Explaining the transient fast blue absorption lines in the massive binary system $\eta$ Carinae

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ABSTRACT
We use recent observations of the He I $\lambda 10\,830$ Å absorption line and 3D hydrodynamical numerical simulations of the winds collision to strengthen the case for an orientation of the semimajor axis of the massive binary system $\eta$ Carinae where the secondary star is toward us at periastron passage. These observations show that the fast blue absorption component exists for only several weeks prior to the periastron passage. We show that the transient nature of the fast blue absorption component supports a geometry where the fast secondary wind, both pre- and post-shock material, passes in front of the primary star near periastron passage.

Key words: binaries: general – stars: individual: $\eta$ Car – stars: massive – stars: mass-loss – stars: winds, outflows – infrared: stars.

1 INTRODUCTION

$\eta$ Carinae ($\eta$ Car) is a very massive stellar binary system, with an orbital period of 5.54 yr (Damineli 1996), as observed in all wavelengths (e.g. radio, Duncan & White 2003; IR, Whitelock et al. 2004; visible, van Genderen et al. 2006; Fernandez-Lajus et al. 2010; UV, Smith et al. 2004; emission and absorption lines, Damineli et al. 2008a,b; Nielsen et al. 2009; X-ray, Corcoran 2005; Corcoran et al. 2010; Hamaguchi et al. 2007). The high eccentricity of $e \simeq 0.9$ results in rapid changes in emission and absorption lines, as well as in the continuum, near each periastron passage. The several weeks of rapid changes occurring every orbital period is termed the spectroscopic event. These lines might originate in different places in the binary system: the primary star, the secondary star, their respective winds and the colliding winds structure which is termed the conical shell.

As $\eta$ Car is the best studied binary luminous blue variable (LBV), it holds the key to our understanding of other LBVs. It is particularly important to understand the behaviour near periastron passage, where the strongest binary interaction takes place, and for that it is crucial to know the orientation of the binary system: namely, the direction of the primary more massive LBV star relative to its less massive but hotter companion at periastron passage. While it is agreed that the inclination of the binary system is $i \simeq 41^\circ$ (Davidson et al. 2001; Smith 2006), there is no agreement on the direction of the semimajor axis, termed periastron longitude. The orientation is measured by the angle $\omega$: $\omega = 0^\circ$ for the case when the secondary moves toward us before periastron passage and the semimajor axis is perpendicular to the line of sight; $\omega = 90^\circ$ when the secondary is toward us at periastron passage; and $\omega = 270^\circ$ when the primary is toward us at periastron passage. Several properties of the binary system have been used to deduce the orbital orientation, with contradicting results (for details see Kashi & Soker 2008b, 2009c).

One of the properties that led to a contradicting conclusion on the orientation is the behaviour of the blue absorption wing of the He I $\lambda 10\,830$ Å line. In Kashi & Soker (2009b) we constructed a toy model where the material responsible for the blue absorption wing was assumed to reside in the colliding winds region – the conical shell – close to the binary system. This model is able to account for the transient appearance of the blue absorbing wing and the finding that the maximum absorbing velocity is reached several days before periastron passage, only if the secondary is toward us near periastron passage, i.e. $\omega \simeq 90^\circ$. In a recent paper Groh et al. (2010, hereafter G2010) reached an opposite conclusion. Comparing their observations with a model based on 3D numerical simulations of the colliding winds structure, G2010 suggested that the orientation is that of $\omega = 243^\circ$. Namely, the primary is closer to us just before periastron passage. In this paper we critically re-examine both models.

2 PROPERTIES OF THE ABSORPTION PROFILE

The He I $\lambda 10\,830$ Å line has been observed for more than a decade, but only occasionally (Damineli et al. 1998, 2008b; Groh, Damineli & Jablonski 2007; G2010). The line shows a P Cygni profile varying in time, especially close to the spectroscopic event. It has a complicated emission with three spikes, and absorbing components with velocities of up to $-v \simeq 1900\,\text{km}\,\text{s}^{-1}$. In this section we describe the relevant properties of the blue absorption wing that rapidly appears and disappears near periastron passages.

G2010 observed the He I $\lambda 10\,830$ Å across the 2009 periastron passage. In Fig. 1 we show the absorption profile at phase 11.998,
the difference to be about \( 200-350 \text{ km s}^{-1} \). G2010 attribute the difference to pre- and post-shock secondary wind material close to the binary system (Kashi & Soker 2009b). The post-shock gas resides in the conical shell. We further assume that the secondary wind gas absorbs most of the continuum emitted by the gas in the conical shell (emission that increases just before periastron passage), in addition to absorbing some fraction of the continuum emitted by the primary wind. It is this component that is in dispute between G2010 and us. Although we and G2010 attribute it to the colliding winds, in the model of G2010 the absorbing gas is at a distance of tens of au from the binary systems, while in our model the absorbing material is relatively close to the binary system.

One thing to notice is that the first observation after the 2009 spectroscopic event is at phase 12.014, before the system exits from the X-ray minimum (Corcoran et al. 2010), and before the hard ionizing radiation from the secondary resumes after exiting the dense primary wind. As we note in Section 3, this holds difficulties for the model of G2010.

3 PROBLEMS WITH THE MODEL OF G2010

The purpose of this section is to set the motivation for a model where the fast absorbing material resides close to the secondary star, and the secondary star is in front of the primary near periastron passage. We critically examine a model with an opposite binary orientation, and reveal its problems.

G2010 present (in their figs 12m–o) the total column density as a function of gas velocity at five phases according to their assumptions. Their main assumptions are as follows. (1) The photospheric radius of the primary at 1.083 \( \mu \text{m} \) is 2.2 au. (2) A point source can be used for the central source of the 1.083 \( \mu \text{m} \) continuum emission. (3) The central source is the only source of the continuum (below we claim that the conical shell is an additional source). (4) G2010 did not consider even qualitatively the change in level population. In their model the change in level population must be significant; below we argue why this is unlikely.

In more detail, their fig. 12 gives the density of material as a function of line-of-sight distance to the primary for five orbital phases ([11.875, 11.991, 11.998, 12.014 and 12.041]) and six orientations (\( \omega = 0^\circ, 50^\circ, 90^\circ, 180^\circ, 243^\circ \) and \( 270^\circ \)). In addition, the column density along the same assumed line of sight to the primary star is given as a function of the line-of-sight velocity, for each orientation and phase. Fig. 12 of G2010 allows us to deduce the basic properties of their model.

G2010 did not relate the total column density to the absorption of the He\( ^{1} \lambda 10,830 \text{ Å} \) line. We attempt to do so and check what the results of G2010 imply. As we now show, their model, with a preferred orientation of \( \omega = 243^\circ \), suffers from severe problems because the column density does not follow even qualitatively the behaviour of the observed absorption. In their attempt to resolve this discrepancy, G2010 claim that the presence of high-velocity gas in our line of sight is a necessary, but not sufficient, condition for the presence of high-velocity absorption. As the amount of absorption depends on the population of the lower energy level of the He\( ^{1} \lambda 10,830 \text{ Å} \) line (\( 2^S \)), they attribute the differences in absorption to different populations of the \( 2^S \) atomic level.

3.1 Pre-periastron passage

For the three phases before periastron passage ([11.875, 11.991, 11.998]), the G2010 model (in their fig. 12o) predicts the absorbing column density in the range \(-u = 2000–3000 \text{ km s}^{-1}\) to be about equal to that in the velocity range \(-u = 1600–1800 \text{ km s}^{-1}\). Observations show substantial absorption in the \(-u = 1600–1800 \text{ km s}^{-1}\) range at phases 11.991 (\( \sim 3–10\) per cent absorption) and 11.998 (\( \sim 5–13\) per cent absorption), while there is no absorption at \(-u > 1900 \text{ km s}^{-1}\) (fig. 1 of G2010). G2010 attribute the difference to stratification in the population of the \( 2^S \) level, from which the He\( ^{1} \lambda 10,830 \text{ Å} \) line is absorbed. However, they do not present a...
A qualitative study of the way in which the population of the 2 $\text{S}$ level can evolve so rapidly. We find it extremely unlikely (unless there is a carefully arranged fine tuning) that differences in populating the 2 $\text{S}$ level can account for this difference. The reason is as follows.

According to G2010’s model during the phase interval 11.991–11.998 the absorbing gas at $-\nu = 2000 \text{ km s}^{-1}$ resides at a distance of $r_a \approx 3.5a$ from the binary system, where $a \approx 16 \text{ au}$ is the semi-major axis (their fig. 12a). They also find that the gas absorbing in the velocity range $-\nu = 1600–1800 \text{ km s}^{-1}$ resides at $r_a \approx 2.5–3a$. During this phase interval, the binary orbital separation is $r \lesssim 0.2a$. Therefore, the differences in the radiation of the two stars at $r \approx 2.5–3a$ and $\gtrsim 3.5a$ are small, and cannot account for the required large differences in the population of the 2 $\text{S}$ level. Moreover, the increase in the amount of absorption as the system approaches periastron in the model of G2010 is attributed to an increase in the population of the 2 $\text{S}$ level. This is probably (G2010 do not specify the reason) because the secondary gets deeper into the primary wind, and less of its radiation reaches the absorbing gas. It is expected that the outer regions, where gas moving at $-\nu = 2000 \text{ km s}^{-1}$ resides, will get less of the secondary radiation, and hence will absorb more. This is opposite to what their model requires.

A potential way to handle the problem is that the material closer in is of higher density, and it recombines first or its collisional excitation is more efficient. This would not work either. The rate of these two processes is linear with density. The density ratio between the region absorbing in the $-\nu = 1600–1800 \text{ km s}^{-1}$ range and that absorbing in the $-\nu \approx 2000 \text{ km s}^{-1}$ range is $\approx 2$ (G2010, figs 12m and n). Therefore, the absorption at $-\nu \approx 2000 \text{ km s}^{-1}$ is expected to be one-half of that in the $-\nu = 1600–1800 \text{ km s}^{-1}$ velocity range. This amounts to $1.5–5\%$ per cent of the flux at phase 11.991 and $2.5–6.5\%$ per cent of the flux at phase 11.998. This is clearly ruled out by observations, as the absorption at $-\nu = 2000 \text{ km s}^{-1}$ observed in these two phases is practically zero.

### 3.2 Post-periastron passage

In phase 12.014 (28 d after phase 12) the column density calculated by G2010 in the velocity range $-\nu = 1200–1400 \text{ km s}^{-1}$ is a factor of 2–3 lower than that at phase 11.998, while in $-\nu = 1600–1800 \text{ km s}^{-1}$ this ratio is $< 2$ (their fig. 12o). At phase 12.014 the secondary radiation has not started yet to ionize the material at large distances, as it is still inside the dense region of the primary wind. We know this from the behaviour of the highly ionized lines, e.g. in the Weigelt blobs, which show that the hard radiation resumed (in the 2003.5 spectroscopic event) well after the X-ray minimum ended (Damineli et al. 2008b; Mehner et al. 2010). In the 2009 spectroscopic event the X-ray minimum ended at phase $\sim 12.014$ (Corcoran et al. 2010), when one of the He1 $\lambda 10830 \text{Å}$ line measurements was conducted. Namely, at this phase the secondary hard ionizing radiation did not ionize the He in the relevant distance of tens of au. The density in the relevant region at phase 12.014 is not much different from that at phase 11.998. If it was for recombination, there should have been more time for the gas at phase 12.014 to recombine.

Overall in the velocity ranges $-\nu = 1200–1400$ and $1600–1800 \text{ km s}^{-1}$ the column density calculated by G2010 at phase 12.014 is $\sim 0.3–1\%$ times that at phase 11.998, and the ionization state should be the same. Therefore, it is expected that the absorption at phase 12.014 in the velocity ranges $-\nu = 1200–1400$ and $1600–1800 \text{ km s}^{-1}$ would be $\sim 0.3–1\%$ times that at phase 11.998, or even above its value at phase 11.998. This is contrary to observations, as there is no absorption at all for $-\nu > 1100 \text{ km s}^{-1}$ at phase 12.014 (fig. 1 of G2010). This is a severe problem for the model presented by G2010.

Not only the model of G2010 but also any other model that would assume absorption by material residing at a large distance (a few $10 \text{ a}$ or more) is problematic. The reason is that the absorption of the He1 $\lambda 10830 \text{Å}$ line in high velocities is a transient event, which occurs very close to periastron, and must be related to variations in the system shortly before periastron. The material far from the binary system is not supposed to show fast variations close to periastron, and for that reason it is a bad candidate for an absorber of the He1 $\lambda 10830 \text{Å}$ line.

### 4 THE MODEL

#### 4.1 The column density of the absorbing gas

We perform hydrodynamic simulations of the colliding winds to show that the column density of the conical shell and the pre-shocked secondary wind at high velocities is high enough to account for the absorption of the He1 $\lambda 10830 \text{Å}$ line. The simulations are performed with Virginia Hydrodynamics-I (vH-I), a high-resolution multidimensional astrophysical hydrodynamics code developed by J. Blondin and collaborators (Blondin et al. 1990; Stevens, Blondin & Pollock 1992; Blondin 1994). The code includes radiative cooling at all temperatures of $T > 2 \times 10^4 \text{ K}$. The radiative cooling is set to zero for temperatures of $T < 2 \times 10^4 \text{ K}$, and the gas cannot cool to lower temperatures. The cooling function $\Lambda(T)$ (for solar abundances) is taken from Sutherland & Dopita (1993, their table 6).

The numerical simulations were performed in the Cartesian geometry ($x$, $y$, $z$) mode of the code (a 3D calculation), where the orbital plane is the $(x, y)$ plane with the $x$-axis taken to be parallel to the line connecting the two stars. Our numerical simulation grid has 112 equal-size grid points along each axis. The primary and the secondary are located in the middle of the $y$- and $z$-axes. The binary separation between the two stars is set to be constant at each numerical run (for the justification see Akashi & Soker 2010). The mass-loss rates and velocities of the winds are $M_1 = 3 \times 10^{-5} \text{M}_\odot \text{ yr}^{-1}$ and $M_2 = 10^{-5} \text{M}_\odot \text{ yr}^{-1}$, and $v_1 = 500 \text{ km s}^{-1}$ and $v_2 = 3000 \text{ km s}^{-1}$, respectively (e.g. Pittard & Corcoran 2002; Kashi & Soker 2008b, and references therein). We use an eccentricity of $e = 0.9$ and semi-major axis of $a = 16.64 \text{ au}$. We performed four runs with binary separation of $r = 2$, $3$, $4$ and $10 \text{ au}$, and in each created a density profile and wind velocity field around the two stars. At the location of each star we inject its appropriate wind. We let the flow reach an approximately steady state. An example of the results of the simulation is shown in Fig. 2.

For each run we calculate the direction to the observer for a system with $(\omega, i) = (90^\circ, 41^\circ)$, and for the phase before periastron corresponding to the binary separation of the run. We take a plane perpendicular to the line of sight and located behind the primary, and from this plane we calculate the column density along a grid of lines of sight to the observer. We select the location of this plane in an approximately optimal way to include as much of the grid as possible. This procedure favours accuracy in the calculation of the column density of the high-velocity gas towards the observer. Each line of sight is divided into cells, as the number of $z$-planes the line of sight crosses in our grid. We calculate the column density along each line of sight as function of the velocity projected along the line of sight. Like G2010 we use velocity bins of $50 \text{ km s}^{-1}$. 

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We adopt the conclusions of G2010 that the main source of the 1.083 \( \mu m \) continuum emission comes mostly from a region of size \( \sim 2.2 \text{ au} \) centred on the primary star. We term it the central source. Though G2010 used a point source for the central source of the 1.083 \( \mu m \) continuum emission, they mentioned that it is of size several astronomical units, based on observations by Weigelt et al. (2007) in the \( K \) band, which were calibrated to 1.083 \( \mu m \) (which is within the \( J \) band), with the help of the theoretical results of Hillier et al. (2001). Weigelt et al. (2007) found the decrease function of the central source intensity with projected distance from the centre \( r_p \), to be close to a Gaussian (their fig. 6). We therefore take the emission to be from a radius of \( R_{\text{em}} = 4.4 \text{ au} \), and weight the intensity as a Gaussian with \( \sigma = 2.2 \text{ au} \):

\[
I = I_0 \exp \left( -r_p^2/2\sigma^2 \right) \quad \text{for} \quad r_p \leq R_{\text{em}},
\]

(1) where \( I_0 \) is the intensity at the centre (the cut-off at \( R_{\text{em}} \) is used due to numerical constraints and results in a negligible error).

The column density from each line of sight is weighted with the Gaussian in equation (1) according to its distance \( r_p \), from the line of sight of the primary (Fig. 2). This procedure gives us an effective column density in each velocity interval and at each phase. The results are presented in Fig. 3.

From Fig. 3 we learn the following. (1) For \( \omega = 90^\circ \) the column density in the conical shell and the undisturbed wind is high enough to account for the absorption of the \( \text{He} \, \lambda \, 10.830 \text{ Å} \) line for our favoured orientation of \( \omega = 90^\circ \). As in the model of G2010, our model is unable to calculate the population of the 2\(^{1}\)S level of He, and hence we cannot calculate the exact absorption in the \( \text{He} \, \lambda \, 10.830 \text{ Å} \) line. (2) The high column density for \( -v \gtrsim 1000 \text{ km s}^{-1} \) is a transient component which appears only for a short period before periastron passage. (3) The column density clearly increases as the system approaches periastron (note that in fig. 12 of G2010 this is not the case). (4) The column density decreases towards higher blue velocities, despite minor fluctuations due to the limited numerical resolution. (5) At short binary separations (\( r \lesssim 4 \text{ au} \); \( t \gtrsim 0.987 \)) there is a plateau in the column density between \( \sim 1400 \) and \( \sim 2100 \text{ km s}^{-1} \), followed by a decrease in column density towards higher blue velocities.

Our model gives that at very high velocities of \( -v > 1900 \text{ km s}^{-1} \) the column density is also large, namely we have more absorbing gas than required to account for the observations. This discrepancy may be the result of an anisotropic secondary wind velocity close to periastron passage, which can occur if the acceleration of the secondary wind is not isotropic, an effect which was not taken into account in our simulation. Such an effect can reduce the amount of gas which outflows at \( -v > 1900 \text{ km s}^{-1} \). The acceleration can be efficient along polar directions, but below \( i \gtrsim 60^\circ \) radiation from the primary and previous accretion of blobs might cause the secondary wind to be slower. This explanation cannot work for correcting the surplus absorbing gas in the model of G2010, as their absorbing material is much further away from the colliding winds region.

### 4.2 Covering the emission source with the conical shell

From Fernandez-Lajus et al. (2010) we find that the \( I \)-band continuum has a quiescence value of \( I = 3.55 \text{ mag} \). We sample the increase in the \( I \)-band continuum flux above the quiescence value, \( f_c(t) \), from the observations of Fernandez-Lajus et al. (2010). These observations show that close to the 2009 periastron passage the \( I \)-band continuum flux (and therefore the 1.083 \( \mu m \) line flux) has increased by \( f_c(t = 0) \approx 20 \text{ per cent} \) above the quiescence value (Fig. 5). We attribute most of this extra emission to the conical shell close to the binary system. We further assume that there is a strong absorption by the conical shell and the pre-shocked secondary wind of the \( \text{He} \, \lambda \, 10.830 \text{ Å} \) line.

We analytically calculate the fraction of the central source of the 1.083 \( \mu m \) continuum emission region that is covered by the conical shell (namely, covered behind the conical shell from the line of sight of the observer). The parameters of the stars and the conical shell are taken as in our previous papers (Kashi & Soker 2009b,c, and references therein). The contact discontinuity is approximated as a hyperboloid with semi-opening angle \( \phi_o \approx 60^\circ \). This is an
25 per cent of the intensity of the $I_\lambda = (2)$ component is the fraction of the conical shell emission that is absorbed by the conical shell close to periastron, as well as $f_\rm{c}$ and $f_\nu$. The conical shell absorbs up to $f_\nu(t = 0) \simeq 25$ per cent of the intensity of the 1.08 $\mu$m continuum emission from the central source (the primary star). When $\omega = 90'$ our model accounts for the fast increase in absorption of the flat part (F component; Fig. 1). Considering the many uncertainties and the simplicity of our model, our results are in reasonable agreement with the observed decrease in the flat part of the F component in the velocity range $-\nu \simeq 1150-1400$ km s$^{-1}$ (the tail to $-\nu = 1900$ km s$^{-1}$ is part of this component, and behaves in the same way).

The sizes of the central and extra emission sources are important for this modelling. G2010 use a point-like continuum source in their quantitative calculation of the column density of the absorbing material (total column density, not only that of the relevant atoms). For the model of G2010, where $\omega = 243^\circ$, it does not make much difference to use a point source, as their absorbing material is several tens of au from the source. However, calculating the column density to a point source fails to reproduce results of a model where the absorption occurs a few au from the stars, such as our model (Kashi & Soker 2009b), which we improve here. G2010 do discuss (in their section 5.3) a 2.2 au extended source for an orientation of $\omega = 90'$, and find the duration of the high-velocity absorption to be too short. Our point here is that an extra source must be included to take into account the increase in the $I$ band and for the extra absorption. In our model the extra source is the conical shell. Our results show that one must use an extended emission source, both for the central source (the primary star) and for the extra source from the conical shell. Using the two extended sources overcomes the objection of G2010 to the $\omega = 90'$ orientation.

5 SUMMARY AND DISCUSSION

The He I $\lambda 10830$ Å line of η Car has been observed across the 2009 periastron passage by G2010. We identify three main absorbing components in the He I $\lambda 10830$ Å line profile (Fig. 1). Two components can be identified with the dense primary stellar wind: the P component (500–650 km s$^{-1}$) and the M component ($-\nu = 620–720$ km s$^{-1}$). The third, more interesting F component shows a flat part in the velocity range $-\nu \simeq 1150-1400$ km s$^{-1}$, with a tail to $-\nu = 1900$ km s$^{-1}$. The tail results from faster moving gas, and not

between the observer and the emission source element, we use our assumption of high optical depth in the conical shell, and assume that the emission from the covered source is totally absorbed. In other words, if the emission source element is either of the two (behind the conical shell or inside it), we consider this element to contribute to the 1.08 $\mu$m line absorption. The contribution of each element is weighed as a Gaussian, with the projected distance to the line of sight, as discussed above.

The calculated flux of the 1.08 $\mu$m flux line according to our model is

$$F_{\text{abs}}(t) = \frac{1 - f_\nu(t) + f_\nu(t)(1 - f_\nu)}{1 + f_\nu(t)}$$

where $F_{\text{continuum}}(t)$ is the 1.08 $\mu$m continuum flux (given by G2010, as defined above), $f_\nu$ is the fraction of the central continuum source covered by the conical shell, $f_\nu$ is the increase in the I-band continuum flux above the quiescence value (Fernandez-Lajus et al. 2010) and $f_\nu$ is the fraction of the conical shell emission that is absorbed by the F component. If the conical shell self-absorbs all its emission then $f_\nu = 1$, while if it absorbs only from its volume that is behind the conical shell then $f_\nu = 0.5$. We present results for both these values that bound our expectation. Fig. 5 presents $F_{\text{obs}}(t)/F_{\text{continuum}}(t)$ close to periastron, as well as $f_\nu$ and $f_\nu$. The conical shell absorbs up to $f_\nu(t = 0) \simeq 25$ per cent of the intensity of the 1.08 $\mu$m continuum emission from the central source (the primary star). When $\omega = 90'$ our model accounts for the fast increase in absorption of the flat part (F component; Fig. 1). Considering the many uncertainties and the simplicity of our model, our results are in reasonable agreement with the observed decrease in the flat part of the F component in the velocity range $-\nu \simeq 1150-1400$ km s$^{-1}$ (the tail to $-\nu = 1900$ km s$^{-1}$ is part of this component, and behaves in the same way).

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The He I $\lambda 10830$ Å line of η Car has been observed across the 2009 periastron passage by G2010. We identify three main absorbing components in the He I $\lambda 10830$ Å line profile (Fig. 1). Two components can be identified with the dense primary stellar wind: the P component (500–650 km s$^{-1}$) and the M component ($-\nu = 620–720$ km s$^{-1}$). The third, more interesting F component shows a flat part in the velocity range $-\nu \simeq 1150-1400$ km s$^{-1}$, with a tail to $-\nu = 1900$ km s$^{-1}$. The tail results from faster moving gas, and not
from line broadening. There is no absorption in this line at $-v > 1900 \text{ km s}^{-1}$.

G2010 present their interpretations of their observations, concluding that the orientation of the binary system is such that $\omega = 243^\circ$ (the primary closer to the observer just before periastron). In Section 3 we point out some problems in the model of G2010, in particular that they cannot account for the transient nature of the line. The model of G2010 fails to reproduce, even qualitatively, the observed absorption profiles of the He $i \lambda 10830$ ā line, and cannot account for the absence of the F component after periastron passage.

In analysing our (Kashi & Soker 2008b, 2009b) preferred orientation of $\omega = 90^\circ$, G2010 use a point-like central continuum source for calculating the column density of the absorbing material. Based on that, they claim that the $\omega = 90^\circ$ orientation is not compatible with their observations. In Section 4 we find that the use of a central point source does not do justice to the $\omega = 90^\circ$ case. This is the main reason why G2010 fail to reproduce results of a model where the absorption occurs a few au from the stars, like in our model.

We improve our pervious model (Kashi & Soker 2009b) which assumed that the conical shell is the main absorber of the high-velocity component of the He $i \lambda 10830$ ā line (Section 4). Our model and results can be summarized as follows.

(i) We assume that the central star is a Gaussian weighted extended continuum source as given by equation (1). This assumption stands on solid ground (Weigelt et al. 2007; G2010).

(ii) We assume that the increase in the 1.083 $\mu$m continuum near periastron passage comes from the conical shell (the collision region of the two winds). The main source is the shocked primary wind. This is based on analysis we performed in previous papers.

(iii) We assume that the main absorbing gas of the He $i \lambda 10830$ ā line is both pre- and post-shock material in the fast secondary wind. This assumption stands on solid ground. Based on recent numerical simulations (Akashi & Soker 2010), we showed in Section 4 that the column density of the fast moving gas is as high as found by G2010. Some segments of the wind are at a temperature of $\sim 10^5$ K, and there are enough recombining He atoms. This will be calculated in a future paper based on high-resolution numerical simulations.

(iv) We concentrate on the absorption of the F component. We assume that in the flat velocity range of the F component (see Fig. 1), the absorbing gas in the conical shell absorbs most of the conical shell emission. We therefore consider two limiting values for this parameter: $f_s = 0.5$ and 1.

(v) We assume that the optical depth of the conical shell in the flat velocity range of the F component is very high, such that it absorbs all the radiation of the central source it hides from our line of sight (in the flat part).

(vi) We assume that the colliding winds shell has a hyperbolic shape. We consider its tilt due to the orbital motion. In calculating the shape and tilt the primary wind acceleration zone is considered.

(vii) We assume, based on our previous papers (Kashi & Soker 2008b, 2009c), that the secondary is toward us near periastron ($\omega = 90^\circ$). We take an inclination angle of $i = 41^\circ$, and the other commonly used binary parameters (semimajor axis, eccentricity etc.).

(viii) We note that after periastron passage some of the assumptions break down, because accretion is likely to occur (Kashi & Soker 2009a; Akashi & Soker 2010).

(ix) We calculate the part of the central source covered by the conical shell, for $\omega = 90^\circ$.

(x) We calculate the covered part of the 1.083 $\mu$m central continuum emission source (equation 2). By that we show that for $\omega = 90^\circ$ our model explains the observed increase in absorption strength of the F component close to periastron passage (Fig. 5), and explains its transient nature.

(xi) We therefore conclude that the orientation is indeed that the secondary is toward us near periastron ($\omega = 90^\circ$).

In addition, using hydrodynamic simulations (Figs 2 and 3) we find that the He $i$ in the conical shell and in the pre-shocked secondary wind has a substantial column density in the velocity range $-v > 1150-1400 \text{ km s}^{-1}$. We assume that the fraction (out of total He atoms and ions) of the He $i$ in the 2S level is high enough to absorb most radiation in the $-v < 1400 \text{ km s}^{-1}$ (with a tail up to $-v \simeq 1900 \text{ km s}^{-1}$).

The finding that the secondary is closer to us near periastron requires that some properties near periastron passage be explained by the accretion of the primary wind on to the secondary star (Kashi & Soker 2008a, 2009d). For accretion to occur on to the secondary star, which has a strong wind of his own, the binary must be close (Akashi & Soker 2010) and interact strongly with the primary. The accretion that occurs near periastron passage is crucial to the understanding not only of the present behaviour of $\eta$ Car but also of its behaviour during the major eruptions it underwent in the 19th century, the Great Eruption (GE) and Lesser Eruption.

The debate on the absorbing source of the blue wing has implications far beyond the specific question on the orientation of the major axis of the binary system. The essence of the debate is the nature of the binary interaction process, which has implications for the nature of LBV major eruptions, and mass loss by very massive stars (e.g. Soker 2001, 2005, 2007; Kashi & Soker 2010; Smith 2010a,b; Smith et al. 2010).

The GE is the best-studied example of a major LBV eruption, and serves as a test case for theories and models. A high rate accretion during the GE could have supplied the extra luminosity for 20 yr, and the accreting secondary star could have launched two jets that shaped the bipolar structure – the Homunculus (Soker 2001). Most likely other LBV major eruptions are also related to binary interaction (Kashi & Soker 2010), as was argued for the 17th century eruption of P Cygni (Kashi 2010), rather than a single star phenomenon as suggested by e.g. Smith (2007), Smith & Owocki (2006) suggested that LBVs lose most of their envelope mass during major eruptions. Therefore, the presence of a strongly interacting companion can play a major role in the evolution of very massive stars. As suggested by Kashi, Frankowski & Soker (2010), major mass transfer events in LBVs are related to optical transient objects and have a common powering mechanism – accretion on to a companion star. Understanding the binary interaction in $\eta$ Car will shed light on other objects where binary interaction is thought to shape circumstellar nebulae, like planetary nebulae, symbiotic systems and related objects such as the Red Rectangle.

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