ORBITAL PARAMETERS FOR THE 250 $M_\odot$ ETA CARINAE BINARY SYSTEM

AMIT KASHI$^{1,2}$ AND NOAM SOKER$^2$

$^1$ Minnesota Institute for Astrophysics, University of Minnesota, 116 Church St. SE, Minneapolis, MN 55455, USA; kashi@astro.umn.edu
$^2$ Department of Physics, Technion—Israel Institute of Technology, Haifa 32000, Israel; soker@physics.technion.ac.il

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ABSTRACT

We show that recent observations of He$\lambda$ and N$\lambda$ lines of $\eta$ Carinae may provide support for an orbital orientation where the secondary star is closest to us at periastron passages. This conclusion is valid both for the commonly assumed masses of the two stars and for the higher stellar mass model where the very massive evolved primary star mass is $M_1 = 170 \ M_\odot$ and its hot secondary star mass is $M_2 = 80 \ M_\odot$. The latter model better explains the change in the orbital period assuming that the nineteenth-century Great Eruption was powered by accretion onto the secondary star. Adopting the commonly used high eccentricity $e \approx 0.9$ and inclination $i = 41^\circ$, we obtain a good fit to newly released Doppler shift observations of He$\lambda$ emission and absorption lines assuming that they are emitted and absorbed in the acceleration zone of the secondary stellar wind. Our model in which the secondary star is in the foreground at periastron is opposite to the view presented recently in the literature.

Key words: binaries: general – stars: individual ($\eta$ Car) – stars: massive – stars: mass-loss

1. INTRODUCTION

$\eta$ Car is a binary system (Damineli 1996; Damineli et al. 1997) composed of a very massive primary star (Davidson & Humphreys 1997) and a hotter and less luminous evolved main-sequence (MS) secondary star. Despite 2 decades of detailed observations (e.g., Smith et al. 2000; Duncan & White 2003; Whitelock et al. 2004; Corcoran 2005; Davidson et al. 2005, 2015; Smith 2006; Hamaguchi et al. 2007, 2014a, 2014b; Damineli et al. 2008b; Corcoran et al. 2010; Martin et al. 2010; Mehner et al. 2010, 2012, 2015; Abraham et al. 2014) and modeling (e.g., Pittard et al. 1999; Soker 2001; Pittard & Corcoran 2002; Akashi et al. 2006, 2013; Okazaki et al. 2008; Kashi & Soker 2009a; Smith 2010; Groh et al. 2012; Madura et al. 2013, 2015; Clementel et al. 2015b), there are disagreements over two important properties of the binary system: the masses of the two stars and the orientation of the eccentric orbit.

The low-mass model assumes that $\eta$ Car is at its Eddington luminosity limit and a mass of $>120 \ M_\odot$ is derived (Hillier et al. 2001). Some studies take it to be the mass of the primary star, while others assume that the combined masses of the two stars amount to that mass with $M_1 \geq 90 \ M_\odot$ and $M_2 \geq 30 \ M_\odot$ (e.g., Okazaki et al. 2008; Clementel et al. 2015b).

The high-mass model was developed by us (Kashi & Soker 2010a) under the assumption that most of the extra energy released during the 1837–1856 Great Eruption (GE) of $\eta$ Car originated from a high accretion rate onto the secondary star. There are models that explain the GE with only one star (e.g., Soker 2010; Pittard et al. 1998; Soker et al. 2001; Pittard & Corcoran 2002; Akashi et al. 2006, 2013; Okazaki et al. 2008; Kashi & Soker 2009a; Smith 2010; Groh et al. 2012; Madura et al. 2013, 2015; Clementel et al. 2015b), there are disagreements over two important properties of the binary system: the masses of the two stars and the orientation of the eccentric orbit.

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The GE was a giant eruption and a supernova impostor, which is the group of eruptive massive stars within the more general group of intermediate-luminosity optical transients (ILOTs; Kashi & Soker 2016). In Kashi & Soker (2016) we presented the high-accretion-powered ILOT (HAPI) model, according to which all ILOTs are powered by a high accretion rate onto a MS, or a star slightly evolved off the MS star (Kashi & Soker 2010a). According to the HAPI model, then, the luminosity peaks of the GE resulted from accretion onto the companion close to periastron passages. Those peaks are $\approx 5.1$–$5.2$ yr apart. If one assumes that the peaks are related to periastron passage and occur about the same time after (or before) periastron, the separation between the peaks can be inferred as the orbital period. The second peak came after the eruption had started and mass was lost. Therefore, the orbital period is smaller than the time interval between the peaks. We adopted a value of 5.1 yr. The present orbital period is 5.54 yr, suggesting that during the GE the orbital period has increased. The orbital period changed as the secondary accreted mass and as mass was lost from the binary system, both as a wind from the primary star and as jets from the secondary star.

In that study (Kashi & Soker 2010a) we found that for the HAPI mechanism to work within the orbital change constraints, the two stars should have significantly larger masses than 120 $M_\odot$. The masses should be in the range of $M_1 \approx 150–200 \ M_\odot$ and $M_2 \approx 60–90 \ M_\odot$. This high-mass model is further supported by evolution of massive stars on the H-R diagram. The calculations of Figer et al. (1998) show that a zero-age main-sequence (ZAMS) star with an initial mass of $M_{\text{ZAMS}} \approx 230 \ M_\odot$ is required to explain the present luminosity of the primary of $\eta$ Car. Indeed, modern stellar evolution tracks of 120 $M_\odot$ stars, even when rotation is considered (Ekström et al. 2012; Georgy et al. 2012), do not reach that luminosity, and more massive models of $M_{\text{ZAMS}} \approx 250 \ M_\odot$ are required, as found by Chen et al. (2015). The primary lost large amounts of mass to the bipolar nebula around $\eta$ Car, the Homunculus (Smith & Ferland 2007; Gomez et al. 2010). When the large mass loss along the evolution is considered, a present mass of $\approx 150–200 \ M_\odot$ is compatible with the ZAMS mass inferred above.

In the debate on the orientation of the binary system, the two sides are holding literally 180° opposite views. One side holds that during periastron passages the primary star is closer to us ($\omega \approx 240^\circ–270^\circ$; e.g., Iping et al. 2005; Nielsen et al. 2007; Damineli et al. 2008b; Henley et al. 2008; Parkin et al. 2009; Groh et al. 2010; Gull et al. 2011; Madura et al. 2012; Clementel et al. 2015a; Richardson et al. 2015; Teodoro et al. 2016), while the other side holds the view that during periastron passages the secondary star is at its closest location to us ($\omega \approx 90^\circ$; e.g., Abraham et al. 2005; Falceta-Goncalves...
The disagreement on the orientation stems mainly from the controversy on the source of some emission and absorption lines, in particular the He I lines. In a recent paper Richardson et al. (2015) present a study of the variations of some spectral lines with the phase of the binary orbit, based on observations with the CTIO 1.5 m telescope. They attributed the He I lines to the primary star. In Kashi & Soker (2007), on the other hand, we assumed that the He I lines observed by Nielsen et al. (2007) are formed in the acceleration zone of the wind blown by the secondary star. We calculated the Doppler shift variations of the lines as a function of orbital phase with the low-mass model of η Car and found that a good fit is obtained if the He I lines are formed in the region where the secondary wind speed is \( v_{\text{zone}} = 430 \text{ km s}^{-1} \).

In the present study we combine the high-mass model of η Car with the assumption that the He I lines originate in the acceleration zone of the secondary stellar wind and try to fit the new Doppler shifts presented by Richardson et al. (2015).

2. THE CONTROVERSY OF THE HELIUM I LINES

The origin of the visible He I P Cyg lines (λ7065, λ8786, λ5015, λ4992, and λ4471) in the binary system η Car is in dispute, with different researchers attributing it to different regions, e.g., the primary star (e.g., Falceta-Goncalves et al. 2007; Humphreys et al. 2008; Richardson et al. 2015). We attribute the He I P Cyg lines to the acceleration zone of the secondary’s wind (Kashi & Soker 2007, 2008). A similar dispute exists for the N II lines λ5686–5712 (Mehner et al. 2011a). While Mehner et al. (2011a) argued that they cannot come from the secondary star, we noted that the N II lines closely follow the behavior of the He I lines and attributed it to the secondary wind (Kashi & Soker 2011).

The effective temperature of the secondary was estimated to be \( T_{\text{eff},2} \approx 34,000–38,000 \text{ K} \) by Verner et al. (2005), and more recently \( T_{\text{eff},2} \approx 40,000 \text{ K} \) by Mehner et al. (2010). The main arguments for the origin of the He I P Cyg lines in the acceleration zone of the wind blown by the secondary star are as follows (Kashi & Soker 2011):

1. The Doppler shift of the P Cyg absorption components follows very well the secondary’s orbit, as we show in Section 3 for the high-mass model, and as was shown before for the low-mass model (Kashi & Soker 2007, 2008).
2. The lines are known to originate in stars with temperatures well above 30,000 K, mostly in hydrogen-deficient stars (e.g., Wessolowski et al. 1988; Leuhenhagen et al. 1996; Crowther & Bohannan 1997; Leuhenhagen & Hamann 1998; Grunhut et al. 2013; further discussion is in Section 5).
3. The secondary can account for the amount of absorption in the He I lines, as we show in Section 4.
4. The Doppler shift of the emission follows that of the absorption, as we show in Section 3.

The secondary mass-loss rate is much lower than the primary’s. It is important to mention that most of the lines observed from the η Car system do originate in the primary and its wind (the best example is probably the hydrogen lines; Davidson et al. 2005; Weis et al. 2005). Take the H Iλ4103 line, for example. This line and many others originate in the primary. But it shows a P Cyg profile that shifts much less in periastron compared to the He I P Cyg lines we discuss here.

It might seem a “strange” coincidence that the place in the secondary wind where the He I lines are formed, according to our model, has about the same velocity as the primary’s wind. However, even a stranger coincidence exists for a model where the lines are formed in the primary’s wind: the area that absorbs the lines would have to change its velocity in the same way that the secondary moves around the center of mass of the binary system.

Using the assumption that the He I lines originate in the secondary wind, in the past we fitted their Doppler shift variations with orbital phase for the low-mass model (the conventional model) of η Car, with \( M_1 = 120 M_\odot \) and \( M_2 = 30 M_\odot \) (Kashi & Soker 2008). The Doppler shift of the P Cyg absorption component of the He I lines was found to be in agreement with the binary orientation with a longitude angle \( \omega = 90^\circ \), i.e., secondary closest to us at periastron. We here upgrade the model to include the new Doppler shifts presented recently by Richardson et al. (2015) and the high-mass model, which better fits the luminosity and the behavior of η Car during the GE according to the HAPI model.

In fitting the He I lines’ Doppler shifts with orbital phase, we scan the following parameter space:

1. The eccentricity is \( e \approx 0.85–0.93 \).
2. The consensus is that the inclination angle (the angle between a line perpendicular to the orbital plane and the line of sight) is \( i \approx 41^\circ \).
3. The orbital period is \( P = 2023 \text{ days} \) (Damineli et al. 2008a).
4. For the masses we use our results (Kashi & Soker 2010a) that the present masses are \( M_1 \approx 150–200 M_\odot \) and \( M_2 \approx 60–90 M_\odot \). We take here for the present masses of η Car components \( M_1 = 170 M_\odot \) and \( M_2 = 80 M_\odot \).
5. We assume that the observer is behind the secondary at periastron, namely, \( \omega \approx 90^\circ \).

We note that there is inconsistency in some papers regarding the exact epoch of periastron, or phase 0. Richardson et al. (2015) used JD 2,454,842.5 for the 2009 periastron passage. Mehner et al. (2011a) used JD 2,454,860 as a reference time for the event (see also discussion in the Appendix of Mehner et al. 2011b). The uncertainty in determining the time of periastron may cause the change in radial velocity to appear after periastron rather than before, or vice versa. Evidently the observations collected so far from η Car are insufficient for determining the exact time of periastron. We will adopt an intermediate value between the references above, \( t_{\text{per}} = \text{JD 2,454,850} \). This value coincides with having the sharp variation in radial velocity of the lines studied here at periastron. However, one should bear in mind that the uncertainty of the periastron epoch is ±10 days. We corrected the orbital phases inferred from the observation dates in this work to have phase 0 at \( t_{\text{per}} \).

3. ORBITAL PARAMETERS

Based only on geometric considerations, i.e., neglecting variations of the wind speed near periastron passage and stochastic wind speed variations, we here use our model to fit the observations of Richardson et al. (2015). The orbital velocity of the secondary relative to the primary, \( v_{\text{orb},i} \), is
converted to the velocity relative to the center of mass

\[ v_m = \frac{M_1}{(M_1 + M_2)} v_{\text{orb}} = \left[ \frac{G^{1/2} M_1}{(M_1 + M_2)^{3/2}} \right] \left[ \frac{2}{r(t)} - \frac{1}{a} \right]^{1/2}. \]

which can be written as

\[ v_m = \frac{M_1}{(M_1 + M_2)^{3/2}} \left[ \frac{2 \pi G}{P} \right]^{1/3} \left[ \frac{2}{r(t)} - 1 \right]^{1/2} = f_M \left[ \frac{2 \pi G}{P} \right]^{1/3} \left[ \frac{2}{r(t)} - 1 \right]^{1/2}, \]

where \( r(t) = r(t)/a. \)

The entire stellar mass dependency is embedded in the factor \( f_M. \) For the low-mass model \( (M_1 = 120 M_\odot \) and \( M_2 = 30 M_\odot) \) its value is \( f_M = 4.25 M_\odot^{1/3}, \) while for the high-mass model \( (M_1 = 170 M_\odot \) and \( M_2 = 80 M_\odot) \) it is \( f_M = 4.28 M_\odot^{1/3}. \) Therefore, the amplitude of the fit with the new parameters is less than 1% larger than the amplitude using the old parameters.

On top of \( v_m, \) there are factors related to the observation angle \( \omega, \) the inclination \( i, \) and the eccentricity \( e. \) From the results we subtract the constant velocity \( v_{\text{zone}} \) of the zone in the secondary wind where the lines are absorbed, or the average velocity of the emitting gas when the peak emission is fitted. Figure 1 shows with a blue solid line our fit to the observed radial velocity absorption component of He I lines from Richardson et al. (2015) and of Nielsen et al. (2007). It is clear from Figure 1 that our fit to the new lines at \( \lambda 4922 \) and \( \lambda 5015 \) is not as good as our fit to the lines studied by Nielsen et al. (2007). We attribute this to contamination of the two \( \lambda 5015 \) and \( \lambda 4922 \) lines by Fe II lines. This contamination was mentioned by Richardson et al. (2015).

More observations of He I lines, specifically the He I \( \lambda 4714 \) line, were taken for the 2009 event by Mehner et al. (2011b) and for the 2014.6 event by Mehner et al. (2015). The latter paper summarizes observations of that line from the previous three events (2003.5, 2009, and 2014.6). Figure 2 shows how our model fits the observations. We used the same model we used for the other He I lines in Figure 1, but with \( v_{\text{zone,abs}} = 370 \) km s\(^{-1}\). We take this slightly different value from the value of \( v_{\text{zone,abs}} = 430 \) km s\(^{-1}\) that was used in Figure 1 to match the average of the absorption component’s radial velocity. The different values mean either that the He I \( \lambda 4714 \) line is absorbed in the wind slightly closer to the wind origin on the secondary star or that there are large variations and uncertainties in the derived Doppler shifts near periastron passages.

Mehner et al. (2015) found that the 2014.6 event was different from previous events, and according to their interpretation in the framework of the accretion model, it showed signs of less accretion onto the secondary close to periastron, indicating weaker primary wind. The He I line flux increased significantly in 2009–2014 compared to 1998–2003. The absorption of the He I \( \lambda 4714 \) line disappeared 8 days before periastron and reappeared 8 days after (assuming our \( f_{\text{orb}} \)). The radial velocities are lower in the 2014.6 event compared to previous events. In fact, for fitting only the data from 2014.6 it would be better to use \( v_{\text{zone,abs}} = 330 \) km s\(^{-1}\), keeping the rest of the parameters unchanged. This behavior, together with the large fluctuations in the Doppler shifts near periastron as seen in the different figures, suggests that the velocities of the regions where lines are formed in the different regions of the secondary wind vary from cycle to cycle and in short timescales near periastron passages. We should therefore aim at fitting the general behavior of the Doppler shift variations with orbital phase; a perfect fit to the Doppler shifts of this interacting binary system cannot be achieved using the geometrical effects alone.

We used the same principles we used for fitting the radial velocity variations of the He I absorption lines to fit the emission peak bisector velocity of the He I \( \lambda 6678 \) line across the 2009 event observed by Richardson et al. (2015). We find that
a value of $v_{\text{zone,emi}} = 60 \text{ km s}^{-1}$ for the average velocity of the gas emitting the line gives the best results. Figure 3 shows the fit we obtained, together with the observations of the emission peak bisector velocity of the He I $\lambda 6678$ line. We present two other cases with $\omega = 90^\circ$ (secondary star closer to the observer at periastron): one has an eccentricity of $e = 0.93$, and the other is the low-mass model from Kashi & Soker (2008). We also show two models where the line is assumed to originate in the primary stellar wind: one is our simple geometric model, but the line is emitted by the primary stellar wind and $\omega = 270^\circ$ (dot-dashed line), and the second is the fit presented by Richardson et al. (2015). It is clear that the models where the line is emitted by the secondary stellar wind and the secondary star is in the foreground at periastron result in a much better fit to the observations.

We next test our model against the variation in the Doppler shift of the absorption component of the N II $\lambda 5668$–$5771$ lines, taken from both Richardson et al. (2015) and Mehner et al. (2011a). We use here $v_{\text{zone,abs}} = 370 \text{ km s}^{-1}$. The N II $\lambda 5668$ line observed by Mehner et al. (2011a) has clear emission peaks close to periastron, but these were not clear in the profiles of Richardson et al. (2015). We fit also the emission component of the N II $\lambda 5668$ line, with $v_{\text{zone,emi}} = 70 \text{ km s}^{-1}$. The fits are presented in Figure 4.

Though the N II and He I lines intensities behave differently, the radial velocity of the N II $\lambda 5668$ emission component follows that of the absorption component amazingly well. Also, the entire line-formation region shows the same Doppler shift variation. Such a behavior cannot be explained in the frame of a model where the N II and He I line-formation regions change their location within the primary wind.

The main driver of the variations in the Doppler shifts is the pure orbital motion. However, it is not the only one. A variation in location within the secondary wind in our model can take place, and it is even expected to occur. As the secondary approaches periastron, its wind properties change, most likely due to accretion of gas from the primary stellar wind (Soker 2005; Akashi et al. 2013). The accretion phase lasts for several weeks, but the influence on the secondary stellar wind properties can last a few months after the event, until the accreted mass is removed by the restoring secondary wind (Kashi & Soker 2009c). It is therefore very reasonable that lines will be absorbed in different locations across periastron. This secondary effect is the main cause for the deviation from our Doppler-based model, as seen in the figures.

4. ABSORPTION OF HELIUM BY THE SECONDARY

According to Nielsen et al. (2007), the amount of absorption of the He I $\lambda 5015$ P Cyg line reaches up to 50%. This line, however, shows different orbital change (probably because it is blended) and is not one of the lines we claim to originate in the secondary wind (see Section 3). The He I lines we attribute to the secondary show much less absorption. The He I $\lambda 7067$ P Cyg line, for example, shows 10% absorption near periastron (Nielsen et al. 2007). We can use this to better constrain the properties of the two stars.

The maximum absorption, assuming that it occurs in the secondary wind, is obtained when

$$A_{\text{max}} = \frac{f_2 L_2}{f_1 L_1 + f_2 L_2},$$

where $L_1$ and $L_2$ are the luminosities of the primary and the secondary, respectively, and $f_1$ and $f_2$ are their fractions within the line absorption waveband.

According to Nielsen et al. (2007), the He I $\lambda 7067$ line shows 10% absorption for a range between $-700$ and $-500 \text{ km s}^{-1}$. Taking $A_{\text{max}} \leq 0.1$ in Equation (3), we get the requirement that

$$\frac{f_1 L_1}{f_2 L_2} \leq 9.$$  

Assuming blackbody radiation, and taking conventional parameters for the temperatures of the primary and the secondary $T_1 = 20,000 \text{ K}$ and $T_2 = 40,000 \text{ K}$, respectively, we obtain $f_1/f_2 = 5.9$. This means that according to Equation (4), the luminosity ratio needs to satisfy
5. SUMMARY AND DISCUSSION

We used spectroscopic observations of η Car close to the 2009 periastron passage (Mehner et al. 2011a, 2011b; Richardson et al. 2015) to show that they support earlier suggestions that the companion is in the foreground at periastron (Kashi & Soker 2011 and references therein).

We assumed that the He i and N ii spectral lines originate in the acceleration zone of the secondary star of η Car (Kashi & Soker 2007, 2011). We then took the secondary to be closest to us at periastron passages, i.e., ω = 90°. We further used the high-mass model of η Car with component masses of $M_1 = 170 M_\odot$ and $M_2 = 80 M_\odot$. These masses better fit evolutionary tracks of massive stars that cross the locations of the two stars on the H-R diagram than the commonly used masses of $M_1 = 120 M_\odot$ and $M_2 = 30 M_\odot$. A massive primary star with initial mass larger than $M_1 = 200 M_\odot$ and a secondary star with an initial mass larger than $M_2 = 50 M_\odot$ are supported by stellar evolution calculations for very massive stars (e.g., Yungelson et al. 2008; Brott et al. 2011; Yusof et al. 2013).

The high masses, more generally in the range of $M_1 \approx 150–200 M_\odot$ and $M_2 \approx 60–90 M_\odot$, can account also for the powering of the nineteenth-century GE by mass accretion onto the secondary star (the HAPI model; Kashi & Soker 2010a). For the eccentricity and inclination angle we used the commonly accepted values of $e \approx 0.9$ and $i = 41°$, respectively. As evident from Figures 1–4, we could fit the general variation of the Doppler shifts with orbital phase. Therefore, the suggestion that the secondary star is in the foreground at periastron (e.g., Kashi & Soker 2008; Tsebrenko et al. 2013) is definitely tenable. The suggestion that the primary star is in the foreground at periastron seems to encounter problems, e.g., as evident from the dashed black line in Figure 2, which is the model proposed by Richardson et al. (2015).

In some cases the opposite model, of a line originating from the primary stellar wind and where the primary star is in the foreground at periastron passages, might fit part of the Doppler shifts, e.g., fitting the data from Richardson et al. (2015) in Figure 1. However, this model has too low amplitudes both at periastron passages, as evident from all figures, and away from periastron passages (e.g., right side of Figure 2).

In the present study we considered only the role of the orbital motion on the variation of the Doppler shift with orbital phase. It appears clear from the fluctuations in the Doppler shift values and from the nonperfect fitting that the velocity of the zone responsible for the formation of each line is changing. Both stochastic variations and variation with orbital phase, noticeably near periastron passages, exist. These variations are another manifestation of the unrelaxed nature of this binary system.

The three unknowns about the binary system discussed here are (1) the masses of two stars, (2) orbital orientation, and (3) exact periastron time. The masses of the two stars were obtained by Kashi & Soker (2010a) as explained in Section 1. Here we showed that the mass estimate obtained by Kashi & Soker (2010a) also allows us to fit radial velocities of the lines. The orbital orientation is the main parameter discussed here in detail. The time of periastron is uncertain. We used a fixed value here and did not fine-tune its value. It may, however, be possible to use the He i and other lines to get a better constraint for its time. What we find here is that our fits are consistent with periastron time of JD 2,454,850, but a few days difference is also possible.

$L_2/L_1 \geq 0.65$. According to the conventional parameters, the ratio $L_2/L_1 = 0.2$, so this leads to a contradiction. It is not possible to find for the conventional model a point in the stellar evolution path, even with a different effective temperature, that would be even close to satisfying that requirement. We therefore conclude that the two stars must have a smaller luminosity ratio, and consequently smaller mass ratio, as is expected in the massive-star model. They should also have a smaller temperature ratio to make the requirement in Equation (4) easier to meet.

For the massive-star model we propose, we can track the evolution of $M_1 = 170 M_\odot$ and $M_2 = 80 M_\odot$ stars (e.g., Ekström et al. 2012; Köhler et al. 2015 and references therein) and try to find a reasonable set of parameters that satisfies the above equation. We find that if we take $T_1 = 25,000$ K (Hillier et al. 2001) and $T_2 = 37,000$ K (Verner et al. 2005), which gives $f_1/f_2 = 2.8$, then the requirement from Equation (4) becomes $L_2/L_1 \geq 0.31$. And indeed, stellar evolution tracks give $L_1 \approx 3 \times 10^6 L_\odot$ and $L_2 \approx 1.2 \times 10^6 L_\odot$, satisfying the condition.
In addition to the Doppler shifts presented here, there are other arguments that support the suggestion that the secondary star is in the foreground at periastron passages. The four supporting arguments listed by Kashi & Soker (2008) include the evolution of the radio emission and the behavior of the He I λ10830 line. In a previous study (Kashi & Soker 2009b) we further argued that the column density toward the X-ray-emitting gas, that is, the postshock secondary wind, is more compatible with a binary orientation where for most of the time the secondary star is in the background, being in the foreground only near periastron passages. Another supporting argument was brought by Tserenpunts et al. (2013). They demonstrated that the asymmetric morphology of the blue- and redshifted components of the outflow at hundreds of astronomical units from η Car can be accounted for by the collision of the free primary stellar wind with the slowly expanding dense equatorial gas closer to us. Namely, for most of the orbital period the primary is in the foreground, and at periastron passages the secondary star is in the foreground.

Humphreys et al. (2008) discovered that the He I lines were absent from η Car’s spectra prior to the mid-1940s. They discussed the various difficulties it may pose to models attributing the required He ionizing photons to the secondary, ionizing the primary wind. They also conclude that even a much denser primary wind could not have obscured the He ionizing photons coming from the secondary. Clementel et al. (2015b) and Mehner et al. (2015) claimed, however, that the He ionizing photons only moderately penetrate the dense postshocked primary wind. Therefore, if the primary wind at that time was 2–4 times denser, it should have been enough to change the ionization structure of He in the primary’s wind and prevent the formation of the lines. These arguments, however, are irrelevant for a model in which the He I lines originate in the secondary’s wind. In the frame of the accretion model, however, it is easier to provide an explanation. A denser primary wind can form a thick accretion belt around the secondary close to periastron (Kashi & Soker 2009c) that would last for the entire orbit, providing a shield for its radiation. Even after the belt is gone, the mass that is accreted onto the secondary changes its photospheric structure and makes it cooler, diminishing the He ionizing photons. This may require that the primary wind before the 1940s was 20–30 times denser. A new study by A. Kashi et al. (2015, in preparation) suggests that the mass loss could have reached that magnitude or even higher.

Mehner et al. (2011a) also observed the N II lines and their velocity shifts from reflected polar spectra at the location known as “FOS4.” They argue that it may be a problematic observation for the orbital motion explanation to the Doppler shift variations. A similar argument appears in Mehner et al. (2011b) regarding the He Iλ4714 line. The only direct comparison of FOS4 and direct view is in Figure 8 of that paper. Though it may at first sight look like the radial velocity of the absorption in FOS4 follows that of the direct view, we notice the following: (1) The observations at −353 and −82 days (phase −0.18 and −0.045) show very high radial velocity in absorption, much above other observations of the same line. (2) At −82 days the value of FOS4 is 40 km s\(^{-1}\) higher. As the observations are sparse, there is no way to know whether this is significant. It may indicate that the FOS4 Doppler shift of the absorption is smaller in amplitude and nonsystematic. Alternatively, it may be a fluctuation. It is therefore impossible to know whether FOS4 persistently follows the direct view or not. A detailed comparison of densely sampled multiple lines is needed in order to check that. Even if it does, it may well be possible that not only polar light is reflected to FOS4 and there is some reflection from equatorial regions.

Mehner et al. (2010) used the distribution of gas and ionizing radiation around η Car to constrain the properties of the secondary. If the limits of Mehner et al. (2010) hold, then the secondary mass should be \(M_2 \leq 60 M_\odot\). A mass of \(M_2 = 60 M_\odot\) is still within the HAPI model for the GE. We here showed that the Doppler shifts can be fitted with \(M_2 = 30 M_\odot\) and \(M_2 = 80 M_\odot\). Any value for \(M_2\) in this range can be fitted. But as stated, because of the luminosity of the primary star and the HAPI model for the GE, we prefer the high-mass model.

P Cyg profiles in He I are found in hot hydrogen-poor stars (Wessel wolveski et al. 1988; Leuenhagen et al. 1996; Leuenhagen & Hamann 1998). We know from observations that the primary’s outer layers consist of about 50% helium (Davidson et al. 1986; Dufour et al. 1997). A few solar masses of material from the primary were accreted onto the secondary during the eruptions. The accreted gas makes the secondary’s envelope enriched with helium. It is very plausible that even though the secondary is hot, its helium lines are stronger than other stars in its evolutionary stage. Clumpiness of the secondary wind (Kashi & Soker 2007) can make part of the gas somewhat cooler, also enhancing the He I lines.

The very massive primary star of \(M_1 > 150 M_\odot\) and the very high eccentricity of the binary orbit hint that the system was once a triple system and that the primary formed by the merger of two (or more) stars. The merger process released large amounts of gravitational energy within weeks to months. Such an event can be classified as ILT. Therefore, it may well be that the nineteenth-century GE was not the first ILT of this system. We note that the estimates for the masses in the HAPI model do not depend on the previous existence or nonexistence of a third star. The masses of only two stars are relevant for both the calculations done in this paper for spectral fitting and the calculations done in Kashi & Soker (2010a) for modeling the light curve. The third star is suggested as a possible easier route to obtain the large mass of the primary, together with a high-eccentricity orbit. But it is well possible that both were obtained with only two stars along the entire evolution.

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