1. INTRODUCTION

For 2023 days we have been waiting for the intriguing periastron passage of the massive binary system $\eta$ Car. And indeed, we were not disappointed, as the new X-ray observations (Corcoran 2009) brought some surprises. The periodicity itself, which is observed in all wavelengths (e.g., radio, Duncan & White 2003; IR, Whitelock et al. 2004; visible, van Genderen et al. 2004; emission and absorption lines, Nielsen et al. 2007; Damineli et al. 1997, 2008a, 2008b; X-ray, Corcoran 2005, 2008; Hamaguchi et al. 2007), is attributed to a binary orbital period (Damineli 1996).

The X-ray light curve was followed by RXTE (Corcoran 2009) during three minima. In all three minima the X-ray intensity increases prior to the start of the X-ray minimum and then drops sharply to minimum, which was about the same level in the three minima (Corcoran 2005, 2009). However, while the 1998 and 2003.5 minima lasted 65–70 days (Corcoran 2005), the exit from the last X-ray minimum started only 27 days after periastron passage (Corcoran 2009); last periastron passage is taken on 2009 January 11.

In Kashi & Soker (2009a; see also Kashi & Soker 2009b) we have already pointed out the possibility that the duration of the X-ray minimum can be shorter or longer. We considered relatively small variations in the primary wind properties, and estimated that the X-ray minimum can be different by several days. In this Letter, we re-examine X-ray variations far from periastron, and deduce that the variations (fluctuations) in the primary wind velocity and mass-loss rate can be up to a factor of 2 (Section 2). We then show (Section 3) that within the accretion model (Soker 2005; Akashi et al. 2006; Kashi & Soker 2008, 2009a) such an increase in the primary wind velocity near periastron passage can account for the early exit of $\eta$ Car from the X-ray minimum. In the accretion model the X-ray minimum is attributed to the accretion of the primary wind by the secondary star. The accretion process suppresses the secondary wind that otherwise is responsible for most of the X-ray emission (Corcoran et al. 2001; Pittard & Corcoran 2002; Akashi et al. 2006; Henley et al. 2008; Okazaki et al. 2008; Parkin et al. 2009). Our discussion and summary is presented in Section 4.

The present study presents neither new ingredients to the accretion model nor a new type of calculations. The essence of this Letter is to strengthen the accretion model by showing that it can easily accommodate the new observations by only changing the variables that are most likely to change from orbit to orbit and along the orbit, namely, the primary wind properties.

2. POSSIBLE FLUCTUATIONS IN THE PRIMARY WIND

The binary parameters are as in our previous paper (Kashi & Soker 2009a, where references are given). The assumed stellar masses are $M_1 = 120 M_\odot$ and $M_2 = 30 M_\odot$, the eccentricity is $e = 0.9$, and the orbital period is $\mathcal{P} = 2024$ days. The stellar winds’ mass-loss rates and terminal velocities that were used are $M_1 = 3 \times 10^{-4} M_\odot \text{yr}^{-1}$, $M_2 = 10^{-3} M_\odot \text{yr}^{-1}$, $v_{1,\infty} = 500$ km s$^{-1}$, and $v_{2,\infty} = 3000$ km s$^{-1}$. While in our previous papers the mass-loss rate and terminal velocity of the primary wind were held constant with the above values, in the present Letter we vary them to account for the early exit from the X-ray minimum.

To estimate the largest fluctuations in the primary wind properties, we use the fluctuations in the X-ray luminosity near periastron in the following manner. The hard X-ray emission observed in $\eta$ Car is emitted by the shocked secondary wind (Corcoran et al. 2001; Pittard & Corcoran 2002; Akashi et al. 2006; Henley et al. 2008; Okazaki et al. 2008; Parkin et al. 2009). For constant secondary wind properties the X-ray luminosity varies as $\sim D_2^{-1}$, where $D_2$ is the distance of the stagnation point of the colliding winds from the secondary star. This can be understood from two different considerations. When the radiative cooling time is long, the X-ray emission is (Akashi et al. 2006) $L_x \simeq 0.5 M_2 v_2^2 (\tau_{f2}/\tau_{\text{cool2}})$, where $\tau_{f2} \simeq D_2/v_2$ is the outflow time of the shocked gas, and $\tau_{\text{cool2}} \propto n^{-1}$ is the radiative cooling time of the shocked secondary wind. The postshock secondary wind density varies as $n \propto D_2^{-2}$. We find therefore $L_x \propto D_2^{-1}$. In the second approach the X-ray emissivity (power per unit volume) $\Lambda n^2$ is used. The luminosity is $L_x = V_2 \Lambda n^2$, where $V_2 \propto D_2^3$ is the volume of the shocked...
secondary wind. The mass in the volume \( V_2 \) is proportional to its outflow time \( t_{\text{pass}} \approx D_2/v_2 \). Therefore, \( n \propto D_2^{-2} \) (as before), and again we recover the relation \( L_\perp \propto D_2^{-1} \).

The distance \( D_2 \) is given by equating the momentum fluxes of the two winds. When \( \eta \) Car is near apastron (hence orbital velocity is negligible) \( D_2 \) is approximately given by \( D_2 = r \xi / (1 + \xi) \), where here we define \( \xi \equiv \sqrt{M_2 v_2 / M_1 v_1} \), and \( r \) is the orbital separation. For our typical parameters \( \xi = 0.45 \). Using this relation in the expression for the X-ray luminosity gives

\[
L_x = K(r, v_2, M_2) \frac{1 + \xi}{\xi},
\]

where the function \( K \) depends on the orbital separation and secondary wind properties. The logarithmic variation of the X-ray luminosity with respect to the primary wind momentum discharge \( p_1 \equiv M_1 v_1 \) is given by

\[
\frac{dL_x}{L_x} = \frac{1}{2(1 + \xi)} \frac{dp_1}{p_1}.
\]

From the X-ray light curve (Corcoran 2005) we find that the variations between cycles and during a short time within one cycle can be \( dL_x/L_x \approx \pm 0.25 \). If we attribute this variation to changes in the primary wind properties, then we find from Equation (2) and \( \xi = 0.45 \) that \( dp_1/p_1 \approx \pm 0.7 \). Basically, if the mass-loss rate does not change, the terminal velocity can vary in the range \( \sim 300 \)–850 km s\(^{-1} \); such changes are seen in the solar wind. If the wind velocity is larger when the mass-loss rate is lower, then the variation in the wind velocity can be even larger. In the acceleration zone close to the primary star the variations can be much larger. In such an eccentric, asynchronous binary system like \( \eta \) Car, tidal interaction between the stars can result in kinetic energy dissipation through viscous shear. This can lead to variations in the mass-loss rate and wind velocity structure, or even asymmetric mass-shedding (Koenigsberger & Moreno 2009).

Our conclusion is that variations in the primary wind velocity by a factor of \( \lesssim 2 \) in the acceleration region are reasonable. As mentioned earlier, in our previous paper (Kashi & Soker 2009a) we assumed variations in \( p_1 \) of no more than \( \sim 10\% \), and predicted the possibility of an early (or late) exit by several days. Motivated by the new observations (Corcoran 2009), we reexamined the primary wind variations, and concluded in this section that we can allow for much larger variations.

3. VARYING THE ACCRETION RATE AT THE LATEST PERIASTRON PASSAGE

In Kashi & Soker (2009a) we took two extreme processes, that we expect to bound the true mass and angular momentum accretion rates, to estimate the mass and angular momentum accretion rate. These are the Bondi–Hoyle–Lyttleton (BHL) accretion process from a wind, and a Roche lobe overflow (RLOF) type mass transfer. Very close to periastron passage, \( t \lesssim 10 \) day, the accretion process is a hybrid of the BHL and the RLOF mass transfer processes, but at the end of the accretion phase the accretion will be of the BHL type. The calculated accreted mass in the different models considered was estimated to be in the range \( M_{\text{acc}} \sim 0.4$–$3 \times 10^{-6} M_\odot \), and the accretion rate was typically \( M_{\text{acc}} = 5 \times 10^{-7}$–$5 \times 10^{-5} M_\odot \) yr\(^{-1} \), with the higher values close to periastron.

The accretion processes close to periastron is very complicated, and for its accurate study one must use three-dimensional hydrodynamical numerical codes. In this highly eccentric binary system the primary angular velocity is expected to be much below the angular velocity of the secondary near periastron. Therefore, the mass transfer process will not be as in the RLOF process in synchronized binary systems. For that reason, in the present Letter, we use only the BHL accretion process.

We take the \( \beta \)-profile to describe the primary wind acceleration

\[
v_1(r_1) = v_r + (v_{1,\infty} - v_r) \left(1 - \frac{R_1}{r_1}\right)^\beta,
\]

where \( R_1 \) is the primary radius, \( r_1 \) is the distance from the primary center, and \( v_r = 20 \) km s\(^{-1} \). For our “standard case” we use the parameters \( \beta = 3 \) and a terminal wind velocity of \( v_{1,\infty} = 500 \) km s\(^{-1} \). The orbital eccentricity is taken to be \( e = 0.9 \).

The mass accretion rate for the standard case was calculated in our previous paper (Kashi & Soker 2009a). The BHL mass accretion rate as calculated there is drawn by the solid very thick blue line in Figure 1. At \( t = 65 \) days, where the system starts leaving the 1998 and 2003.5 X-ray minima, the mass accretion rate is

\[
M_{\text{ref}} \equiv M_{\text{acc}}(t = 65 \text{ days}, \beta = 3, v_{1,\infty} = 500 \text{ km s}^{-1}) = 8.7 \times 10^{-7} M_\odot \text{ yr}^{-1}.
\]

This is depicted by the dashed horizontal thin blue line in Figure 1. We take this value to be the reference value for the accretion rate at which the secondary wind rebuilds itself after the accretion phase. We note that for the present goal the exact value of \( M_{\text{ref}} \) is not important. What is important is how we vary the primary wind properties to obtain the same value at a much earlier time.

We emphasize that in our model for an early exit relative to the previous two cycles, it is required that the primary wind velocity in the last minimum was higher than the wind velocity in the previous two minima. It is not required that the primary wind velocity in the last minimum was higher than the wind velocity in the previous two minima. It is not required that the primary wind velocity in the last minimum was higher than the wind velocity in the previous two minima. It is not required that the primary wind velocity in the last minimum was higher than the wind velocity in the previous two minima. It is not required that the primary wind velocity in the last minimum was higher than the wind velocity in the previous two minima.
wind velocity after periastron be higher than the primary wind velocity far from periastron. In the present Letter, we take the velocity of the primary wind in the previous two minima to be \( v_1 = 500 \text{ km s}^{-1} \).

We now search for the value \( v_{1,\text{New}} \) in the \( \beta = 3 \) profile that would give an accretion rate of \( 8.7 \times 10^{-7} \, M_\odot \, \text{yr}^{-1} \) at \( t = 27 \) days, the time when the early exit from the 2009 X-ray minimum started. We keep the mass-loss rate at \( M_1 = 3 \times 10^{-4} \, M_\odot \, \text{yr}^{-1} \). We find that \( v_{1,\text{New}} = 900 \, \text{km s}^{-1} \) gives the desired accretion rate, as shown by the solid thick red line in Figure 1. This is within the reasonable range of the primary wind velocity fluctuations we estimated in the previous section.

We also find that if we keep \( v_{1,\infty} = 500 \, \text{km s}^{-1} \) and \( M_1 = 3 \times 10^{-4} \, M_\odot \, \text{yr}^{-1} \), as in the standard case, then a value of \( \beta = 0.35 \) gives the desired accretion rate at \( t = 27 \) days. This case is presented by the solid thin green line in Figure 1.

It is likely that a more efficient acceleration process occurs when the mass-loss rate is lower. We assume now that the primary mass-loss rate was lower in the 2009 minimum, which lead to a more efficient acceleration. To demonstrate the feasibility of our model, we take the mass-loss rate to have been half its typical value \( M_{1,\text{New}} = 1.5 \times 10^{-4} \, M_\odot \, \text{yr}^{-1} \). For \( M_{1,\text{New}} \) and keeping \( \beta = 3 \), we find that \( v_{1,\text{New,2}} = 780 \, \text{km s}^{-1} \) gives the reference accretion rate \( M_{\text{ref}} \) at \( t = 27 \) days (dashed thick red line in Figure 1). For \( M_{1,\text{New}} \) and keeping \( v_{1,\infty} = 500 \, \text{km s}^{-1} \), we find that \( \beta = 1.05 \) gives the reference accretion rate at \( t = 27 \) days (dashed thin green line in Figure 1).

As well, our model might account for the change in the rate of the exit from the two events. We quantify the observed exit rate by defining the average value of \( \Delta L_x / \Delta t \) over the exit from minimum time period. Here, \( \Delta t \) is the exit time interval between the last epoch in which the X-ray luminosity has been at its minimum value and the first epoch in which the X-ray luminosity has returned to its quiescent level, and \( \Delta L_x \) is the difference in the corresponding X-ray luminosities. Using the RXTE results (Corcoran 2005, 2009), we find that the (averaged) observed exit rate of the 2003.5 minimum was \( \Delta L_x / \Delta t = 1.92 \times 10^{28} \text{ erg s}^{-2} \). The observed exit rate of the 1998 was lower by 11%, while the observed exit rate of the 2009 minimum was substantially lower, with \( \Delta L_x / \Delta t = 1.39 \times 10^{28} \text{ erg s}^{-2} \), which is 72% of the observed exit rate of the 2003.5 minimum.

We check whether the change in time evolution of the mass accretion rate during the exit from the X-ray minimum might explain the change in the observed exit rate. For that, we measured the average rate of change in the mass accretion rate, \( \Delta M_{\text{acc}} / \Delta t \), as given in Figure 1. The average is over the exit time interval of each event. We summarize the results in Table 1. We find that the ratio in the average values (\( \Delta M_{\text{acc}} / \Delta t \)) during the 2009 and the 2003.5 minima is 0.68. The proximity of the ratio 0.68 (ratio of the modeled accretion rate in the two minima) to 0.72 (ratio of the observed X-ray flux time evolution in the two minima) should not be given a strong weight, as we do not expect a simple relation between the mass accretion rate and the X-ray luminosity. What is important is the general qualitative change. We conclude that our model can account, with the same change in parameters, to both the 2009 early exit from the minimum, and for the 2009 slower rate of increase in the X-ray flux during the exit from minimum.

### 4. DISCUSSION AND SUMMARY

Our aim was to explain the early exit of \( \eta \text{ Car} \) from its X-ray minimum in the last cycle. Whereas in the previous two cycles the exit occurred \( \sim 10 \) weeks after periastron passage, in the last cycle it occurred only \( \sim 4 \) weeks after periastron passage. It was known that in the accretion model variations in the primary wind mass-loss rate and/or velocity can cause variations in the duration of the X-ray minimum (Kashi & Soker 2009a). However, the exit was earlier than anticipated in our earlier paper. The reason is that in our previous paper we considered relatively small variations in the primary wind properties.

In the accretion model, the secondary star accretes mass from the primary wind near periastron. While for most of the \( \sim 5.54 \) yr orbital period the secondary gravity has a negligible effect on the colliding winds cone, near periastron the shocked primary wind is very close to the secondary star and very dense, and the secondary gravitational field becomes non-negligible. As was shown in previous papers (Soker 2005; Akashi et al. 2006; Kashi & Soker 2008a, 2009a) the gravitational field of the secondary ensures accretion. The accretion process is assumed to shut down the secondary wind, hence the main X-ray source; the system then enters the X-ray minimum.

Although \( \eta \text{ Car} \) had an early exit from the X-ray minimum in the last cycle, the beginning of the minimum was as in the previous two cycles, and occurred shortly before phase zero. The onset of the accretion phase requires an almost extinction of the secondary wind, and therefore a high-mass accretion rate that occurs just before periastron. During the phase interval \( \sim 0.01 \) to \( -0.01 \) (\( -20 \leq t \leq -20 \) days) the two stars are very close \( (r \lesssim 3AU) \), and the mass accretion rate is a hybrid of a RLOF and an accretion from a wind, with the RLOF type most likely the dominant process very close to periastron passage (Kashi & Soker 2009a; for \( t \approx 20 \) days the accretion from the wind is the relevant process, and for that it was used in the paper). Therefore, the primary wind velocity does not influence much the mass accretion rate during the onset of the X-ray minimum.

The above explanation holds for small and moderate fluctuations in the primary wind properties. The very early exit from the X-ray minimum in the last cycle suggests that the changes in the primary wind properties were large. Therefore, for our model to work we require that the changes occurred near periastron passage, most likely due to the strong tidal interaction. Most likely, the tidal interaction amplified a small internal change in the wind properties, e.g., as might result from magnetic activity. Koenigsberger & Moreno (2009) calculations show indeed that

| Cycle   | 2003.5 | 2009 |
|---------|--------|------|
| \( t_1 \) (days after periastron) | 64.7 | 26.3 |
| \( t_2 \) (days after periastron) | 91.0 | 64.7 |
| \( L_{x,1} \) (erg s\(^{-1}\)) | \( 1.9 \times 10^{34} \) | \( 1.9 \times 10^{34} \) |
| \( L_{x,2} \) (erg s\(^{-1}\)) | \( 6.3 \times 10^{34} \) | \( 6.5 \times 10^{34} \) |
| \( \Delta L_{x,\Delta t} \) (erg s\(^{-2}\)) | \( 1.92 \times 10^{28} \) | \( 1.39 \times 10^{28} \) |
| Ratio (2003.5/2009) | 0.72 |

Note. Comparison of the observed exit rates ratio to the one obtained from our model, if we assume that the X-ray exit rate is proportional to the change in the mass accretion rate (although in reality no simple relation is expected).
tidal interaction can cause large changes in the wind properties
of LBV stars in binary systems.

Following recent RXTE observations by Corcoran (2009), we re-examined the behavior of the X-ray emission when the system is far from the X-ray minimum, i.e., it is near apastron. Based on the behavior of the X-ray emission, in Section 2 we found indeed that the variations (fluctuations) in the mass-loss rate and/or velocity of the primary wind can be up to a factor of 2.

Armed with this finding, we examined the possible implications for the accretion model. We assumed that the secondary wind, and hence the X-ray emission, is recovered when the accretion rate is as in \( t = 65 \) days (after periastron) in the previous cycles. The case with the parameters used to explain the previous two cycles is termed “the standard case.” We found that by increasing the primary wind velocity by a factor \( \leq 2 \), and possibly with lowering the primary wind mass-loss rate, we can have the mass accretion rate at \( t = 27 \) days as in \( t = 65 \) days in the previous cycles. We examined several cases, as drawn in Figure 1.

It should be emphasized that we did not add any new ingredients to the accretion model, nor did we change the type of calculations. The new addition is simply repeating the calculation from our previous papers with different primary wind properties. As discussed, these properties are likely to vary by a large factor from orbit to orbit and along the orbit. This new part shows that the accretion model is quite robust.

One implication of our finding is that in some lines that come from the primary wind during the minimum the radial velocity in the last minimum was larger than in the previous minima. We emphasize that what matters to the early exit from the minimum is the primary wind velocity in the last cycle compared with the previous two minima, and that the wind velocity in the minimum can be lower than the average wind velocity far from the minimum. We note also that for accretion the velocity of the wind expelled in and near the equatorial plane matters. The wind toward our line of sight can have somewhat different value. We observe the binary system at inclination angle of 41° (Smith 2006), therefore such variations might not be as large, as tidal effects are stronger in the equatorial plane.”

The shorter X-ray minimum might have further implications. As the secondary accreted less mass than in the previous two cycles, the accretion disk (or belt) formed around it may be thinner, and its dissipation time would be shorter. Therefore, the recovery time of different spectral lines and electromagnetic bands from the minimum can change.

In the same way as the last X-ray minimum was shorter, future X-ray minima might be longer than 70 days. The point is that any fluctuation in the wind, even a moderate one, can change the duration of the X-ray minimum.

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