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ON THE MULTIPLICITY OF η CARINAE

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ABSTRACT

The nebula around the luminous blue variable (LBV) η Car is extremely N rich and C and O poor, which is indicative of CNO-cycle products. On the other hand, the recent *Hubble Space Telescope*–Goddard High-Resolution Spectrograph observation of the nucleus of η Car shows the spectrum of a star with stellar-wind lines of C II, C IV, Si II, Si IV, etc. The spectrum is very similar to those of the LBV star P Cygni and of WN9/Ofpe stars. This line spectrum is indicative of a photosphere that is only mildly enhanced by CN-cycle products. This situation of a nebula that is chemically more advanced than the central star cannot be reached by the evolution of a single star. The dichotomy shows that the star whose spectrum now dominates the nucleus was not the star that ejected the nebula. We discuss this evidence for multiplicity and combine it with the information about the 5.5 yr periodicity in the emission lines.

Subject headings: binaries: close — stars: abundances — stars: early-type — stars: individual (η Carinae) — stars: variables: other — supergiants

1. INTRODUCTION

The luminous blue variable (LBV) η Car is well known for its dramatic outburst in 1840 and its present spectacular bipolar nebula (Humphreys & Davidson 1994; Davidson & Humphreys 1997; Dufour et al. 1997; Ebbets, Walborn, & Parker 1997b). The star was previously suspected to be a binary on the basis of its light variations with a period of about 60 days (van Genderen et al. 1995); however, since this period is not stable and since it is similar to the pulsation period of other LBVs (Lamers et al. 1998), this is probably not a binary period. A much more convincing period of 5.52 ± 0.01 yr has been found by Damineli (1996, 1997) on the basis of large variations in the strength of the He I 10830 Å emission line and in the *H*-band magnitude. The evidence has been traced back as far as 1948. The prediction and the subsequent verification of the decrease in line strength at the end of 1997 December (Jablonski, Lopes, & Damineli 1998) is a beautiful confirmation of this periodicity.

The strict periodicity over such a long timescale suggests a binary that somehow changes the ionization conditions in the nebula and the infrared emission either due to changes in the viewing angle or due to an elliptical orbit (Damineli, Conti, & Lopes 1997; Davidson 1997). The question is, Do we see additional evidence for the presence of a second star? In this Letter, we shall argue that the recent *Hubble Space Telescope* (*HST*)–Goddard High-Resoluton Spectrograph (GHRS) spectrogram of the central object of η Car (Ebbetts et al. 1997a, 1997b) can only be explained if the system contains a binary.

2. THE CHEMICAL COMPOSITION OF THE NEBULA AND THE CENTRAL OBJECT

The chemical composition of the η Car nebula has been studied by Davidson et al. (1986) and Viotti et al. (1989) and recently on the basis of *HST*–Faint Object Spectrograph data by Dufour et al. (1997). These authors find that the nebula has a very high N abundance and very low C and O abundances. (Davidson et al. [1986] have shown that the C-depletion of the nebula is not due to condensation on grains. The main argument is that O is also depleted, and that cannot be due to silicate formation because strong Si features are observed in the condensations.) This shows that the nebula consists of the ejected stellar outer layers with typical equilibrium CNO-cycle products. The nebular abundances are listed in Table 1, where they are compared with those of other LBV nebulae. We also show the abundances for H II regions in the Galaxy (for comparison with η Car and AG Car) and in the LMC (for comparison with R127 and S119). The other LBV nebulae are also N enriched as compared to H II regions but not nearly as extremely as in the case of η Car. For example, [N/O] = 1.4–1.9 for LBV nebulae, whereas it is 2.9 for the η Car nebula.

The *HST*-GHRS spectrogram of the nucleus of η Car (from Ebbets et al. 1997b) is compared with an *IUE* observation of P Cygni in Figure 1. As already noticed by Ebbets et al., the similarity is remarkable. The spectrum of η Car shows many P Cyg profiles of abundant elements over a wide range of ionizations, e.g., from C IV to C II. The strong C II resonance lines near 1335 Å and the weaker C IV lines near 1550 Å are particularly interesting because we have shown above that the spectrum of the nebula is strongly depleted in C with $\log C/H = -5.00$, compared to the value of -3.5 in H II regions. Ebbets et al. also compared the spectrum of η Car with those of other supergiants and found that it resembles a linear combination of the spectra of the B2 Ia star χ^2 Ori and the B8 Ia star β Ori. C. Leitherer (1998, private communication) noted that the spectra of η Car and P Cyg are very similar to those of the WN9/Ofpe stars (Pasquali 1997). These comparison objects all have either normal or only slightly N-enhanced and C-depleted atmospheres. This similarity suggests very strongly that the apparent nucleus of η Car is a star with a wind of normal or slightly N-enhanced and C-depleted composition.

We can estimate a lower limit to the C abundance in the wind of the nucleus by comparing the strength of the low-ionization lines of C II λ1335 with those of Si II $\lambda\lambda$1264, 1533. The profiles are overplotted on a velocity scale in Figure 2. The line of C II λ1335 is obviously very strongly saturated. It is as saturated or stronger than the Si II λ1264 line. The Si II λ1264 line has an optical depth that is about 8 times larger

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TABLE 1

Logarithmic Abundance Ratios in the Nebulae of η Car and Other LBVs

Name	N/H	N/O	N/C	N/Ne	N/S	References
η Car	−3.10	1.73	1.90	0.83	1.67[a]	Dufour et al. 1997
AG Car	−3.78	0.75	...	...	<1.66	Smith et al. 1997
R127	−3.95	−0.05	...	...	<1.5	Smith et al. 1998
S119	−3.77	0.24	...	...	<1.9	Smith et al. 1998
Galactic H II	−4.43	−1.13	−0.89	−0.33	0.51	Shaver et al. 1983
LMC H II	−4.98	−1.40	...	...	...	Russell & Dopita 1990

[a] Derived from the Ne/H ratio with log Ne/S = 0.84.

than that of the Si II λ1533 line because the lines originate from the same lower level and their *gf*-values differ by a factor 8. So the C II λ1335 line is at least a factor 8 stronger than the Si II λ1533 line. Since the *gf*-value of the C II line is twice as large as that of the Si II λ1533 line, the abundance ratio C II/Si II must be at least a factor 4. A similar comparison between the profiles of the C IV and the Si IV resonance lines shows that the C IV lines are about 2 or 3 times weaker than the Si IV lines. Using the ratios of the *gf*-values, we find a number ratio of C IV/Si IV of about unity. The spectrum of P Cyg, which has a moderately N-enhanced photosphere (Luud 1967), shows about the same ratios in the strengths of the Si II/C II and the Si IV/C IV lines.

This very crude analysis suggests that the abundance ratio C/Si in the wind of the nucleus of η Car is between about 1 and 5, compared to a solar value of C/Si = 10. This result indicates a *mild depletion* of C, with [C/Si] = -0.65 ± 0.35, in the apparent nucleus of η Car, in contrast to the η Car nebula, where C is depleted relative to H by a factor of about 30 and relative to Ne (and hence also to Si) by [C/Si] $\simeq$ [C/Ne] = -1.6.

3. ABUNDANCES AND STELLAR EVOLUTION

According to basic concepts of stellar evolution, the strong N enhancement and the strong C and O depletion in the nebula show that it was ejected from a star whose surface layers consist of CNO-cycle products. These elements were produced in the H-burning core and mixed into the layers above the core by convection and possibly also by overshooting. Mass loss in the previous phase must have peeled off the surface layers with the initial abundances so that the layers with CNO-equilibrium composition appeared at the surface. The ejection of these outer layers then resulted in a nebula with this same composition. We stress that these considerations are independent of the details of the stellar evolution and independent of the ejection mechanism.

After the ejection of the nebula, the remnant star should show either the same surface composition as the nebula (if only a part of the layer with CNO-equilibrium products was ejected) or the subsequent more advanced composition, i.e., an He-rich, N-rich, and C-depleted layer (as in Wolf-Rayet stars of type WN) or an He-rich, N-depleted, and C-rich layer (as in Wolf-Rayet stars of type WC). The latter composition occurs when the products of triple-α burning reach the surface. We have shown above that the photospheric and wind composition of the nucleus of η Car shows a considerably higher C-abundance than expected for a WN composition. (The UV spectra of WN stars do show strong C IV resonance lines despite the reduced C abundance owing to the sensitivity of these transitions; Walborn, Nichols-Bohlin, & Panek 1985).

Could the high C-composition be due to triple-α products appearing at the surface? If this were the case, then there should be no H left in the photosphere and He would be the dominant constituent. In that case, we would expect the star to be a Wolf-Rayet star, which is not in agreement with the observed spectrum. The observations by Hillier & Allen (1992) also argue strongly against an He star as a central source. They show that the spectrum of the homunculus arises from a combination of nebular emission lines and of scattered radiation from the central source. This scattered radiation in the visual shows P Cyg emission lines of H I, He I, Fe II, and Na I. Hillier & Allen conclude that the central source must have the spectrum of a B star, similar to P Cyg, which is nicely confirmed in the *HST*-GHRS UV data by Ebbets et al. (1997b). The fact that the visual spectrum shows H I and He I lines similar to P Cyg shows that the apparent nucleus is not a helium star. Together with the C/Si ratio of about 1–5, derived from the UV spectrum,

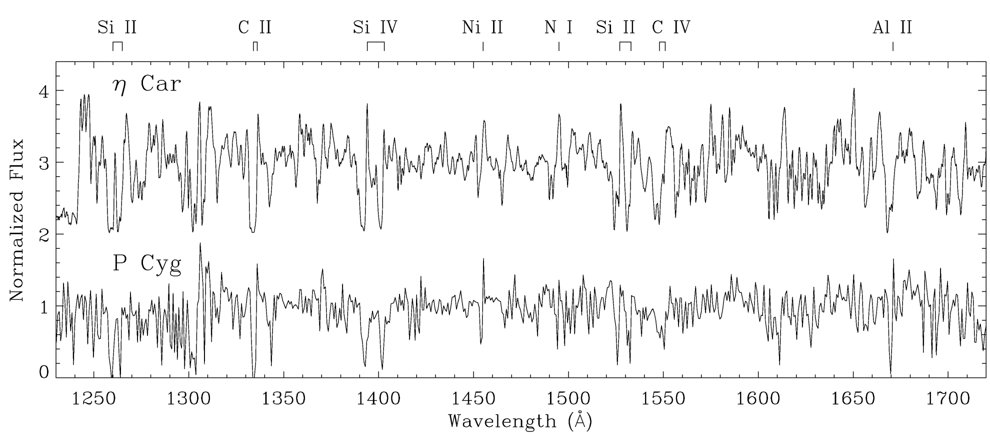

Fig. 1.—UV spectrum of the nucleus of η Car compared with that of the LBV P Cyg; from Ebbets et al. (1997b).

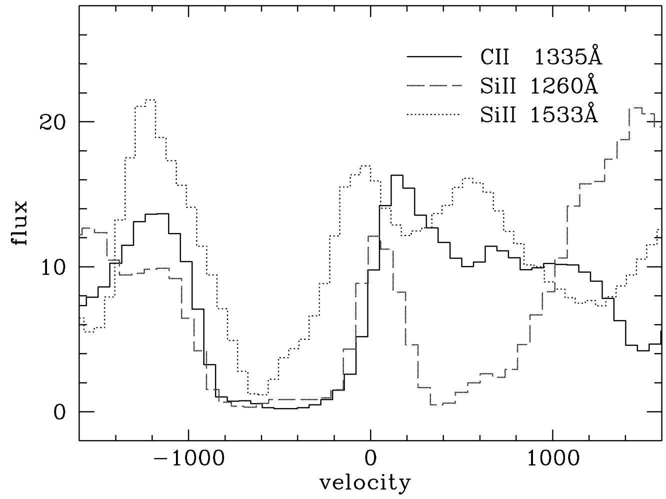

FIG. 2.—UV resonance lines of C II and Si II in the UV spectrum of η Car.

this indicates that the surface of the apparent nucleus consists of mildly enhanced CN-cycle products.

We conclude that the spectrum of the apparent nucleus of η Car is not in agreement with that expected of a star that has ejected a nebula with CNO-equilibrium composition. This conclusion implies that *the star that produces the spectrum of the apparent nucleus is not the one from which the nebula was ejected*. So there are at least two stars in the system.

4. DISCUSSION

Let us assume that the 5.5 yr periodicity, found by Damineli (1996), is due to a binary period and that one of the components ejected the nebula and the other one presently dominates the light of the nucleus. The luminosity of the nucleus indicates that the initial mass of the star was about 100 $M_\odot$. The star that ejected the nebula was chemically more evolved, so it was most likely more massive. For a conservative estimate, let us assume that the present-day masses are about 60–80 $M_\odot$ for the star that produces the spectrum and about 50–70 $M_\odot$ for the star that ejected the nebula. With a total mass of about 110–150 $M_\odot$, the period of 5.5 yr corresponds to a mean separation of 15 AU. The mild degree of ionization of the homunculus shows that the star that ejected the nebula has $T_{\rm eff} \leq 30{,}000$. This suggests that the star still has an extended envelope which prevents it from being a hot "bare core" He star.

The presence of at least two massive stars at such a close distance, each one with a strong stellar wind, will lead to a nonspherical configuration of colliding winds. If such colliding winds produce dust, the variability in the emission-line strength might be due to aspect-angle effects. If the orbits are elliptical (see Davidson 1997), the variable distance between the two objects might also contribute to the observed changing ionization conditions.

Recently P. Morris, N. Trams, & L. Waters (1998, private communication) have found, on the basis of the *ISO* spectrum of η Car, that there is an optically thick dust disk around the central object. We suggest that this disk is responsible for the obscuration of the star that ejected the nebula.

Livio & Pringle (1998) have shown that if the 5.5 yr emission-line period and the suggested (less well-defined) 85 day period in the X-ray flux (Corcoran et al. 1997) are taken at face value, they might indicate a triple system. Livio & Pringle speculate that the interchange of the components in such a system might have triggered the great 1840 outburst. Interestingly, they argue that if that is the case, the present spectrum is from the star in the wide orbit and not from the star that ejected the nebula. Our analysis does not give information about a possible triple system, but it does indicate that the nebula was not ejected by the presently observed star.

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