max, *H* band	4
1992.42	1992.4	⋯	Hard X-ray minimum	10
1992.42	1992.49	⋯	Radio flux minimum	11
1997.94	⋯	⋯	Next predicted event	⋯

REFERENCES.—(1) Innes 1903; (2) Gaviola 1953; (3) Rodgers & Searle 1967; (4) Whitelock et al. 1994; (5) van Genderen et al. 1994; (6) Zanella et al. 1984; (7) Altamore et al. 1994; (8) Bandiera et al. 1989; (9) Daminelli et al. 1995; (10) Corcoran et al. 1995; (11) Duncan et al. 1995; (12) Baratta et al. 1993; (13) Viotti 1968.

tween the He I W_{eq} variations and the NIR light curve, the minimum excitation phases corresponding to the maximum continuum brightness. This behavior characterizes η Car as a bona fide S Dor variable. In this case, the low-excitation phases would be caused by the radial expansion and photospheric cooling of the central star (Lamers 1995). The amplitude of the S Dor variability is smaller in shorter wavelengths (van Genderen et al. 1994), probably because of the light absorption and scattering inside the Homunculus. Light-curve peaks, however, can be seen up to the *V* band in some shell events.

At close inspection, it can be noticed that for almost each feature in the NIR light curve there is a corresponding one in the He I W_{eq}. The long-term decrease in He I W_{eq} has a corresponding trend in the brightening of the continuum. This trend could be explained by a secular expansion and photospheric cooling of the central star, rather than the decrease in the circumstellar reddening (van Genderen et al. 1994). The *H*-band maxima culminate in narrow peaks coinciding with the sharp minima of the He I W_{eq}, which indicates that the variations are not sinusoidal.

The NIR light curve gives support to the 5.52 yr period in two ways. The first is that a shell event predicted to have occurred in 1975.88 coincides with a photometric peak, observed in 1976.1. The difference in phase is only 0.04, despite the poor sampling in the NIR light curve at that epoch.

Second, the period derived only on the basis of the NIR light curve is very similar to the spectroscopic one. In order to derive an independent period, I averaged the time interval from peak to peak in the Whitelock et al. (1994) *H*-band data. The recurrence time is 1971 days, with an uncertainty of 43 days, close to the observational time sampling. This recurrence time is indistinguishable from the spectroscopic 2014 day cycle (5.52 yr), although it was derived using different techniques in different time intervals. Whitelock et al. (1994) obtained a somewhat shorter period (1870 days) by Fourier analysis of their NIR data. However, in the present case, the method based on the sharp peaks must be preferred, because the light-curve irregularities can contaminate the results. I assumed, in this Letter, that the period is best represented by the spectroscopic data, because it spans a longer time interval.

If the periodicity is as stable as it seems to be, it could be seen in other time intervals. Epochs of zero phase (maximum light or minimum excitation) were predicted for the past centuries and compared with the observations reported by Innes (1903). The most ancient data are not very reliable, but the magnitudes after 1811 are referred to a system of known stars. Before entering in the big fading phase, after 1850, η Car underwent three great bursts, in 1827, 1838, and 1843, reproduced from Innes (1903) in Figure 2. According to the 5.52 yr period, peaks should have occurred in exactly those years and quite close to the predicted zero phases, as seen in Table 2 and Figure 2. The mean deviation in phase, derived from this set of epochs, is $|O - C| = 0.03$ and is of the same order of magnitude as the time sampling. It is unlikely that this coincidence is accidental.

I have surveyed all the historical data, excluding the time interval in which η Car was faint (1860–1948), when the light curve oscillations disappeared or decreased strongly in amplitude. In the papers of Innes (1903) and of Polcaro & Viotti (1993) I found additional events in which the star was noted as bright. The 5.52 yr period predicts epochs of zero phases not far from some of these events. This is very curious but cannot be used to give further support to the 5.52 yr period because of the low confidence of the data. On the other hand, I did not find a single evidence against the proposed periodicity.

If the three great bursts of the last century were really connected to the present ongoing oscillations, the giant eruptions of the LBVs would be due to the same mechanism that drives the S Doradus variability. This point deserves further attention, especially through carefully planned observations of the next minimum excitation phase of η Car.

4. DISCUSSION

The inversely correlated variations of the He I W_{eq} and the NIR light curves seem to be a new cornerstone to understanding the nature of η Car. They resemble those of S Dor

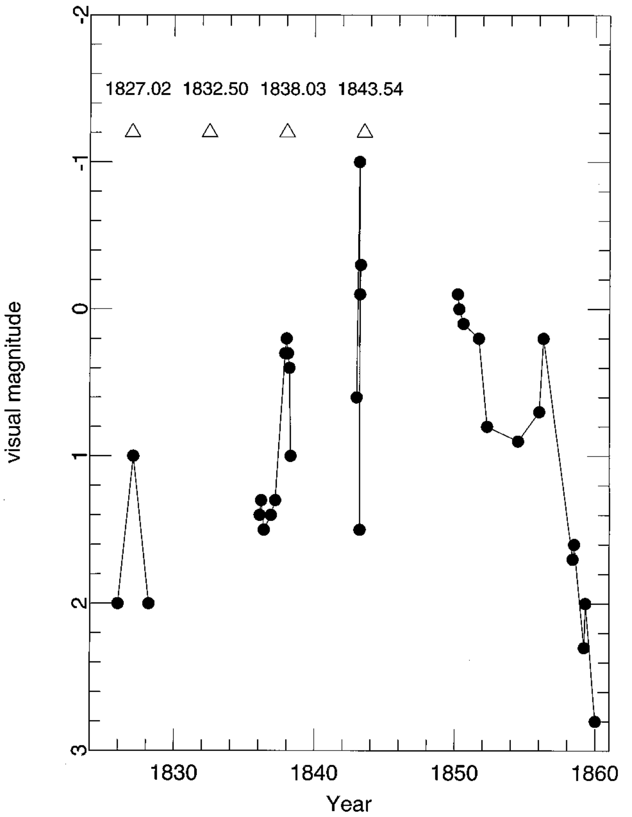

FIG. 2.—η Car light curve during the epoch of the great bursts, reproduced from Innes (1903); triangles and dates at the top: predicted epochs of minimum excitation.

variables, although the amplitude of the light curve is smaller and only the higher excitation lines show remarkable variations. The lack of corresponding variations in the UV and the low amplitude in the V band could be explained by light absorption and scattering inside the Homunculus. The 5.52 yr cycle, however, is unusually stable for the standards of the S Doradus class. If η Car is a pulsating star, it would be different from all other known luminous stars because their cycles are much less stable.

A binary hypothesis seems to be plausible, in a scenario of coherent cycles. A low-mass secondary star would orbit a $M = 120\,M_{\odot}$, $R_* = 10^3\,R_{\odot}$ primary one at a distance of about $D = 3\,R_*$, in a period of 5.52 yr. An elliptic orbit inside the dense circumstellar region could provide a variable mass accretion onto a compact star, in order to explain the NIR light curve. In this case, however, the photometric peaks would be expected to coincide with the high-excitation phases, contrary to the observations.

A critical test is proposed to the 5.52 yr period by the prediction of a new shell phase to occur in 1997 December or 1998 January. The next low-excitation phase will be important to study not only the central star but also the associated nebula. The Homunculus is mainly a reflection nebula, and so the variations of the central star can be traced through it by the "light echoes." As can be seen in Figure 1, the larger variations are in the He I $W_{\rm eq}$ rather than in broadband filters. The equivalent width, on other hand, is preserved when the light is scattered and dimmed by the dust. The best season to apply this technique is during the 6 months time interval around the epoch of minimum excitation, when the He I $W_{\rm eq}$ declines and rises again in a rate of nearly 60 Å per month. It can give an independent check of the presently accepted model of a bipolar flow of the Homunculus (Warren-Smith et al. 1979; Hyland et al. 1979; Mitchell et al. 1983; Allen & Hillier 1993; Meaburn et al. 1993; Frank et al. 1995).

The most recent spectra show that the He I $W_{\rm eq}$ curve is declining. After a phase of constancy in 1994, the He I $W_{\rm eq}$ decreased by nearly 60 Å from 1995 May to November, with a gradient that is similar to the rate of changes in 1991. This seems an announcement that a new low-excitation event is forthcoming, as predicted by the 5.52 yr cycle.

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