PLINIAN ERUPTIONS À LA ETA CARINAE

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Eta Carinae is at once our *most notable* LBV but also a *doubtful* LBV, because its Great Eruption observed 150 years ago was so unique. Since that event exceeded other major LBV outbursts by orders of magnitude in ejected mass and energy, we are not certain that it really was an example of S Dor, P Cyg, R127-type behavior. But even if it turns out to be a freak, η Car has provided either the original example or one of the earliest hints for several facets of the LBV phenomenon, *e.g.*:

-- Visual-wavelength brightening with little change in luminosity during each major mass-loss event;
-- The idea of a modified Eddington limit causing instability in a critical range of surface temperature;
-- CNO-processed surface material;
-- Bipolar structure in the ejecta.

The first two of these were recognized nearly 20 years ago for this star (Westphal and Neugebauer 1969, Davidson 1971). So Eta has given us clues to the topic even if it turns out not to be a proper LBV! But I think that it probably is one, and that its extreme nature makes it more interesting as a physical puzzle than the other famous LBV's.

Since many references to the history and nature of η Car can be found in (*e.g.*) van Genderen and Thé (1985), Davidson *et al.* (1986, hereinafter "DDWG"), Meaburn *et al.* (1987), and Davidson (1987a, "D87"), I shall omit some primary references in this brief commentary. Some points made at the Lunteren meeting in 1986 (D87) are worth repeating here -- they are pertinent especially to Maeder's, Appenzeller's, and de Jager's discussions in these proceedings -- but I'll try to add a few other points and to emphasize those that seem most interesting now. First, though, some essential facts:

The light curve (see figure on following page) shows why 19th-century commentators from John Herschel to Agnes Clerke ascribed such great importance to η Car. It was a first-magnitude star for about 20 years, briefly flickering brighter than Canopus during 1843 -- an impressive performance for a star more than 2 kpc away.[1] Astronomers became less aware of Eta during most of the 20th century and vaguely supposed it to be a weird nova, or an unusual supernova, or a strange red supergiant. Then Westphal and

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[1] In those days they hadn't yet decided what to call it: η Navis, η Argus, even η Roburis. In the old map shown on the front of the American Astronomical Society's Membership Directory in recent years, Eta appears in "Karlseiche" = Robur Carolinum = Charles' Oak, a constellation invented by Halley around 1680 to commemorate a hiding place that Charles II of England had once found useful. It's a pity that we can't name constellations to appeal to potential funding agencies any more.

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Neugebauer (1969) found it to be the brightest extra-solar-system object in the sky at IR wavelengths around 20 μm, which eventually inspired us to recognize that it is a very luminous **blue** star surrounded by dusty ejecta. Infrared observations of η Car have been crucial in two or three ways (here I assume that $D = 2.5$ kpc):

(1) They indicate the present luminosity, about $10^{6.6} L_\odot$, requiring $M >$ about $90 M_\odot$ according to the classical Eddington limit. (A naïve Zanstra estimate gives the same result but depends on more assumptions.) *Caveat:* If there are holes in the dusty envelope, say in the polar directions, then the luminosity just quoted is an underestimate -- though a large error seems unlikely.

(2) The mass of the IR-emitting dust is of the order of $0.01 M_\odot$ (see, *e.g.*, Robinson *et al.* 1987, DDWG, Hackwell *et al.* 1986), showing that at least $1 M_\odot$ of gas has been ejected in less than 200 years. If the dust/gas ratio is lower than "normal" because carbon and oxygen are relatively scarce (most of the CNO is in the form of N), then 2 or even $3 M_\odot$ seems a plausible guess for the mass ejected in the Great Eruption -- implying a temporary mass-loss rate of the order of $0.1 M_\odot/y$. The present rate is not known but is probably less than $10^{-3} M_\odot/y$, possibly far less. (Any larger value must be confined near the equatorial plane -- see DDWG and Davidson 1987b.)

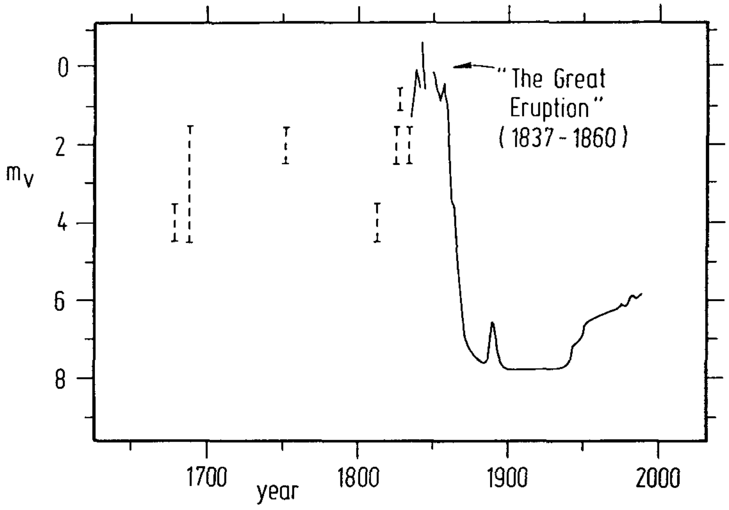
(3) Infrared data are also important in showing more clearly that bipolar structure or axial symmetry is present in the ejecta (see, *e.g.*, Meaburn *et al.* 1987, Hackwell *et al.* 1986, and refs. therein). This may be quite important, and personally I hope that the axis is defined by rotation rather than by a close binary orbit, because a binary scenario for the Great Eruption seems ill-adapted to explaining recurrent eruptions (see below) -- although a close companion might help by inducing rapid rotation.

UV and visual-wavelength observations have also been essential, giving us indications of the surface composition (He-rich, N > C, N > O) and of the star's effective temperature; see DDWG and refs. therein. T_{eff} is most likely in the 24000 -- 32000 K range, close to the hypothetical modified Eddington limit instability as mentioned earlier. With a bold surmise one could have *predicted* the IR brightness in 1967 by a Zanstra argument based on visual-wavelength data then available; so in a sense the UV and visual wavelengths are more essential here than the infrared -- I say this to foster a sense of proportion on the part of IR astronomers!

Weigelt and Ebersberger (1986) used speckle observations at $\lambda \sim 8500$ Å to discover that the central object in η Car appears multiple, one dominant object plus 3 fainter companions. We are still not certain whether the secondary components are stars or nebular blobs; either alternative presents difficulties (Davidson and Humphreys 1986), which, however, have been reduced somewhat by Hofmann and Weigelt's (1988) revision of the brightness ratios. At red wavelengths the brightest object is roughly 12 times as bright as each of its companions. A nebular blob model is difficult because the fainter components seem too small to intercept enough energy to explain their brightnesses. One problem with a multiple-star model is that the apparent separations are all comparable, making it an unstable "trapezium" system unless it really consists of two pairs almost superimposed along the line of sight.

If the three fainter components are stars, they are probably 30-to-50 $M_\odot$ O-type stars with separations of a few hundred a.u. -- too far apart for much interaction. This model would give the primary a luminosity close to $10^{6.4} L_\odot$ (abs. bol. mag. ~ -11.2, $M_{Edd} \sim 55 M_\odot$) and an initial mass around $120 M_\odot$; but obviously we need more speckle results and some observations with a space telescope. At least tentatively, we can use Ockham's Razor to suppose that the brightest component was the site of the Great Eruption; any alternative model would be less straightforward.

The foregoing page is an outline of the probable present condition of η Car. With this in mind, now let me mention a few points that I think are interesting, including some possible clues to the eruptive phenomenon. Let's begin with the light curve.



Historical visual-wavelength brightness of η Carinae. See D87 for refs.

Since 1860 the brightness has been reduced by circumstellar dust that began to form around that time. Without that circumstellar extinction, the apparent magnitude would now be about $m_V \sim 4.0 - 4.5$, comparable to the low state sometimes seen before 1820. The light curve has the following points of interest -- these seem obvious when they are pointed out, but I emphasize them here because they are important and because they have never been used in a genuine physical model of the system:

(1) Before 1820 the star was noticeably unstable; the 2-magnitude discrepancies among various observers were too large to be mistakes. But then *the Great Eruption apparently relieved the immediate cause of instability* and the star has not been so erratic during this century. (This is why I like the term "eruption"; the light curve is reminiscent of a volcano or maybe a geyser.) However, the outburst around 1890, which was indeed a mass-loss event (see Walborn and Liller 1977), seems mildly inconsistent from this point of view and needs some explanation.

(2) *The star was behaving like a 2-mode or 2-state system before 1820.* Sometimes it was a 2nd-magnitude star, sometimes 4th, but seldom 3rd magnitude. Presumably the fainter state resembled its present condition, a hot luminous star. In the brighter state there was a dense wind that looked like a cooler photosphere and therefore was brighter at visual wavelengths, the now-familiar LBV style of brightening. Since any mass-loss rate above about $10^{-3.6} M_\odot/y$ will give about the same visual appearance (Davidson 1987b), "on" and "off" are adequate descriptions of the two states to explain the brightness changes semi-quantitatively.

(3) *The luminosity must have increased during the big event.* So far as I know, van Genderen and Thé (1985) were the first to clearly note this ironic point, ironic because the idea of an LBV visual-wavelength outburst at near-constant luminosity originated in connection with this event, as I mentioned at the beginning of this discussion. The brightest visual magnitude that can be attained at the present luminosity, even without

any circumstellar dust, is roughly in the range $m_V \approx 1.5 -- 2.0$, which was approached or attained in the pre-1820 maxima. From 1840 to 1860 the average brightness was about a magnitude brighter than this; in 1843 it briefly reached $m_V \approx -1$, corresponding to absolute magnitude < -14! The average total luminosity during the 20-year event was probably about $10^7 L_\odot$, almost certainly exceeding the classical Eddington limit. A luminosity change large enough to be noticed may be a trait that distinguishes giant LBV eruptions from the more normal variety (*cf.* Wolf, these proceedings).

(4) The luminosity fluctuated during the Great Eruption. The photosphere was then located in the dense wind, at $r \sim 10^{14.2}$ cm $\sim 2000 R_\odot$, $T \sim 7000$ K, with bolometric correction near zero. Therefore the observed fluctuations in visual brightness, *e.g.* in 1843, were not merely variations in bolometric correction. They cannot all have been errors, either; the observers described η Car relative to specific bright stars that are well known today, including Canopus, $m_V \approx -0.7$.

Having seen the light curve, we can ponder the energy budget. The "extra" energy radiated between 1840 and 1860 was roughly $10^{49.2}$ ergs -- about 60 years' worth of radiation at the normal luminosity. (The eruption was synergistic: Radiation caused the gas to escape, which in turn allowed radiation to escape.) If the mass of the ejected gas was around $2 M_\odot$, then each of the other contributions to the energy budget is also about 10^{49} ergs. The kinetic energy of $2 M_\odot$ is 10^{49} ergs at a velocity of 700 km/s, close to the observed expansion speed. If the star's mass was (*e.g.*) $80 M_\odot$ before the eruption, then a simplified calculation shows that its outer $2 M_\odot$ extended quite deeply (to $r \sim 0.7 R_*$, $T \sim 10^{6.3}$ K) and had thermal energy $\approx 10^{49}$ ergs, gravitational potential energy $\approx -10^{49}$ ergs. I suppose that the readjustment energy of the remaining star after removal of the outer layers would have been similar. Anyway, the conjecture that the mechanical and radiative energies released in the event were roughly equal is consistent with the idea that the ejected mass was of the order of $2 M_\odot$.

Regarding energy balance, and assuming that it was a single-star event, the eruption was strangely reminiscent of autoionization in a doubly-excited atom. The initial state looked like a hot star, the final state looks like a hot star plus ejecta plus radiation, and somehow the initial state had as much energy as the final state but was bound. As in the atom, characteristic energies are much larger in the stellar core but we suspect that the core is not directly relevant to the process. This analogy, in addition to the suspected bipolar morphology, is why I fear that rotation may prove crucial even if we dislike the extra parameters involved (see Sreenivasan's discussion, these proceedings). As in an atomic transition, the initial and final states might differ mainly in their angular momentum distributions. In any case we need a model of the "before-and-after" energy balance.

Next let's consider timescales, particularly the duration of a major outburst and the recurrence time between outbursts. The *dynamical* time for the outer layers of η Car is ~10 days for the basic star, or 30 to 100 days for the pseudo-photosphere during an eruption. Large fluctuations in brightness did occur this quickly between 1820 and 1860, and this fact may eventually prove significant for modeling the instability, but the characteristic duration of a major event appears to be longer. The *thermal* timescale for just the outer layers, containing roughly the mass that was ejected, is obviously comparable to the duration of the Great Eruption (*cf.* remarks by Maeder and by Appenzeller, these proceedings). However, the pre-1820 outbursts probably involved much less mass but did not have proportionally shorter durations. The characteristic duration of an outburst for η Car as well as other LBV's seems to be about equal to the thermal timescale for the outer 0.1 to 1 percent of the mass; maybe this is a hint that the eruptive process has a deep-seated cause, or maybe not! A calculative experiment proposed in D87 is pertinent here: Instantaneously remove outer layers Δm from an equilibrium stellar model, and then give it enough time to return to dynamical equilibrium but not thermal equilibrium. Both the luminosity and the radius are temporarily changed; then, as a function of Δm, does the star become more stable or less stable according to the modified Eddington limit or any other hypothetical criterion? Maeder and also Appenzeller (these proceedings) and Heisler and Alcock (1986) have discussed almost, but not quite, this experiment, and the results seem ambiguous to me.

A few outlying nebular blobs around η Car have proper motions indicating ages of several hundred years (Walborn *et al.* 1978); therefore some of the pre-1820 outbursts must have ejected significant amounts of mass. Perhaps the recurrence time between major eruptions is again related to a thermal timescale, but on the other hand, it may instead be related to a nuclear/evolutionary timescale -- the time needed to evolve just a tiny bit, to become unstable again. I wish that we knew whether any giant outbursts of this star were seen thousands of years ago; pertinent but unrecognized records may exist somewhere (see D87, DDWG). Finally, regarding timescales: If rotation is crucial, then the characteristic recurrence time between outbursts may be related to a fourth physical timescale, that for diffusion of angular momentum (see Sreenivasan, these proceedings).

We do not have any well-studied extragalactic examples of LBV eruptions as large as that of η Car. A giant outburst of variable V12 in NGC2403 was observed during the 1950's (see Tammann and Sandage 1968); it probably attained an absolute magnitude of -11 or brighter, and, like η Car, it fluctuated wildly just before the outburst and faded quickly afterward, perhaps as dust formed in the ejecta. However, the duration of the event was much briefer than in the case of η Car. We don't know much about the present state of V12; maybe it is a worthwhile IR object. An explosion called SN1961V, in NGC1058, was likened by Zwicky (1964) to η Car, but it was extremely luminous and may have been a supernova. In terms of observational technique, looking for giant LBV eruptions in nearby galaxies is an extension of the idea of seeking low-luminosity supernovae like SN1987A.

Now, at last, for my main point. Eta Carinae is a beautiful, tantalizing physical system; we have some clues to its causes of instability, though we cannot say exactly what caused its eruptions; we suspect that this is essentially the same phenomenon that occurs in other LBV's; but *no serious attempt has yet been made to model the instability.* A number of people have calculated evolutionary tracks or detailed atmospheres and winds for this part of the H-R diagram, but we need something different, namely a stability analysis of a **simplified** equilibrium star. Simplification is essential, I think, not merely to reduce the calculative effort, but more importantly to eliminate distracting details that are not crucial to the eruptive process.

With Ockham's Razor in mind, what do we expect to be necessary in an idealized theoretical configuration to be examined for LBV-like behavior? (1) The L/M ratio must be within shouting distance of the classical Eddington Limit. (2) The surface temperature should be LBV-like. (3) A CNO-processed chemical composition, with helium abundance around $Y \sim 0.4$, is most likely adequate for the outer layers. (4) Only the outer layers of the star, perhaps the outer 10% or so of the mass, seem crucial at the outset. This means that there is no obvious need for evolutionary calculations of the interior structure; suitable inner boundary conditions can probably substitute. (5) There is also no obvious need for a fancy non-LTE atmosphere model; even if the instability is triggered in the photosphere and involves opacity dependences, a simplified atmosphere is likely to include the the essential physics of the outburst phenomenon. (6) Realistic hydrodynamics, on the other hand, may be essential (see de Jager, these proceedings). (7) Initially the star should be non-rotating. If such a star refuses to behave like an LBV, then the next step may be to introduce rotation; whether or not rotation is essential is one of the main questions here. As for binary scenarios, I suspect that a rotational model would be able to simulate the most likely effects of a close companion. (8) If the program outlined above unexpectedly fails to produce eruptions, then one can justifiably devise more complicated models!

Some cleverly simple form of analysis might reveal the desired instability. More likely, a careful plasma-physics-style linearized analysis is appropriate. But it is also conceivable that the phenomenon is intrinsically hydrodynamic and non-linear. An obvious approach would be to construct equilibrium outer layers for a star, put this equilibrium configuration in a supercomputer with a hydrodynamic code (keeping the radiative transfer simple), and see what happens! It is remarkable that none of these approaches has yet been undertaken by anybody, so far as I know. By now we are fairly sure that a simple zeroth-order modified Eddington limit does not suffice to explain LBV outbursts, and we suspect, variously, that the true explanation is a more subtle instability involving either a modified Eddington limit (Maeder's as well as Appenzeller's discussions in these proceedings fall in this category), or de Jager's turbulent pressure, or rotation as discussed by Sreenivasan... Which of these ideas actually work? Which are *sufficient* and which are *necessary* for LBV's?

(*Addenda* -- A few recent papers are notable in connection with η Car:)

(1) Bandiera *et al.* (these proceedings) have found a dramatic change in the profile of the He I $\lambda5876$ emission line. Ruiz *et al.* (1984) previously described rapid changes in the Hα profile. The interesting point is that small velocity dispersions of the order of 30 km/s are involved. The speeds and timescales suggest that the relevant gas is in a region only a few a.u. across. This compact gas with a small velocity dispersion may be a circumstellar disk and may be evidence *against* the presence of a companion star close enough to affect the primary star; some special trick would seem necessary to allow circumstellar gas to have a small velocity dispersion in a binary system with orbital velocities of hundreds of km/s.

(2) Walborn and Blanco (1988) report evidence for deceleration of the outlying ejecta around η Car. They suggest that pre-1820 ejection dates deduced from proper motions of the outermost visible blobs are invalid. However, the proposed rates of deceleration seem implausible on energetic grounds.

(3) Goodrich *et al.* (1989) have obtained spectra of the site of "SN 1961V" in NGC 1058, mentioned above. They believe that this object was indeed an LBV outburst rather than a supernova, and that it was more extreme than η Car.

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DISCUSSION

Zickgraf: Were the brightness variations of η Car before the Great Eruption similar to the variations of S Dor and other LBV's? The amplitude seems to be of the same order of magnitude. This could mean that LBV's are in a pre-η Car phase.

Davidson: Indeed the pre-1820 behavior may have been a series of "normal" LBV outbursts. Of course we do not know whether LBV behavior normally leads to a dramatic catharsis à la η Car; but I suspect that for LBV's that are significantly less luminous, it does **not**. The similarity in photometric amplitude among various "normal" LBV eruptions is merely a consequence of just 3 circumstances: (1) the stars are fairly hot when quiescent ($T_{\rm eff} \sim$ 15000--30000 K?), (2) their luminosities don't change much during eruptions, and (3) their coolest pseudo-photospheric temperatures (giving maximum visual brightness) are around 7000 K for the same reasons as in supernovae (see *Astrophys. J.* **317**, 760). So, unfortunately, eruptions caused by various different mechanisms might look photometrically alike.

De Groot: It is interesting to see that the oscillations of V 12 may be similar to the to the pre-1830 oscillations of η Carinae. Do you have an explanation for the difference in time-scale?

Davidson: I can offer only the usual vague generalities. Many of us suspect that the thermal time-scale for some outer portion of the star is relevant, but we don't really know whether this outer portion consists of the ejected layers, or a critical depth for the instability mechanism, or something else. And the rate of interior evolution may also be pertinent: conceivably each ejection event temporarily stabilizes the star until just a little bit of further evolution de-stabilizes it again. It seems intuitively plausible that for a given star the recurrence time should be correlated with the violence of the most recent event (this is another sense in which the term "eruption" evokes colorful geological analogies). Comparisons between stars with different L and M are not safe, but one obvious idea is that the typical recurrence time may be longer for lower luminosities.

Humphreys: (1) Regarding V 12 in NGC 2403, I have deep CCD frames of that field, showing stars of 22nd magnitude or fainter. V 12 is not present on the B and V frames but is there in R and I. So it is red today, maybe because of dust in the ejecta. (2) You mentioned a change in the structure of the H and He lines in η Car. The narrow component was absent between 1984 and 1987, but had reappeared in 1988. This time-scale seems very short.

Davidson: Maybe the short time-scale for this change indicates that the narrow-line gas is photoionized. A few years ago Zanella, Wolf, and Stahl proposed that a temporary disappearance of [Ne III] emission was due to an outburst that temporarily reduced the far-UV luminosity (*Astr. Astrophys.* **137**, 79). Admittedly this scenario seems inconsistent with the simplest stellar interpretation of Weigelt's faint objects, wherein the bright component is the LBV but most of the far UV is likely to come from the other components.