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RECURRENT X-RAY EMISSION VARIATIONS OF η CARINAE AND THE BINARY HYPOTHESIS

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ABSTRACT

Recent studies by Damineli and coworkers suggest that the supermassive star η Carinae may have a massive stellar companion, although the dense ejecta surrounding the star make this claim hard to test using conventional methods. Settling this question is critical for determining the current evolutionary state and future evolution of the star. We address this problem by an unconventional method: If η Carinae is a binary, X-ray emission should be produced in shock waves generated by wind-wind collisions in the region between η Carinae and its companion. Detailed X-ray monitoring of η Carinae for more than 2 years shows that the observed emission generally resembles colliding-wind X-ray emission, but with some significant discrepancies. Briefly, the presence of enhanced absorbing material—such as a circumstellar disk—has been examined to explain the discrepancies. Furthermore, periodic X-ray "flaring" may provide an additional clue to determine the presence of a companion star and for atmospheric pulsation in η Carinae.

Subject headings: stars: early-type — stars: individual (η Carinae) — X-rays: stars

1. INTRODUCTION

Massive stars are key astronomical objects because of their important role in cosmic chemical enrichment and galactic evolution. They mark the end of their stellar lives as supernovae whose peak luminosity can equal the entire radiant output of a galaxy of a trillion stars. The extreme members of this class might produce "hypernovae" (Paczyński 1998), cataclysms hundreds of times more energetic still, and a postulated source of gamma-ray bursts. Such extraordinary explosions require stellar precursors of unusually large mass, and so should be rare. The Milky Way contains at least one possible member of this putative class of hypernova progenitors, the massive, luminous, and relatively nearby star η Carinae.

Recent observations of periodic variations in some emission lines of the η Carinae spectrum suggest that η Carinae has a companion (Damineli, Conti, & Lopes 1997, hereafter DCL) in a long-period ($P = 5.52$ yr) eccentric ($e > 0.6$) orbit. Such a companion potentially provides a crucial key to understanding η Carinae. At the very least, the presence of a companion offers the most direct measure of the current mass of η Carinae and so would provide an important empirical point for the mass-luminosity relation in the upper H-R diagram. In addition, the companion can possibly interact with η Carinae and so change the course of the evolution of the star. In principle the companion's presence could help resolve some outstanding mysteries (such as the nature of the large eruptions that took place during the 1840s and 1890s), especially if tidally induced mass transfer or other interaction effects are important.

Unfortunately, the spectrum of the star and its close neighborhood is contaminated by emission lines that are formed in thick clouds of circumstellar ejecta, so the interpretation of the spectral variations as a signature of binarity is by no means clear. Periodic mass ejections from a single star have also been suggested as a possible explanation of the observed emission-line changes (Davidson 1997). Clearly, to understand the present and future state of the star, we need to determine whether η Carinae has a companion.

A direct consequence of the presence of a companion is that the wind from η Carinae should collide with the wind or surface of this companion. This wind collision would necessarily produce substantial amounts of hot, shocked gas (Prilutskii & Usov 1976; Usov 1992; Stevens, Blondin, & Pollock 1992) and observable X-ray emission. These "colliding-wind" X-rays would be characteristically hard ($kT \sim$ a few keV), would be absorbed ($N_{\rm H}$ greater than a few times 10^{22}), and, most important, would vary with the orbital cycle. Thus the X-ray emission from η Carinae provides important evidence to prove or disprove the binary hypothesis.

We already know that η Carinae is a strong source of hard, highly absorbed X-rays. Previous observations of the X-ray spectral and spatial distributions (Chlebowski et al. 1984; Tsuboi et al. 1997; Corcoran et al. 1998) show that

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the emission closest to the star is hard ($kT \approx 4$ keV) and highly absorbed ($N_H \approx 3.5 \times 10^{22}$ cm^{-2}). As discussed earlier (Corcoran et al. 1998) these characteristics are extremely unusual for X-ray emission from single massive stars, which is typically softer, much less absorbed and substantially weaker (see, e.g., Berghöfer et al. 1997). Even more interesting, the X-ray emission from η Carinae is known to vary by large factors (Corcoran et al. 1995). Such large-amplitude variations are not typical of the X-ray emission from single early-type stars (e.g., Berghöfer & Schmitt 1995). Thus the X-ray emission from η Carinae bears at least superficial resemblance to the expected emission from colliding winds in a massive binary system. An important question remains to be answered: is the variability periodic? To answer this question we have studied the X-ray light curve in detail since 1996 April using the Proportional Counter Array (PCA) on board the *Rossi X-Ray Timing Explorer* (*RXTE*; see Bradt, Rothschild, & Swank 1993).

2. OBSERVATIONS

The X-ray observations of η Carinae presented here were obtained at daily to biweekly intervals between 1996 April 22 and 1998 October 10. We processed the PCA standard 2 mode data taken with three of the five proportional counter units (PCUs 0, 1, and 2). The other two PCUs were frequently turned off during our observations, and for the time being we excluded any science data from these counters. Furthermore, we rejected any data bins taken during or immediately after passage through the South Atlantic Anomaly; and we also excluded any data taken with an elevation angle (i.e., the angle between the Earth limb and the pointing direction of the collimator) less than 3°. The observed PCA/*RXTE* X-ray data are shown in Figure 1. Each observation was corrected for internal particle background using the best currently available background model (the L7 + 240 model for faint X-ray sources), and for external "cosmic" background through comparison with a few contemporaneous X-ray observations of η Carinae made by the *ASCA* X-ray observatory.

Corcoran et al. (1997) noted an overall increase in the mean *RXTE* X-ray flux, which had accelerated after 1997 January, with unexpected periodic "flares" occurring every 84.8 days. Our newer data show that the X-ray variability through 1998 January proved to be more extreme than previously suspected. The most fundamental result of this monitoring campaign is that the X-ray "low state" first observed in 1992.5 (Corcoran et al. 1995) did indeed recur after an interval of 5.5 yr. Figure 1*a* shows that the observed X-ray flux F_X^{obs} in the 2–10 keV energy band reached its maximum ($F_X^{obs} \approx 2 \times 10^{-10}$ ergs s^{-1} cm^{-2}) on 1997 November 9, and plummeted thereafter. In only a month's time the observed X-ray flux dropped by 2 orders of magnitude ($F_X^{obs} < 2 \times 10^{-12}$ ergs s^{-1} cm^{-2}), reaching a minimum on 1997 December 26, and the star became nearly undetectable to the PCA. The star remained faint for more than 2 months before the X-ray emission began to recover substantially.

By fitting the PCA spectra with optically thin, collisionally ionized thermal models (Mewe, Gronenschild, & van den Oord 1985; Mewe, Lemen, & van den Oord 1986; Kaastra 1992) used in the analysis of previous *ASCA* observations (Corcoran et al. 1998), we examined the variation in source X-ray temperature and intervening column density N_H as a function of time. The detailed model parameters are

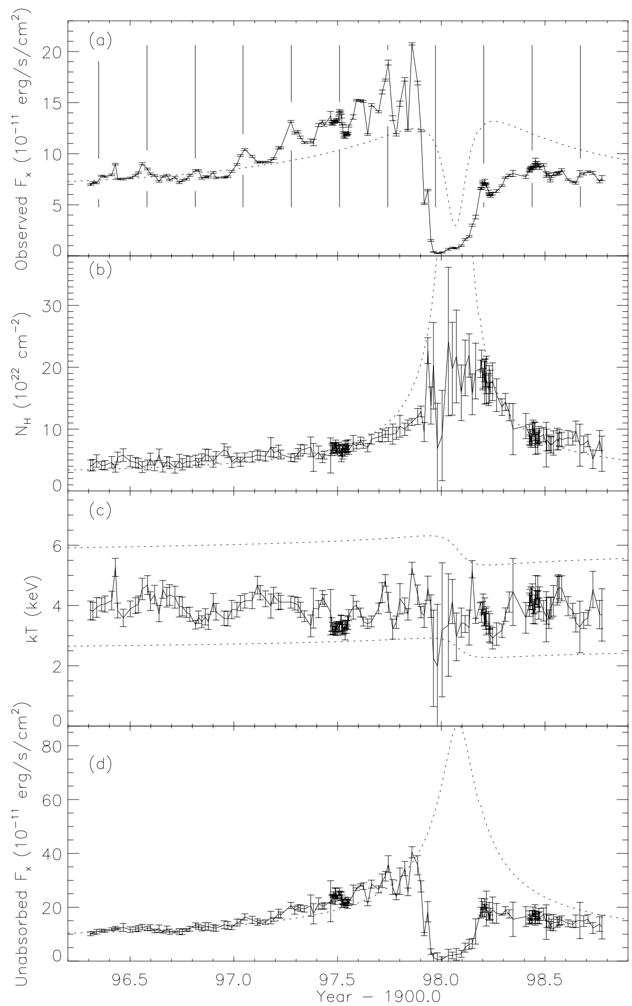

FIG. 1.—Results of PCA/*RXTE* monitoring of η Carinae in the interval 1996 April–1998 October. (*a*) Observed X-ray flux in the 2–10 keV energy range. (*b*) Observed variation in the column density N_H. (*c*) Derived variation in the characteristic X-ray temperature kT. These temperatures have been corrected for the orbital motion of the stars. (*d*) Unabsorbed X-ray flux in the 2–10 keV energy range. The unabsorbed flux is the quantity most sensitive to both background subtraction and detector calibration. The vertical lines in (*a*) indicate 84.8 day X-ray "flare" intervals, and the dotted curves in (*a*)–(*d*) show the expected variations in the observed quantities based on an analytic approximation to X-ray emission generated by colliding winds in an eccentric binary system. These curves are *not* the best fit to the data but merely serve to characterize the type of variability expected from colliding-wind X-ray emission for a particular model. We use published orbital parameters by Davidson (1997) and take $\dot{M}_\eta \approx 2.4 \times 10^{-4}\, M_\odot$ yr^{-1}, $\dot{M}_c \approx 2.8 \times 10^{-6}\, M_\odot$ yr^{-1}, $V_\eta \approx 1000$ km s^{-1} (derived from unpublished analysis of *HST* STIS data), and $V_c \approx 1500$ km s^{-1} as reasonable model parameters. We have also adopted $D = 2.3$ kpc as the distance to η Carinae.

listed in Table 1 for a typical observation. In the modeling, we fit for the plasma temperature, emission measure, and absorbing column of the hard X-ray component, and the line strength of the Fe K fluorescent line (Corcoran et al. 1998; in practice, though, no real information regarding the variation of the Fe K line could be obtained, because of the low intrinsic resolution of the PCA). Figure 1*b* shows the derived variation in N_H versus time, while Figure 1*c* shows the variation in source temperature. These data suggest that N_H increased up to a maximum that occurred midway through the X-ray low state, and declined thereafter, while the plasma temperature showed small (but significant) variations. Figure 1*d* shows the unabsorbed X-ray flux

TABLE 1

TYPICAL MODEL PARAMETERS FOR FITTING THE *RXTE*/PCA SPECTRA

Parameter[a]	Initial Value
T_1 (keV)	0.28
log EM_1 (cm^{-3})	56.97
NH_1 (10^{22} cm^{-2})	0.37
T_2 (keV)	5.4*
log EM_2 (cm^{-3})	57.64*
NH_2 (10^{22} cm^{-2})	3.8*
Gaussian line equivalent width (eV)[b]	126*
Nonsolar abundances ($\times Z_\odot$):[c]	
N/H	47
Mg/H	1.3
Si/H	1.8
S/H	1.2
Fe/H	0.75

NOTE.—Quantities marked by an asterisk were allowed to vary; all other parameters were held fixed.

[a] The subscripts 1 and 2 denote the cooler and hotter components, respectively. We assume $D = 2.3$ kpc throughout.

[b] Fe fluorescent at 6.44 keV.

[c] Abundances of N, Mg, Si, S, and Fe are fixed to nonsolar abundance (Corcoran et al. 1998); other elements are fixed at solar abundance from Anders & Grevesse 1989.

$F_X^{\rm unabs}$ (i.e., the X-ray flux at Earth from the source in the absence of losses produced by absorption in intervening material). The unabsorbed X-ray flux shows a minimum beginning in 1997 December. Our determination of the maximum N_H and maximum unabsorbed flux $F_X^{\rm unabs}$ are actually gross lower limits, since the residual emission we see during the low state could be due to contamination by weak, unabsorbed, hard emission outside the star. Eta Carinae is in fact surrounded by extended X-ray emission (produced by collisions of stellar ejecta with the ISM), but this emission is thought to have a characteristic temperature of a few tenths of a keV (Corcoran et al. 1995).

3. A SIMPLE COLLIDING-WIND MODEL OF η CAR

We can compare the observed X-ray spectral variability to the expected variations for a simple colliding-wind model in which the winds from the two stars collide at terminal velocities (Usov 1992). In the simplest case, in which the winds from the stars are spherically symmetric and the shock is adiabatic, the total X-ray luminosity integrated over all energies generated at the colliding-wind shock can be written as (Usov 1992)

$$L_X \approx 2.7 \times 10^{35} \dot{M}_\eta^{1/2} \dot{m}_c^{3/2} \times (V_\eta^{1/2} V_c^{-3/2} + 0.6 V_\eta^{-5/2} V_c^{3/2}) R^{-1} \text{ ergs s}^{-1} , \quad (1)$$

where $\dot{M}_\eta$ is the mass-loss rate of η Carinae in 10^{-4} $M_\odot$ $\rm yr^{-1}$, $\dot{m}_c$ is the mass-loss rate of the companion in 10^{-6} $M_\odot$ $\rm yr^{-1}$, V_η, V_c are the wind speeds in 1000 km $\rm s^{-1}$ from η Carinae and the companion, respectively, at the point of collision, and R is the separation between the two stars in astronomical units. For the spherically symmetric case, the effective column density in front of the X-ray–emitting region is

$$N_H(R) \equiv \int n_{\rm wind}\, ds \approx \int \frac{\dot{M}}{4\pi V R^2 \mu m_H}\, ds , \quad (2)$$

where μ is the mean mass per particle, and the integration is from the Earth to the boundary where the wind momentum ratio is unity. We make the simplifying assumption that the wind from η Carinae dominates, especially near periastron, so that the quantities relevant to the calculation of N_H are the mass-loss rate and velocity of η Carinae's wind only. The mass-loss rates are presumably constant. However, since R varies around the elliptical orbit, the unabsorbed X-ray luminosity and N_H should both reach maximum near periastron because of their inverse dependences on separation. Near periastron, the increase in N_H should dominate so that the apparent X-ray luminosity should be *minimum* at this time.

If the orbital motion of the shock stagnation point is much less than the wind speeds, the temperature of the shocked gas facing η Carinae can be expressed as:

$$kT_\eta \approx 2.59 \mu V_\eta^2 \text{ keV} \quad (3)$$

(cf. eq. [51] in Usov 1992), where $\mu = A/(1 + Z)$ is the mean mass per particle. For simplicity we assume $\mu \approx 1$; however, this value may not be representative of the chemical composition of the winds of the η Carinae system. The temperature of the shock facing the companion can be derived by replacing V_η with V_c.

Using published orbital elements (Davidson 1997), we calculated the variations in apparent X-ray flux, N_H, kT, and unabsorbed X-ray flux. The calculated variations in these parameters are shown by dashed curves in Figures 1*a*–1*d*. Given the expected shock temperatures, the X-ray luminosity restricted to the 2–10 keV energy is about 36% of the total L_X given by equation (1). This correction factor remains nearly constant throughout the orbit, since the temperature of the X-ray spectrum changes very little. Since the colliding-wind model considered here is merely a crude representation of the actual physical conditions at the shock, we have not attempted to adjust parameter values to derive a "best fit" to the observed data; the curves shown are merely representative of the character of the X-ray variation expected in the colliding-wind model.

This simple model generally shows the same characteristics as the observed emission: a slow rise through "periastron passage" (in both luminosity and column density), followed by a substantial drop in observed flux (accompanied by a continued rise in N_H), with a slow recovery in X-ray flux (and slow decline in N_H) to what might be characterized as the "quiescent" level. Furthermore, our simple model has successfully reproduced the overall level of the X-ray emission and column density far from periastron and generates emission at the right temperature.

In addition, the X-ray temperatures imply a photospheric escape velocity for the companion which is interestingly close to that derived first by DCL from the analysis of spectroscopic radial velocity variations. From Figure 1*c*, the X-ray temperature is about 4 keV, with no large variations as a function of time. From equation (3), this temperature implies a velocity of $V \approx 1200\mu^{-1/2}$ km $\rm s^{-1}$. Since the wind speed of η Carinae is thought to be only 500–700 km $\rm s^{-1}$ or so (Lamers 1989; Hillier & Allen 1992), then this velocity should be representative of the terminal velocity of the companion. If the terminal velocity of the companion is $1200\mu^{-1/2}$ km $\rm s^{-1}$, then the companion's photospheric escape velocity is $V_{\rm esc} \approx 400\mu^{-1/2}$ km $\rm s^{-1}$, since $V_\infty \approx 3V_{\rm esc}$ (Abbott 1978). If the chemical composition of the wind from the companion is highly abundant in He or other metals (i.e., $\mu \geq 1$), then the value of the escape velocity for the companion star is $V_{\rm esc} \approx 400$ km s^{-1}. Analysis of the spectra of nebular material outside the star by Davidson et al. (1984, 1986) and Allen, Jones, & Hyland (1985) suggests that $Y = 0.4$ and thus $\mu \approx 0.6$, which implies that the escape velocity of the companion is somewhat higher, $V_{\rm esc} \approx 520$ km s^{-1}. According to DCL, the mass, luminosity, and temperature of the companion are $M \approx 67\ M_\odot$, $L \approx 1.5 \times 10^6\ L_\odot$, and $T \approx 28{,}000$ K. The radius of the companion is $R \approx [L/(4\pi\sigma T^4)]^{1/2} \approx 52\ R_\odot$, where σ is the Stefan-Boltzmann constant. The escape velocity is $V_{\rm esc} = [2GM(1 - \Gamma_c)/R]^{1/2}$, where M and R are the mass and radius of the companion and G is the gravitational constant. The quantity Γ_c is the ratio of stellar to Eddington luminosity for the companion star, given by $\Gamma_c = (\sigma_e L)/(4\pi GMc) \approx 0.69$, where σ_e is the electron scattering opacity, taken to be 0.40 cm^2 g^{-1} for $\mu = 1$. Thus, according to DCL, the escape velocity of the companion is $V_{\rm esc} \approx 390$ km s^{-1}, slightly below the range 400–500 km s^{-1} derived from the X-ray temperatures.

However, there are obvious differences between the model predictions and the observed X-ray emission near the "periastron passage." The most significant differences are that (1) the duration of the X-ray low state apparently lasted for at least 3 months, much longer than predicted by the model considered here; (2) the minimum in the observed X-ray flux was unexpectedly deep; (3) our best estimate suggests that the unabsorbed X-ray flux $F_{\rm X}^{\rm unabs}$ was in reality *low* near the proposed periastron passage; (4) the observed decline and rise in X-ray emission were asymmetric around the minimum; and (5) the observed maximum value of $N_{\rm H}$ was much lower than the predictions of the simple model, and the rise of $N_{\rm H}$ to maximum was more gradual than the decline from maximum. Clearly these discrepancies suggest that the η Carinae system is more complex than the simple colliding-wind binary model.

It seems possible that many of these discrepancies could be resolved by refinement of the orbital parameters, through contamination of the X-ray emission in the low state by faint, hard emission far from the star, and/or by allowing for a nonspherical distribution of wind material which is optically thick to hard X-rays, such as a trailing wake or "disk" around η Carinae. As a geometrically simple example, we consider the eclipse of a large fraction of the wind shock by a dense disk around η Carinae (see the cartoon in Fig. 2). Such a structure could occult the bulk of the emission from the shock, producing an extended "low state" near periastron; unocculted outer regions of the shock (with relatively low column densities) could then provide the observed residual X-ray emission during the "low state." To determine whether such a structure is plausible, we consider a simple disk eclipse where the disk is centered on η Carinae and oriented (for geometrical simplicity) parallel to the plane of the sky. The size of the disk from the center of the primary is $R_d \sim D_{\rm shock} \cos i$, where $D_{\rm shock}$ is the distance from the primary to the shock and i is the inclination of the binary orbit, taken as 5×10^{13} cm and 57°, respectively. We assume that the thickness of the disk, h, is much less than the disk radius, i.e., $R_d/h \sim 10$. Using $i = 57°$, R_d and h are $\sim 3 \times 10^{13}$ and $\sim 3 \times 10^{12}$ cm. The column density through the disk is related to the ratio of the unabsorbed to the absorbed flux as $N_{{\rm H},d} \sim \log_e(F_{\rm X}^{\rm unabs}/F_{\rm X}^{\rm obs})\sigma^{-1}$, where $\sigma \sim 5 \times 10^{-24}$ cm^2 is the mean absorption cross section in the 2–10 keV energy range (Morrison & McCammon 1983). From our calculations (see Fig. 1*d*) at periastron $F_{\rm X}^{\rm unabs} \sim 8 \times 10^{-10}$ ergs s^{-1} cm^{-2}, while the *RXTE* observations show that $F_{\rm X}^{\rm obs}$ is $\sim 10^{-11}$ ergs s^{-1} cm^{-2}. Thus we need $N_{{\rm H},d} \sim 10^{24}$ cm^{-2} to block most of the X-rays from the shocked region. The density in the disk is roughly $n_d \sim N_{\rm H}/h \sim 10^{11}$ cm^{-3}. The mean density in the wind out to a distance of R_d is 10^9 cm^{-3}, so that the density of the disk would be roughly a factor of 100 larger than the ambient wind density. The total mass in the disk is $M_d \sim \pi n_d \mu m_{\rm H} R_d^2 h$, where μ is the mean mass per particle, assumed to be 1. Thus in this example the total disk mass would only be $10^{-6}\ M_\odot$. The total mass-loss rate through the disk is $\dot{M}_d \sim 2\pi R_d \mu m_{\rm H} N_{{\rm H},d} V_d$, where V_d is the wind speed in the disk. Even with $V_d \sim 1000$ km s^{-1}, the mass-loss rate through the disk would be less than $10^{-3}\ M_\odot$ yr^{-1}, which is reasonable for η Carinae. Thus a relatively small modification to the standard colliding-wind binary model (such as inclusion of a disk or a similar nonspherical distribution of wind material) may be a plausible way to resolve the discrepancies between the observations and the simple, spherically symmetric colliding-wind model.

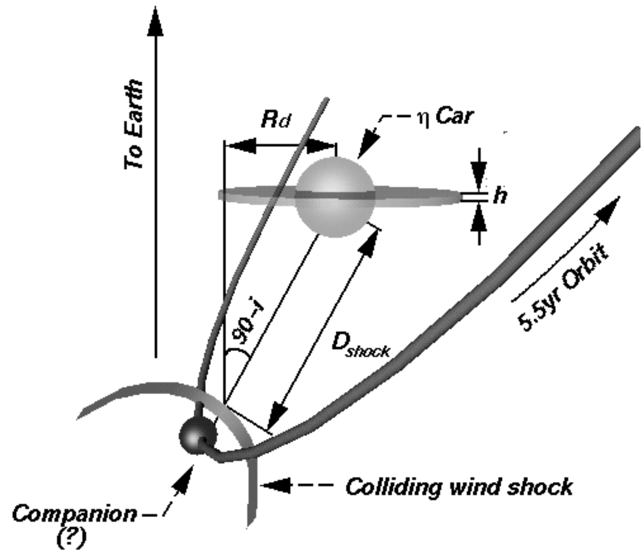

FIG. 2.—Schematic model of a binary system with a thin disk. The cartoon shows the position of the hypothetical companion star at periastron. The objects are not to scale.

4. "QUASI-PERIODIC" FLARING AND BINARITY

Another important characteristic of the X-ray variability is quasi-periodic flaring (Corcoran et al. 1997 and references therein). The X-ray flaring recurred approximately every 84.8 days, although, as Figure 1*a* shows, the flare behavior became quite complicated approaching the X-ray low state. A cause of these flares may be periodic pulsations (Corcoran et al. 1997; Davidson, Ishibashi, & Corcoran 1998), possibly of the type described in the dynamical atmospheric models of Guzik et al. (1997). Such outwardly expanding "shells" of enhanced density should periodically increase the emission measure in the colliding-wind shocks, which in turn would be observed as increased X-ray luminosity from the system. A prediction of this model is that the interval between flares should lengthen appreciably after the X-ray low state due to a "Doppler" effect; as the two stars separate, the ejected "shell" requires additional time to catch up to the X-ray–emitting region in the colliding-wind shock (Davidson et al. 1998). Although the apparent behavior of the X-ray flux variability is complicated going into and out of the X-ray low state, evidence suggests that such a lengthening indeed may have occurred. The first flare maximum after the X-ray low state was on 1988 March 13. The next two flares peaked on 1998 June 15 and 1998 September 15, 9–13 days later than expected from a strict 84.8 day periodicity. However, an "interflare" maximum was seen to occur on 1998 May 6, while a flare predicted on 1997 December 21 (just after the start of the X-ray minimum) was not seen; furthermore, there were numerous "interflare" peaks just before the onset of the X-ray minimum, as well as an anomalous increase in the X-ray flux on 1997 December 7 (see Fig. 1*a*). Because of complicated variations seen in the X-ray light curve—in particular the presence of "interflare" peaks for which we currently have no explanation—the apparent lengthening of the flare period is supportive of the binary model but does not yet provide conclusive proof by itself. Firmly establishing a lengthening of the flare period is of real astrophysical importance, since, in the binary + pulsation model, timing of the observed flares provides important constraints on the orbital and wind parameters and the first direct measure of the dynamical timescale of the interior of the primary star as well.

5. CONCLUSION

In this paper, we have connected the 5.5 yr periodic variation of X-ray emissions from η Carinae to a colliding-wind binary system. We have done so because of the following: the recurrence of the X-ray minimum after 5.5 yr, and the fundamental trends seen in the observed X-ray flux (F_X^{obs}) and the column density (N_H) that are generally similar to the variations expected from wind-wind collisions in a binary system. Moreover, during the *RXTE*/PCA monitoring of η Carinae, the presence of quasi-periodic flares was discovered. The flares last a very short time (of the order of a month), which further suggests that it may no longer be correct to assume that the X-ray emission of η Carinae originates from a collision of its stellar wind with a dust shell at a distant location (~ 1500 AU) from the star, as believed for many years (Chlebowski et al. 1984; Koyama et al. 1990; Corcoran et al. 1995). On the other hand, the size of the postulated binary orbit is consistent with the scale implied from the short-time variations (~ 10 AU or so for a disturbance propagating at the wind speed of 500–1000 km s^{-1}). This evidence suggests that η Carinae is a good candidate for a colliding-wind binary system, although the model we have examined here does not fully describe every detail of the observed X-ray variability from η Carinae. More complex physical models allowing for non–spherically symmetric winds and/or better estimates of the mass-loss rates and wind speeds may yield better agreement.

The death of η Carinae is likely to be one of the most explosive events ever experienced in the Galaxy. If η Carinae truly has a massive companion, interpretation of the binary orbit provides the best method for determining the physical parameters of the component stars, the current evolutionary state of the system, and the length of time until its eventual end as a supernova or hypernova. In this case colliding-wind X-ray emission is unique because it arises from a known volume in a known location between the two stars. Because the orbital parameters cannot be well constrained from ground-based radial velocity curves (primarily because of contamination by the ejected material near the star), analysis of the 5.5 yr X-ray cyclic variation, timing of flares, and variations in column density may be the best means to fully determine the physical parameters of η Carinae, and so determine its evolutionary state.

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