THE DEPARTURE OF $\eta$ CARINAE FROM AXISYMMETRY
AND THE BINARY HYPOTHESIS

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ABSTRACT

I argue that the large scale departure from axisymmetry of the $\eta$ Carinae nebula can be explained by the binary stars model of $\eta$ Carinae. The companion diverts the wind blown by the primary star, by accreting from the wind and possibly by blowing its own collimated fast wind (CFW). The effect of these processes depends on the orbital separation, hence on the orbital phase of the eccentric orbit. The variation of the mass outflow from the binary system with the orbital phase leads to a large-scale departure from axisymmetry along the equatorial plane, as is observed in $\eta$ Car. I further speculated that such a companion may have accreted a large fraction of the mass that was expelled in the Great Eruption of 1850 and the Lesser Eruption of 1890. The accretion process was likely to form an accretion disk, with the formation of a CFW, or jets, on the two sides of the accretion disk. The CFW may have played a crucial role in the formation of the two lobes.

Key words: binaries: close – stars: early-type – stars: mass loss – stars: individual ($\eta$ Carinae)
1. INTRODUCTION

One of the open questions regarding the massive star \( \eta \) Carinae and its nebulosity is whether the nucleus is a single or a binary stars system. The main argument used by the binary model supporters is the \( P = 2020 \pm 5 \) days = 5.5 yr periodicity of the spectroscopic event—fading of high excitation lines (Damineli 1996; Damineli et al. 2000, and references therein). There are other, though weaker, supporting observations in favor of a massive companion. Ishibashi et al. (1999) find that the X-ray emission, which follows the 5.5 yr periodic variation, can in principle be explained by colliding winds, where the two winds are blown by the two components of a binary system. However, not everyone supports the binary model. Smith et al. (2000) attribute the 5.5 yr periodic variation to variation in the ionizing hard-UV flux reaching the equatorial gas, and argue that presently there is no advantage to a binary model over a stellar inherent instability model (e.g., Stothers 2000) to account for the periodicity. In particular they argue against the suggestion raised by Damineli et al. (2000) that the ionizing flux is emitted by the companion, and that the periodic variation is caused by absorption of the companion’s radiation by the primary stellar wind during periastron passages. Davidson et al. (2000) claim that it is not clear yet whether \( \eta \) Car is a binary system, but if it is the parameters of the companion and orbit are not those found by Damineli (2000), and presently remain unknown (some new parameters are suggested by Corcoran et al. 2001).

In the present paper I argue that the departure of the nebula around \( \eta \) Car from axisymmetry can be explained by the central close binary model. By departure from axisymmetry I refer to a large-scale departure, and do not consider small blobs, filaments, and other small-scale features. In that respect a binary companion in an eccentric orbit offers an answer to question 14 raised by Davidson & Humphreys (1997; hereafter DH97): “Why was the eruption azimuthally asymmetric; . . . ” (they refer also to the small blobs, but here I refer only to the large-scale asymmetry). In §2 I describe the departure from axisymmetry of the nebula around \( \eta \) Car. I then demonstrate that the parameters suggested for the binary system can in principle lead to the formation of a nebula possessing a large-scale departure from axisymmetry. In §3 I discuss some implications of the binary model for the formation of the bipolar structure of the Homunculus and the dense equatorial flow. I summarize in §4.

2. DEPARTURE FROM AXISYMMETRY

Although the Homunculus seems quite axisymmetrical, it is not perfectly so. Morse et al. (1998) argue that “the lobes exhibit a slight banana-shaped symmetry . . ”. The “banana-shaped” structure is more prominent in the velocity maps presented by Allen & Hillier (1993), which show the structure in planes parallel to the line of sight. These maps show that the departure
of the Homunculus from axisymmetry is mainly along the line of sight, hence hard to detect in simple imaging of η Car. Many other structural features show a highly prominent departure from axisymmetry in the plane of the sky. Figure 3 of Morse et al. (1998, see their Erratum for high quality images), shows a clear departure from axisymmetry on the outskirts, ∼ 10′′ from the nucleus. On the south-west side of the equatorial plane there is a dense arc of gas, termed S-Ridge, while on the north-east side there is no such an arc, but rather the “jet” and the “NN bow”. It is clear that this departure from axisymmetry along the equatorial plane has a large-scale structure, and can’t be attributed to instabilities in the flow or in the mass loss process. A same sense of asymmetry is seen in the radial velocities map presented by Weis, Duschl & Bomans (2001). On the south-west side the measured radial velocities are higher than those on the north-east side. A large scale departure from axisymmetry is clearly seen also in recent X-ray images (Weis et al. 2001; Seward et al. 2001). Other departures from axisymmetry along the equatorial plane are seen much closer to the nucleus. The 10µm image of Morris et al. (1999) shows that the peak on the north-east side of the equatorial plane is much stronger than the emission on the south-west side. The same sense of departure from axisymmetry is seen at shorter IR bands (e.g., fig. 5 of Smith, Gehrz & Krautter 1998 and fig. 1 of Smith & Gehrz 2000). There are indications for displacement from axisymmetry in the equatorial plane along the south-east to north-west direction as well, e.g., figure 3 of Smith et al. (1998) shows the two sides of the equatorial plane to be bent toward the south-east.

Soker, Rappaport, & Harpaz (1998; hereafter SRH) demonstrate via analytical calculations that when a companion is close enough to influence the mass-loss process from an evolved star and/or from the binary system as a whole, and the eccentricity is substantial, the nebula around the mass-losing star will acquire a large-scale departure from pure axisymmetry. An essential ingredient is that the mass-loss rate and/or geometry varies systematically with orbital phase, due to the periodic change in the orbital separation. SRH examine the displacement of the central star from the center of the nebula, e.g., as in the planetary nebula Hu 2-9 (Miranda et al. 2000), but the departure from axisymmetry can manifest itself in other ways, e.g., one side will contain a denser section (Soker & Rappaport 2001). SRH consider two effects of the companion on the mass-loss process: a tidal enhancement of the stellar wind near periastron, and a cessation of the stellar wind when the Roche lobe of a mass-losing asymptotic giant branch (AGB) star encroaches on its extended atmosphere near periastron passage. With regard to the first mechanism, in a recent paper Corcoran et al. (2001) argue, based on the X-ray light curve, that the mass loss rate from η Car increases by a factor of 20 following periastron passage. Soker & Rappaport (2001) consider other processes by which a companion can influence the mass-loss process from the system; the direct gravitational influence on the wind (Mastrodemos & Morris 1999), and the formation of a collimated fast wind (CFW) by the companion (Morris 1987; Soker & Rappaport 2000; hereafter SR00). In the later process the companion is assumed to accrete from the mass-losing star, to form an accretion disk, and to blow a CFW. The interaction between the CFW, if strong enough, and the AGB wind will form a bipolar planetary nebula (Morris 1987; SR00). Another process relevant to the binary system proposed for η Car is the interaction of the stellar wind blown by the companion with the wind blown by the primary.
I now show that a companion star to η Car can strongly modulate the mass-loss process from the binary system along its orbital motion, naturally leading to the formation of a nebula which possesses a large-scale departure from axisymmetry. I scale the binary parameters by values which were quoted in recent years (e.g., Ishibashi et al. 1999; Damineli et al. 2000; Corcoran et al. 2001): for the mass of the primary (mass-losing) star and eccentricity I take $M_1 = 80M_\odot$ and $e = 0.8$, respectively. For the present primary’s wind I take a mass-loss rate of $\dot{M}_1 = 3 \times 10^{-4}M_\odot$ yr$^{-1}$ and a velocity of $v_1 = 500$ km s$^{-1}$. For the companion mass I take $M_2 = 30M_\odot$ and for the companion’s wind I take a mass-loss rate of $\dot{M}_2 = 3 \times 10^{-6}M_\odot$ yr$^{-1}$, and a velocity of $v_2 = 2000$ km s$^{-1}$. The semimajor axis is $a = 15$ AU. The proposed mechanism for the departure from axisymmetry, including the calculations below, is applicable to a more massive model of η Car, as suggested by DH97, who argue that the initial and present masses of η Car are $160M_\odot$ and $120M_\odot$, respectively.

The accretion radius of the companion, for accretion from the primary’s wind, is

$$R_a \simeq \frac{2GM_2}{v_1^2} = 0.2 \left( \frac{M_2}{30M_\odot} \right) \left( \frac{v_1}{500 \text{ km s}^{-1}} \right)^{-2} \text{AU}.$$  \hspace{1cm} (1)

The distance $D_2$ of the stagnation point of the colliding winds from the companion along the line between the stars is given by equating the ram pressures of the two winds $\rho v^2$. For spherically symmetric winds

$$D_2 = r\beta(1 + \beta)^{-1} \simeq r\beta = a \left( \frac{1 - e^2}{1 + e \cos \theta} \right) \left( \frac{M_2v_2}{M_1v_1} \right)^{1/2},$$  \hspace{1cm} (2)

where $r$ is the orbital separation, $\theta$ is the angular distance along the orbit ($\theta = 0$ at periastron), and $\beta \equiv [(M_2v_2)/(M_1v_1)]^{1/2}$. In the second equality I assumed $\beta \ll 1$. The stagnation point should be compared with the accretion radius. For the present winds’ parameters used above $\beta \simeq 0.2$ and at periastron $r = a(1 - e) = 3$ AU, so that $D_2 = 0.5$ AU. The accretion radius is smaller than $D_2$, hence no accretion will take place. Also, the accretion radius is quite small compared with the orbital separation even at periastron, hence the companion will not influence the mass-loss process much.

If, however, during a mass loss episode the primary’s wind velocity decreases to $v_1 \lesssim 300$ km s$^{-1}$, as may be suggested by some condensations along the orbital plane of η Car (Davidson et al. 1997; Smith & Gehrz 1998), the accretion radius will be $R_a \gtrsim 0.6$ AU, and the companion will deflect a substantial portion of the primary’s wind at periastron, since $R_a \gtrsim 0.2r$. For the parameter chosen above and $v_1 = 300$ km s$^{-1}$, I find that at periastron $D_2 = 0.65$ AU $\sim R_a$, hence some accretion may occur, but only near periastron. At other orbital phases $D_2 > R_a$, and no accretion to the companion will take place. If in addition to the slower equatorial flow the mass-loss rate is much higher, $\dot{M}_1 = 0.1M_\odot$ yr$^{-1}$ as suggested for the eruption of 1850 (the Great Eruption) that formed the lobes (DH97), then $\beta \simeq 0.01$ and even at apastron $D_2 \simeq r\beta = 0.4$ AU $< R_a$, hence significant accretion will occur during the entire orbital motion. For a mass loss rate of $\dot{M}_1 = 0.1M_\odot$ yr$^{-1}$ and wind velocity of $v_1 = 500$ km s$^{-1}$ the accretion rate by the companion at periastron, without wind disruption, is $\dot{M}_{\text{acc}} \simeq \dot{M}_1R_a^2/4r^2 \simeq 10^{-4}M_\odot$ yr$^{-1}$. At other orbital phases the accretion rate is lower, and may cease near apastron. This may be enough for the companion to
blow a CFW (SR00), with a varying strength along its orbit. However, it seems (see next section) that during the Great Eruption of 1850 and the Lesser Eruption of 1890, the equatorial mass flux was higher than the average, and the velocity much lower, making the accretion rate by the companion much higher, and the proposed mechanism for causing departure from axisymmetry much more efficient.

For an illustration, I assume that near periastron ($\theta = 0$, $r_p = 3$ AU) the accretion rate from the equatorial flow is very high, preventing any mass loss from the system when the orbital separation is $r < 4$ AU. This is case 2 of mass-loss process considered by SRH. For $a = 15$ AU and $e = 0.8$, this corresponds to no wind being blown from the binary system during orbital phases of $|\theta| < 65^\circ$. From the left panel of figure 2 of SRH I find that for these parameters $< \dot{y} > /\Omega_K a = 0.1$, where $< \dot{y} >$ is the average speed of the outflowing matter in the equatorial plane (SRH eq. 5), and $\Omega_K$ is the Kepler frequency. Here $\Omega_K = 2\pi/5.5$ yr$^{-1}$ and $\Omega_K a = 81$ km s$^{-1}$, from which I find $< \dot{y} > = 8$ km s$^{-1}$. The offset of the nucleus from the center of the equatorial flow is (SRH eq. 7) $\delta = < \dot{y} > /v_1$, which for a slow equatorial flow of $v_1 = 50$ km s$^{-1}$ (Davidson et al. 1997) gives $\delta \approx 0.15$. I argue that this explains the departure from axisymmetry of the equatorial ejecta near the nucleus of $\eta$ Car. It should be noted that for a slower flow near the binary system, the accretion rate will be higher near apastron rather than near periastron passages (see next section). As can be noticed from the right panel of figure 2 of SRH, this will lead to a much larger departure from axisymmetry. A CFW blown by the accreting companion may also increase the departure from axisymmetry.

Finally, we note the following mechanism to cause departure from axisymmetry, which can operate even for a circular orbit. If there is an eruption which lasts for a time much shorter than the orbital period, the wind will be blown while the mass-losing star is moving in a specific direction along its orbital motion. This will cause the center of the structure formed by this impulsive mass loss to be displaced from the central binary system by $d = (v_o/v_1)R_n$, where $v_o$ is the orbital velocity of the mass-losing star around the center of mass at the moment of mass loss, $v_1$ is the expansion velocity of the mass being blown, and $R_n$ is the distance of the ejecta from the binary system (increasing with time). For the binary system consider here, the primary orbital velocity changes from 27 km s$^{-1}$ at apastron to 242 km s$^{-1}$ at periastron. For $v_1 = 500$ km s$^{-1}$ we find for this pure impulsive mass-loss episode that $d/R_n$ can be in the range of 0.05 – 0.5. Of course, we do not expect such a mass-loss event, though it is possible that the mass-loss rate has increased substantially during a time shorter than the orbital period, say 2 years. It will then collide with previously ejected mass and mass blown later to form a more complicated structure. The overall departure will be less than for a pure impulsive mass-loss episode $d/R_n < v_o/v_1$, but still may be noticeable if it has occurred not too close to apastron passage, if it occurs for a short time, and if the increase in the mass-loss rate during the impulsive mass-loss episode is significant.

The conclusion from this section is that for typical parameters used by the binary model proponents, the secondary can have an influence on the mass-loss process which varies with orbital phase, in particular if the primary’s wind velocity is $v_1 \lesssim 300$ km s$^{-1}$. This may naturally ex-
plain the large-scale departure from axisymmetry observed in some structural features of η Car. Although the arguments presented here suggest that a binary companion can explain in principle the departure from axisymmetry, I can’t predict the exact shape and degree of departure from axisymmetry. For this 3D gasdynamical numerical simulations are required.

3. IMPLICATIONS OF THE BINARY MODEL

In the previous section I demonstrated that a large accretion rate was likely to have occurred during the eruption of 1850, and possibly during that of 1890. What is the effect of such an event? The answer depends strongly on the accretion rate, which itself is very sensitive to the relative velocity between the accreting body and the wind. The wind could be moving very slowly at a distance of several AU in an “extended envelope”, which was formed during the eruption, with the “photosphere” almost as big as the orbit of Saturn (DH97). I now speculate that the accretion rate by the companion was high, and the companion blew a collimated fast wind (CFW) which led to the formation of the bipolar shape. Bipolar symbiotic nebulae, similar in many properties to the bipolar shape of η Car, are known to result from binary interaction (e.g., Corradi et al. 2000), and so is the common view regarding the formation of bipolar planetary nebulae (SR00).

First let me point to a difficulty with the energy budget in models which assume a spherical mass ejection in the 1850 eruption (e.g., Frank, Balick, & Davidson 1995). For a total ejected mass of 2.5$M_\odot$ and with an initial velocity of $\sim 650$ km s$^{-1}$, which is the current expansion velocity of the lobes (Smith & Gehrz 1998), the total kinetic energy of the ejected gas is $E_{ks} \simeq 10^{49}$ erg. This is $\sim 1/3$ of the total energy radiated during the Great Eruption of η Car, $E_r = 3 \times 10^{49}$ erg (DH97). Such a high efficiency of radiation to kinetic energy conversion can occur in an explosion. However, the duration of the Great Eruption was much longer than the dynamical time scale (see below), hence it wasn’t a regular explosion. Shaviv (2000) proposes a model to explain the super-Eddington luminosity during the Great Eruption, where some of the radiation escape while exerting a smaller average force on matter. This seems to reduce the efficiency of energy transfer. The sum of the absolute values of the momentum along all directions is $p_s = 3 \times 10^{41}$ g cm s$^{-1}$, whereas the total momentum that can be supplied by the radiation during the eruption is $p_r = \zeta E_r/c = 10^{39} \zeta$ g cm s$^{-1}$, where $\zeta$ is the average number of times a photon is scattered by the ejected gas. To account for the wind’s momentum, on average each photon must be scattered $\sim 300$ times, which again means a very efficient acceleration mechanism. This can be compared to another intensive mass-loss process, but in AGB stars. Progenitors of most planetary nebulae terminate the AGB phase with an intensive mass-loss phase, the “superwind”, which lasts $\sim 1 - 2 \times 10^3$ yrs. This time is several hundred times the Keplerian orbital time along the AGB stellar equator, e.g., for $M_*=0.6M_\odot$ and $R_* = 2$ AU the Keplerian orbital time is 3.7 years. The same ratio holds for the Great Eruption of η Car, which lasted 20 years, $\sim 500$ times the Keplerian orbital time on the surface of a 80$M_\odot$ star with a radius of $R_* = 0.5$ AU. From observations it is found (e.g.,
Knapp 1986) that in most cases the momentum flux in the superwind is \( \lesssim 3 \) times the momentum flux in the stellar radiation, i.e., \( \zeta \lesssim 3 \). In a minority of the cases with a higher momentum flux, dynamical effects due to a binary companion probably play some role. But in all cases the total kinetic energy in the superwind is much smaller, by a factor of \( > 100 \), than the total radiated energy in the same period of time. The present momentum flux in the wind of \( \eta \) Car is only 20\% of the radiation momentum flux (White \textit{et al.} 1994), and therefore the wind can be explained by radiation pressure. From this discussion it seems that it is possible to explain the kinetic energy of the Grat Eruption with a single star model (e.g., Shaviv 2000), but a very efficient acceleration mechanism is required. As I suggest below, an accreting binary companion can supply some of the kinetic energy.

The present kinetic energy of the lobes is much lower than that required in a spherical eruption. Assume for simplicity spherical lobes, i.e., a shape of \( r = 2r_0 \sin \phi \), where \( \phi \) is the angle from the equatorial plane, \( r \) is the distance from the nucleus, and \( 2r_0 \simeq 3 \times 10^{17} \) cm is the diameter of each lobe (DH97). I assume for simplicity that most of the mass is on the outer boundary of the lobes, and that each mass element is expanding at a constant velocity since eruption, so that the velocity as a function of angle from the equatorial plane is

\[
v_w(\phi) = 650 \sin \phi \text{ km s}^{-1}.
\]  

For the distribution of mass with the angle \( \phi \) I take a simple form for the mass density per unit solid angle, defined from the center of \( \eta \) Car (not from the centers of each of the spherical lobes),

\[
m = m_0 (1 - K \sin^\gamma \phi),
\]

where \( m_0 \), \( K \) and \( \gamma \) are constants. For a constant mass per unit solid angle \( K = 0 \), whereas for a concentration of mass toward the equatorial plane \( 0 < K \leq 1 \). We can integrate for the kinetic energy \( E_{kns} = \int (mv^2_{w}/2)2\pi \cos \phi d\phi \) and for the total mass in the lobes \( M_{ns} = \int 2\pi m \cos \phi d\phi \). Evaluating the integrals gives the total kinetic energy in the lobes under these assumption as

\[
E_{kns} = 10^{49} \left(1 - \frac{3K}{3 + \gamma}\right) \left(3 - \frac{3K}{1 + \gamma}\right)^{-1} \left(\frac{M_{ns}}{2.5M_\odot}\right) \left(\frac{v_{po}}{650 \text{ km s}^{-1}}\right)^2 \text{ erg},
\]

where \( v_{po} \) is the wind velocity along the polar directions. For a constant mass per unit solid angle \( K = 0 \), and the kinetic energy of the ejected mass is a third of that in a spherical ejection \( E_{kns} = (1/3)E_{ks} \). The case where \( 2/3 \), instead of \( 1/2 \), of the total mass is within \( |\phi| < 30^\circ \) and \( \gamma = 1 \), has \( K = 0.8 \). In that case the kinetic energy of the ejected mass is \( E_{kns} = (0.22)E_{ks} \). Since more mass is actually concentrated toward the equator (DH97), the kinetic energy is even lower, and we can safely take here \( E_{kns} \simeq 0.1 - 0.2E_{ks} \simeq 1 - 2 \times 10^{48} \) erg. This means that models in which the fast ejecta is mainly along the polar directions (e.g., Frank, Ryu & Davidson 1998), require an order of magnitude less energy than models with spherical ejection. In the binary model the CFW (or jets) along the polar directions is (are) blown by the companion (SR00). The CFW can form a hot bubble inside each lobe, and efficiently accelerate the slowly moving gas, ejected by the mass-losing star, to higher velocities (SR00).
I now examine the feasibility of such a scenario. A rotating star close to the Eddington luminosity limit will form a slow equatorial flow (Maeder & Meynet 2000), having an expansion velocity of the order of the rotation velocity, which will be slower than the orbital velocity along most of the orbit of the companion. Zethson et al. (1999) have detected slowly expanding equatorial gas, which they claim originated hundreds of years before the Great Eruption of 1850, although fast equatorial ejecta exit as well (Morse et al. 1998). Substituting the Keplerian velocity in the expression for the accretion radius of the companion (eq. 1) gives, for the ratio of the accretion radius to the orbital separation

$$\frac{R_a}{r} = \left( \frac{2M_2}{M_1 + M_2} \right) \left( \frac{1 + e \cos \theta}{1 + 2e \cos \theta + e^2} \right).$$

For the parameters used in the previous section, $M_1 = 80M_\odot$, $M_2 = 30M_\odot$, and $e = 0.8$, I find $R_a/r = 0.3$ at periastron ($\cos \theta = 1$), and $R_a > r$ at all phases where $\cos \theta < -0.9$. This large $R_a/r$ ratio means that the companion in such a system accretes a large fraction of the slowly expanding equatorial flow. The density at the location of the companion can be much higher than that expected for a pure wind, especially near periastron, since some of the material in the extended envelope may fall back on the primary star. This means that the total accreted mass maybe much larger than that expelled during the eruption. I scale the mass blown in the CFW with $M_c = 0.25M_\odot$, which is the case if the accreted mass is equal to the ejected mass of $2.5M_\odot$, and a fraction 0.1 of it is blown in the CFW (or jets), and the CFW speed is scaled by the escape velocity $v_c \simeq 2000$ km s$^{-1}$ from the companion. The total kinetic energy of the CFW is $E_c = 10^{49} (M_c/0.25M_\odot)(v_c/2000$ km s$^{-1})^2$ erg. This is more than the required energy in the non-spherical mass ejection to form the lobes, as mentioned above.

That a fast mass loss along the polar directions can form the desired morphology was demonstrated by numerical simulations performed by Frank et al. (1998), although their idea was of a single star, whereas in the present scenario the companion blows the CFW simultaneously with the eruption of the primary star (SR00). This scenario, like that of Frank et al. (1998), avoids the problems of the interacting winds model, some of which are summarized by Dwarkadas & Balick (1998). One of the problems mentioned by Dwarkadas & Balick is that the massive disk required in the interacting wind model to confine the spherical ejection is not found. The claim by Morris et al. (1999) for the presence of a massive, $\sim 15M_\odot$, torus of cold gas around the nucleus of $\eta$ Car is disputed by Davidson & Smith (2000), who claim that a correct model gives an equatorial gas distribution which is “incapable of generating the pinched waist”. Dwarkadas & Balick (1999) proposed instead that the spherically ejected mass (during the eruption) interacts with a very dense torus at several AU around the nucleus. The main problem in this scenario, in addition to the energy and momentum budget problem mentioned above, is the formation of a dense torus around and close to the nucleus. A massive companion can play a significant role here (Mastrodemos & Morris 1999).

Finally we note the high velocity gas ejected in the equatorial plane. The flow in the equatorial plane is very complicated, with both slowly expanding, $v \sim 50$ km s$^{-1}$ gas (e.g., Zethson et al.
1999); and fast moving, velocity of $\sim 300 \text{ km s}^{-1}$, features (e.g., Smith & Gehrz 1998). A large fraction of the equatorial gas was ejected in the Lesser Eruption of 1890 (Davidson et al. 1997; Smith & Gehrz 1998), rather than during the Great Eruption of 1850. The equatorial ejecta possesses departure from axisymmetry, as noted in the previous section. As noted by SR00, when the momentum flux of the CFW (or jets) blown by the companion is much smaller than the momentum flux of the primary’s wind, the CFW will be strongly bent so that it will flow close to the equatorial plane. Based on that, I suggest that some of the fast moving gas in the equatorial plane was ejected by the companion at high speed, but because of the relative (to the primary’s wind) low momentum flux of the CFW it was bent toward the equatorial plane. The ratio of the momentum fluxes of the primary’s wind and CFW depends mainly on the accretion rate and primary’s wind concentration toward the equator. It is possible that during the Great Eruption of 1850 the conditions were favorable for the formation of a very strong CFW (e.g., slowly expanding wind concentrated toward the equatorial plane), which forms the two lobes, whereas during the Lesser Eruption of 1890, only a weak CFW was formed, but still strong enough to form fast moving gas in the equatorial plane.

4. SUMMARY

In the present paper I argue that the large-scale departure from axisymmetry of the $\eta$ Carinae nebula can be explained by the binary nucleus model. Using binary parameters as quoted by the binary supporters, I found that the companion was likely to substantially influence the mass-loss process from the binary system. The degree by which such a companion diverts the outflow depends on the orbital separation, hence on the orbital phase in the eccentric orbit. The modulation of the mass loss process with the orbital phase may lead to a detectable departure from axisymmetry (SRH), as is observed in $\eta$ Car.

I speculated that if such a companion exists, it may have accreted a large fraction of the mass that was expelled in the Great Eruption of 1850 and the Lesser Eruption of 1890. This requires that the matter in the equatorial plane was moving very slowly, at $\sim 50 \text{ km s}^{-1}$, during these eruptions. The accretion process was likely to form an accretion disk, with the formation of a collimated fast wind (CFW), or jets, on the two sides of the accretion disk. I showed that a CFW of $\sim 0.25M_\odot$, which could be formed if the accreted mass was equal to the mass that was blown into the lobes in the Great Eruption, $2.5M_\odot$, and $\sim 10\%$ of it was blown into the CFW, which was blown at $2,000 \text{ km s}^{-1}$, can account for the total kinetic energy of lobes of $\eta$ Car. The CFW, therefore, was likely to be a significant factor in shaping the lobes of $\eta$ Car.

If the CFW blown by the companion is weak, i.e., its momentum flux is small, it will be sharply bent by the slow wind blown by the primary star. The CFW will flow parallel to the equatorial plane, leading to fast outflowing material near the equatorial plane. I therefore speculated that
during the Lesser Eruption of 1890 the CFW was indeed weak, leading to the formation of the fast equatorial outflow which was expelled then.

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