A LIGHTHOUSE EFFECT IN ETA CARINAE*

THOMAS I. MADURA AND JOSE H. GROH
Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
Received 2011 November 17; accepted 2012 January 6; published 2012 January 30

ABSTRACT

We present a new model for the behavior of scattered time-dependent, asymmetric near-UV emission from the nearby ejecta of \( \eta \) Car. Using a three-dimensional (3D) hydrodynamical simulation of \( \eta \) Car’s binary colliding winds, we show that the 3D binary orientation derived by Madura et al. in 2012 is capable of explaining the asymmetric near-UV variability observed in the Hubble Space Telescope Advanced Camera for Surveys/High Resolution Camera F220W images of Smith et al. Models assuming a binary orientation with \( i \approx 130^\circ–145^\circ \), \( \omega \approx 230^\circ–315^\circ \), P.A.\(_z\) \approx 302^\circ–327^\circ \) are consistent with the observed F220W near-UV images. We find that the hot binary companion does not significantly contribute to the near-UV excess observed in the F220W images. Rather, we suggest that a bore-hole effect and the reduction of Fe\( \text{II} \) optical depths inside the wind–wind collision cavity carved in the extended photosphere of the primary star lead to the time-dependent directional illumination of circumbinary material as the companion moves about in its highly elliptical orbit.

Key words: stars: atmospheres – stars: individual (Eta Carinae) – stars: mass-loss – stars: variables: general – supergiants

Online-only material: color figures

1. INTRODUCTION

Multi-wavelength observations obtained over the past 20 years strongly indicate that \( \eta \) Carinae is a highly eccentric (\( e \approx 0.9 \)) colliding wind binary with a 2022.7 ± 1.3 day orbital period (Damineli 1996; Pittard & Corcoran 2002; Corcoran 2005; Damineli et al. 2008a, 2008b). With a total luminosity \( \geq 5 \times 10^5 L_\odot \), dominated by the primary star \( \eta_A \), a luminous blue variable (Davidson & Humphreys 1997), \( \eta \) Car’s total binary mass is \( \geq 120 M_\odot \) (Hillier et al. 2001, 2006, hereafter H01, H06).

One topic that remains the subject of debate is the orientation of \( \eta \) Car’s orbit. Most favor an orbit in which the less-massive, hotter companion star \( \eta_B \) is behind \( \eta_A \) at periastron (Damineli et al. 1997, 2008b; Pittard & Corcoran 2002; Corcoran 2005; Iping et al. 2005; Hamaguchi et al. 2007; Nielsen et al. 2007; Okazaki et al. 2008; Gull et al. 2009, 2011; Parkin et al. 2009; Groh et al. 2010b). However, others place \( \eta_B \) on the near side of \( \eta_A \) at periastron (e.g., Falceta-Gonçalves & Abraham 2009; Kashi & Soker 2009, and references therein). Settling this debate is crucial as a precise set of orbital parameters is key for determining the individual stellar masses.

Smith et al. (2004, hereafter S04) attempted to constrain the geometry of \( \eta \) Car’s orbit using asymmetric variability seen in near-ultraviolet (NUV) images of the Homunculus nebula obtained with the Hubble Space Telescope Advanced Camera for Surveys/High Resolution Camera (HST ACS/HRC). Alternating patterns of bright spots and “shadows” observed on opposite sides of \( \eta \) Car before and after its 2003.5 spectroscopic event are interpreted by S04 as being due to a time-variable, asymmetric NUV radiation field that arises from (1) intrinsic NUV emission from \( \eta_A \)’s outer wind and (2) UV radiation from \( \eta_B \) that preferentially escapes in directions away from \( \eta_A \). In the scenario proposed by S04, a dark shadow appears on the opposite side of \( \eta_A \) near periastron because its dense wind blocks \( \eta_B \)’s far-UV radiation over a large, time-varying solid angle. Using this interpretation, S04 suggest that \( \eta \) Car’s orbital major axis is nearly perpendicular to the observer’s line of sight, with \( \eta_B \) on the far side of \( \eta_A \) before periastron, on the near side after, and orbiting clockwise on the sky (see their Figure 2).

Recently, Madura et al. (2012, hereafter M12) tightly constrained, for the first time, the three-dimensional (3D) orientation of \( \eta \) Car’s orbit using a 3D dynamical model for the broad, spatially extended [Fe\( \text{II} \)] emission observed by the HST Space Telescope Imaging Spectrograph (STIS; Gull et al. 2009). M12 find that the observer’s line of sight has an argument of periapsis \( \omega \approx 240^\circ–285^\circ \), with the binary orbital axis closely aligned in 3D with the Homunculus polar axis at an inclination \( i \approx 130^\circ–145^\circ \) and position angle on the sky P.A.\(_z\) \approx 302^\circ–327^\circ , implying that \( \eta_B \) indeed orbits clockwise on the sky.

Using a 3D hydrodynamical model of \( \eta \) Car’s binary colliding winds, we show in this Letter that the orbital orientation derived by M12 is consistent with the asymmetric NUV variability observed in the HST ACS/HRC images of \( \eta \) Car presented in S04. The model in this Letter builds on the earlier work of S04, but differs in a key respect, accounting for the wind–wind collision (WWC) cavity created by \( \eta_B \) in \( \eta_A \)’s dense wind (Pittard & Corcoran 2002; Okazaki et al. 2008; Parkin et al. 2009, M12). This cavity reduces the H and Fe\( \text{II} \) optical depths in the line of sight to \( \eta_A \) (Groh 2011; Groh et al. 2012, hereafter G11, G12, respectively), and causes a bore-hole effect (Madura & Owocki 2010; Madura 2010; Madura et al. 2011), wherein the WWC cavity allows increased escape of continuum radiation from the hotter/deeper layers of \( \eta_A \)’s extended wind photosphere at phases near periastron. The results of this Letter provide insights into how/where NUV light escapes the \( \eta \) Car binary system and the time-dependent illumination of \( \eta \) Car’s ejecta in various directions.

2. OBSERVATIONS AND MODELING

We use the same difference images of \( \eta \) Car as shown in Figure 1 of S04, to which we refer the reader for further details. We examine the F220W filter NUV images (probing

---

* Based on HST ACS/HRC observations.
the wavelength region from $\sim$1800 to 2600 Å; Sirianni et al. 2005) where the observed NUV excess is greatest. Each image frame shows the result of subtracting the average of all six observations from the original image at the indicated date.

We use the two-dimensional (2D) radiative transfer code and a 3D hydrodynamical model of $\eta$ Car's colliding winds to interpret the phase-dependent HST ACS/HRC F220W images. To determine the influence of $\eta_A$, its low-density wind cavity, and the dense WWC region walls on the observed spectrum of $\eta$ Car, we use the 2D radiative transfer models described in Groh et al. (2010a), G11, and G12. A 3D smoothed particle hydrodynamics (SPH) simulation is used to understand the effects of orbital motion on the WWC region formed between $\eta_A$ and $\eta_B$, and the spatial orientation of the WWC surface on the sky as a function of phase. The 3D SPH simulation in this Letter is identical to that used in M12, with the exception of the size of the computational domain, which here is a factor of 10 smaller in order to focus on the dynamics of the inner WWC zone. The adopted stellar, wind, orbital, and orientation parameters are in Table 1.

3. ORIGIN OF THE NEAR-UV FLUX IN THE F220W IMAGES

Before examining the directional illumination of $\eta$ Car's circumstellar ejecta, it is important to understand the physical origin of the observed NUV flux. According to the 2D radiative transfer model of G11, G12, regions in line of sight to the wind cavity carved by $\eta_A$ have a flux that is roughly an order of magnitude higher than the flux of $\eta_B$. We assume $\eta_B$ a temperature of 35,000 K and a luminosity of $10^6 L_\odot$ (H06). Since $10^6 L_\odot$ is an upper limit for the luminosity of $\eta_B$ (Mechner et al. 2010), the flux contribution from $\eta_B$ could very likely be even less than what is shown in Figure 1. Therefore, we find that $\eta_B$ does not contribute a substantial fraction of the observed F220W NUV flux in directions away from $\eta_A$ and cannot explain the observed F220W NUV excess. Rather, we suggest that the NUV excess in the F220W images is regulated by the time-dependent nature of the WWC cavity carved by $\eta_B$, which has two very important effects on $\eta_A$'s extended wind photosphere.

First, lines of sight through the low-density WWC cavity have significantly reduced Fe II optical depths (G11, G12). This reduction is especially pronounced in the F220W spectral region, which is full of Fe II lines (H06; G12). Second, $\eta_A$'s photosphere is extremely extended at UV wavelengths (H06), leading to a significant bore-hole effect (Madura & Owocki 2010; Madura 2010; Madura et al. 2011) at phases around periastron, wherein the WWC cavity creates a hole, allowing increased escape of continuum radiation from the exposed hotter, deeper layers of $\eta_A$'s photosphere.

Because $\eta_B$ is located well within the WWC cavity, $\lesssim10\%$ of the F220W flux that reaches circumstellar ejecta exposed to the cavity comes from $\eta_B$. Therefore, the time-dependent directional exposure of circumstellar material to excess F220W NUV flux most likely depends on the phase-dependent spatial orientation of the WWC cavity, and not just the obstruction of $\eta_B$'s NUV flux by $\eta_A$'s wind.

4. THE LIGHTHOUSE EFFECT: CONSTRAINTS ON THE ORBITAL ORIENTATION PARAMETERS

Using our 3D SPH model, we investigated the phase-dependent spatial orientation of the WWC cavity for different orbital orientations with the goal of determining which orientations are capable of explaining the HST F220W NUV images of S04. For simplicity, each orientation discussed in this Letter assumes that the orbital axis of the binary system is closely...
Madura & Groh

Figure 2. Comparison of observed HST F220W images (left column, S04) with the 3D SPH model (right two columns) discussed in the text at phases (rows, top to bottom) $\phi = 0.865$, 0.925, and 0.985. Middle column: 3D isovolume renderings of the SPH simulation assuming the parameters in Table 1, illustrating the orientation of the WWC cavity (dark purple) carved in $\eta_A$’s extended wind (in red) as it would appear projected on the sky. The surface of the WWC cavity is color coded to radius, i.e., dark purple indicates material at larger radii ($\approx 75$–$125$ AU) from the central stars, while green indicates material near the apex of the WWC region ($\approx 15$ AU from $\eta_A$ for these phases). Right column: same as middle column, but with material below the orbital plane removed in order to show the complex dynamics of the inner WWC cavity. The inset in the lower left shows the orientation of the binary orbit (yellow) projected on the sky, along with the semimajor ($x$, red), semiminor ($y$, green), and orbital ($z$, blue) axes. The black arrows indicate the clockwise orbital motion of the stars. North is up and east is left in all panels.

(A color version of this figure is available in the online journal.)

aligned in 3D with the polar axis of the Homunculus nebula at an inclination $i = 138^\circ$ and a position angle on the sky of $312^\circ$ (M12).

A quantitative description of changes in the amplitude of the flux in the F220W images is deferred to future work as a 3D radiative transfer code is necessary for such an analysis. Below, we compare the spatial location of features in the individual F220W images to those expected from the model based on the 3D orientation of the WWC cavity opening. Compass directions (NE = northeast, etc.) are used in the descriptions below.

Figures 2 and 3 show that the binary orientation proposed by M12 is capable of reasonably explaining the observed time-variable NUV “excess” emission seen in the F220W images. Hereafter, the terms “NUV excess” and “NUV deficit” refer to an increase and decrease, respectively, in the F220W NUV flux as compared to the average NUV flux of phases between 0.865 and 0.061.

At $\phi = 0.865$ and 0.925, the observed NUV excess emission in the F220W images is brightest in regions in line of sight to the central stellar source and is elongated from NE to SW (S04). $\eta_B$ is far enough from $\eta_A$ at these phases that orbital velocities are low and the WWC cavity maintains a simple axisymmetric cone-like shape (top two rows of Figure 2; also Okazaki et al. 2008; Parkin et al. 2009, 2011; M12). For $\omega \approx 260^\circ$, the WWC cavity is open mostly toward the observer and is elongated in directions from the NE to the SW on the sky, causing the FeII optical depths in those directions to be reduced (G12). As a result, material in these directions should be exposed to a higher F220W NUV flux than the one-year average flux of phases between 0.865 and 0.061. The NUV excess thus occurs in these directions at these two phases because at later times the inner WWC cavity has a different 3D spatial orientation (Figure 3). Moreover, the models predict that because orbital velocities are low, the orientation of the WWC cavity should not change much between $\phi = 0.865$ and 0.925, implying that the spatial orientation and amount of observed NUV excess should also not change much. The F220W images show that this is the case.

By $\phi = 0.985$ (bottom row of Figure 2), the spatial orientation of the inner WWC cavity has changed, pointing more in
directions to the SW on the sky. The WWC cavity at this phase is warped due to orbital motion. The F220W image shows an observed NUV excess in directions to the NW, SW, and SE, with darker, below-average-flux regions to the NE (S04). According to our model and interpretation, material to the NW, SW, and SE should have an NUV excess as it is exposed to a heavily modified primary wind. The darker region to the NE is likely due to there being more primary wind material in this direction at this phase compared to the average of all phases.

At $\phi = 0.003$, the inner WWC region has started to take on a spiral shape and points mainly in directions to the S on the sky and partly away from the observer (top row of Figure 3). Interestingly, the F220W image shows NUV excesses to the S and E on the sky, with dark NUV-deficit regions to the N and W (S04). At $\phi = 0.003$, there is a significant bore-hole effect concentrated in directions to the S on the sky. The primary wind is carved to the S as well, which should allow the increased flux from the bore-hole to reach material in this direction. Since there is no bore-hole effect to the S at the other phases, we expect an NUV excess in material there at $\phi = 0.003$. Similar reasoning explains why there is also an NUV deficit to the N and W.

At $\phi = 0.031$ (middle row of Figure 3), the inner $\pm 2''$ region of the F220W image is very dark (S04). The inner WWC cavity gets highly distorted and the additional NUV radiation that would escape from the inner layers of $\eta_A$ becomes embedded and trapped by its dense wind (M12). Therefore, an NUV deficit and a large dark region appear in the F220W difference image.

By $\phi = 0.061$ (bottom row of Figure 3), orbital speeds have decreased and the WWC cavity has started to increase in size in directions to the north–northeast (NNE) on the sky, significantly carving the wind of $\eta_A$ in this direction. Consequently, one would expect a significant decrease in the amount of Fe $\text{II}$ absorption in directions to the NNE compared to the average, and thus an observed NUV excess. There is also more wind material from $\eta_A$ in directions to the S compared to the average, which should cause an NUV deficit. The F220W image shows that there is indeed an observed NUV excess to the NNE and a dark region to the S (S04).

We find that only binary orientations with $230^\circ \lesssim \omega \lesssim 15^\circ$ are capable of reasonably explaining the extended ($\sim 0.2' - 2''$) NUV excess emission observed in the F220W images. Other orientations appear to have extreme difficulty explaining the NUV variability. For example, at an orientation of $\omega = 90^\circ$ (top row of Figure 4), during most of the binary orbit, the WWC cavity is open and pointing away from the observer to the E/SE. Thus, between $\phi = 0.865$ and 0.985, the observer should detect the NUV radiation field from the unmodified wind of $\eta_A$ on the central stellar source, and a possible NUV excess to the E/SE. At $\phi = 0.061$, due to the wrapping of the WWC region, an NUV excess would be expected to the S. Yet, the
spatial location of the observed bright and dark spots is nearly the exact opposite.

However, we find that the NUV variability on the central stellar source (central ±0′′2) additionally constrains the orbital orientation to values of $\omega \approx 230^\circ$–$315^\circ$. The F220W images at $\phi = 0.865, 0.925,$ and $0.985$ show an observed NUV excess on the central stellar source, while $\phi = 0.003, 0.031,$ and $0.061$ show a deficit (S04; see also Martin et al. 2006; Mehner et al. 2011). In order to have an NUV excess on the central source before periastron, the WWC cavity should be open mostly toward the observer at these phases. NUV deficits after periastron are due to increased amounts of primary wind material (compared to the average) at these times. This appears to be the case for $\omega \approx 230^\circ$–$315^\circ$. In contrast, assuming $\omega = 0^\circ$, for example, the WWC cavity opens away from the observer at phases $\phi = 0.865$–$0.003$ (Figure 4). At $\phi = 0.061$, the WWC spirals in between the observer and $\eta_A$ (bottom row, Figure 4). This would lead one to expect an NUV deficit before periastron and an excess after if $\omega = 0^\circ$, which is not seen in the observations.

Moreover, binary orientations that lie significantly outside the range $\omega \approx 230^\circ$–$315^\circ$ have great difficulty explaining other multi-wavelength diagnostics of $\eta$ Car since such orientations place the observer’s line of sight through $\eta_A$’s optically thick wind for most of the orbital period (Pittard & Corcoran 2002; Okazaki et al. 2008; Parkin et al. 2009, 2011; Groh et al. 2010b; M12; G11, G12). In contrast, the 3D orientation and direction of orbit proposed by M12 appears consistent with all known observations of $\eta$ Car to date, including those analyzed here.

The results of this Letter go well beyond constraining the orientation of $\eta$ Car’s binary orbit. It is clear that the motion of the WWC cavity as $\eta_B$ moves about in its highly elliptical orbit leads to an important “lighthouse effect” in $\eta$ Car, wherein circumbinary ejecta is exposed to a time- and direction-dependent modified NUV radiation field of $\eta_A$ caused by a bore-hole effect and decrease in Fe ii optical depths. This lighthouse effect is crucial for understanding how NUV light escapes the $\eta$ Car system and the phase-dependent illumination of distant ejecta in different directions.

The lighthouse effect also provides a valuable diagnostic for helping constrain the exact timing of periastron. Based on the available observations of S04 and the simple model in this Letter, periastron should occur between $\phi = 0.985$ and $\phi = 0.031$, most likely very close to $\phi = 0.003$ since this is when some...
NUV excess is still visible to the SE in the difference images (i.e., before distortion of the WWC cavity causes the NUV radiation to be trapped by $\eta_A$’s dense wind).

Future spatially resolved observations with better time sampling, together with detailed 3D radiative transfer models, can help place much tighter constraints on the exact timing of periastron, and possibly the orbital eccentricity. We emphasize that future observations of $\eta$ Car should focus not only on phases around $\phi = 0$, but also on the extended recovery period up until $\phi \approx 0.2$, during which time the WWC cavity is increasing in size and reestablishing its axisymmetric cone-like shape. Future monitoring of these phases is crucial for determining when various forms of radiation can escape via the WWC cavity in directions away from $\eta_A$.

We wish to thank S. Owocki, N. Smith, and T. Gull for interesting discussions relevant to this work. We thank D. J. Hillier for making available, and providing continuous support for, the CMFGEN and 2D Busche & Hillier (2005) radiative transfer codes, and the models of $\eta_A$ and $\eta_B$. We also thank C. Kruij for assisting in the 3D visualization of the SPH code output, and the Max-Planck-Gesellschaft for financial support.

REFERENCES

Busche, J. R., & Hillier, D. J. 2005, AJ, 129, 454
Corcoran, M. F. 2005, AJ, 129, 2018
Damineli, A. 1996, ApJ, 460, L49
Damineli, A., Conti, P. S., & Lopes, D. F. 1997, New Astron., 2, 107
Damineli, A., Hillier, D. J., Corcoran, M. F., et al. 2008a, MNRAS, 384, 1649
Damineli, A., Hillier, D. J., Corcoran, M. F., et al. 2008b, MNRAS, 386, 2330
Davidson, K., & Humphreys, R. M. 1997, ARA&A, 35, 1
Falceta-Gonçalves, D., & Abraham, Z. 2009, MNRAS, 399, 1441
Groh, J. H., Hillier, D. J., Madura, T. I., & Weigelt, G. 2012, MNRAS, submitted
Groh, J. H., Madura, T. I., Owocki, S. P., Hillier, D. J., & Weigelt, G. 2010a, ApJ, 716, L223
Groh, J. H., Nielsen, K. E., Damineli, A., et al. 2010b, A&A, 517, A9
Gull, T. R., Madura, T. I., Groh, J. H., & Corcoran, M. F. 2011, ApJ, 743, L3
Gull, T. R., Nielsen, K. E., Corcoran, M. F., et al. 2009, MNRAS, 396, 1308
Hamaguchi, K., Corcoran, M. F., Gull, T., et al. 2007, ApJ, 663, 522
Hillier, D. J., Davidson, K., Ishibashi, K., & Gull, T. 2001, ApJ, 553, 837
Hillier, D. J., Gull, T., Nielsen, K., et al. 2006, ApJ, 642, 1098
Iping, R. C., Sonneborn, G., Gull, T. R., Massa, D. L., & Hillier, D. J. 2005, ApJ, 633, L37
Kashi, A., & Soker, N. 2009, MNRAS, 397, 1426
Madura, T. I. 2010, PhD thesis, Univ. Delaware
Madura, T. I., Gull, T. R., Groh, J. H., et al. 2011, arXiv:1111.2280
Madura, T. I., Gull, T. R., Owocki, S. P., et al. 2012, MNRAS, in press (arXiv:1111.2226)
Madura, T. I., & Owocki, S. P. 2010, RevMexAA Conf. Ser., 38, 52
Martin, J. C., Davidson, K., & Koppelman, M. D. 2006, AJ, 132, 2717
Mehner, A., Davidson, K., Ferland, G. J., & Humphreys, R. M. 2010, ApJ, 710, 729
Mehner, A., Davidson, K., Martin, J. C., et al. 2011, ApJ, 740, 80
Nielsen, K. E., Corcoran, M. F., Gull, T. R., et al. 2007, ApJ, 660, 669
Okazaki, A. T., Owocki, S. P., Russell, C. M. P., & Corcoran, M. F. 2008, MNRAS, 388, L39
Parkin, E. R., Pittard, J. M., Corcoran, M. F., & Hamaguchi, K. 2011, ApJ, 726, 105
Parkin, E. R., Pittard, J. M., Corcoran, M. F., Hamaguchi, K., & Stevens, I. R. 2009, MNRAS, 394, 1758
Pittard, J. M., & Corcoran, M. F. 2002, A&A, 383, 636
Sirianni, M., Jee, M. J., Benítez, N., et al. 2005, PASP, 117, 1049
Smith, N. 2006, ApJ, 644, 1151
Smith, N., Morse, J. A., Collins, N. R., & Gull, T. R. 2004, ApJ, 610, L105 (S04)