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η Carinae – A Massive Star In Its Death Throes?

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Abstract. The very name of η Carinae conjures up the spectre of unsolved problems and challenging physics in the minds of many stellar astrophysicists. High spatial resolution spectroscopy and imaging of η Car during the past few years have answered some questions, but new and even more puzzling ones have appeared. In this review we highlight some of the recent discoveries and the still outstanding questions - what causes its 5.5 year spectroscopic cycle, what is the origin of its famous "great eruption," and what is the underlying source of its instability?

1. Introduction

η *Carinae*, the most massive, most luminous star in our region of the Milky Way, is a naked–eye object that briefly became the second brightest star in the sky. During its "great eruption" 160 years ago, its total energy output rivalled that of a supernova, it ejected 2 – 3 $M_\odot$, and survived. In the past 30 years or so we have learned an amazing amount about massive stars in general, their instabilities and mass loss and about η Carinae in particular. However, an understanding of this most extreme example and its great eruption still eludes us. Without this, we cannot legitimately claim to understand the most massive stars, their extreme stellar winds, their outbursts and eruptions, and of course how these most massive stars end their brief lives. The first steps to understanding η Car are its long–term light curve, its energetics and its spectroscopic history.

2. The Historical Light Curve

Beginning about 180 years ago η Carinae entered a period of remarkable variability culminating in its famous *"great eruption"* from 1837 to 1858 when it became one of the brightest stars in the sky. Earlier observations show that it had oscillated between fourth and second apparent magnitude for centuries in possible S Dor–type outbursts (Humphreys & Davidson 1994; Humphreys, Davidson, & Smith 1999). Fortunately John Herschel and several others recorded η Car's behavior during its eruption when for 20 years it oscillated between apparent magnitudes 0 and 1.5, briefly reaching −1. It then rapidly declined in about 10 years to below naked–eye visibility, eventually to $\sim$ 7–8th in apparent magnitude due both to the cessation of the eruption and the formation of dust. Figs. 1 and 2 show its historical light curve up to the present and the details of its variability during the 19th century. A recent discussion of its light curve with the historical references can be found in Humphreys, Davidson, & Smith (1999).

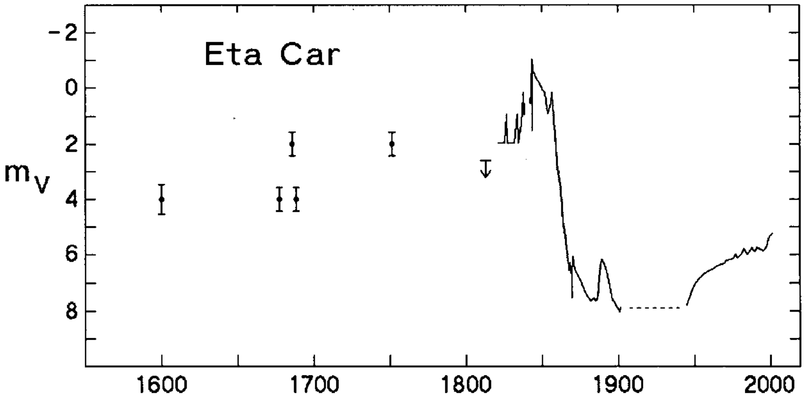

Figure 1. The historical light curve of η Car from 1600 to the present. Note the two–magnitude oscillations prior to the "great eruption." Magnitudes after the great eruption refer to the integrated light of the Homunculus nebula. This figure originally appeared in the Publications of the Astronomical Society of the Pacific (Humphreys, Davidson, & Smith, 1999, PASP, 111, 1124). ©1999, Astronomical Society of the Pacific; reproduced with permission of the Editors.

η Car's second or lesser eruption began in 1887 and lasted seven years. The first photographic spectrum, obtained in 1892-1893 during this outburst, resembled an F–type supergiant with strong hydrogen emission lines. This second eruption had many characteristics in common with what we think of as an S Dor or normal LBV–type outburst including its duration, change in apparent brightness and spectral type. When corrected for a reasonable estimate of the circumstellar extinction at that time (Fig. 2) we see that this second outburst was not so minor and that the star rose significantly above its normal quiescent level (Humphreys, Davidson, & Smith 1999).

The star was then apparently quiescent near 8th magnitude until the 1940's. In 1942, it began to brighten rapidly and in less than 10 years was near naked-eye visibility again (de Vaucouleurs & Eggen 1952). It was also during this time that images clearly revealed the nebula we now identify with the great eruption and that Gaviola (1950) nicknamed the "Homunculus" or "little man." Visual observers in the early years of the 20th century had previously noted that η Car was non–stellar. It is important to realize that the ground-based magnitudes shown in Figs. 1 and 2 since the great eruption refer to the integrated light over the nebula and not the central star. So why did it brighten so quickly? Most astronomers assume that the rapid brightening was caused by the destruction of dust. That may be correct, but why were at least two magnitudes of circumstellar extinction by dust removed so quickly? During the past 50 years the Homunculus has continued to brighten much more slowly due to expansion of the nebula with small oscillations observed in both the visible and near-infrared

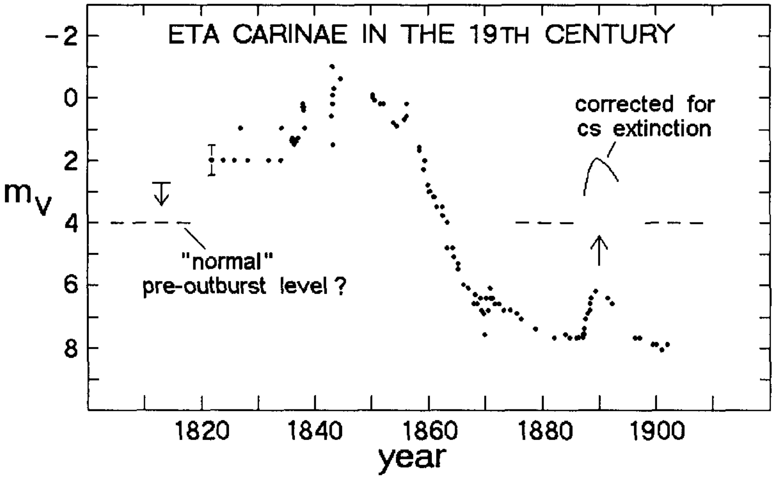

Figure 2. The light curve during the 19th century showing the details of the "great eruption" and the second eruption with a correction for the probable circumstellar extinction at that time. This figure originally appeared in the Publications of the Astronomical Society of the Pacific (Humphreys, Davidson, & Smith, 1999, PASP, 111, 1124). ©1999, Astronomical Society of the Pacific; reproduced with permission of the Editors.

until very recently when HST/STIS observations showed that the central star itself brightened significantly between 1997 and 2001.

3. A Summary of Its Physical Parameters

η Car's luminosity, mass, mass-loss rate, and its energetics during the great eruption are all keys to understanding its evolutionary state and critical for any physical model to explain its current behavior and the origin of its instability.

Distance: $\sim 2.2 - 2.3\,\mathrm{kpc}$ (Davidson & Humphreys 1997; Allen & Hillier 1993; Meaburn 1999; Davidson et al. 2001).

Total luminosity from the thermal infrared: (Westphal & Neugebauer 1969; Cox et al. 1995) – $L \sim 5 \times 10^6\,\mathrm{L}_\odot$ ($\mathrm{M_{bol}} \sim -12\,\mathrm{mag}$) which implies a zero age mass $\sim 150 - 200\,\mathrm{M}_\odot$.

Current mass loss rate: $\sim 10^{-3}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ (White et al. 1994; Cox et al. 1995; Davidson et al. 1995; Hillier et al. 2001).

η Car is evolved: Its ejecta and its wind are N and He enriched (Davidson et al. 1982, 1986; Dufour 1989; Dufour et al. 1999). It must be near or past the end of central hydrogen burning.

Current mass: Combined with its evolved state, high mass loss rate, and mass lost during one (or more?) great eruptions, we estimate a current mass of $\sim 120 - 140\,M_\odot$. Its *L/M is then within 10–30% of the Eddington Limit.* See comments by Shaviv (2000).

Temperature? – We observe its *wind*, not the star itself. Apparent or characteristic temperature estimates range from 20,000 – 30,000 K (Hillier et al. 2001) with the corresponding radius between 0.4 and 0.9 AU. The underlying star could be hotter.

Dynamical timescale: A few weeks.

Thermal timescale: This depends on the outer fraction of the star considered, but is of the order of a few decades to a few centuries.

During the *"great eruption"* η Car visually brightened more than 2 magnitudes above its normal S Dor–like (or LBV) outburst state, and therefore more than 4 magnitudes above what we think is its *quiescent state.* It was brighter than $M_{\rm bol} \sim -13$ for several years, and briefly reached $M_{\rm bol} \sim -14$! It therefore *exceeded the Eddington limit for a protracted time.* It expelled $2 - 3\,M_\odot$ for a mass loss rate of $10^{-1}\,M_\odot\,{\rm yr}^{-1}$.

Total luminous energy released in the eruption: $\sim 3 \times 10^{49}$ ergs, where the kinetic energy is approximately equal to the luminous energy.

The total stellar lifetime expected for a star of this mass is $\sim$ 3 million years. When combined with its highly unstable nature, its dense wind, evolved composition, and mass loss rate(s), we usually assume that η Car is near the end of its brief life. Once a star of this mass begins helium burning, nucleosynthesis will proceed very rapidly to the end, in only $\sim 10^4$ years. At a distance of $\sim$ 7500 ly, the information of its demise may already be on its way.

4. Recent Results

During the past decade a number of major discoveries have been made about η Car, the star, its ejecta and its Homunculus nebula, many of them benefiting from the high spatial resolution of HST.

4.1. Results from HST/FOS, GHRS and STIS

All ground-based spectroscopy of the central star includes light from a mixture of sources: the star itself, or rather its dense wind; its high-excitation nearby ejecta; other ionized gas and scattered light in the aperture. Observations with HST/FOS and GHRS (Davidson et al. 1995, 1997) first showed that the narrow high excitation lines that dominate η Car's ground-based spectra actually arise in compact, dense ejecta $\leq 0\farcs3$ from the central star known as the "Weigelt

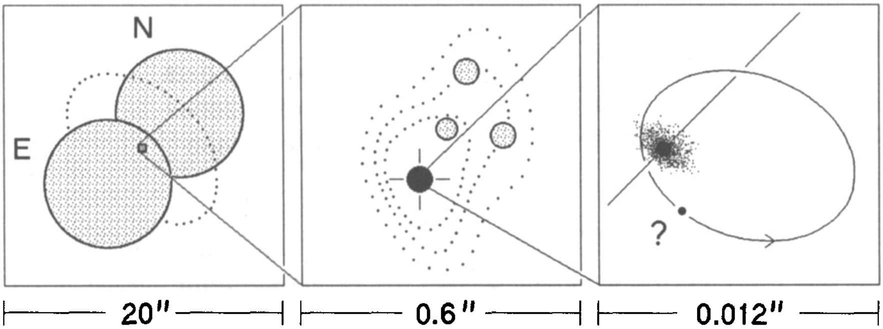

Figure 3. The three panels show schematic diagrams of the structure of η Car on three different spatial scales. The center panel shows the primary star in black plus the three Weigelt blobs in grey within 0.″3. HST/STIS has a resolution of 0.″1 and can separate the spectra of these objects and the surrounding ejecta which all contribute to ground-based spectroscopic observations. The right panel shows a type of binary orbit and illustrates that it cannot be resolved even with HST.

blobs" (Weigelt & Ebersberger 1986; Hofmann & Weigelt 1988). See Fig. 3 for a diagram of the central region. For example, the complex Hα profile (Fig. 4) previously ascribed to the star is really a smooth stellar wind profile contaminated by emission and absorption in the nearby ejecta.

The high-excitation lines in η Car's spectrum are observed to dramatically weaken for short periods of time. These "spectroscopic events" recur regularly with a 5.5 yr period (see Section 5), and the last such "event" occurred in 1997-98. We have been monitoring η Car during its current 5.5 yr spectroscopic cycle with HST/STIS and have obtained excellent data on more than a dozen occasions with full wavelength coverage from 1700 – 10000 Å on 1998.2, 1999.1, 2000.2 and 2001.4 and with less complete wavelength coverage at other times. During the 1997-98 event (1998.0) our STIS spectra cover the wavelength ranges 2760–2910, 3800–4070 and 6490–7050 Å. The He I and other high excitation-lines in the Weigelt blobs almost disappeared for a few weeks then. Strong UV absorption by Fe II reached near zero intensity making the star virtually dark between 2200 and 2600 Å. The Balmer lines developed strong P Cygni profiles that they do not normally have and the column densities of the low ionization species increased considerably; the absorption increased in the Ca II, Mg II and Fe II lines. These changes are not due simply to an eclipse of a hot secondary's UV photons because the same lines increased in other spatial samples along the slit representing different lines of sight through the stellar wind. The equivalent widths of the hydrogen and Fe II emission showed virtually no change (Davidson et al. 1999a). Therefore *the spectroscopic changes observed in the star and in the Weigelt blobs cannot be interpreted as due to a simple eclipse of a hotter star but represent real changes in the wind of the star.*

By March 1998 the spectrum had begun to return to normal and we think that the 1999.1 spectrum represents the near normal state of the star; the high-

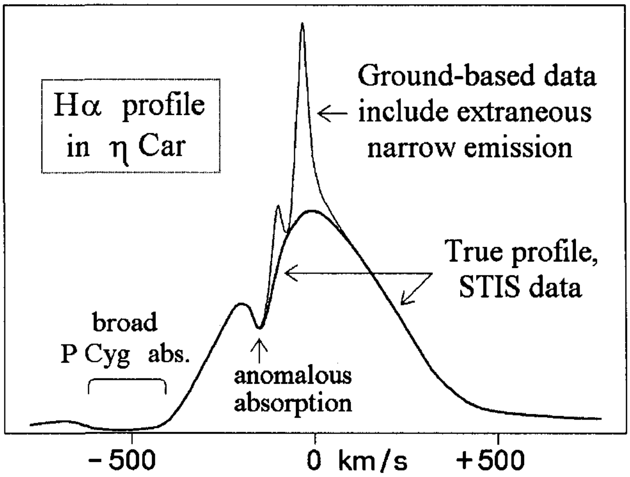

Figure 4. The Hα profile illustrating the difference between the observed ground-based profile and the true profile from the star observed with STIS. The narrow "anomalous" absorption at $-140\,\mathrm{km\,s^{-1}}$ occurs far outside the wind.

excitation lines are at or near their maximum strength in the Weigelt blobs. Nevertheless the line profiles of the hydrogen and helium lines continue to vary. The behavior of the helium lines are especially perplexing in connection with the possible presence of a hot companion. In a conventional stellar wind model for η Car the helium lines are expected to originate deep in the wind and the He I profiles from 1998.2 are consistent with this. By 1999.1, however, the profile is sloping to the blue which could be due to ionization by a hot companion in the outer parts of the wind, but only on one side of it. But by 2001.2 the He I profile had changed again in a way inconsistent with this suggestion (Davidson 2001).

When applied to the HST/STIS spectra of η Car, Hillier's (Hillier et al. 2001) non-LTE stellar wind model confirms the existence of its very dense, optically thick wind with a terminal velocity of $\sim 500\,\mathrm{km\,s^{-1}}$, its extreme mass loss rate, and the presence of CNO processed material (C and O are deficient, N is enhanced) in its wind. Although a reasonably good fit is obtained to the overall spectrum, the discrepancies are significant. The model was fit to the 1998.2 spectra soon after the 1997-98 event when the star was not in its normal state. For example, the Balmer lines still showed strong P Cygni absorption components which are not observed later when the spectrum is in its more "normal state." Nevertheless, the model-predicted P Cyg absorption components are much stronger than observed which is especially true for the He I 5876 Å line and the Fe I lines. The model's UV spectrum ≤ 3000 Å does not match the observed spectrum well due to a forest of Fe II absorption lines, emission lines and P Cygni profiles plus an uncertain extinction law. The model of course assumes a spherical geometry, but it is unlikely that η Car is spherically symmetric and rotation will likely be important, especially near its equator. It is likely that modeling the wind in its "normal" state will be even more difficult with more uncertainties.

And finally it is important to realize that the reflection of the stellar wind by dust in the Homunculus allows us to view the star from different directions. The spectrum at different positions in the two lobes is not the same as that seen when we view the star directly, see Section 5.2 below.

4.2. More than One Eruption: Mass Lost and Energetics

Proper motion measurements of the Homunculus from ground-based and HST images (Currie et al. 1996; Smith & Gehrz 1998; Morse et al. 1999) confirm that the bipolar lobes of the Homunculus were created in the 1840's eruption and are expanding at $\sim 300 - 700\,\mathrm{km\,s^{-1}}$. Using proper motions from historical photographs from 1945 (Gaviola 1950) and 1972 (Gehrz & Ney 1972) combined with HST/WFPC2 images, Smith & Gehrz (1998), however, found that some material in η Car's equatorial skirt was ejected during its second eruption in the 1890's. Proper motions and velocities of the slow moving Weigelt blobs (Weigelt et al. 1996; Davidson et al. 1997) indicate that they also originated in the lesser eruption and are in the plane of the equatorial ejecta (Davidson et al. 1997). In an independent measurement of Doppler velocities along the STIS slit, Davidson et al. (2001) found material in the equatorial debris from the 1840's eruption plus slow moving material ($100\,\mathrm{km\,s^{-1}}$) ejected about 1900.

Ishibashi et al. (2002) have identified a small bipolar velocity structure inside the central region of the Homunculus, nearly symmetric about the star, extending $\pm\,2''$ along the major axis. It is identified by a recognizable "integral sign" in the two-dimensional emission spectrum of the strongest lines. Proper motions give an age of $\sim$ 100 years for the gas producing the emission which was therefore ejected during the second eruption but in the polar direction. The authors have consequently named this structure the "little homunculus" because it is a second, smaller bipolar outflow within the two prominent lobes.

Some outlying condensations (see Walborn 1976), beyond the bipolar lobes, but probably in or near the equatorial plane, are very fast–moving and were apparently ejected at about the time of the "great eruption." Velocities in the outer ejecta increase to $\geq 1000 - 2000\,\mathrm{km\,s^{-1}}$. Several highly collimated rope-like features or strings (Meaburn et al. 1993; Weis, Duschl, & Chu 1999) are also observed outside the lobes. Some appear to be in the equatorial plane while others are polar. There is no satisfactory explanation for these structures. Thus in addition to the familiar bipolar lobes and equatorial debris or spray associated with the two 19th century eruptions, a number of unexplained features in the outer ejecta were expelled at much higher velocities than the bipolar lobes during the "great eruption." Furthermore, some of the outlying nebulosities have proper motions (Walborn, Blanco, & Thackeray 1978; Walborn & Blanco 1988) that suggest they were either ejected in earlier outbursts centuries before the "great eruption" or that they have been greatly decelerated in contrast to the fast moving gas in the outer ejecta.

The total mass in the two lobes is $\sim 2 - 3\,\mathrm{M}_{\odot}$ as estimated from numerous studies including visual wavelength scattering (Davidson & Ruiz 1975) and infrared emission from grains (Mitchell & Robinson 1978; Hackwell et al. 1986; Cox et al. 1995; Smith, Gehrz, & Krautter 1998). Using high resolution $10\,\mu$m imaging, Smith, Gehrz, & Krautter (1998) estimate an additional $0.5\,M_\odot$ in the equatorial skirt, although this debris is a mixture of material from the 1840's and 1890's eruptions. Since some of the material in the outer ejecta was also expelled during the great eruption, a reasonable estimate of the total mass lost is $\sim 3\,M_\odot$. It is more difficult to estimate the mass shed during the lesser 1890's eruption since the material in the equatorial region is mixed. However, Ishibashi et al. (2002) estimate $\sim 0.1\,M_\odot$ in the "little homunculus." Another estimate can be obtained by assuming that this second outburst was like a normal LBV eruption with a mass loss rate $\sim$ 10 times normal; then in seven years, $\sim 0.2\,M_\odot$ was shed.

The total luminous energy during the great eruption is well established at $\sim 3 \times 10^{49}$ ergs. Assuming η Car shed about $2.5\,M_\odot$ and an average expansion speed of $650\,\mathrm{km\,s^{-1}}$ for the gas in the bipolar lobes, the kinetic energy is 10^{49} ergs, comparable to the luminous energy. We can estimate the energy associated with the 1890's eruption by assuming it was like a normal LBV outburst at $\sim$ constant luminosity ($M_{\mathrm{bol}} = -12$ mag), for an about 6×10^{48} ergs outburst. The gas associated with the lesser eruption shows a very wide range of velocities. Using $300\,\mathrm{km\,s^{-1}}$ with $0.2\,M_\odot$ shed, the kinetic energy is 2×10^{47} ergs which is probably a bit high. Thus its luminous energy is significantly greater than the kinetic energy, like that of the LBV eruptions. *The energetics of η Car's great eruption are very different from those of the LBV's.*

These observations and results leave us with two intriguing questions. How was so much mass ejected from both the polar and equatorial regions of the star in two separate eruptions with such a wide range of velocities? Has η Car had outbursts like the 1840's eruption every few hundred or few thousand years?

4.3. The Recent Brightening

η Carinae never fails to surprise us. In 1999 observations of the central star with HST/STIS showed that its optical flux had increased by a factor of two between 1998 and 1999 (Davidson et al. 1999a), see Fig. 5. Ground based measurements of the integrated light over the whole Homunculus also showed a more rapid increase than had been observed over the previous 50 years, although the integrated light had not increased as much as the central star itself. As Fig. 5 illustrates, the STIS observations show that the central star has continued to brighten since 1999, although not as rapidly, and appears to have levelled off in 2001-02. Why did the star brighten? This was not an LBV–type eruption as the corresponding spectroscopic changes were not observed as they were in the 1890's. Davidson et al. (1999b) attribute it to the rapid destruction of warm dust near the star, but propose that the star itself must have changed, probably by increasing its UV flux by 10% or less. Given that the star is so close to the Eddington limit anything greater would have induced a high mass loss episode.

5. The 5.5 yr Spectroscopic Cycle

For many years astronomers noticed that the high excitation lines such as He I, [Ne III], [N III] and radiatively excited Fe II, which we now know arise in the nearby ejecta, would occasionally weaken and disappear for a few weeks or months leaving only the low excitation emission lines. These "events" might

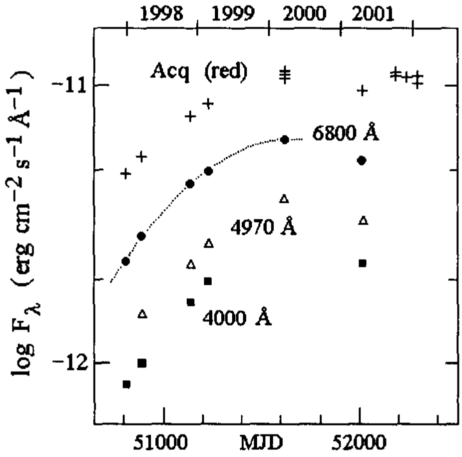

Figure 5. The recent brightening of the central star as measured from the HST/STIS acquisition image and the continuum flux at different wavelengths. Measurements from the recent acquisition images show that the brightening has leveled off.

be caused by irregular shell ejections as first suggested by Zanella et al. (1984). Whitelock et al. (1994) were the first to report a $\sim 5-6$ yr cycle in near–infrared photometry and in 1996 Damineli recognized that the spectroscopic events occurred regularly with a period of 5.5 yrs and correctly predicted the next event at the end of 1997. The 5.5 yr period is extremely important and should eventually provide important information about the nature and structure of η Car.

Using velocities from ground-based spectra, Damineli et al. (1997), see also Davidson (1997), suggested a binary orbit and a possible explanation for the events: a second, hotter star, responsible for the UV radiation, excites and ionizes the strong emission lines, and is eclipsed at the time of the "event." But our HST/STIS observations during the event rule out an eclipse and also do not confirm the ground-based velocities (Davidson et al. 2000). We now know that the ground-based spectra are seriously contaminated by emission from the ejecta, see above, and the line profiles from the stellar wind are variable, not only during the event, but throughout the spectroscopic cycle. In 1997-98, η Car either had an outburst or shell ejection, or else the ionization structure of the wind changed in such a way to mimic such an outburst, but why?

So what can we say about a possible binary model for η Car? The only evidence for a binary is the 5.5 yr periodicity and the X–ray light curve. At the time of the event, the X-radiation becomes increasingly unstable and chaotic and "crashes" to a near zero level (Ishibashi et al. 1999). A colliding wind binary model has been proposed in several papers by Corcoran and his collaborators (Pittard et al. 1998; Corcoran et al. 2001) to explain the observations although the model fit depends on adopted parameters. The observed X-ray minimum is not adequately explained by a simple eclipse as the model's proponents often claim (see Davidson 1999).

A possible "binary" explanation for the spectroscopic events is that the primary star is very close to its stability limit and the approach of the secondary triggers a shell ejection probably in the equatorial region. The sudden, brief spectroscopic events and the X-ray minimum require an eccentric orbit with $\epsilon \geq 0.75$. The high X-ray temperatures require a $3000\,\mathrm{km\,s^{-1}}$ wind from the companion, implying that it must be a hot, main sequence star in the 30–40 $M_\odot$ range. In the Damineli orbit (Damineli, Conti, & Lopes 1997; Damineli et al. 2000), however, the two stars are of comparable mass (75 $M_\odot$ each), the event occurs *before* periastron passage and the closest approach of the two stars is only 3 AU. Ishibashi (2001) has proposed an orbit based entirely on the X-ray light curve, with a major-axis perpendicular to the Damineli orbit and with periastron prior to the event. In Ishibashi's model the companion star is 40 $M_\odot$ and the primary or η Car itself is $\sim 130\,M_\odot$. This is a more satisfactory model, but periastron is still at 3 AU, making a tidal interaction difficult.

Could η Car be a single star, and if so, what is the origin of the periodicity? If there is no companion, the 5.5 yr period must be due to some internal timescale such as the thermal timescale for the outer fraction of the star, an angular momentum diffusion timescale or a magnetic timescale. Although these are all hypothetical and require theoretical work, they offer some intriguing possibilities for very massive stars.

The binary question needs more observations for confirmation, especially near the time of the next event (May–June 2003) at high spatial and spectroscopic resolution to determine what actually occurs in the wind of the "primary" star and what causes it. Some historical observations offer an interesting insight into η Car's past behavior and raise some questions about the simple binary explanation for its spectroscopic cycle.

5.1. A Historical Complication

What we now think of as the "normal" ground-based spectrum of η Car with its very complex spectrum of high excitation emission lines was first described by Gaviola (1953) based on spectra obtained between 1944 and 1948. We now know that the high excitation lines arise in the nearby ejecta and during the "spectroscopic event" these lines weaken and the low excitation lines dominate the spectrum. Feast, Whitelock, & Marang (2001) examined the historical spectra in the plate collection at the South African Astronomical Observatory. They found that while the spectroscopic behavior of the star fits the spectroscopic 5.5 yr pattern beginning in 1947, the spectrum of *the star was always in the "low excitation state"* prior to 1920 (1899-1919). Unfortunately, there are no spectra available from 1920 - 1947.

This is not what one would expect in the simple binary model described above. To prevent the high excitation lines from being observed, a mass loss rate more than five times the current rate would be required to absorb the UV ionizing photons from a hot companion throughout its orbit. In that case the primary's wind would have been optically thick, and would have had to fill the orbit out to apastron at 17 AU. It would have been cool (7000 – 8000 K), in an eruptive state with the spectrum of an F supergiant like that seen during the 1890 eruption, not the low excitation emission line spectrum that was observed.

We suspect that some major change occurred between ~ 1920 and 1947 in the star, or in the system, if it is a binary. The light curve in Fig. 1 shows a dramatic and relatively rapid brightening of the Homunculus by at least two magnitudes in the 1940's in less that ten years. This implies a large increase in the luminous output of the star, probably mostly in the UV to destroy the innermost warm dust at distances of 100 – 200 AU. But why? The star may have been experiencing some internal adjustments, 100 yrs after the great eruption, but it is curious that the high excitation spectrum only appears after this brightening.

5.2. One Star, Two Winds

A recent discovery from our HST/STIS program to monitor η Car may have some direct bearing on our understanding of the spectroscopic event. With long slit spectroscopy across the Homunculus, we can in effect observe the star from more than one direction. Using our HST/STIS data from 2000 with a $0\farcs2$ slit width, Smith et al. (2002) examined the profiles of the Hα, Hβ and He I emission lines in the reflected spectrum of the star along the slit, and therefore as a function of latitude in the star's wind. The strength and velocities of the P Cygni absorption profiles depend on the polar angle with the strongest absorption and highest velocities observed at the poles ($1000\,\mathrm{km\,s^{-1}}$). Thus η Car is aspherical. It has a bimodal wind with a slow, low density equatorial/low latitude wind and a faster, denser polar wind. A denser wind is somewhat surprising but is predicted in some of Owocki's models (Owocki, Cranmer, & Gayley 1998). The existence of these two winds raises interesting questions about the origin of its spectroscopic cycle, because at the time of the "event," the spectrum of the entire star resembles the polar wind.

6. The Great Eruption

The most outstanding question about η Car, the origin of its "great eruption," is still unexplained. The total luminous energy during the "great eruption" was $\sim 3 \times 10^{49}$ ergs which is approximately equal to the kinetic energy of the ejecta and comparable to the thermal energy stored in the outer few solar masses of the star's envelope which interestingly have a thermal timescale on the order of 30 years.

There have been several theoretical suggestions for the "great eruption." The underlying idea behind many of them is that an instability originates in the outer layers and moves downwards like a geyser:

1. The opacity–modified Eddington limit is an instability in or near the photosphere that is temperature and density or opacity dependent (see Section 5 in Humphreys & Davidson 1994). In the classical Eddington limit for L/M, the opacity is due entirely to electron scattering. As the star's photosphere evolves below 30,000 K the absorption opacity increases and an instability may arise just below the classical limit, at $\Gamma \sim 0.8 - 0.9$ near temperatures around 20,000 K. Lamers (1997) later proposed the same idea, but with a different name.

2. A dynamical instability below the surface where the high opacity due to iron at $T \sim 10^{3.5}$ may lead to high radiation pressure and strong convection. The outer layers can thus be unstable. A variety of mechanisms have been proposed

by Stothers & Chin (1997), Glatzel (1999), Guzik et al. (1999a,b). One of these similar theories may explain the underlying source of η Car's instability and/or normal LBV instabilities.

3. Langer's Ω limit (Langer 1998, 1999) is really the Eddington limit, either classical or modified, with the addition of rotation; although, the situation is more subtle than Langer described. Our evidence for a bimodal wind and latitude-dependent effects in η Car, combined with rotation, could lead to a surface instability that grows with decreasing temperature as the star evolves. So an eruption could develop near the equator with the low ejection speeds observed in the equatorial debris and a slow rotation rate would be sufficient.

4. Guzik et al. (1999a,b) have also suggested an interior instability deep inside the star occurring on the thermal timescale and involving a large fraction of the star's mass.

η Car's second eruption in the 1890's indicates that it was far from equilibrium 50 years after the great eruption. The brightenings in the 1940's and very recently suggest that the star is still adjusting or recovering from the eruption.

Finally, it is very unlikely that a companion star is responsible for the basic instability, via either mass exchange or tidal forces, that led to the "great eruption." In the current proposed orbits periastron is at 3 AU and the separation would have been even greater prior to the great eruption. Thus it is difficult to make the tidal forces adequate to explain the luminous and kinetic energy and the mass lost during the eruption.

But, is η Car unique and its great eruption some rare, freakish event that we don't have to be very concerned about?

7. Supernovae Impostors

There is growing evidence that evolved massive stars pass through a highly unstable state near the end of their main sequence lifetimes. These stars are called Luminous Blue Variables (LBVs) or S Doradus variables. In a "normal" outburst or eruption they will typically brighten 1 – 2 magnitudes in the visual but maintain nearly constant bolometric luminosity with the corresponding changes in their spectra and apparent temperature (Humphreys & Davidson 1994). A small subset of this group that we have called "giant eruption" LBVs or "η Carinae" variables (Humphreys, Davidson, & Smith 1999) experience eruptions during which their total luminosities increase significantly and the star survives. Given the very high luminosities reached during these giant eruptions and because several members of this group have been called supernovae at various times, a catchier name for them is "supernovae impostors."

η Car is of course the best known example. Other members of this small group include P Cygni in the 17th century (de Groot 1988; Lamers & de Groot 1992), SN 1961v in NGC 1058 (Goodrich et al. 1989; Filippenko et al. 1995), V12 in NGC 2403 (SN 1954j, Tammann & Sandage 1968), and V1 in NGC 2363 (Drissen, Roy, & Robert 1997). The "pistol" star near the galactic center (Figer et al. 1998) may be a similar object. Several candidates have been discovered in the recent supernovae surveys among the Type IIn's including SN 1997bs (Van Dyk et al. 2000), SN 1999bw (Filippenko, Li, & Modjaz 1999), and SN 2000ch (Filippenko 2000; Wagner et al. 2000).

The increasing number of objects displaying characteristics similar to great eruption of η Car suggests that these "giant eruptions" are not so very rare, therefore raising some interesting questions about how the most massive stars end their lives.

8. Final thoughts and Future Work

We have just briefly touched on some of the recent discoveries and still outstanding problems concerning η Car, the most enigmatic naked-eye star in the sky.

What is the source of η Car's underlying instability? How many times does a very massive star experience a great eruption like that of η Car and how much mass does it shed before it eventually goes supernova? Very massive stars like η Car with its complex circumstellar environment are now considered the most likely sites for gamma ray bursters. What happens when a star with an initial mass upwards of $120 - 150\,\mathrm{M}_\odot$ goes supernova? Is η Car a binary? What actually happens during its spectroscopic events every 5.5 years and do these events provide any clues to the underlying instability and the cause of the great eruption? If it is a binary, what role does the companion play in its instability if any?

We hope to get answers to at least some of the latter questions with our HST Treasury program on η Car during its next event in 2003 during which we will have frequent multi-wavelength coverage with HST/STIS and complementary ground-based observations.

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