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ETA CARINAE — an evolved triple-star system?

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Abstract From the wealth of data on the source η Carinae it is concluded that it consists of two moderately massive (ordinary) stars plus a neutron star, the latter in close orbit around the secondary. As an extreme case among high-mass stars, η Car may teach us that stellar masses do not exceed $60\,M_\odot$. Several of η Car's peculiar properties are due to its three interacting wind zones. Its transient super-Eddington outputs — during the years 1843 and 1887 — are blamed on the assemblance of a heavy accretion disk around the neutron star (near peri-astron), and the disk's occasional discharging towards it.

Key words: η Carinae – stars: most massive – super-Eddington sources – triple-star system

1 THE MOST MASSIVE STARS

The stellar luminosity function of the Local Group of galaxies terminates sharply at a luminosity of $10^7\,L_\odot = 10^{40.6}$ erg s^{-1}, corresponding to the Eddington luminosity of a star of $10^{2.5}\,M_\odot$ (Humphreys & McElroy, 1984; Kundt, 2001). Such high masses, if real, would conflict with earlier wisdom, that stellar masses cannot exceed $90\,M_\odot$ (Kippenhahn & Weigert, 1990), and also with the steepness of the luminosity function at the high-mass end, according to which stars above $30\,M_\odot$ are extremely rare. Nir Shaviv (2000) has offered a way out of this conflict: two-stream instabilities permit a stellar atmosphere to be porous, and allow a super-Eddington luminosity to escape without (radiatively) ejecting most of the blanketing atmosphere. In other words: the Eddington criterion can overestimate the stellar mass.

Among the most luminous stars of the Galaxy is Eta Carinae (η Car), with its presently $10^{6.7}\,L_\odot$ (corresponding to $L = 10^{40.3}\,\mathrm{erg\,s^{-1}}$, or $M_{\mathrm{bol}} = -12\,\mathrm{mag}$), which it exceeded by a factor of 10 at the peak of its outburst in 1843, and again (by a factor of $\lesssim 4$) towards the end of the 19th century, cf. Fig. 1. The mass of η Car is often estimated above 10^2, or even above $10^{2.2}\,M_\odot$. Below we shall model the η Car system as a triple-star system with component masses no larger than $60\,M_\odot$.

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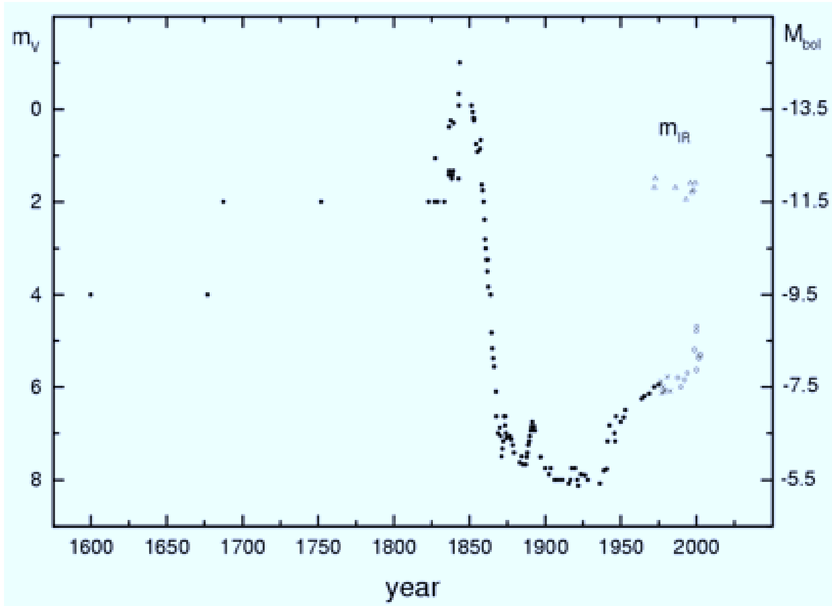

Fig. 1 Visible (dots, crosses, and circles) and infrared (10 μm, triangles) lightcurve of the system η Carinae, after Feinstein & Marraco (1974), Walborn & Liller (1977), Cox et al. (1995), Davidson et al. (1999), and www.aavso.org (April 2000); see also Viotti (1995). During the past 300 yr, its bolometric luminosity is likely not to have fallen (much?) below $M_{\rm bol} = -12$ mag, or $10^{6.7}\,L_\odot = 10^{40.3}\,{\rm erg\,s^{-1}}$. But η Car has exceeded this threshold by $\lesssim 2.5$ mag between 1827 and 1858, and probably by $\lesssim 1.4$ mag between 1886 and 1896.

Besides η Car, there are more than 15 stars near the upper end of the Galactic brightness scale, above $10^{6.1}\,L_\odot$ (or $M_{\rm bol} \lesssim -10.5$) — discussed e.g. by Massey & Hunter (1998) — candidates for extreme masses. But if the Eddington constraint can be relaxed, and if there is an accreting neutron star hidden in those systems, none of their components need exceed a mass of $60\,M_\odot$. In particular, an isolated star should never be able to exceed its Eddington luminosity, not even during outburst. Our subsequent analysis of the η Car system will touch upon a few possible pitfalls in the mass determination of luminous stellar objects.

2 ETA CARINAE

At a somewhat uncertain distance of (2.3 ± 0.2) kpc, the luminous blue variable η Car has a bolometric luminosity of some $10^{40.3}\,{\rm erg\,s^{-1}}$, whereby νS_ν peaks presently at $\lambda = 10\,\mu$m, due to a high column density of dust in the system. Eta is one of the most luminous stars in the Galaxy, at least it has been from 1670 until 1870, whereafter it faded rapidly in the visible, see Fig. 1. In between, Eta underwent giant optical outbursts lasting for months, whose integrated luminosity equalled that of a dim supernova, and whose peak value (in 1843) reached the Eddington luminosity of $10^{3.2}\,M_\odot$. Many of η Carinae's outstanding properties are presented in the survey article by Davidson & Humphreys (1997); see also Damineli et al. (1997, 2000), Morse et al. (1998), Ishibashi et al. (1999), Corcoran et al. (2001), Hillier et al. (2001), Pittard (2003), and Kundt & Hillemanns (2003).

Eta forms the center of the spectacular 'homunculus' nebula, of diameter $\lesssim 0.2\,\mathrm{pc}$, estimated mass $\lesssim 2M_\odot$, whose bizarre 'artichoke' geometry — with a 'conical collar', or 'double-flask' morphology (Currie et al. (2000)) — are unique among stellar nebulae, cf. Morse et al. (1998), and Fig. 4b. This nebula owes its existence to repeated mass ejections. Smith & Gehrz (1998) found from proper-motion measurements that its dominant motions consist of two approximate Hubble flows, $\boldsymbol{v}\,(\boldsymbol{r}) \sim \boldsymbol{r}$, which were launched in the years $\{1843.8{\pm}7.3, 1885.8{\pm}6.5\}$ respectively, at typical velocities of $10^3\,\mathrm{km\,s^{-1}}$, the later one being slightly faster and less massive, $\lesssim 0.2\,M_\odot$, and lying in the equatorial (symmetry) plane of the homunculus which will be identified below with the orbital plane of a binary system. Weis et al. (1999), Currie et al. (2002), and Redman et al. (2002) have found extensions of the first Hubble flow to velocities of $\lesssim 10^{3.5}\,\mathrm{km\,s^{-1}}$, which are traced to distances of $\gtrsim 0.2$ pc from the center, Corcoran et al. (1998) detect X-ray emissions out to 0.6 pc, and Bohigas et al. (2000) find a bipolar geometry even out to 1.3 pc.

In other words: the homunculus nebula is essentially the product of two forceful mass ejections, coinciding with the two luminosity spikes in the years 1843 and 1887. The fact that their kinematics are blurred — with a kinky, curved morphology of the ejecta, and not strictly linear flows — implies that post-accelerations have taken place in the windzone, both accelerating and braking, with negligible net speedup, unlike in a supernova explosion whose ejecta satisfy the kinematics of a splinter explosion, with $\approx$ ten-times higher speeds (Kundt, 2001). Such violent events are more energetic and abrupt than mass ejections from ordinary stars; they ask for a compact star in the system. Similarities are noticed with the Red Rectangle, and with IR source I in Orion (Greenhill et al., 1998).

3 THE BINARY-STAR INTERPRETATION

A periodicity of $P = 5.534\,\mathrm{yr}$ (= 2020 d, [Damineli et al., 2000]) has been detected in the radial-velocity curves of Paγ, Paδ, and HeI as well as in their equivalent widths, and in the lightcurves in H-band (1.6 μm), V-band (5.5 μm), W-band (3235Å), most clearly at X-rays, and vaguely at radio frequencies (Duncan & White, 2003), see Figs. 2, 3 and their refs. They have been widely taken as evidence for binarity, though not by Davidson et al. (2000) who present a number of irregularities at high spatial resolution, probably due to windzone emissions. Note that the above period fits 28 times between the (assumed) periastron passages in 1843 and 1998.0.

A modelling of the assumed binary has often been done with less equations than available, and resulted in inconsistent mass determinations. We follow Damineli et al. (1997) in assuming a primary (hot) B2Ia star (with $T_\mathrm{s} = 22.5\,\mathrm{K}$, not hot enough for HeII 4686) around a (slightly cooler) B8Ia star (with $T_\mathrm{s} = 12.5\,\mathrm{K}$, and about half the primary's luminosity), in a strongly eccentric orbit with (an uncertain) line-of-sight (LOS) velocity amplitude Δv_1 of star 1 of $42\,\mathrm{km\,s^{-1}}$. The mass function (with $\omega = 2\pi/P$) reads:

$$M_2\ \sin^3 i\ /\ (1 + M_1/M_2)^2\ =\ (\Delta v_1)^3/\omega\ G\ . \tag{1}$$

Here the orbital inclination $i \approx 40^\circ$ (Currie et al. 2000) is related to the relative LOS velocity amplitude Δv of the two stars by:

$$\omega\ a\ =\ \Delta v/\sin i \approx 1.5\ \Delta v\ , \tag{2}$$

and yields $a = 12.3$ a.u. $(\Delta v\ /\ 42\,\mathrm{km\,s^{-1}})$. The total mass M in the system then follows from the Kepler equation

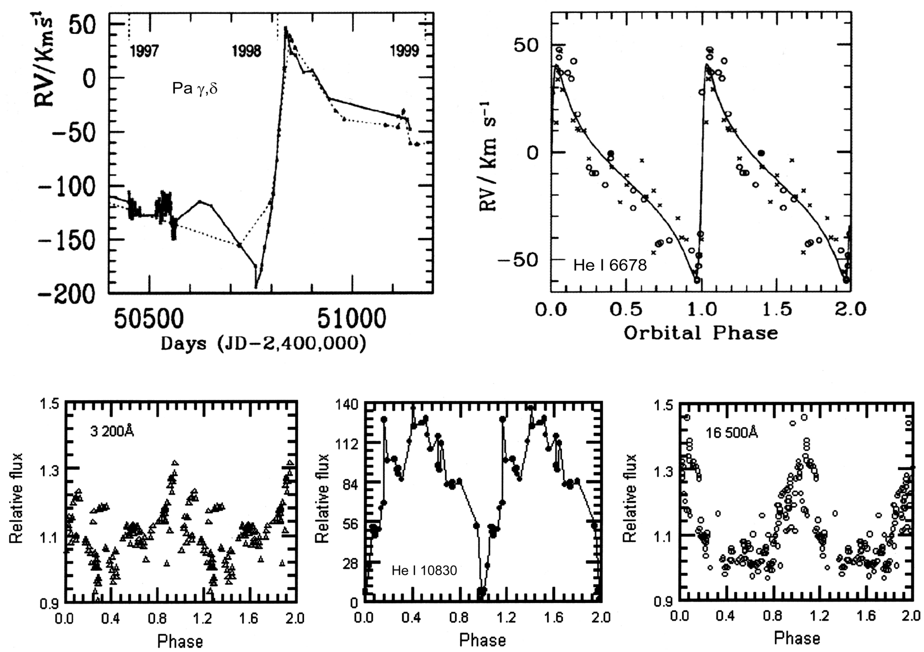

Fig. 2 (*a,b*) Radial-velocity curves for Paschen and HeI lines, and (*c-e*) lightcurves of η Carinae at various UV to infrared frequencies, both line and continuum, w.r.t. the orbital period (of 5.53 yr) proposed by Damineli et al. (1997); taken from Damineli et al. (2000) and from the homepage of Augusto Damineli: www.iagusp.usp.br/ damineli/plots/allph.gif (Feb. 1999). Note that (*d*) is the equivalent width of HeI 10830, and that the UV through IR intensities (3200 Å, 5500 Å, 16500 Å) are strongly correlated, (unlike for S Dor-type variations, for which the bolometric luminosity would be conserved). JD = 2 448 800 corresponds to 27 June 1992. Note that at phase 1.0, the radial velocity of the Pa lines jumps by more than twice as much as that of HeI.

$$a^3\omega^2/G \;=\; M \;=\; 60\,M_\odot\;(\Delta v/42\,\mathrm{km\,s^{-1}})^3\;. \tag{3}$$

in which Δv is thought to be comparable to Δv_1: $1 \leq \Delta v/\Delta v_1 \lesssim 1.3$. Finally, we divide the mass function by M, express M_1 as $M - M_2$, take the cubic root, and insert eq. (3) to obtain:

$$M_1/M_2 \;=\; \Delta v/\Delta v_1 - 1\;. \tag{4}$$

The literature has occasionally proposed mass ratios $\mu = M_1/M_2 \gtrsim 1$, which would ask for a (large, undetected) velocity-amplitude ratio $\Delta v/\Delta v_1 \gtrsim 2$. We find: $M_2/M_\odot = 60(1+\mu)^2\nu^3$ with $\nu = \Delta v_1\;/\;42\,\mathrm{km\,s^{-1}} \lesssim 1$, and $M_1 = \mu M_2$, and favour $0 < \mu \lesssim 0.3$, yielding $60 \lesssim M/M_\odot \lesssim 142, 40 \lesssim M_2/M_\odot \lesssim 107, 20 \lesssim M_1/M_\odot \lesssim 35$, implying orbital diameters $2a$ between 25 and 33 a.u. More precise numbers require more reliable determinations of Δv_1 and Δv.

4 THE TRIPLE-STAR INTERPRETATION

Once the binary-star interpretation of the preceding section is considered plausible, it still leaves a number of observed facts ill understood: (i) What caused the ($\geq$ 2) historical outbursts,

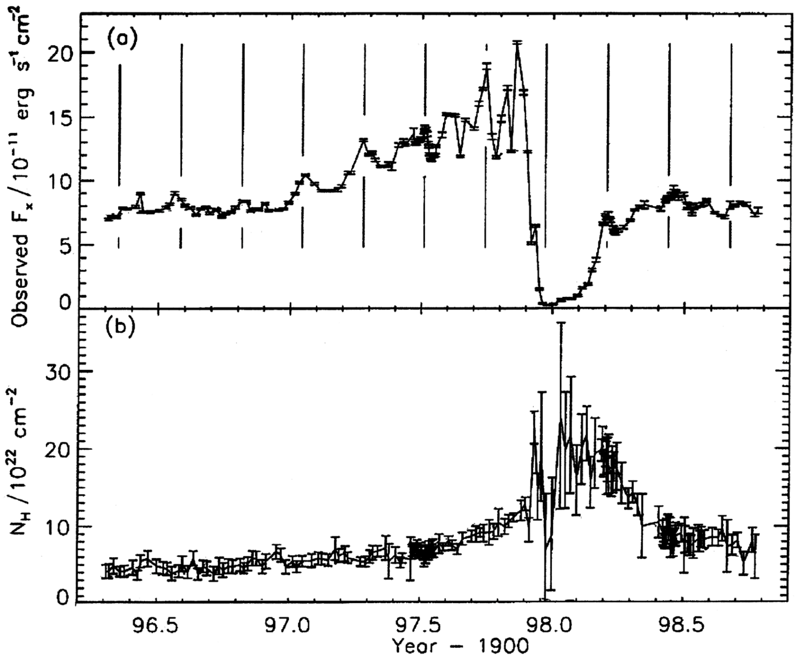

Fig. 3 Almost half a cycle of the X-ray lightcurve of η Car, from which an 85-day flaring periodicity has been found; (peaks are identified by vertical lines). The figure is taken from Mike Corcoran's homepage: http://lheawww.gsfc.nasa.gov/corcoran/eta_car/eta_car.html (April 2000); also from Ishibashi et al. (1999), and Corcoran et al. (2001). Note that the column density N_H passes through a deep minimum at year 1998.0. In the meantime, more than one complete cycle has been monitored, and the 85-day period has been found to lengthen: Pittard & Corcoran (2002), Pittard (2003).

whose visible power exceeded $L_{\rm Edd}(10^3\,M_\odot)$? (ii) What caused the gigantic mass ejections, which formed the bispheric kinematics of the homunculus and beyond, and (iii) the anisotropic ejections of massive blobs in the orbit plane? (iv) What causes the quasi-periodic peaks in the X-ray lightcurve, at intervals of 85 d (Fig.3) ? (v) What causes the almost luminal flares of the radio morphology, on scales of $\gtrsim 10^{16.5}$ cm, i.e., several 10^2 orbital diameters (Duncan et al., 1995, 2003)? (vi) What liberates the huge amount of iron, evidenced by the strong emission lines from FeII, both permitted and forbidden (Viotti, 1995)? (vii) What formed the unique morphology of the homunculus? To us, each of these seven facts evidences the presence of a neutron star in the system, including its accretion disk, and relativistic (pair-plasma) wind.

Our interpretation starts from the conviction that (i) stars above $30\,M_\odot$ are extremely rare, (in disbelief of the Livio & Pringle [1998] scenario), that (ii) super-Eddington variability of the bolometric luminosity is unlikely for single stars, including luminous blue variables, (in disbelief of Stother's [2000] periodic outbursts), and that (iii) the 'artichoke' geometry of the homunculus stressed by Morse et al. (1998) is difficult to blow with ordinary (non-relativistic) stellar winds, (in disbelief of the reality of the Langer et al. [1999] simulations).

To begin with: varying, broad emission lines — like the Pa ones from H, or HeI 6678, 10830, of width $0.5\,\mathrm{Mm\,s^{-1}}$ — signal an extended, non-rigid, optically thin emitter at high relative velocities; we identify this emitter with the joint windzone of stars 1 and 2, including its quasi-hyperboloidal boundary layer. The peak flux of the emission lines reaches 30 times that of the continuum (Hillier et al., 2001), implying emission areas $\geq$ 30 times that of the continuum source.

Once their relative impact velocity exceeds several 10^2 km s^{-1}, particle collisions extend up in energy to the X-ray range (Chlebowski et al., 1984). An emission temperature of $T = 10^{7.8}\,$K, inferred by Corcoran et al. (1998) from the presence of He-like Fe XXV and H-like Fe XXVI in the hard X-ray spectra, asks even for collision velocities of $v = 10^{3.25}\,\mathrm{km\,s^{-1}}$, according to the shock balance

$$T_{\rm sh} \;=\; 2(\kappa-1)(\kappa+1)^{-2} m v_{\rm sh}^2/k \;=\; 10^{7.3} K v_8^2 (m/m_p) \;,\; \kappa = c_p/c_v = 5/3 \;. \qquad (5)$$

The average emitted X-ray power, corrected for internal absorption, $L_{\rm X} \gtrsim 10^{35.3}\mathrm{erg\,s^{-1}}$, agrees with $\gtrsim 10^{-3.4}$ of the stellar-wind power $\dot{M}v^2/2$ for a mass loss rate of $\dot{M} = 10^{-3.5} M_\odot/\mathrm{yr}$ at $v = 10^{3.25}\,\mathrm{km\,s^{-1}}$, i.e. is convincingly interpreted as due to wind-wind collision. Clearly, orbital velocities of $v_{\rm K} \lesssim 10^2\,\mathrm{km\,s^{-1}}$ yield only small corrections to the wind velocities, hence require extreme care in a determination of the orbiting masses.

A similar conclusion can be drawn from the quasi jumps of the H and He emission-line LOS velocities at orbital phase zero, from significant negative values, between -50 and $-200\,\mathrm{km\,s^{-1}}$, to $+50$ km s^{-1}, Fig. 2: an approaching sector of the windzone appears to be suddenly occulted, probably when the boundary layer between the two stars swings tangentially through the line of sight. Occultations occur once per orbit (only!), coincide with a maximum in blueshifted line velocity, with a maximum in the X-ray intensity, a minimum in HeI-10830 emission, and with a maximum in (equivalent hydrogen) column density $N_{\rm H}$ (inferred from the line spectrum), Fig. 3, hence should happen near peri-astron, when star 1 crosses the plane of the sky in approach, as marked in Fig. 4c. Then, according to the geometry found by Currie et al. (2000), the boundary layer has an asymptotic opening angle of 50°, pointing away from star 2 (which blows harder, and is more massive: eq. (4)).

Adjacent to their quasi jumps from blueshift to redshift at phase zero, the H and He LOS velocity curves are some 5-times steeper than in between, suggesting an orbital-velocity contrast $(1+\epsilon)(1-\epsilon) \approx 5$, hence an orbital eccentricity $\epsilon \approx 2/3$, because the Kepler velocity $v_{\rm K}$ satisfies

$$v_{\rm K}^2 \;=\; (GM/a)\;[(1-\epsilon\;\cos\phi)/(1-\epsilon^2) - 1/2]\;. \qquad (6)$$

In this way, we have more or less arrived at the kinematics of Damineli et al. (1997), but without a clear identification of phase zero relative to the two stars' elongation (which they put at phase 0.008). Above we have concluded at a quasi-hyperbolic windzone-boundary layer of opening angle 50°. The radial forces $\dot{M}_j v_j$ of the two stellar winds are expected to scale as their corresponding spherical angles Ω_j:

$$\dot{M}_1 v_1/\dot{M}_2 v_2 \;=\; \Omega_1/\Omega_2 \;\approx\; (5/13)^2 \;\approx\; 1/7\;, \qquad (7)$$

and a balance of ram pressures $\rho_j v_j^2$ for the two winds holds at respective distances r_j given by $r_2/r_1 = (\dot{M}_2 v_2/\dot{M}_1 v_1)^{1/2} = 7^{1/2} = 2.6$, because of $\dot{M} \;=\; 4\pi r^2 \rho(r) v$. This fixes the position of the boundary layer, which is thought to move through the line of sight at phase zero, cf. Fig.4c.

For an eccentric orbit, the shocked power of the two colliding winds should peak near peri-astron because of the enhanced mutual irradiation of the two stars. Moreover, the relative

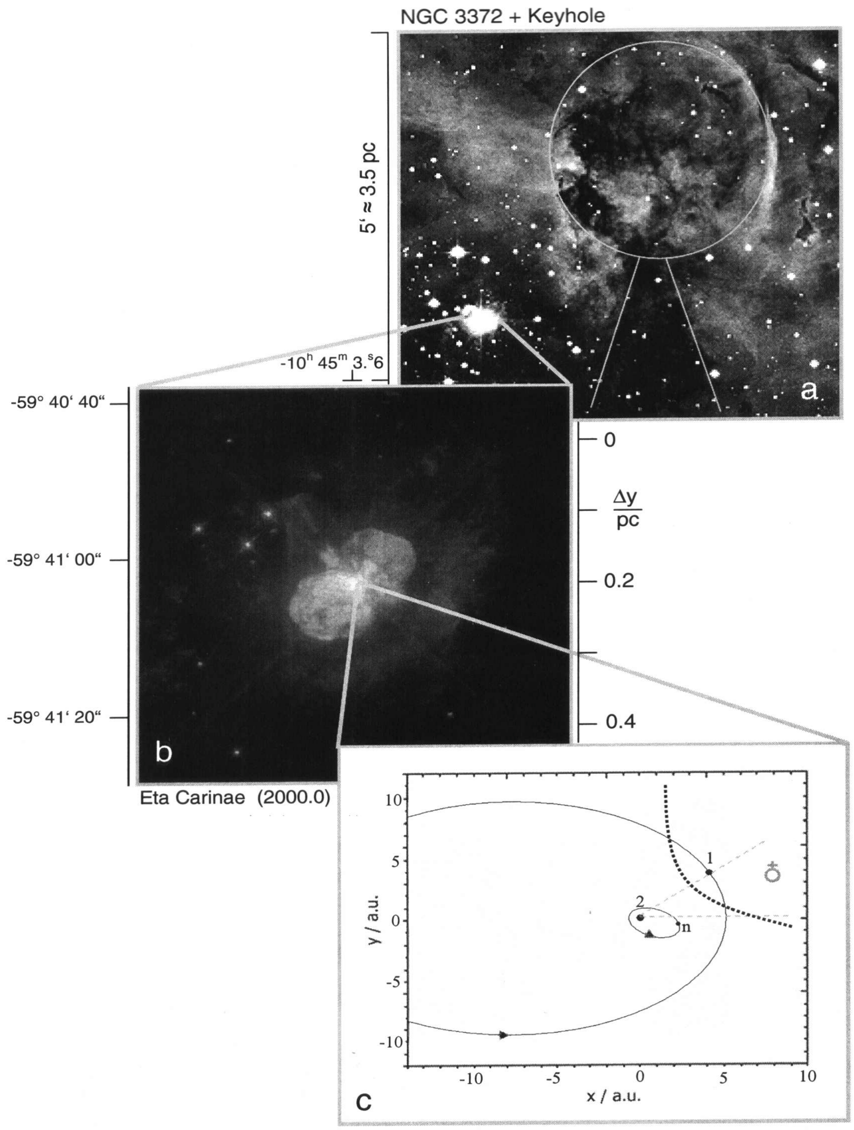

Fig. 4 Maps of η Car on 3 successive scales: (*a*) The several-pc scale shows both η Car and the 'keyhole' (whose visible appearance has changed in the past); (*b*) the middle scale shows the surrounding 'homunculus' nebula, $\lesssim$ one lyr across; and the highest-resolution drawing (*c*) shows our 'updated' triple-star version of the Damineli et al. (1997) binary interpretation, with star 2 taken at rest. The keyhole is David Malin's map taken from the AAO homepage: http://www.aao.gov.au/local/www/dfm/aat032.html, ref.nr. AAT32. The homunculus is John Morse's HST map: http://oposite.stsci.edu/pubinfo/pr/96/23.html. And the triple-star model proposes a neutron star ('n') surrounded by a massive accretion disk, in eccentric orbit around star 2. The somewhat uncertain direction towards Earth is indicated. See also Damineli's homepage quoted in Fig. 2.

velocity of the two windzones is larger on mutual approach, and smaller on recession, so that the thermalized power flux density $\rho v_{\rm rel}^3/2$ is expected to peak before closest approach, and to be more modest thereafter. Finally, there is the strong self-absorption, by a factor of 10^2, when the line of sight swings tangentially through the boundary layer. All these effects can be readily verified in Fig.2 and Fig.3. We get reasonable agreement with the data by impacting the powers $\Delta\dot{M}_j v_j^2/2$ of the two windsectors onto their joint boundary layer, which is closer to star 1. Concerning Fig.2d, we interpret the deep minimum in the strength of He I as a joint effect of stronger ionisation near peri-astron (factor of 2), and of boundary-layer occultation (factor of $10^{1.7}$).

Still, the X-ray lightcurve shows details which cannot easily be accounted for in terms of only two stars: there are quasi-periodic intensity peaks once every 85 d, and smaller additional peaks in between whose power scales as $L_{\rm X}$; they ask for an additional X-ray source in the system, of relative power some 10%. We interpret it as the inverse-Compton losses of the pair-plasma wind from a neutron star, which peak whenever the neutron star approaches one of the two other (luminous!) stars. Even these additional (continuum) X-rays are occulted during half a month near peri-astron, which wants the neutron star to be screened by the boundary layer at that time; thereafter, it can be seen to 'reappear' gradually, during the following two months. According to eq. (3), an orbital period of 85 d around the secondary star corresponds to a semi-major axis $a_{\rm n*}/a = (P_{\rm n*}/P)^{2/3}(M_2/M)^{1/3} = 0.12(M_2/M)^{1/3}$, where M_2 is the sum of the (three) masses of the proposed B8Ia star, its neutron-star satellite, and a massive disk around it. We expect $M_2/M \gtrsim 2/3$, hence $a_{n*}/a \gtrsim 0.09$, cf. Fig.4c. Note that this orbit is not secularly stable, including its period, as it repeatedly approaches star 1 at comparable separation from star 2, reminiscent of the gravitational swingby of a spacecraft around a planet.

This interpretation of the finestructure of the X-ray lightcurve is corroborated by the radio lightcurve which requires a relativistic excitation in the system, of power $L_{\rm R} \lesssim 10^{32.1}$ erg s^{-1}, and of (mapped) radial extent several $10^{16.5}$ cm, (Duncan et al., 1995, 2003). Its almost luminal flaring — far from the (illuminating) central binary — and its lack of (strict) orbital periodicity and phasing ask for a windlike relativistic excitation. We consider the injection of a relativistic pair-plasma wind from the neutron star into the joint windzone a plausible source (Kundt, 1998). It agrees with the facts that the radio intensity had a steep minimum near peri-astron, during high inverse-Compton losses, and recovered (and dropped thereafter) faster at shorter wavelengths (7 mm) than at longer wavelengths (3 cm).

A third reason for the presence of a neutron star in the system is the enormous luminosity around the year 1843: At least eight super-Eddington X-ray sources are known in the Local Group (of galaxies), with luminosities reaching $10^{40}\,{\rm erg\,s^{-1}}$ (Kundt, 1998). Even point-source luminosities as high as $10^{41}\,{\rm erg\,s^{-1}}$ (at X-rays) have been detected in nearby galaxies (Fabbiano, 1995). They are believed to result from clumpy accretion onto the surface of a neutron star, with a massive disk around it as the donator, and/or from the forming massive disk, which is thought to emit 'supersoft' X-rays, between 20 and 60 eV (Kundt, 1998). η Car may well have been in a similar state, during the years around 1843. If the total mass-loss rate of the system is as high as the reported $\gtrsim 10^{-3}\,M_\odot\,{\rm yr}^{-1}$, (Davidson & Humphreys, 1997; Hillier et al., 2001; Boekel et al., 2003), we should not be surprised to deal with a record case of (occasional) super-Eddington output; whereby the windzone should have been opaque at soft X-rays, yielding super-Eddington luminosities at visible frequencies.

A very different kinematic structure appears to be simultaneously present in the orbit plane, already mentioned above, in the shape of radial 'streaks', or 'fans', 'paddles', 'spokes', or 'streamers', whose velocity field realizes a 2-d Hubble flow launched around 1886; cf. Currie et al. (1996), Smith & Gehrz (1998). Such a 2-d pointlike ejection of massive blobs, of mass $\lesssim 0.2 M_\odot$, appears to require a new mechanism. Could it have been a slingshot release of matter at super-revolution speeds, viz. chunks of material transiently accreted by an orbiting neutron star and its surrounding massive disk, which are subsequently released in the process of the disk's reconfiguration? Such discrete mass ejections have been considered since some 25 yr, suggested by numerical simulations of merging events in compact binaries. They have been found at the level of a few percents of the involved mass, cf. Rosswog et al. (1999). Note that the Kepler speed around a neutron star exceeds $10^3\,\mathrm{km\,s^{-1}}$ for orbits closer than 10^2 stellar radii (10^3 km), so that ejections would have to originate inside of there, as expected. Ejections must (and will) take place within less than 1% of the orbital period (of 85 d), in order to account for the sharpness of the streaks.

Independently, we hold relativistic pair plasma plus enhanced radiation pressure responsible for the (smooth!) launching of the homunculus, and its (conical) collars: The piston should have been light-weight and inmiscible, as in a supernova (Kundt, 2001), in order to achieve Hubble-flow kinematics and artichoke geometry at moderate speeds. Note that the threadlike collars are reminiscent of the radial streaks in the Cat's Eye nebula, and in the Helix and Eskimo nebula, where they have been tentatively identified as blown-off tails of clumps of a slow wind swept up by a subsequent fast wind (cf. Kundt, 1996, p.4). The threads are not straight enough – and lack the outgoing head-tail structure — for being interpreted as ejecta from a pointlike explosion. In the case of the homunculus, this fast, sweeping wind is likely to have been the neutron star's relativistic wind. It is independently indicated by the cometary-head-tail morphology (pointing inward!) stressed by Morse et al. (1998), beyond the outer confines of the homunculus.

Finally, the mass involved in the (expanding) homunculus is thought to come from the winds of the two BIa stars, but transiently released at much higher rates because of photospheric over-heating during the super-Eddington outburst of the neutron star and its disk — whose power is expected to peak at X-ray energies. I.e. excess wind matter is boiled off the two stars when X-ray-irradiated by their flaring compact companion, and post-accelerated by the pressurized pair plasma which fills a large fraction of the core volume.

Why is the (presently) hotter star the lighter of the two? In our interpretation, star 2 was formerly a close double star with mass exchange and the subsequent formation of a neutron star (in a SN explosion), both of whose components were initially heavier than star 1. During mass exchange, star 2 has gained weight. At present, its mass appears enhanced by the orbiting neutron star plus its heavy disk, some $7\,M_\odot$ together. Suggestive initial masses of stars 1, 2, and 3 are $\{30, 50, 60\}\,M_\odot$, respectively, which have evolved into (present) $\{30, 55 \pm 5, 7\}\,M_\odot$.

5 SUMMARY

Our model for η Car uses conservative building blocks: two stars below $60\,M_\odot$ and a neutron star, the latter in eccentric orbit around the cooler component. The neutron star is forced upon us by the (i) almost-periodic (85 d) X-ray flares, (ii) almost luminal variations of the radio morphology during flares, and the radio lightcurve, (iii) a transiently super-Eddington bolometric lightcurve, (iv) ejection and bispheric kinematics of the homunculus and its threadlike collars, by the (v) blobs ejected around 1886 in the (dividing) orbit plane, and by the (vi) strong emission from Fe II.. The phenomena (iii) and (v) want the neutron star to be surrounded by a massive accretion disk.

This new interpretation of η Car revives the debate on the most massive stars, whose mass may well be below $60\,M_\odot$. Earlier estimates were based on (j) the Eddington constraint, which has been invalidated by Nir Shaviv, (jj) forgot the likely presence of a neutron star in the system, and are (jjj) unexpected by the luminosity function of the Local Group, which saturates around (the luminosity of) stars of $30\,M_{\odot}$. (jv) η Car, the brightest known star, need not involve component masses above $60\,M_{\odot}$.

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DISCUSSION

N. PANAGIA: What is the physical process that allows the observed jet-like features to 'puncture' the bubbles around η Carinae and still preserve a Hubble-type velocity field?

W. KUNDT: To me, the skies around η Car look rather clear, meaning that the local temperatures are rather high, and densities correspondingly low, cf. Currie et al. (2000). The clumped ejecta, on the other hand, appear to have optical temperatures. No deceleration of knots is visible, e.g., in the kinematic plots by Weis et al. (1999).

J. BECKMAN: There is now increasing direct evidence of stars with masses greater than 100 $M_\odot$. I quote the work by Massey et al. (1998) and Oly & Kennicutt (1997) who observe stars in clusters in the SMC with masses well over 100 $M_\odot$, and find no upper limit to the IMF at well over 100 $M_\odot$; these are perfectly resolved individual objects, and could not be unresolved clusters.

W. KUNDT: I do not trust the mass estimates of bright objects unless they are based on orbital reconstructions, because the luminosity function of the Local Group argues against (many) high masses. As said in my lecture, Nir Shaviv has invalidated the method based on the Eddington constraint, which has been the criterion most frequently used in mass determinations. Also, brightness outbursts in massive systems can be caused by a so far undetected neutron star in the system. Calculated evolutionary tracks need not be realistic. See also the Summary of my lecture.

S. EIKENBERRY: Following on John Beckman's point, the Pistol Star has a measured luminosity 10 times higher than η Car. Humphreys claims this is an unresolved cluster, but we have found a similar star with 30 times η Car's luminosity and diffraction-limited images from Palomar which place an upper limit of 100 AU on its size. So, it cannot possibly be a cluster ...

W. KUNDT: How certain is the Pistol star's luminosity? Najarro & Figer (1998) estimated $10^{6.7\pm0.5} L_\odot$, i.e. a comparable bolometric luminosity to η Car. And: can you rule out a nearby neutron-star companion? See also my above reply to John Beckman.

F. GIOVANNELLI: I did not show on Monday afternoon a table (because of lack of time) derived by Ødegaard (1996) in which they present the computation of the evolution of a star with the initial mass of 120 $M_\odot$, in order to reproduce the composition of heavy elements in a WR star. They are quite convincing. Then, I would like to say that really we can think to the possibility of having stars with masses higher than 100 $M_\odot$. However, their detection is of course difficult because of the fast evolution time.

W. KUNDT: 1) From unrealistic assumptions you can calculate whatever you wish. Physics requires solving the inverse problem: which interpretation is the correct one? 2) Lifetime considerations are important but do not affect the luminosity function (which is evaluated for a snapshot); incompleteness of detections decreases with the luminosity of a source, i.e. is least at the high-luminosity end.

D. FARGION: I guess that the η Carinae thin 'fingers' are indebted to thin beamed precessing jets which are pushing the external matter into a piston-like acceleration leading to the observed Hubble-law flow.

W. KUNDT: Jets can be prepared in two very different ways: either by punching (two antipodal) holes into a central overpressure box containing a very light medium, or by continually firing heavy bullets into certain (antipodal) directions. They are called 'soft beams', and 'hard beams', respectively, and behave quite differently. In my understanding, all the bipolar flows (from AGN, YSOs, and binary compact stars) are driven by relativistic pair plasma, i.e. are of the soft type, whereas those in the homunculus are probably heavy. But an exact Hubble flow, realized by freely coasting clumps, requires not a continual injection but an instantaneous, explosion-like, multi-velocity injection – that of a splinter bomb.