COMPARING η CARINAE WITH THE RED RECTANGLE

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ABSTRACT

I compare the structures of the bipolar nebulae around the massive binary system η Carinae and around the low-mass binary system HD 44179. While η Car is on its way to becoming a supernova, the Red Rectangle is on its way to forming a planetary nebula. Despite the 2 orders of magnitude difference in mass, these two systems show several similarities, both in the properties of the stellar binary systems and in the nebulae. From this comparison and further analysis of the accretion process during the 20 yr Great Eruption of η Car, I strengthen the binary model for the formation of its bipolar nebula—the Homunculus. In the binary model a large fraction of the mass lost by the primary star during the Great Eruption was transferred to the secondary star (the companion). An accretion disk was formed around the companion, and the companion launched two opposite jets. I show that the gravitational energy of the mass accreted onto the secondary star during the Great Eruption can account for the extra energy of the Great Eruption, both the radiated energy and the kinetic energy in the Homunculus. I also conclude that neither the proximity of the primary star in η Car to the Eddington luminosity nor the rotation of the primary star are related directly to the shaping of the Homunculus. I speculate that the Great Eruption of η Car was triggered by disturbance in the outer boundary of the convective region, most likely by magnetic activity, that expelled the outer radiative zone.

Subject headings: accretion, accretion disks — binaries: close — circumstellar matter — stars: individual (AFGL 915, η Carinae, HD 44179) — stars: mass loss

Online material: color figure

1. INTRODUCTION

Many diverse astrophysical objects possess bipolar structures composed of a low-density bubble pair and a narrow waist between the bubbles, where each bubble is fully or partially bounded by a thin dense shell. Examples include clusters of galaxies, e.g., Perseus (Fabian et al. 2002) and A2052 (Blanton et al. 2001), symbiotic nebulae, e.g., Henize 2-104 (Corradi & Schwarz 1995; Corradi et al. 2001), planetary nebulae (PNs), e.g., NGC 3587 (PN G148.4+57.0; e.g., Guerrero et al. 2003), and the bipolar nebula of η Car—the Homunculus (e.g., Morse et al. 1998; Davidson et al. 2001; Smith 2006). The similarity between bipolar PNs and bipolar symbiotic nebulae was discussed by Corradi & Schwarz (1995), and the bipolar nebula of η Car—the Homunculus (e.g., Morse et al. 1998; Davidson et al. 2001; Smith 2006). The similarity between bipolar PNs and bipolar symbiotic nebulae was discussed by Corradi & Schwarz (1995), the similarity between bipolar PNs and bubble pairs in clusters of galaxies was discussed in a series of papers (Soker & Bisker 2006 and references therein), and the similarity of η Car and its Homunculus to the other classes was discussed by Soker (2001b, 2004, 2005b), Smith (2003), and Smith et al. (2005). The nuclear spectrum of the PN M2-9 was compared to that of η Car by Balick (1989) and Allen & Swings (1972).

The similarity of the bipolar structures in the different classes hints at a common shaping mechanism (Soker 2004). In clusters of galaxies such bubbles are known to be formed by opposite jets, ejected by an accretion disk, which are detected by radio emission (e.g., Hydra A; McNamara et al. 2000); the jets expand into a previously existing medium. The only source of angular momentum sufficient to form accretion disks, around the primary or (more likely) the secondary star, in evolved stars is the orbital angular momentum of a stellar (or in some cases substellar) companion (Soker 2004; Soker & Livio 1994; Morris 1987; Soker & Bisker 2006). This led me to suggest that during the Great Eruption the secondary star in η Car accreted mass, formed an accretion disk, and for the ~20 yr (1837–1856) duration of the Great Eruption blew two jets that shaped the Homunculus (Soker 2001b, 2004).

Nota et al. (1995) noted that many nebulae around luminous blue variables (LBVs) possess axisymmetrical structure (see also O’Hara et al. 2003). Nota et al. (1995) also attributed the bipolar shape of the Homunculus to the binarity of η Car, but using a different model from what I proposed. They use the interacting wind model, where a very dense and slow equatorial flow constrains the fast wind to form a bipolar structure. This mechanism not only cannot work in clusters of galaxies and was found inapplicable to PNs (Balick 2000; Soker & Rappaport 2000), it also cannot work in the case of η Car (Dwarkadas & Balick 1998; Smith 2006).

On the other side of the debate on the shaping mechanism of η Car, there are models for the shaping of the Homunculus by the primary star itself (at most, the companion spins up the primary, but it does not interact with the wind itself and does not blow a significant wind; e.g., Langer et al. 1999; Maeder & Desjacques 2001; Dwarkadas & Owocki 2002; Smith et al. 2003a; Gonzalez et al. 2004; van Boekel et al. 2003; Matt & Balick 2004). In a previous paper (Soker 2004; also Soker 2005b) I listed several great difficulties with single-star models for the shaping of η Car. Smith (2006) used observational results to conclude, contrary to these arguments, that the secondary star could not have directly shaped the Homunculus during the Great Eruption, and that the bipolar shape must come from the rapid rotation of the primary star. In this paper I dispute Smith’s conclusions and show that the mass distribution he finds in η Car supports the binary shaping model.

2. ENERGY AND ANGULAR MOMENTUM CONSIDERATIONS

2.1. Energy Budget

The source of the kinetic energy of the expanding bipolar nebula in the binary model is mainly the accretion energy onto
the companion, not the orbital gravitational energy (Soker 2001b, 2004). For that reason, I find the claim that the mass loss during the Great Eruption could not have been redirected toward the poles by deflection from its companion star, because the amount of kinetic energy in the polar ejecta is greater than the binding energy of the current putative binary system (Smith 2006), unjustified.

I will upscale quantities in the expression derived in Soker (2001b) according to the new estimate of the Homunculus mass (Smith et al. 2003b; Smith 2006). I take a main-sequence binary companion of preoutburst mass $M_{G-E-1} \approx 30 M_\odot$ and an initial radius of $R_{20} \approx 10 R_\odot$. The primary star lost $M_{G-E-1} \approx 20 M_\odot$ in a more or less spherical geometry. Say $\sim 12 M_\odot$ was captured by the secondary, out of which $M_{G-E-acc} \approx 8 M_\odot$ was accreted and $M_\sim 4 M_\odot$ blown as a collimated fast wind (CFW, defined as not well collimated jets) by the accretion disk. This CFW mass shaped the $8 M_\odot$ blown by the primary, mainly toward the polar directions, and was not captured by the secondary star. The total mass in the Homunculus is $M_{G-E-1} = 12 M_\odot$. (The calculations in this section can be easily scaled to a higher Homunculus mass of up to $\sim 20 M_\odot$, as claimed for by Smith & Ferland 2007). Taking the average radius and mass during the accretion phase of the Great Eruption, we find the total gravitational energy released by the accreted mass,

$$E_{G-E-2} \approx \frac{GM_2 M_{G-E-acc}}{R_2}$$

$$= 6 \times 10^{49} \left( \frac{M_2}{30 M_\odot} \right) \left( \frac{M_{G-E-acc}}{8 M_\odot} \right) \left( \frac{R_2}{15 R_\odot} \right)^{-1} \text{erg.} \quad (1)$$

The speed of the CFW is about the escape speed from the secondary star $v_\sim 1000 \text{ km s}^{-1}$, which amounts to a total energy of $E_{jet} = 4 \times 10^{49} \text{ erg s}^{-1}$ (for a CFW mass of $M_\sim 4 M_\odot$), which is more than the present kinetic energy of the Homunculus, $3 \times 10^{49} \text{ erg}$ (for a mass of $M_{G-E-1} = 12 M_\odot$). Taking the speed of the primary wind to be $100 \text{ km s}^{-1}$, the total momentum deposited into the Homunculus is $(8 \times 1000) + (4 \times 10000) = 4800 M_\odot \text{ km s}^{-1}$. This is close to the total momentum of the Homunculus I calculated from the mass and velocity distribution given by Smith (2006) of $5600 M_\odot \text{ km s}^{-1}$ (for a mass of $12 M_\odot$). The energy and momentum budget shows that the interaction between the CFW and the primary mass was between purely momentum conserving and purely kinetic energy conserving; i.e., some of the initial kinetic energy in the CFW was radiated away.

The total radiated energy from the Great Eruption is $E_{G-E-rad} = 3 \times 10^{49} \text{ erg}$ (Humphreys et al. 1999). Considering that the primary itself has a luminosity of $\sim 5 \times 10^6 L_\odot$ (Humphreys et al. 1999), it contributed $E_{G-E-1} = 1.2 \times 10^{49} \text{ erg}$ during the Great Eruption. Examining equation (1), one finds that the energy liberated by the accreted mass can easily account for the extra radiated energy and the kinetic energy in the Homunculus, which are summed up to $\sim 5 \times 10^{49} \text{ erg}$.

In the binary model the extra radiated energy of $\sim 2 \times 10^{49} \text{ erg}$ came from the gravitational energy of the accreted mass. Namely, the primary luminosity did not change during the Great Eruption. This suggests that the primary eruption was not much different from S Dor-type eruptions, where the stellar bolometric luminosity does not change (Humphreys et al. 1999). The erupting primary star mainly supplied the mass to the secondary and the Homunculus, but it did not supply the extra radiated energy.

### 2.2. Angular Momentum Evolution

Consider an envelope of a giant star rotating as a solid body. The dimensionless quantity $\beta$ is defined by taking the angular momentum loss rate from the envelope to the wind to be $J_{wind} = \beta \omega R^2 M$, where $\omega$ is the stellar angular velocity, $R$ the stellar radius, and $M$ the mass-loss rate. The value of $\beta$ depends on the mass-loss geometry: for a constant mass-loss rate per unit area on the surface $\beta = \frac{3}{5}$, while for an equatorial mass loss $\beta = 1$. The moment of inertia of the envelope is $I = \alpha M_{env} R^2$.

For the mass-loss geometry found by Smith (2006) I calculate that $\beta = 0.38$. As discussed in Soker (2004) I take $\alpha = 0.1$ for the eruptive $\eta$ Car model. I assume that during the eruption the star continued to rotate as a solid body. This implies that during the eruption the angular velocity of the star evolved according to

$$\frac{\omega}{\omega_0} = \left( \frac{M_{env}}{M_{env0}} \right)^{\beta/\alpha - 1} = \left( \frac{M_{env}}{M_{env0}} \right)^{2.8} \quad (2)$$

As in Soker (2004) I take an envelope mass of about half the stellar mass, or $M_{env} = 70 M_\odot$, at the beginning of the Great Eruption. As stated in Soker (2004), this is an upper limit on the envelope mass; the envelope mass is likely to be lower, increasing the spin-down rate. The mass lost at the eruption into the Homunculus according to the single-star model is $M_{G-E-1} \approx 12 M_\odot$ (Smith et al. 2003b). I find that at the end of the eruption $\omega/\omega_0 \approx 0.6$. Namely, the star had substantially spun down. Even for the extreme case of $\alpha = 0.2$ the progenitor of $\eta$ Car would have spun down during the Great Eruption. This finding, based on the assumption of solid-body rotation, is contrary to the claim made by Smith (2006) that the postoutburst star had higher angular momentum per unit mass than the preoutburst star.

According to the single-star model, it is still possible that the star was not rotating as a solid body but rather that the angular velocity closer to the rotation axis was lower than near the equator. In such a case the specific angular momentum of the star could have increased for the mass-loss geometry found by Smith (2006). However, there is no model for such a behavior. For example, if magnetic fields play a role, then, based on results of magnetically active main-sequence stars, e.g., the Sun, we know that even with higher mass-loss rate along the polar directions these stars spin down.

Alternatively we can consider mass loss due to radiation pressure. During the Great Eruption the stellar envelope was optically thick to a huge radius (Davidson & Humphreys 1997). In such a case we would expect spherical mass-loss geometry, as radiation pressure would act in all directions. Another problem with a polar outflow from the primary star is that there is not enough radiation energy and momentum to drive the outflow if only the polar direction contributes to the mass loss (Soker 2004).

Groh et al. (2006) found the LBV AG Car to be a fast rotator. They, as well as Smith (2006), viewed this finding as a support for models of axisymmetrical wind from rotating stars as the main shaping process. However, the behavior of AG Car is opposite the behavior required during the Great Eruption. Groh et al. (2006, Table 2) found that the mass-loss rate increases when the star radius increases, its effective temperature decreases, and its rotation velocity decreases. As the mass-loss rate increases by a factor of 2.6 the ratio of rotation to critical velocity decreases from 0.86 to 0.57. Namely, the high mass-loss rate is expected to become more spherical when the mass-loss rate is higher in single-star models. A high mass-loss rate episode, such as the Great Eruption, will not be highly asymmetrical if the shaping results from behavior like that of AG Car. In the binary model the launching of jets by the accreting companion is more likely to occur as the primary wind velocity decreases, as is expected to be the case when the mass-loss rate is higher, as in the Great Eruption (see § 3.2).
In summary, I disagree with the claim made by Smith (2006) that a single star can account for the mass-loss geometry he finds and that the postoutburst star had higher angular momentum per unit mass than the preoutburst star.

3. COMPARING THE RED RECTANGLE WITH η CAR

3.1. Similar Properties

Some similarities between η Car, PNs, and other related objects were noticed before (Allen & Swings 1972; Balick 1989; Soker 2001b, 2004 2005b; Smith 2003; Smith et al. 2005). In particular, the detailed comparison of the PN M2-9 to η Car conducted by Smith et al. (2005) also shows that such a comparison can shed light on the evolution of these systems. The new results of Smith (2006) allow a better comparison between the Homunculus and the Red Rectangle, the nebula around the binary system HD 44179. In this section I summarize and extend the list of similarities between the Red Rectangle and η Car.

3.1.1. Eccentric Binary System

At the center of the Red Rectangle Nebula is the HD 44179 binary system. This binary system has an orbital period of $T_{\text{orb}} = 322$ days, a semimajor axis of $a \sin i = 0.32$ AU, and an eccentricity of $e = 0.34$ (Waelkens et al. 1996; Waters et al. 1998; Men'shchikov et al. 2002). Men'shchikov et al. (2002) suggest that the orbital separation is $a = 0.9$ AU and the masses of the two components are $M_1 \approx 0.6 M_\odot$ and $M_2 \approx 0.35 M_\odot$.

Based on several papers (e.g., Ishibashi et al. 1999; Damineli et al. 2000; Corcoran et al. 2001; Hillier et al. 2001; Pittard & Corcoran 2002; Smith et al. 2004), I take the following parameters of η Car. The stellar masses are $M_1 = 120 M_\odot$, $M_2 = 30-40 M_\odot$, the eccentricity is $e = 0.9$, and orbital period is $T_{\text{orb}} = 2024$ days, hence the semimajor axis is $a = 16.64$ AU (for $M_2 = 30 M_\odot$), and the orbital separation at periastron is $r = 1.66$ AU. The mass-loss rates are $\dot{M}_1 = 3 \times 10^{-4} M_\odot \text{ yr}^{-1}$ and $\dot{M}_2 = 10^{-5} M_\odot \text{ yr}^{-1}$. The terminal wind speeds are taken to be $v_1 = 500$ km s$^{-1}$ and $v_2 = 3000$ km s$^{-1}$.

Some similar aspects of the evolution of the two binary systems were discussed in Soker (2005b). Here I add that the primary stars in both systems are evolved stars and are much larger than their respective sizes on the main sequence and that both have a relatively high mass-loss rate. Both stars are not far from filling their Roche lobe; both have $R_1/a_\text{p} \approx 0.3$, where $a_\text{p}$ is the separation at periastron. In the past, episodically the radius of the primary star of both systems could have been much larger, filling its Roche lobe (see §3.2). While the primary in η Car is more massive than half its birth mass, the primary in the Red Rectangle seems to be less than half its birth mass. In addition, while the primary in η Car is close to its Eddington luminosity, the luminosity of the primary (a post-AGB star) in HD 44179 is ~$6000 L_\odot$ (Men'shchikov et al. 2002), only ~0.3 of its Eddington limit.

3.1.2. General Shape

Smith (2006) gives the mass in the Homunculus as function of angle (measured from the equatorial plane). There is a high mass concentration in the range ~45°–65°, with a higher concentration in the range ~50°–65°, and a peak at ~53°. The maximum in mass per unit solid angle is in the range ~50°–65°. The shape of the Homunculus as given by Smith (2006) is shown in Figure 1 by the dashed thick line. Also marked are the directions containing high mass concentration.

The general structure of the inner region of the Red Rectangle is presented in Figure 10 of Cohen et al. (2004). Each pair of

![Image](https://example.com/image.png)
(Soker 2000b; Men’shchikov et al. 2002) or in a long-lived disk (e.g., Jura et al. 1995; Jura & Kahane 1999).

3.2. Conclusions from the Similarities

The comparison made in §3.1 is meaningful only if the same basic mechanism is responsible for the shaping of the Red Rectangle and the Homunculus. Following previous papers (Soker 2001b, 2004, 2005b) I assume that this is indeed the case, and come to the following conclusions.

1. The shaping is not related to the proximity of η Car’s luminosity to the Eddington limit. As stated above, the primary in the Red Rectangle is far from its Eddington limit.

2. Fast rotation of the primary is not likely to be behind the bipolar structure. Since the primary in the Red Rectangle lost most of its envelope mass, it must be rotating very slowly (Soker 2004). Even if it was spun up by tidal interaction and reached synchronization with the orbital angular velocity, the rotation velocity of the primary is <0.2 times its breakup rotation velocity. No rotating-star model predicts much deviation from spherical mass loss in such a case.

3. In both systems the companion is outside the envelope. This means that the shaping is done by a companion that avoided a common-envelope evolution. The applicable binary mechanism is one where the companion accretes mass and launches two jets during high mass-loss rate episodes (Soker 2001b, 2005b for η Car; Soker 2005a for the Red Rectangle).

4. During the high mass-loss rate episodes, mainly in η Car, the primary expanded such that the accretion process is a mixture of accretion from a wind and a Roche lobe overflow. I will now show this.

For pure accretion from a wind, namely, when the wind is considered to be at a large distance from the star and at its terminal speed, the Bondi-Hoyle accretion process is applicable. The Bondi-Hoyle accretion radius is

\[ R_{\text{acc}} = \frac{2GM_2}{v_{\text{rel}}^2} = 5\left(\frac{M_2}{30 M_\odot}\right)\left(\frac{v_{\text{rel}}}{100 \text{ km s}^{-1}}\right)^{-2} \text{AU}, \]

where \( v_{\text{rel}} \) is the relative velocity between the primary wind and the secondary wind. The primary’s present wind terminal speed in η Car is \( \sim 500 \text{ km s}^{-1} \). However, I assume it was much slower during the Great Eruption. To be considered as a free wind, the speed at apastron, \( v_{\text{rel}} \sim 30 \text{ AU} \), should exceed the escape velocity from the system, \( v_{\text{esc}}(30 \text{ AU}) \approx 85 \text{ km s}^{-1} \). The accretion radius is much smaller than the orbital separation, and the fraction of the accreted mass from the wind near apastron would be \( \sim (R_{\text{acc}}/2a_0)^3 \sim 0.015 \), much less than that required by the model presented in §2. Near periastron the distance is much smaller, but the orbital velocity increases, and this fraction increases, but only to ~0.25, and only for the relatively short time the secondary spends near periastron.

The situation with the Red Rectangle is better (Soker 2005a). The wind from post-AGB stars is very slow, ~10 km s\(^{-1}\), and the orbital velocity is larger than the wind’s speed. The relative orbital velocity between the two stars in HD 44179 is ~30 km s\(^{-1}\). Taking the orbital separation to be ~1 AU, I find the fraction of mass that would be accreted from a free wind to be ~0.5, as required by the model (Soker 2005a).

For the companion to blow a jet an accretion disk should be formed. The condition for the formation of an accretion disk is that the specific angular momentum of the accreted matter \( j_a \) must be larger than the specific angular momentum of a particle in a Keplerian orbit at the equator of the accreting star of radius \( R_2: j_a = (GM_2R_2)^{1/2} \). When a compact secondary star moves in a circular orbit at radius \( a \) and accretes from the wind of a mass-losing star, such that the accretion flow reaches a steady state, the condition for the formation of an accretion disk reads (see Soker 2001a for more detail and previous references)

\[ 1 < \frac{j_a}{j_2} \approx 0.1 \left(\frac{\eta}{0.2}\right) \left(\frac{M_1 + M_2}{150 M_\odot}\right)^{1/2} \left(\frac{M_2}{30 M_\odot}\right)^{3/2} \left(\frac{R_2}{20 R_\odot}\right)^{-1/2} \times \left(\frac{r}{30 \text{ AU}}\right)^{-3/2} \left(\frac{v_{\text{rel}}}{100 \text{ km s}^{-1}}\right)^{-4}, \]

where \( \eta \) is the ratio of the accreted angular momentum to that entering the Bondi-Hoyle accretion cylinder. In an eccentric orbit near apastron, the value of \( j_a \) will be smaller due to lower azimuthal velocity than in a circular orbit. I conclude that in the case of pure accretion from the wind, no accretion disk could have been formed during the Great Eruption of η Car. This suggests that during the Great Eruption the primary swelled, and its extended envelope overflowed and transferred mass to the secondary, substantially increasing both the mass transfer rate and the specific angular momentum of the accreted mass compared with pure wind accretion.

Substituting typical values for the HD 44179 binary system at the center of the Red Rectangle I find the coefficient in equation (4) to be ~10 for an accreting white dwarf and ~1 for an accreting low-mass main-sequence star. Therefore, in the case of the Red Rectangle an accretion disk can be formed even by pure accretion from a wind. However, the similarity of the Red Rectangle and η Car raises the possibility that during episodes of high mass transfer rate in the Red Rectangle, the primary forms an extended envelope, which is overflowing to the companion.

Accretion of more mass at large separations (near apastron) increases the eccentricity. The change in eccentricity due to a mass \( \delta M_{\text{trans}} \) transferred from the primary to the secondary is given by (Eggleton 2006)

\[ \delta e = 2\delta M_{\text{trans}} \left(\frac{1}{M_1} - \frac{1}{M_2}\right)(e + \cos \theta), \]

where \( \theta \) is the orbital angle, with \( \cos \theta = 1 \) at periastron and \( \cos \theta = -1 \) at apastron. For a mass of 12 \( M_\odot \) captured by the secondary during the Great Eruption (out of which 8 \( M_\odot \) was accreted and 4 \( M_\odot \) blown in the jets; see §2), most of it near apastron, I find that \( \delta e \approx 0.1 \) for an initial eccentricity of \( e_0 = 0.8 \). Therefore, a few such repeated eruptions (Smith 2007; Smith & Owocki 2006) can be responsible for the high eccentricity of η Car. The same process can work in the case of HD 44179.

4. SUMMARY

In this paper I continued and updated the comparison of η Car and its bipolar nebula—the Homunculus—with other astrophysical objects (Soker 2005b) and the comparison of the binary model with single-star models for the shaping of the Homunculus (Soker 2004). Basically I strengthened the binary model for the formation of the Homunculus. In the binary model (Soker 2001b, 2004, 2005b) a large fraction, and even most, of the mass lost by the primary star during the 20 yr Great Eruption was transferred to the secondary star (the companion). An accretion disk was formed around the companion, and the companion launched two opposite jets (or a collimated fast wind). These jets shape the circumbinary gas to the observed bipolar structure.
The main results are as follows.

1. The source of the extra energy of the Great Eruption, both the radiated energy and the kinetic energy in the Homunculus, is easily accounted for by the gravitational energy of the mass accreted onto the secondary star (§ 2.1). This suggests that the eruption of the primary star was not much different from SDor-type eruptions, where the stellar bolometric luminosity does not change (Humphreys et al. 1999). The periodic peaks during the Great Eruption (Damineli 1996) support the claim of this paper that accretion onto the secondary star supplies the extra energy in the Great Eruption. I also suggest that other giant eruptions of LBV stars are caused by mass transfer onto the secondary star. Unlike Humphreys et al. (1999), I do not find the assumption that the other three LBVs they list as having giant eruptions have binary companions unreasonable. The claim that the mass loss during the Great Eruption could not have been redirected toward the poles by deflection from its companion star because of energy considerations (Smith 2006) is not relevant to the binary model.

2. Using the new mass distribution in the Homunculus reported by Smith (2006), I find that in the single-star models the primary star in $\eta$ Car must have spun down substantially during the Great Eruption (§ 2.2). This further strengthens earlier claims (Soker 2004) that single-star models encounter severe problems in explaining the bipolar structure of the Homunculus. The axi-symmetrical structure of the nebulae of many LBVs also supports the binary model (Nota et al. 1995).

3. I made a point that the mass distribution in the Homunculus reported by Smith (2006) is similar to that in the Red Rectangle, a nebula around the post-AGB binary system HD 44179 (§ 3.1). This is in addition to other similarities between the two systems (Soker 2005b): a central eccentric binary system where the primary is an evolved star, slow equatorial outflow, and departure (Soker 2005b): a central eccentric binary system where the primary is an evolved star, slow equatorial outflow, and departure (Nota et al. 1995).

4. Assuming that the Red Rectangle and the Homunculus share the same basic shaping process, I reached the following conclusions (§ 3.2):

   a) The proximity of the luminosity of the primary star in $\eta$ Car to the Eddington limit is not directly related to the shaping of the Homunculus. However, the luminosity is very likely to be responsible for the large amount of mass that was lost during the Great Eruption.

   b) Fast rotation of the primary star in $\eta$ Car is not the cause of the bipolar structure.

   c) The secondary star did not go through a common-envelope evolution. If it did, it was for a short time, and this is not the mechanism behind the shaping of the Homunculus. The shaping took place while the secondary was mainly outside the envelope.

   d) The mass transfer mode was more like a Roche lobe overflow than accretion from a wind. At the beginning of the Great Eruption, the primary formed an extended envelope, to a radius of $\sim 20$ AU. This envelope overflowed and transferred mass to the secondary. Most of the mass transfer occurred at large orbital separations (near apastron), increasing the eccentricity of the binary system.

The results listed above are not extremely sensitive to the parameters of either $\eta$ Car or the Red Rectangle. The conclusions are only based on the presence of a companion close enough to accrete mass and angular momentum at a high rate from the primary wind. The companion must be outside the primary envelope in order to blow the jets. Overall, the periastron distance should be $\sim 1.5 - 3$ times larger than the primary stellar radius when mass transfer occurs. What is sensitive to the parameters of $\eta$ Car and the Red Rectangle is the exact shape of the bipolar nebula. For example, the ratio of the radiative cooling time in the jet and the flow time of the jet determines the shape of the bubble (lobe) inflated by the jet. Fast and low-density jets have a long radiative cooling time and are more likely to form “fat” lobes. The many shapes of PNs show that many types of nebulae can be formed by binary systems. If $\eta$ Car experiences another great eruption, it will again form a bipolar structure composed of two lobes, but the details of the structure will be different. The departure from axisymmetry is somewhat sensitive to the jet launching period and to the eccentricity. For example, long active jets launched in a circular-orbit binary system will not lead to a departure from axisymmetry.

What could have caused the primary to lose a huge amount of mass, $\sim 20 M_{\odot}$, in only $\sim 20$ yr of the Great Eruption? It seems that nuclear eruptions in the core, as well as other eruptive events in the core, can be ruled out from what we know about AGB stars. Helium shell flashes (thermal pulses) on the outskirts of cores of AGB stars reach luminosities of $>10$ times the normal nuclear luminosity in the core, but the surface luminosity does not change, or it even decreases (e.g., Iben & Renzini 1983). Most of the liberated energy goes to lift mass in layers deep in the envelope. The disturbance should take place close to the stellar surface. I speculate that magnetic activity is behind the Great Eruption of $\eta$ Car.

Soker (2000a) and García-Segura et al. (2001) propose magnetic activity cycles to explain the semiperiodic enhanced mass-loss rate episodes observed in progenitors of some PNs and proto-PNs (e.g., Hrivnak et al. 2001) and around AGB stars (e.g., Mauron & Huggins 2000). The time intervals between consecutive eruption events are $200 - 1000$ yr (Hrivnak et al. 2001). I take the high mass-loss rate into each shell to last several $\times 10$ yr and the mass-loss rate to be $\sim 10 M_{\odot}$, where $M_{\odot} = 10^{-5} M_{\odot}$ yr$^{-1}$ is the normal mass-loss rate at the end of the AGB. I crudely find that a plausible value for the mass in each shell might be $M_t \sim 3 \times 10^{-3} M_{\odot}$. With typically 20 shells at the last $\sim 10^4$ yr of the AGB, I find that $\sim 0.05 M_{\odot}$ is lost in the shells.

It is interesting that the estimated mass in each of the semiperiodic concentric shells (arcs) around AGB stars, $M_t \sim 3 \times 10^{-3} M_{\odot}$, is of the order of the mass residing above the convective region of AGB stars, namely, in the outer radiative zone. Using the evolving AGB stellar model of Soker & Harpaz (1999), I find that when the envelope mass is $M_{\text{env}} = 0.3$, $0.1$, and $0.03 M_{\odot}$ (the effective temperature at these three evolutionary points is $2700$, $2700$, and $3100$ K) the mass in the outer radiative zone is $M_{\text{rad}} = 0.007$, $0.005$, and $0.003 M_{\odot}$. This suggests that during eruptive phases AGB stars expel a mass about equal to that in the outer radiative zone. A magnetic activity on the outer boundary of the convective region might disturb this region, which would lead to its expulsion.

The mass estimated to be ejected by $\eta$ Car and similar very luminous stars is $\sim 10 - 15 M_{\odot}$ (Smith & Owocki 2006). In the binary model, some mass is accreted by the secondary, so this mass can be as large as $\sim 20 M_{\odot}$. This is of the order of the mass residing in the outer radiative zone of very massive ($M_1 \sim 80 M_{\odot}$) stars when they are at the same stage as $\eta$ Car (Meynet & Maeder 2003, 2005). Namely, the age is a few $\times 10^4$ yr, the effective temperature is $\sim 20,000 - 25,000$ K, and the luminosity is $\sim 10^6 L_{\odot}$. I speculate that the Great Eruption was an event in

2 Note that the density scale in Figs. 1–5 of Soker & Harpaz (1999) is too low by a factor of $10$; the correct scale is displayed in their Fig. 6.

3 For details see http://obswww.unige.ch/Recherche/evol/spip.php?rubrique7.
which magnetic activity in the convective region strongly disturbed the outer radiative zone and formed an extended envelope. One way to form an extended envelope is by the contraction of the inner layers. Thus, it is possible that the magnetic activity in the convective zone caused, in a yet unsupervised process, the contraction of the convective envelope. As a result the radiative zone above it expanded to huge dimensions. Radiation pressure aided in uplifting the mass in the radiative zone, in forming the extended envelope, up to ~20 AU, and in expelling mass.

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