Eta Carinae

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Abstract. The very massive star η Car presents a number of significant, well-defined, disconcertingly basic, unsolved problems in several branches of astrophysics. This and related objects now constitute a rather large topic with diverse implications and many recent surprises. Being relatively unexplored ground, the subject offers extraordinary opportunities for theoretical work.

I INTRODUCTION

At this meeting I've been impressed by how far most of the topics have been developed: GRB's, for instance, have received a truly large amount of observational and theoretical effort, until they no longer seem quite so miraculous. The subject we come to now, however — eruptive behavior *à la* Eta Carinae — is relatively unexplored territory, with entertaining surprises and wider implications than one might have expected. Despite a wealth of good data (most of it acquired rather cheaply, compared to extragalactic projects), a number of puzzles are Not Understood at an almost alarmingly basic level. They concern diverse branches of astrophysics; until η Car has been explained better, astrophysicists cannot prudently claim to understand the most massive stars, extreme stellar winds, gas dynamics in slow and fast ejecta, stellar X-ray production, or certain types of spectroscopic excitation processes. And there's a certain romanticism in Eta's role as the only naked-eye star whose basic nature remains unsettled, and the only one except the Sun which, according to a fevered extrapolation of some talks at this meeting, might do us harm! (Technological and economic harm above Earth's atmosphere, that is, not biological below it; a workable premise for a mass-market paperback thriller?) In this review I hope, frankly, to encourage fresh theoretical work.

For our purposes here, "Eta Carinae" is a wonderfully broad *topic,* not just one peculiar star. The problems are diverse, unfamiliar, and unsolved as I just said; a few special extragalactic objects appear to belong to the same category; and modern instruments revolutionized our knowledge in the 1990's even more than enthusiasts expected. A combination of technical factors has made η Car one of the most productive of all targets for HST and some X-ray telescopes, producing several discoveries which are among the most notable developments in recent stellar

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astrophysics. The topic is big enough to fill a whole meeting or a sizable book, and here I can attempt only a sketchy view of the main problems and ideas.

First, though, three references together give a decent introduction to the subject, pre-1999. (I had something to do with all of them, but honestly they are the best reviews available.) For general information on η Car, citing most essential papers before 1997, see our *Annual Reviews* article [1]. Many authors recount the developments of 1996–1998 in [2]. This object *may* be the most extreme known example of a class of very massive stars somewhat inadequately called Luminous Blue Variables, and the best review of LBVs is still a 1994 article [3]. The last sections of that review mention several theoretical points that were later noted by other authors. Many problems of five or more years ago remain unsolved while new ones have appeared; but this is partly because only a corporal's guard of theorists have even discussed them yet.

II BASIC FACTS AND PARAMETERS

Let's begin with a few essential, long-known, uncontroversial facts. With apologies to many authors, the primary references are too numerous to cite here but are listed in [1]. First, η Car is located about 2300 pc from us, near the big "Carina Nebula" NGC 3372. Several other stars with $M > 50\ M_\odot$ are there too, exemplifying an old puzzle: why do freakishly massive stars tend to occur in groups?

We can estimate Eta's luminosity by measuring thermal IR from circumstellar dust that absorbs most of the UV and visual-wavelength light. $L \approx 5{\times}10^6\ L_\odot$ is often quoted, but $L > 3{\times}10^6\ L_\odot$ is a more robust statement. The luminosity implies a zero-age mass of $\sim$150 $M_\odot$ or more and an Eddington-limit minimum $\sim$100 $M_\odot$. Since we know the star is evolved and has lost mass, often we adopt a compromise guesstimate of, say, 130 $M_\odot$ for the present-day value. The L/M ratio is probably within 30% of the Eddington limit, maybe within 15%. If this object is a binary system, then the values just quoted probably remain more or less valid for the primary component, because the hypothetical secondary star is probably much less massive. (In this review, the name "η Car" usually refers to just the primary component if a companion star exists.) Surface temperature and radius are poorly known because the stellar wind is opaque at most wavelengths, but most likely the underlying star is 20000 K or hotter with $R \sim 150\ R_\odot \approx 0.7$ AU.

We know that η Car is moderately evolved because its ejecta are observed to contain more nitrogen than oxygen and carbon; some stuff has been in the CNO cycle, transported to the surface, and ejected. Helium seems moderately, but not extremely, overabundant. The star's total lifetime should be roughly 3 million years, and since it resembles an LBV with its dense wind, evolved composition, and eruptive behavior, we usually assume that it's near the end of that lifetime. The stellar wind speed is around 500 km s^{-1} with considerable variation, and the current mass-loss rate is something like 10^{-3} to $3{\times}10^{-3}\ M_\odot$ yr^{-1}. This rate,

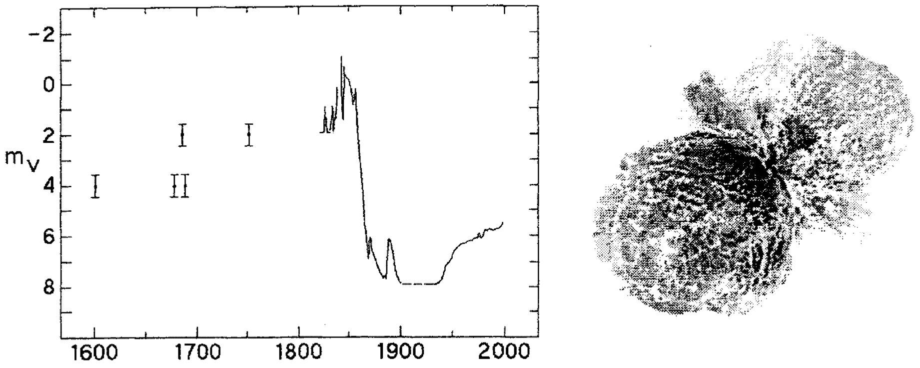

FIGURE 1. Left: Historical light curve of η Car. Right: The Homunculus.

though prodigious compared to any normal stars, seems to represent a relatively "quiescent" state of the object. Imagine what the *active* state must be like!

— Which brings us to the role of η Car in this meeting on Cosmic Explosions: Its famous "Great Eruption" observed 160 years ago was the biggest non-terminal stellar outburst that we know much about. That 1830–1860 event is conspicuous in the historical light curve, Fig. 1. To fully appreciate it, note that astronomers before 1830 sometimes reported the brightness as fourth magnitude but sometimes as second, a big difference. Today this object would appear as a fourth-magnitude blue star if its dusty circumstellar ejecta were not present. The second-magnitude episodes are thought to have been LBV-style eruptions when the wind became denser and more opaque, causing the photosphere to move outward until its characteristic temperature fell below 9000 K. Then most of the light emerged at visual rather than UV wavelengths, so the star appeared brighter to the eye with little or no increase of total luminosity. It was flip-flopping between two stellar-wind modes. Here's the important point for the Great Eruption: The preceding second-magnitude outbursts, with their photospheric temperatures around 7500 K, represented nearly the highest visual brightness allowed by the star's normal luminosity. Between about 1837 and 1858, however, η Car was appreciably brighter, first or zeroth magnitude. Its luminosity must then have increased by a factor of two or more, so *L/M was substantially above the classical Eddington limit for about twenty years.* The phenomenon resembled a slow-motion supernova, with a photosphere as big as the orbit of Saturn and a mass-loss rate of the order of 0.1 $M_\odot$ yr^{-1} at an ejection speed around 500 km s^{-1}. Unlike a supernova, though, it fluctuated rapidly and irregularly by a magnitude or more.

The star survived the eruption, temporarily hidden by dust that formed in the ejecta. After a somewhat puzzling aftershock thirty years later [4], it appears to have been more stable in the 20th century than it was in the 17th and 18th. A gradual brightening can be attributed to decreasing circumstellar extinction as the ejecta expand, and 100 years in the future the star should appear much as it did 400 years ago — unless, of course, a new unexpected event occurs.

The bipolar ejecta-nebula formed by the Great Eruption (Fig. 1) was made famous by the oft-reprinted color HST/WFPC2 images, especially those prepared by Jon Morse. Called the "Homunculus" for reasons that needn't concern us here, at visual wavelengths it shines mainly by reflecting light from the star rather than by intrinsic emission, though some emission is present. Today the polar diameter is 6.5×10^{17} cm ≈ 0.7 ly ≈ 0.2 pc, corresponding to a speed of about 660 km s^{-1} at each pole. An ejected mass of 2 or 3 $M_\odot$ is often quoted, based on IR emission from the dust; but this, like the luminosity, is really a lower limit and no one will be very surprised if additional material with poorly heated dust is present, especially near the equatorial plane [5]. If earlier giant eruptions occurred many hundreds of years ago, as suggested by the new AXAF/Chandra X-ray image and other data, then the dust in their ejecta is now too cool and thin to be obvious. The Homunculus is even more complex than it looks in pictures, and I'll say more about it later.

Concerning the energy budget of the Great Eruption: The kinetic energy of ejecta was comparable to the extra luminous energy radiated, each of the order of 10^{49} ergs. A quick crude estimate shows that 2×10^{49} ergs of thermal energy should be stored in, very roughly, the outer 10 $M_\odot$ of the star. The thermal timescale for those layers is normally of the order of 30 years.

III THE CENTRAL PROBLEM

Why did the Great Eruption occur? We don't know its cause or mechanism. In fact we don't understand the more moderate LBV-type events either, which occur also in stars like S Doradus. The LBV phenomenon is probably crucial for the exterior evolution of stars with $M > 50 M_\odot$ and modern "theoretical" evolutionary tracks need empirical allowances for the resulting mass loss, though most authors don't often say so very clearly. We usually suppose that the instability occurs in the outer layers of the star and moves downward during a major eruption ("as in a geyser"). Two plausible locations have been suggested for the instability, and both may play a role. Again I omit many older references listed in [1,3].

First, the "modified Eddington limit" is a hypothetical instability in or near the photosphere. "Modified" signifies a temperature- and density-dependent opacity; more generally the Eddington limit is less straightforward than we used to imagine, and I'm ignoring some other related effects [6,7]. In the classical Eddington limit for L/M, opacity is due entirely to scattering by free electrons. Absorption opacity, however, becomes significant as a photosphere with a somewhat smaller L/M ratio evolves below 30000 K. Eta Car, LBVs, and the empirical upper boundary in the H-R diagram might all be explained if an instability arises for L/M perhaps 5% to 20% below the classical limit, at temperatures around 20000 K. This conjecture is decidedly non-trivial, for reasons noted in section 5 of [3]. (Ref. [8] invents a new name for the idea but repeats the same points made earlier in [3,11].) Alas, by now the modified Eddington limit has grown old without ever getting a proper analysis. I mentioned it in print as long ago as 1971, then repeatedly after 1979 (e.g. [9–11]), and Appenzeller, Lamers, Fitzpatrick, et al. discussed it in the late 1980's. But *no one has ever seriously attempted to demonstrate the hypothetical instability,* so far as I know, either by quasi-analytic analysis or by gasdynamic simulation. Specific appeals to theorists long ago [11,12] failed to inspire suitable efforts. This remains an opportunity for theoretical exercise; an instability may prove easy to demonstrate, or may not exist. Surely the opacity behavior causes some interesting effects; "bi-stable stellar winds" [13,14] are closely related to the modified Eddington limit.

Other instabilities which arise below the photosphere seem even more promising, but they're bewilderingly complex. Very high opacity around $T{\sim}2{\times}10^5$ K, due to iron, increases the local radiation pressure and allows vigorous local convection. The outer layers are therefore dynamically undamped by interior material, and can be unstable in various ways proposed by Stothers, Glatzel, Kiriakidis, Cox, Guzik, et al.; see [15–18] and other refs. cited there. Unfortunately this subtopic is so intricate that a non-specialist can't easily identify the points of agreement and disagreement. My own impression is that one or more of these theories may offer the current Best Bet to explain Eta's Great Eruption and/or ordinary LBV eruptions. Such instabilities may operate along with other effects.

Rotation has long been recognized as a potentially critical factor for η Car [3]. Langer's "Omega limit" [19,20] is really the Eddington limit affected by rotation, and the bi-stable wind effect can obviously lead to latitude-dependent effects in the presence of rotation [21–23]. Rotation has a particularly synergistic relationship with surface instabilities that grow with decreasing temperature, so an eruption may begin near the equator with low ejection speeds [24]. A surprisingly slow rotation rate is adequate.

Guzik et al. [16,17] have noted a reason to suspect that Eta's instability may not arise near the surface as assumed above. Observed timescales range from several years to a century or more (Fig. 1), far too long to be dynamical times. If these are thermal timescales, then a substantial fraction of the star's mass is represented, perhaps suggesting an instability deep within the star. I bet, on the other hand, that the instability is indeed near the surface, that each eruption produces temporary stability, and that thermal and/or angular momentum flow from a considerable fraction of the star eventually returns the surface to an unstable state. Eta Car must have been far from thermal equilibrium after its Great Eruption, and may still be recovering. Incidentally, the timescale for diffusion of angular momentum, required to spin up the outer layers, is most likely comparable to the thermal timescale for much of the star. As for magnetic effects, please let's not acknowledge them yet! — If we're lucky they may be insignificant. Finally, ideas for deep-seated instabilities remain welcome despite what I've just said.

IV A 5.5-YEAR CYCLE

Long ago astronomers noticed occasional "spectroscopic events" in η Car, when, among other things, the highest-ionization emission lines in nearby ejecta disappeared for a few weeks. These were thought to be irregular shell-ejection events that reduced the UV radiation [25], resembling brief LBV eruptions but not exactly the same. Whitelock et al. then found a pronounced 5- or 6-year cycle in near-IR photometry [26]. In 1996 Damineli, aided by new data, recognized that the spectroscopic events recur faithfully with a period of 5.5 years [27]. His specific and well-founded prediction that such an event would occur near the end of 1997, though disbelieved by at least two telescope allocation committees, was dramatically vindicated when the spectrum changed and the X-ray flux abruptly crashed in late November 1997. Observations of the event produced too much new information to recount here [2]. The 5.5-year cycle promises to be one of our most important clues to the structure of η Car, but we haven't deciphered it yet! This period surprised us because it's far too long for either the star's dynamical timescale or a close interacting binary with a circular orbit, but shorter than thermal and diffusion timescales that had been discussed before 1996.

An obvious possible interpretation, of course, is that η Car has a companion star with a highly eccentric 5.5-year, $a \approx 16$ AU orbit, and that each spectroscopic event occurs near periastron. Colliding stellar winds may then account for the unusual hot thermal X-rays [28–30]. The binary hypothesis, however, is far less straightforward than some of its advocates usually acknowledge, and produced a set of <u>un</u>successful predictions for the 1997–1998 spectroscopic event and aftermath [31]. Our HST/STIS data [35] show that either η Car had an outburst in 1997–1998 as expected in the old single-star discussions [25], or else the ionization structure in its wind changed in a way that mimicked such an outburst. The same observations also show that "orbital velocity" variations measured in ground-based data [32,33] and used to derive orbit solutions [31,34] are probably illusory. Extravagant claims have been made for binary interpretations of the 1997–1998 X-ray and spectroscopic behavior, but in fact the models have been vague, qualitative, and variable as new data have appeared. In summary, and contrary to widespread assertions, the binary idea has *not* been proven. My own opinion is that a binary scenario is fairly likely but needs theoretical development, and its parameters will differ from specific models proposed so far. If a companion object exists, it's most likely an unevolved O-type star much less massive than the primary. A compact object (black hole?) is conceivable, but in that case we'd expect accretion to produce stronger X-rays. A companion star at periastron may trigger Eta's basic instability (though it's not easy to make tidal forces adequate), but probably doesn't account for the instability itself. Most of Eta's other puzzles are primarily opportunities for theoretical work, but for the binary question we equally need more observations.

The single-star possibility seems, from a theoretical point of view, more novel and therefore more fun even though most astronomers feel that it's less likely. If there is no relevant companion star, then the 5.5-year period presumably represents either a thermal timescale for some outer fraction of the star, or an angular-momentum-diffusion timescale, or, heaven forfend, a magnetic timescale. Stothers and Chin have found cycles with similar periods in stellar models adapted to η Car [15]. Complex surface activity and/or fast wind streams would probably be necessary to produce the X-rays. No detailed or quantitative effort has yet been made to develop a model of this type [31].

V THE RECENT BRIGHTENING

Studies of η Car in recent years have moved in a frenetic, variegated, surprise-after-surprise manner that a Hollywood director would appreciate. Whenever our attention has focussed on a discovery like the 5.5-year period (several preceding ones, mostly involving the ejecta, haven't been described here), we've been hit from the side by a new, utterly unexpected development. This happened again when the star brightened by a factor of two in 1998 [36].

Nothing similar has been seen in any very massive star during the past few decades. This was not a normal LBV-like eruption; the spectrum didn't behave that way, and the apparent brightening was a comprehensive UV-to-near-IR affair. Close to the Eddington limit, the luminosity obviously cannot double without inducing mass loss on a Great Eruption scale. We think, instead, that the circumstellar extinction decreased as dust grains were rapidly destroyed in the innermost ejecta. (Motion of the ejecta can't do the trick.) But what destroyed them? — The most obvious possibility is that the luminosity increased by some fraction of the order of 10 percent. Such a phenomenon would seem to violate traditional lore concerning very massive stars. We truly don't know yet what has happened or whether it will continue.

VI THE HOMUNCULUS EJECTA-NEBULA

Familiar HST/WFPC2 images printed in books and magazines don't show the full complexity of the Homunculus; one really needs to view these data in computer displays, noting many fine-scale details and changes that have occurred [37]. We expected the bipolar lobes, but their granulated structure and especially the skirt-like equatorial debris surprised most people and are not yet understood [1,2,37]. The gasdynamics of narrow radial structures and of small, slow-moving condensations there merit further study, while other, even narrower radial structures exist far outside the Homunculus.

Emission-line spectra at some locations near the star may be unique among known astronomical objects (Fig. 3 of [24]); I have an unverified hunch that some of these may be related to the UV spectra of AGNs. The strangest well-defined puzzle, though, concerns a set of narrow Fe II emission features near 2507 Å, seen in dense slow blobs a few hundred AU from the star. The brightest two of these lines are amazingly bright, and the intensity ratios defy the known fundamental branching ratios. Johansson has proposed stimulated emission — a natural UV laser! — to explain them [38]. By normal astrophysical standards this idea seems preposterous, because one would expect the relevant photon occupancy numbers to be insufficient by factors of the order of 10^7; but we have been unable to devise any other remotely plausible explanation. This and a host of other problems in and around the Homunculus deserve theoretical studies quite different from those involving the star [2].

Considering the high level of weirdness acknowledged throughout this brief review, some astronomers may feel that "Homunculus" would be a good name for Eta Carinae in general [39].

VII OTHER CONSIDERATIONS

Many additional, possibly essential facts and puzzles can only be acknowledged in a few words here. For instance, one reason why we don't regard η Car as merely an isolated freak is that giant eruptions have also been seen in a few other objects [3,4]. The most grandiose was "SN 1961v" in NGC 1058, which was even brighter than Eta's Great Eruption but was also briefer so its energy was probably comparable [40,41]. Long ago Zwicky called η Car and SN 1961v "type V supernovae" [42].

In this review I have alluded to, but haven't described, the immense volume of STIS data obtained in only a few HST orbits [35,43]. Initial examinations of these data have already produced several discoveries concerning the stellar wind and the central parts of the Homunculus. Similarly the X-ray observations deserve far more attention [28,29]. Aside from the 1997–1998 event, they appear to show a periodicity of roughly 90 days which may, if real, be almost as significant as the 5.5-year cycle [44].

I've also had to neglect the radio and mm-wavelength story, as well as the 1890 secondary eruption and a current dispute about whether some equatorial material was ejected at that time [2]. One of the first images obtained with AXAF/Chandra shows the soft X-rays which extend out to about 3 times the radius of the Homunculus; these remind one of an old question, did η Car have earlier giant eruptions hundreds or thousands of years ago? There is a shadowy, faint but tantalizing possibility that ancient observations may have survived but we don't know where to look for them [3].

In summary: I used to think of η Car as "the Crab Nebula of the southern hemisphere," i.e., as the one particular, famous object that continues to reward new observational and theoretical efforts more and longer than we had any right to expect. After many years, Eta now appears to surpass even the Crab in that sense, and so far has been inexhaustible — in some respects it's still a fresh topic. Observational astronomers have been doing pretty well with many projects, but *theoretical* work has been scarce. I earnestly recommend the mysteries outlined above to theorists of all persuasions.

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