A HIGH-VELOCITY TRANSIENT OUTFLOW IN η CARINAE

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ABSTRACT

We analyze velocity profiles of the X-ray spectral lines emitted by the η Carinae (η Car) stellar binary at four epochs, just before the X-ray minimum (associated with periastron) and more than 2 years before the minimum (~apastron). The profiles are nicely resolved by the HETGS spectrometer on board Chandra. Far from periastron, we find symmetrical lines that are more or less centered at zero velocity. Closer to periastron, the lines broaden, shift toward the blue, and become visibly asymmetric. While the quiescent X-ray emission and slight (<200 km s⁻¹) centroid shifts can be ascribed to the ordinary continuous binary wind interaction and to the orbital velocity of the secondary star, the observed high-velocity emission up to ∼2000 km s⁻¹ and the abrupt flares during which it occurs cannot. This leads us to interpret the high-velocity flaring emission as due to a fast collimated outflow of ionized gas.

Subject headings: stars: individual (η Carinae) — stars: mass loss — techniques: spectroscopic — X-rays: stars

Online material: color figures

1. INTRODUCTION

Despite being studied for many years and in all wave bands, the η Carinae system (η Car), best known for its spectacular nebula (Morse et al. 1998) that can be tracked back to the Great Eruption of 1840 (Davidson & Humphreys 1997), is still much of a mystery. It is now believed to be a stellar binary system with a period of 5.54 yr (Damiani 1996). The primary star is one of the brightest and most massive (∼120 M☉) stars in our galaxy. Although the X-rays detected from η Car can be largely explained by the collision of the two stellar winds (Corcoran et al. 2001a; Pittard & Corcoran 2002), the ∼70 day X-ray minimum that is periodically observed around periastron is still not well understood.

Currently, the mass-loss rate of the primary exceeds 10⁻⁴ M☉ yr⁻¹ (Smith et al. 2003) and that of the secondary is an order of magnitude lower (Pittard & Corcoran 2002). The wind of the secondary is much faster (a few thousand kilometers per second; Pittard & Corcoran 2002) than that of the primary (∼600 km s⁻¹ and depending on latitude; Smith et al. 2003). The X-ray flux between 2 and 10 keV during the past 12 years is normally at a level of 5 × 10⁻¹³ ergs s⁻¹ cm⁻², as expected from the collision of the two stellar winds (Usov 1992; Corcoran et al. 2001a; Pittard & Corcoran 2002; Akashi et al. 2006). The X-ray light curve is roughly constant throughout most of the orbit but rises gradually by a factor of 3–4 on approach to periastron, at which time short flares appear (Corcoran et al. 1997), before it drops sharply and stays in an X-ray low state (∼10% of normal brightness) for approximately 70 days. The full X-ray light curve can be found in Corcoran (2005). Although absorption by the dense primary wind plays a certain role in attenuating the X-ray emission from η Car, both spectral and temporal arguments have been put forward to reject absorption or an eclipse as the prime reason for this persisting low state (Hamaguchi et al. 2004; Soker 2005; Akashi et al. 2006), which is unique to η Car. It has been proposed that if the binary separation during periastron is small enough, the massive primary wind could smother the secondary wind and shut down the X-ray emission (Soker 2005; Akashi et al. 2006). Recently, a detailed study of the broadband X-ray behavior around the 2003 periastron passage was conducted by Hamaguchi et al. (2007), who claim the unchanged temperature during the X-ray minimum argues against accretion. However, if the X-ray emission during the minimum is due to the secondary’s residual fast polar wind (Akashi et al. 2006), it would indeed result in unchanged X-ray temperatures.

In this work, we wish to add to the temporal aspects of the η Car tale a high-resolution X-ray spectroscopic dimension. This is achieved by using five deep archival exposures of η Car with the High Energy Transmission Grating Spectrometer (HETGS) on board the Chandra X-Ray Observatory, only the first of which has been published (Corcoran et al. 2001a, 2001b). Theoretical variations of spectral line profiles in binary colliding wind systems have been modeled by Henley et al. (2003). The varying line profiles presented here for η Car, however, do not follow these models, at least not in a straightforward way, as we explain in § 3.

2. OBSERVATIONS AND RESULTS

The log of the Chandra observations is given in Table 1. Two observations (3745 and 3748) coincide with the short intense flares just before periastron. The exact orbital parameters of η Car are not well determined, but we assume throughout this Letter a period of 5.54 yr (2024 days) and periastron to be at 2003 June 29. The X-ray low state, thus, occurs during φ = 0–0.035. The data were retrieved from the Chandra archive and processed using standard software (CIAO ver. 3.2.2). Chandra’s high-energy grating (HEG) and medium-energy grating (MEG) spectrometers operate simultaneously in the 3.5–7.5 Å band of interest. Aiming at the highest possible kinematic resolution, the higher spectral resolving power of the HEG in this band (factor of 2) is favored over the slightly higher effective area of the MEG (factor of 2), especially since the co-added plus and minus first-order HEG data are already of sufficiently high signal-to-noise ratio (S/N).

To reveal the dynamics of the X-ray gas, we transferred each spectral line profile to line-of-sight velocity space (vₗ) using the nonrelativistic Doppler shift vₗ = c(λ – λ_o)/λ_o, where λ and λ_o represent the observed and rest-frame wavelengths of the line, respectively, and c is the speed of light. Negative and positive velocities represent approaching and receding gas, respectively. Figure 1 shows the broad and variable X-ray line profiles of η Car demonstrated on the Si XI 13 Lyα doublet at 6.18 Å. As expected, the MEG profile represents a smoothed version of the higher resolution HEG profile. The observed line is much broader than the instrumental line spread function (also shown). Figure 1 also demonstrates how the line profile varies dramatically
TABLE 1
CHANDRA HETG OBSERVATION LOG

| Chandra Archive ID | Start Time       | Exposure (ks) | Assumed Orbital Phase (\(\phi\)) | 2–10 keV Flux (10^{-10} ergs s^{-1} cm^{-2}) |
|--------------------|------------------|---------------|----------------------------------|---------------------------------------------|
| 632…………………. | 2000 Nov 19 02:46:40 | 90.69         | -0.470                           | 0.50                                        |
| 3749………………. | 2002 Oct 16 08:08:49 | 93.96         | -0.130                           | 0.98                                        |
| 3745………………. | 2003 May 02 11:56:16 | 97.29         | -0.028                           | 2.2                                         |
| 3748………………. | 2003 Jun 16 05:35:28 | 100.1         | -0.006                           | 0.97                                        |
| 3747………………. | 2003 Sep 26 22:45:53 | 72.16         | 0.044                            | 0.48                                        |

* One additional observation was carried out during the X-ray minimum (ID 3746 at 2003 July 20 01:46:22) for which no useful spectrum could be obtained.

b Phase is approximated based on the assumption of a 5.54 yr (2024 day) orbit, where phase zero is set at 2003 June 29 and the X-ray low state occurs during phase 0–0.035.

from phase \(\phi = -0.470\) (observation 632) to \(\phi = -0.028\) (observation 3745). The early-phase (\(\phi = -0.470\)) line is centered around zero velocity with no significant emission beyond 700 km s^{-1}. The line closer to periastron (\(\phi = -0.028\)) features high-velocity gas up to \(\sim 2000\) km s^{-1}.

In each observation, the kinematic profiles of the bright spectral lines are fairly similar. This is demonstrated in Figure 2, where the four best S/N lines of observation 3745 (\(\phi = -0.028\)) are shown. In order to elucidate how the line profiles vary as a function of phase, we co-added the profiles of nine bright lines in each observation, namely, the Ly\(\alpha\) (1s–2p), He\(\alpha\) resonance (1s^2–1s2p), and He\(\alpha\) forbidden (1s^2–1s2s) lines of the Si, S, and Ar ions. The similarity of the profiles of these lines in a given observation (see also Henley 2005, Figs. 4.9–4.12) justifies the co-adding procedure, which yields an average profile with improved S/N. The sufficiently large separation of the resonance to forbidden lines (3400–4100 km s^{-1}) and the weak intensity of the intercombination lines in the He-like triplets ensure that the average profiles are not confused by blends. Individual Fe lines below 2 Å could not be included in this analysis, despite their high intensity, since the HETGS resolving power decreases strongly at these low wavelengths to the extent that the He-like Fe line complex is unresolved. The blue wing of the He\(\alpha\) Fe resonance line is consistent with, although not resolved as well as, the other line

![Si Ly\(\alpha\) λ6.18](image1)

![Si He\(\alpha\) (r) λ6.65](image2)

![Si Ly\(\alpha\) λ6.18](image3)

![S He\(\alpha\) (r) λ5.04](image4)

![S Ly\(\alpha\) λ4.73](image5)

![Line-of-sight velocity (km s^{-1})](image6)

Fig. 1.—Velocity profiles of the Si\(^{13}\) Ly\(\alpha\) unresolved doublet (6.180 and 6.186 Å). Top: Consistent HEG (higher spectral resolution) and MEG (smoother) data from observation 3745 (\(\phi = -0.028\)). The profile is clearly broadened up to 2000 km s^{-1}, much beyond the instrument line spread functions (dashed lines). Bottom: HEG profile of observation 632 (\(\phi = -0.470\), dashed line) and observation 3745 (\(\phi = -0.028\)). The scaled-up line from the early phase is rather symmetrical and much narrower, showing no line emission beyond 700 km s^{-1}. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 2.—Profiles of four bright spectral lines from observation 3745 (\(\phi = -0.028\)) showing asymmetric profiles with blueshifts of up to \(\sim 2000\) km s^{-1}. Horizontal bars represent the shift and FWHM Gaussian-fitting results by Henley (2005) for these lines, which are not inconsistent with the present profiles. [See the electronic edition of the Journal for a color version of this figure.]
profiles presented here. The resulting mean profiles have been normalized (except for observation 3747) to facilitate the comparison and are presented in Figure 3.

A clear trend can be seen in Figure 3. Far from periastron, the line profile is relatively symmetric and narrow. Closer to periastron, bright components of gas moving toward us at velocities as high as $-2500$ km s$^{-1}$ start to develop. As the system further approaches periastron, the outflow dominates the line profile to the point where the bulk of the emission is clearly blueshifted. After periastron, the emission lines are considerably weaker. Line profiles from a binary wind system are not expected to be Gaussian (Henley et al. 2003). Nevertheless, in order to get an idea of the line shifts and widths, we tried to fit Gaussians to the mean profiles in the range $-2500$ to $+1300$ km s$^{-1}$ (Fig. 3). The results are presented in Table 2. For the two late-phase observations ($\phi = -0.028$, $-0.006$), single Gaussians provide poor fits that can be significantly improved by adding a second component. This does not imply there are necessarily exactly two velocity components but merely that the velocity distribution at these phases is more complex than Gaussian. The double-Gaussian best fits are plotted in Figure 3. A second isolated peak at $\phi = -0.028$ is not as conspicuous as at $\phi = -0.006$, hence, the broad high-velocity component and the larger errors at $\phi = -0.028$ (Table 2).

3. INTERPRETATION AND DISCUSSION

The colliding wind binary model, which is generally accepted for explaining the X-ray emission of $\eta$ Car, has several clear predictions regarding the spectral line profiles expected at different orbital phases. The Doppler shifts are the result of shocked gas flowing along the contact discontinuity (CD) surface and away from the stagnation point (SP). If the shock opening half-angle is between 45$^\circ$ and 90$^\circ$, the broadest line profiles are expected when the system is observed perpendicular to the line connecting the two stars, as the hottest gas formed around the SP flows directly toward and away from the observer. In this case, the lines are centered at zero velocity and are intrinsically symmetrical but could be skewed by absorption of the far (red) emission. On the other hand, when the system is observed from behind one of the stars, shifted centroids are expected. If the system is observed from behind the weaker (stronger) wind, downstream shocked gas flows along the CD surface in the general direction of (opposite) the observer, producing blue-(red)-shifted centroids. The maximum velocities in this case would be less than those in the first (orthogonal) orientation. For a complete and detailed calculation of line profiles from colliding winds, see Henley et al. (2003). In the following, however, we argue that the current line profiles observed at the different phases of the $\eta$ Car orbit are in contradiction, even qualitatively, with the simple colliding wind scenario.

If the major axis of the $\eta$ Car binary is perpendicular to our line of sight (Smith et al. 2004), the broadest profiles are expected at apastron (see above), but that is when the observed profiles are narrowest ($\phi = -0.470$). Also, with this geometry, the secondary would have to pass in front of the primary before periastron (cf. Smith et al. 2004) to explain the blueshifted centroids at $\phi = -0.028$, $-0.006$, but that would produce symmetric (blueshifted) profiles as absorption through the secondary wind is weak, while asymmetric profiles are observed. In any case, the lower velocities observed near apastron appear to rule out this orientation if the colliding wind geometry is to produce the observed X-ray line profiles.

Alternatively, if the projection of the line of sight on the orbital plane is along the major axis and the viewing angle at apastron is from behind the secondary (Corcoran et al. 2001a), the observed blueshifts at $\phi = -0.028$, $-0.006$ could be ascribed to gas flowing from the SP toward the observer and the unobserved red wing of the line to absorption by the primary wind. However, according to this scenario, at apastron ($\phi = -0.470$) one would expect blueshifted centroids of at least a few hundred kilometers per second due to downstream gas (see above), which are not observed. For an observer above the binary plane ($i < 90^\circ$), as seems to be the case in $\eta$ Car (Corcoran et al. 2001a), the problem becomes more severe (higher blueshift is expected but not observed). Indeed, Kashi & Soker (2007) showed that the X-ray line shifts with orbital phase cannot be due to the change in orientation of the colliding winds region when the inclination of the orbital plane is considered (cf. Corcoran 2007).

Apparently, the naive wind-collision scenario alone is in-

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**TABLE 2**

**KINEMATIC PARAMETERS OBTAINED FROM GAUSSIAN FITS TO THE MEAN LINE PROFILES PRESENTED IN FIGURE 3**

| Assumed Phase | $v_1$ | FWHM$_1$ | $v_2$ | FWHM$_2$ | $\chi^2$/dof$^*$ |
|---------------|-------|----------|-------|----------|-----------------|
| $\phi$        | (1)   | (2)      | (3)   | (4)      | (5)             |
| $0.470$       | $-25 \pm 5$ | $710 \pm 60$ | ... | ... | 0.36 |
| $-0.130$      | $-50 \pm 20$ | $730 \pm 40$ | ... | ... | 0.43 |
| $0.028$       | $-110 \pm 30$ | $730 \pm 100$ | $-830 \pm 110$ | $2030 \pm 400$ | 0.39 |
| $-0.006$      | $-180 \pm 30$ | $620 \pm 60$ | $-1030 \pm 30$ | $840 \pm 90$ | 0.68 |

* Double-Gaussian fits to the profiles at $\phi = -0.470$ and $\phi = -0.130$ yield an unconstrained second component. Single-Gaussian models for the profiles at $\phi = -0.028$ and $\phi = -0.006$ yield visibly inferior fits with $\chi^2$/dof of 1.16 and 1.02, respectively.
sufficient to explain the observed Doppler shifts of the X-ray line profiles of η Car at all binary phases. Henley (2005) compared the same data with line profiles calculated from his hydrodynamical simulations and reached a similar conclusion. A recent attempt has been made by Henley et al. (2007) to propose yet another orientation. However, we note that the asymmetric line profiles are observed during strong peaks in the X-ray light curve. These peaks too cannot be accounted for by the simple colliding wind models. As far as we understand, the high X-ray velocities remain unexplained, and we ascribe them to a transient outflow that arises just before the onset of the X-ray minimum and is coincident with the X-ray flaring.

Kashi & Soker (2007) suggested orbital motion to be important before periastron. This could account for small X-ray line shifts but not for the highest velocities observed. Utilizing the two-Gaussian fits in Table 2, however, we can confront the orbital solution of Kashi & Soker (2007) with the low-velocity fitted component (col. [2] in Table 2). We assume an eccentricity of $e = 0.9$, stellar masses of $M_1 = 120 M_\odot$ and $M_2 = 30 M_\odot$, and an observer $37^\circ$ above the orbital plane ($i = 53^\circ$), whose projection on the orbital plane is exactly behind the secondary at periastron. This geometry was invoked by Kashi & Soker (2007) to explain the shifts of the He $\text{ii}$ lines (but cf. Corcoran et al. 2001a; Henley et al. 2007). The calculation shows that the orbital velocity of the X-ray gas is $\sim 80\%$ that of the secondary. We added $\sim 8$ km s$^{-1}$ to the model for the systemic velocity of η Car (Smith 2004). The resulting theoretical velocities of the X-ray gas as a function of phase are seen in Figure 4 to formally agree with the observed Doppler shifts of the low-velocity component, except at $\phi = -0.006$, where the model velocity is slightly smaller. Given the many uncertainties of the binary parameters, this discrepancy may not be significant.

The high-velocity X-ray emission (col. [4] in Table 2), on the other hand, is not explained by the orbital motion and could be due to a transient collimated flow ejected from the immediate vicinity of the binary system. The peaks in the X-ray light curve hint that the outflow may be in the form of blobs. The unresolved hard X-ray $\text{Chandra}$ images restrict the outflow to within $2 \times 10^{16}$ cm of the center ($0.5^\circ$, assuming the distance of 2.3 kpc). The appearance of the same charge states during all phases implies that the temperatures of the X-ray gas and line-emitting outflow remain in the range of $kT = 2-5$ keV. Hence, the outflow likely consists of gas shocked by the collision of the winds (as observed throughout the orbit) and is boosted near periastron. The widths of the major peaks seen in Figures 2 and 3 suggest that the outflow is only moderately collimated to within $\sim 30^\circ$. The compression of shocked gas provides a natural explanation for the short intermittent flares in the X-ray light curve. A collimated outflow from the secondary has also been suggested to explain the enhanced He $\text{ii}$ λ4686 emission before periastron (Soker & Behar 2006). Interestingly, both proper motion and Doppler shifts have been measured for high-velocity visible-light knots much farther out from the center (Walborn et al. 1978; Meaburn et al. 1993). The optical knots were ejected more than 100 years ago along the minor axis of the nebula (Meaburn et al. 1993). We would expect the present outflow to be directed along the major axis of the nebula, although we have no pertinent information on its present direction with respect to the system’s geometry. As the massive η Car primary is a short-lived star shedding considerable mass, it may be a supernova in the making. At the very least, it highlights the next periastron passage on 2009 January 12 as a faithfully scheduled experiment for the astrophysically common, but poorly understood, phenomenon of collimated flows.

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