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DETECTION OF A HOT BINARY COMPANION OF η CARINAE[1]

Rosina C. Iping,[2,3] George Sonneborn,[2] Theodore R. Gull,[4] Derck L. Massa,[2,5] and D. John Hillier[6]
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ABSTRACT

We report the detection of a hot companion of η Carinae using high-resolution spectra (905–1180 Å) obtained with the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) satellite. Observations were obtained at two epochs of the 2024 day orbit: 2003 June, during ingress to the 2003.5 X-ray eclipse, and 2004 April, several months after egress. These data show that essentially all the far-UV flux from η Car shortward of Lyα disappeared at least 2 days before the start of the X-ray eclipse (2003 June 29), implying that the hot companion, η Car B, was also eclipsed by the dense wind or extended atmosphere of η Car A. Analysis of the far-UV spectrum shows that η Car B is a luminous, hot star. The N II $\lambda\lambda$1084–1086 emission feature suggests that it may be nitrogen-rich. The observed far-UV flux levels and spectral features, combined with the timing of their disappearance, is consistent with η Car being a massive binary system.

Subject headings: binaries: eclipsing — circumstellar matter — stars: individual (η Carinae) — stars: mass loss

1. INTRODUCTION

The star η Carinae (HD 93308), a prominent member of the Trumpler 16 (Tr 16) association, is undoubtedly the most well known and well studied luminous blue variable (LBV). It is possibly the most massive star in the Galaxy, and its unstable nature has attracted many investigators (see Davidson & Humphreys 1997 for a review). There is now strong evidence that η Carinae is a binary. A period of ~2023 days is inferred from periodic spectral and light changes in the visual (Damineli 1996; Damineli et al. 2000) and the near-IR (Whitelock et al. 1994, 2004). The X-ray light curve varies strongly with a 2024 $\pm$ 2 day period (Ishibashi et al. 1999; Corcoran 2005). Two X-ray eclipses (1998.0 and 2003.5) have been observed in which the X-ray flux dropped to less than 15% of its peak for ~3 months. The hard X-ray spectrum suggests a colliding-wind binary (Ishibashi et al. 1999; Pittard & Corcoran 2002; Corcoran 2005), with the dense stellar wind from the massive LBV primary (η Car A) colliding with the higher velocity, lower density wind of a hot O-type secondary (η Car B) in a highly eccentric 5.54 yr orbit. The presence of a hot secondary is also inferred from photoionization modeling of the variability of doubly ionized lines from the Weigelt blobs (Verner et al. 2005).

Until now η Car B has evaded direct detection, because η Car A dominates the systemic light from the infrared through the UV longward of Lyα. Furthermore, η Car A's dense wind and dusty ejecta extinguish much of its own UV and visible luminosity, which drop dramatically below 1250 Å (Hillier et al. 2001; Gull et al. 2005a).

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[2] Laboratory for Observational Cosmology, Code 665, NASA Goddard Space Flight Center, Greenbelt, MD 20771; rosina@taotaomona.gsfc.nasa.gov, george.sonneborn@nasa.gov, massa@taotaomona.gsfc.nasa.gov.

[3] Department of Physics, Catholic University of America, 620 Michigan Avenue, NE, Washington, DC 20064.

[4] Laboratory for Exoplanets and Stellar Astrophysics, Code 667, NASA Goddard Space Flight Center, Greenbelt, MD 20771; theodore.r.gull@nasa.gov.

[5] SGT, Inc., 7701 Greenbelt Road, Suite 400, Greenbelt, MD 20770.

[6] Department of Physics and Astronomy, University of Pittsburgh, 3941 O'Hara Street, Pittsburgh, PA 15260; djh@rosella.phyast.pitt.edu.

In this Letter, we report the first spectroscopic evidence and direct detection of η Car B using *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) spectra from two epochs. One is a series of large-aperture (LWRS) far-UV (FUV) spectra obtained in 2003 June as η Car approached and entered the X-ray eclipse. The second is a set of LWRS and narrow-slit (HIRS) spectra obtained in 2004, 6 months after the end of the X-ray eclipse. The LWRS observations of η Car also include two 11th magnitude B stars that lie close to η Car, which, as we shall see, account for about half of the observed FUV flux in the LWRS observations. Luckily, during some of the LiF1-channel HIRS observations of η Car, we serendipitously obtained spectra of the B stars through the HIRS slit of the SiC1 channel. Comparison of the SiC1 HIRS observation and the eclipse ingress observation enables us to disentangle the LWRS spectra and reveal the spectrum of η Car B. However, because the LWRS spectra contain the B stars, it is necessary to employ a three-step process to establish that the LiF1 HIRS spectrum of η Car is dominated by the flux of η Car B, and not η Car A.

First we demonstrate that the LiF1 HIRS spectrum of η Car plus the SiC1 HIRS spectrum of the nearby B stars accounts for all FUV flux from the system obtained through the LWRS aperture at nearly the same epoch. This implies that the LWRS spectra are dominated by η Car and the nearby B stars and that there is very little contribution from other sources, such as the surrounding nebulosity. Second, we show that the LWRS spectrum of η Car at the start of the X-ray minimum (when the secondary is expected to be eclipsed) is nearly all due to the B stars and that η Car A contributes very little to the FUV flux of the system. Third, we show that the FUV spectrum outside of eclipse (when η Car B is expected to contribute to the flux) is much stronger and consistent with a source of higher effective temperature than η Car A.

2. OBSERVATIONS

FUSE observed η Car multiple times between 2000 and 2004 using the LWRS aperture (30″ × 30″). This Letter utilizes a subset of these data (see Table 1). The observations were processed with the *FUSE* data processing and calibration pipeline (CalFUSE 3.0). Spectra from the individual exposures were co-added with the IDL program FUSE_REGISTER.[7]

[7] See the *FUSE* data analysis link at http://fuse.pha.jhu.edu.

TABLE 1
FUSE Observation Parameters

ObsID	Date	UT	ϕ[a]	Exp. (s)	Aperture	p.a. (deg)
D0070102 ……	2003 Jun 10	14:36	0.9888	15282	LWRS	195.3
D0070103 ……	2003 Jun 17	03:33	0.9922	14311	LWRS	201.1
D0070104 ……	2003 Jun 27	00:21	0.9972	4531	LWRS	209.5
D0070107 ……	2004 Mar 29	14:36	0.1335	9202	LWRS	119.4
D0070108 ……	2004 Mar 30	09:42	0.1340	34281	LWRS	120.2
D0070210 ……	2004 Apr 9	03:23	0.1390	34476	HIRS	131.3
D0070311 ……	2004 Apr 10	07:18	0.1395	24795	HIRS	132.7
D0070109 ……	2004 Apr 11	21:16	0.1400	17118	HIRS	134.5

[a] Phase defined by the X-ray ephemeris 2,450,799.792 + 2024*E* (Corcoran 2005).

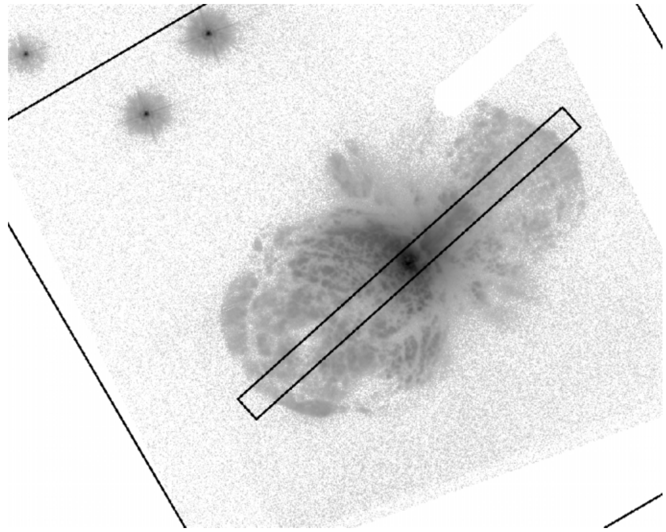

Fig. 1.—*HST* ACS 2200 Å (F220W) image of η Car obtained on 2003 June 13. The *FUSE* apertures are shown for 2004 March 30 (LWRS, 30″ × 30″, p.a. = 120°) and 2004 April 9–11 (LiF1a HIRS, 1.″25 × 20″, p.a. = 134°). The stars Tr 16-64, 16-65, and 16-66 are clearly visible. North is up, and east is to the left.

The *FUSE* instrument (Moos et al. 2000; Sahnow et al. 2000) obtains spectra in four independent optical channels: LiF1 and LiF2 (995–1185 Å), and SiC1 and SiC2 (900–1100 Å). Each channel has two segments (e.g., LiF1a, LiF1b) that each covers ~100 Å. The relative alignment of the four channels is influenced by the thermal history of the satellite in the days preceding a given observation. Thermal flexure in the instrument often results in alignment shifts of 10″–20″ in the other three channels relative to LiF1, which is held fixed by the offset-guiding system. For HIRS-aperture (1.″25 × 20″) observations, this often means the target is only in LiF1.

The SiC2 (920–1100 Å) HIRS aperture was on η Car for 6.9 ks of the 17.1 ks April 11 observation. After scaling the flux by a factor of 5, the SiC2b HIRS spectrum is essentially identical to that of LiF1a HIRS, indicating that the SiC2 aperture was not perfectly centered on target. SiC2 adds the 1082–1100 Å region, containing the important N II λλ1084–1086 and He II λ1085 lines.

Given η Car's spectroscopic variability and probable binary nature, we anticipated that its FUV flux would significantly decrease as it approached the X-ray eclipse. However, a surprising amount of FUV flux was present in all LWRS spectra of η Car. This resulted from spectral contamination of the LWRS observations by two 11th magnitude B stars, Tr 16-64 and Tr 16-65 (Feinstein et al. 1973), also members of Tr 16, located just under 14″ from η Car (see Fig. 1 and Table 2). They lie just inside the edge of the LWRS aperture at all position angles. A third B-type star, Tr 16-66, is located 20.″0 from η Car and could, therefore, contribute to the LWRS flux only in a narrow range of aperture position angles (p.a. = 16° ± 4°, and increments of 90°). *Hubble Space Telescope* (*HST*) Advanced Camera for Surveys (ACS) near-UV images from 2003 June 13 provide astrometry and UV photometry for these stars. The 2200 Å flux from Tr 16-64 is 4.5×10^{-13} ergs cm^{-2} s^{-1} $Å^{-1}$ and the Tr 16-64 : -65 : -66 brightness ratio is 1.00 : 0.55 : 0.20 at 2200 Å. Tr 16-64 has spectral type B1.5 V (Levato & Malaroda 1982). With Tr 16 membership and similar *V*, visual, and UV colors (implying no significant extinction differences), Tr 16-65 must also be an early B star. Comparison of *V* and UV brightnesses indicates that Tr 16-66 would contribute less than 10% of the combined FUV flux of Tr 16-64 and Tr 16-65 to LWRS observations.

Serendipitously, the aperture position angle and thermal alignment shifts during the LiF1 HIRS observations in 2004 April brought the SiC1 HIRS aperture to the location of Tr 16-64 and Tr 16-65. Examination of the time-tag data shows steady count rates in SiC1 HIRS for 48 out of 59 ks on April 9 and 10. No signal from the B stars was present in the SiC1 HIRS channel on April 11. Although the exact SiC1, SiC2, and LiF2 aperture locations during the LiF1 HIRS observation are not known, there are no other stellar sources of FUV flux within the range of HIRS aperture motion. The B star spectrum recorded in SiC1 is a combination of Tr 16-64 and Tr 16-65.

3. RESULTS

The *FUSE* LiF1 HIRS spectrum gives the intrinsic FUV spectrum of η Car, without contributions from Tr 16-64 and Tr 16-65. Figure 2*a* shows the 1045–1090 Å region of this observation, and the SiC1a HIRS spectrum of Tr 16-64 plus Tr 16-65 is shown in Figure 2*b*. Given the observed flux levels (~2×10^{-12} ergs cm^{-2} s^{-1} $Å^{-1}$), a significant fraction of the flux of these stars was in the SiC1 HIRS aperture. The B stars and η Car share a rich interstellar spectrum that is characteristic of *FUSE* spectra of other Carina early-type stars (e.g., H_2, C II, Fe II, and Ar I). Strong blueshifted absorptions are also present in many transitions in the FUV spectrum of η Car. These include atomic lines also seen in the interstellar medium (ISM) and Fe II absorption from levels within 1000 cm^{-1} of the ground state (Nielsen et al. 2005; Gull et al. 2005a, 2005b). These high-velocity features are circumstellar in origin and are seen in two principal groups (−150 km s^{-1} and −450 ± 80 km s^{-1}). The stronger of these circumstellar features are marked in Figure 2*a* as "CSM." There is no evidence of high-velocity absorption in the H_2 Lyman lines.

The SiC1 HIRS spectrum (Fig. 2*b*) is characteristic of early main-sequence B stars (see Pellerin et al. 2002). The S IV 1073 Å line shows only a photospheric line profile, that is, no

TABLE 2
Stars near η Carinae

Name	*r* (arcsec)	p.a. (deg)	*V*[a]	*B*−*V*[a]	*U*−*B*[a]	$F_{\lambda 2200}$[b]
Tr 16-64 ……	13.97	41.0	10.72	0.10	−0.74	4.5
Tr 16-65 ……	13.84	60.3	11.09	0.14	−0.65	2.5
Tr 16-66 ……	20.00	61.0	11.98	0.16	−0.57	0.9

[a] Data from Feinstein et al. 1973.
[b] UV flux from *HST* ACS F220W image; units are 10^{-13} ergs cm^{-2} s^{-1} $Å^{-1}$.

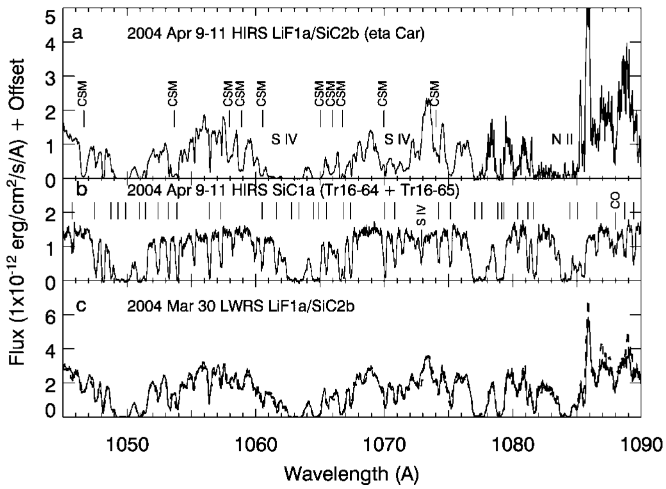

FIG. 2.—(*a*) *FUSE* LiF1a (1045–1077 Å) and SiC2b (1077–1090 Å) HIRS aperture spectra of η Car, corrected for HIRS point-source throughput of 65%. Locations of high-velocity circumstellar absorption are marked by "CSM." The locations of S IV $\lambda\lambda$1062–1073 are also indicated. (*b*) SiC1a HIRS spectrum of Tr 16-64 and Tr 16-65. The vertical tick marks are the locations of H_2 Lyman lines with $J \leq 6$. (*c*) *FUSE* LiF1a LWRS spectrum of η Car (η Car itself plus Tr 16-64 and Tr 16-65) from 2004 March 30. The dashed line is the sum of (*a*) and (*b*), which almost exactly reproduces the LWRS spectrum.

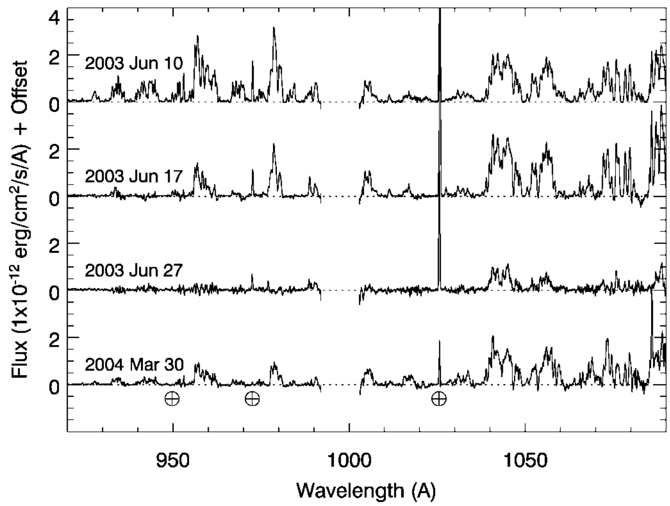

FIG. 3.—*FUSE* LWRS aperture spectra (920–1090 Å) of η Car in 2003 and 2004 after subtracting the SiC1 HIRS spectrum of Tr 16-64 and Tr 16-65. Note that the net η Car spectrum on 2003 June 27 is mostly consistent with zero flux, implying that the source of FUV radiation in η Car has been eclipsed by η Car A. The break in spectral coverage at 990–1002 Å is the result of a gap between detector microchannel plates.

stellar wind feature in S IV λ1062 or λ1073, and indicates a low $v \sin i$ (<50 km s^{-1}).

Figure 2*c* shows that the addition of the LiF1 HIRS and SiC1 HIRS spectra very accurately reproduces the LWRS spectrum of η Car taken in 2004 March, indicating that the only significant sources of FUV flux in the LWRS aperture are η Car and the Tr 16 B stars. We now have the ability to extract the intrinsic FUV spectrum of η Car from other LWRS observations by subtracting the SiC1 HIRS spectrum of Tr 16-64 and Tr 16-65.

The point-source throughput of the HIRS aperture is ~65% ± 10% for targets centered in the aperture. The flux for the HIRS spectra presented here have been corrected assuming a nominal 65% throughput. While this yields very satisfactory results, a uniform scaling of the HIRS fluxes may in fact not be a unique solution.

Several LWRS spectra of η Car were obtained in 2003 June. The X-ray flux was decreasing during this time frame as η Car approached the X-ray eclipse. The LWRS spectra on June 10 and 17 are nearly identical to spectra obtained in 2004 March. The spectrum on 2003 June 27, however, is completely different, being nearly identical to the SiC1a HIRS spectra (Fig. 2*b*). The 2003 June and 2004 March LWRS spectra with the B stars subtracted are shown in Figure 3. There is almost a complete cancellation on June 27, with only a small amount of residual flux from η Car present in limited wavelength regions (e.g., 1040–1046 Å). In the 1100–1185 Å region, the June 27 spectrum has normal interstellar line profiles in many Fe II lines, N I $\lambda\lambda$1134–1135, etc. (R. Iping et al. 2005, in preparation). All the strong high-velocity absorption present in every other LWRS observation of η Car is not present, indicating that the primary source of FUV flux on that date is located outside of the η Car Homunculus, that is, the stars Tr 16-64 and Tr 16-65.

4. DISCUSSION

Our results show that essentially all the FUV flux from η Car shortward of Lyα disappeared at least 2 days before the start of the X-ray eclipse (2003 June 29; Corcoran 2005), implying that the source of the FUV flux was also eclipsed. This conclusion is also supported by *HST* Space Telescope Imaging Spectrograph (STIS) observations. Examination of archival STIS FUV echelle spectra obtained with a 0″.2 × 0″.3 slit in 2003 show that above 1300 Å there were increases in the strength of many absorption features on July 5 relative to earlier spectra. From ~1160 to 1200 Å the spectrum was little changed on June 22 compared with earlier observations, but on July 5 this region had nearly zero flux.

The FUV flux shortward of 1000 Å implies that η Car B has a higher $T_{\rm eff}$ than η Car A ($T_{\rm eff} = 15{,}000$ K). The Hillier et al. (2001, 2005) model of η Car A fades significantly below Lyα, and the flux from η Car B is expected to dominate η Car A only at these short wavelengths. Verner et al. (2005) found that η Car B should have $T_{\rm eff} \sim 35{,}000$ K in order to provide sufficient ionizing flux to excite Weigelt blob emission. The *FUSE* spectrum is consistent with this result.

The *FUSE* wavelength region contains several features that should be key spectral diagnostics for the spectral classification and stellar wind properties of η Car B. These include O VI $\lambda\lambda$1032–1038, S IV $\lambda\lambda$1062–1073, C III] $\lambda\lambda$1175–1176, N II $\lambda\lambda$1084–1086, Si IV $\lambda\lambda$1122–1128, and P V $\lambda\lambda$1118–1128. Few, if any, of these transitions are cleanly observed in the *FUSE* spectrum of η Car, at least not in the form of profiles seen in other OB stars (see Pellerin et al. 2002; Willis et al. 2004). The strong, nearly saturated high-velocity Fe II and Fe II* absorption by Homunculus gas obliterates the Si IV $\lambda\lambda$1122–1128 and P V λ1128 lines. The O VI $\lambda\lambda$1032–1038 region does not have a clear P Cygni line profile, but the general depression of the 1025–1038 Å spectrum in η Car relative to the B stars is characteristic of late O supergiants (e.g., HD 210809, O9 Iab; Pellerin et al. 2002).

S IV, C III], and N II line profiles (Fig. 4) have broad absorption (600–1000 km s^{-1}) and redshifted emission that is strong in N II and weaker in S IV and C III]. S IV usually has a P Cygni profile only in O supergiants (Pellerin et al. 2002). If formed in a wind of η Car B, the S IV and C III] features indicate a late O spectral type.

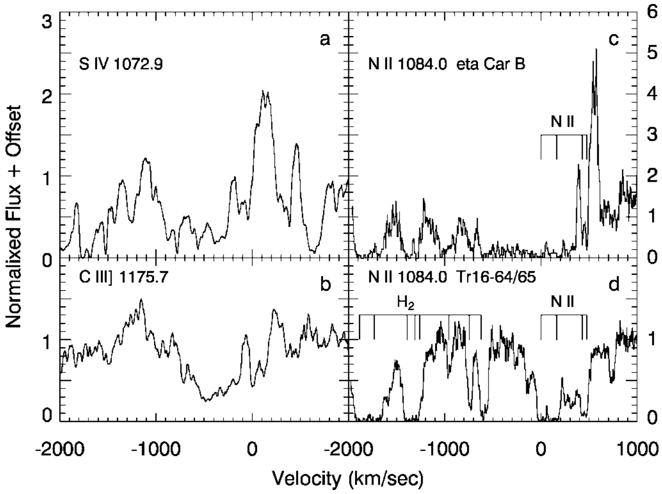

FIG. 4.—Comparison of normalized line profiles of (*a*) S IV λ1072.9, (*b*) C III] λλ1175–1176, and (*c*) N II λλ1084–1086 from the HIRS spectrum of *η* Car B. Tr 16-64/65 is shown in (*d*) to illustrate the ISM features in the N II region. The spectra were normalized over a wide (∼10 Å) region around each feature. The rest wavelengths for the ISM lines of the N II multiplet and adjacent H_2 are marked. The zero point of the velocity scale is the wavelength given in each panel.

The 1085 Å region has a strong emission feature at 1085.8 Å (Fig. 2*a*, Fig. 4). This is the expected position for a P Cygni feature from the N II λλ1084–1086 multiplet, and not emission from He II λ1084.9. Significantly, this emission feature disappears in the June 27 observation, indicating that it is closely associated with *η* Car B, and not *η* Car A or the surrounding nebulosity. The full width of the N II emission is at least ∼130 km s^{-1}, although this is a lower limit because of strong interstellar absorption by N II** λ1085.55 and λ1085.71 near their laboratory wavelengths (about −450 km s^{-1} in Figs. 4*c*–4*d*). The saturated absorption is consistent with other transitions that have strong high-velocity features (−100 to −600 km s^{-1}) from the expanding ejecta of *η* Car.

A wind velocity of ∼3000 km s^{-1} for *η* Car B, as postulated in the Pittard & Corcoran (2002) colliding-winds model, is not evident in our data. The upper limit on the wind velocity for *η* Car B is ∼1100 km s^{-1}, based on S IV λ1062 and λ1073 and the C III] λλ1175–1176 multiplet. The profiles significantly overlap the CSM absorption velocities, making it more difficult to disentangle the two. The higher wind velocity of the Pittard & Corcoran model may not be observable if the wind of *η* Car B is highly distorted by the collision bow shock with the wind of *η* Car A, but this effect could be phase dependent in the eccentric orbit of the model.

FUSE spectra of *η* Car and their timing relative to the X-ray light curve demonstrate that there is a second, hotter star in the *η* Car system. The *FUSE* data do not conclusively identify the stellar type, but there are clues from several lines, including N II λλ1084–1086. This line is not observed as a P Cygni profile in normal O stars (Pellerin et al. 2002; Walborn et al. 2002); it is *only* seen in late-type nitrogen-rich O and Wolf-Rayet stars (see Walborn et al. 2002; Willis et al. 2004). This raises the possibility that *η* Car B could be nitrogen-rich and possibly a Wolf-Rayet star. Our upper limit on the *η* Car B wind velocity is consistent with a late O/WR spectral type. Alternatively, the N II emission might arise from the colliding-wind shock interface and still be occulted during eclipse ingress. Better understanding of the *η* Car system could come from integrated modeling of *η* Car B seen through the extended, expanding atmosphere and circumstellar material of *η* Car A.

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