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η Carinae – The Observational Story, 1600 to 2004

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Abstract. η Car's remarkable observational record is reviewed in the context of this meeting beginning with the earliest visual observations to recent discoveries with HST.

1. Introduction – Why η Car?

Whenever we talk about very massive stars and their final stages, η Car is always pre-eminent in the discussion. Its unique status as the most luminous ($5 \times 10^6 L_\odot$), most massive star in our region of the Galaxy is well known. It is also highly evolved and unstable and the site of a famous major eruption $\sim$ 160 years ago. η Car is thus our local and best studied example of a "supernova impostor", and it may be our only example of a *very massive* star in a pre–supernova state close enough to be studied in detail. With its well–defined axis of symmetry, it could also be a candidate for a gamma ray burst as well. Fortunately, its rotational/axis of symmetry is pointed away from us. It is also our closest example of a > 100 $M_\odot$ star – like the presumed "first stars", although its chemical composition is obviously quite different. Thus in many ways η Car is a prototype for several of the topics at this meeting.

2. The Historical Light Curve

η Car is most famous for its "great eruption" from 1837 – 1858 when it oscillated between apparent magnitudes ≈ 0 and $\approx +1$. In 1842 it briefly became the second brightest star in the sky reaching $m_v \approx$ -1 mag. This was followed by a decline in apparent brightness over 10 years due to the cessation of the eruption and the probable formation of dust. By 1880 it had declined below naked–eye visibility to $\approx$ 8th magnitude. But then in 1887, a second or lesser eruption occurred lasting $\sim$ 7 years. The first photographic spectra obtained in 1892–93 showed an F supergiant–like absorption line spectrum with strong hydrogen emission (Cannon 1901, Bok 1930, Hoffleit 1933 and Walborn & Liller 1977). Figure 1 shows the light curve from 1800 to 1900 and the second eruption corrected for circumstellar extinction. During this second outburst, the star brightened $\approx$ 2 magnitudes above its presumed pre-outburst quiescent state. Humphreys, Davidson, and Smith (1999) suggested that this second, less energetic eruption was like a "normal" LBV or S Dor type event based on its 7 year duration, F supergiant spectrum and $\approx$ 2 magnitude brightening.

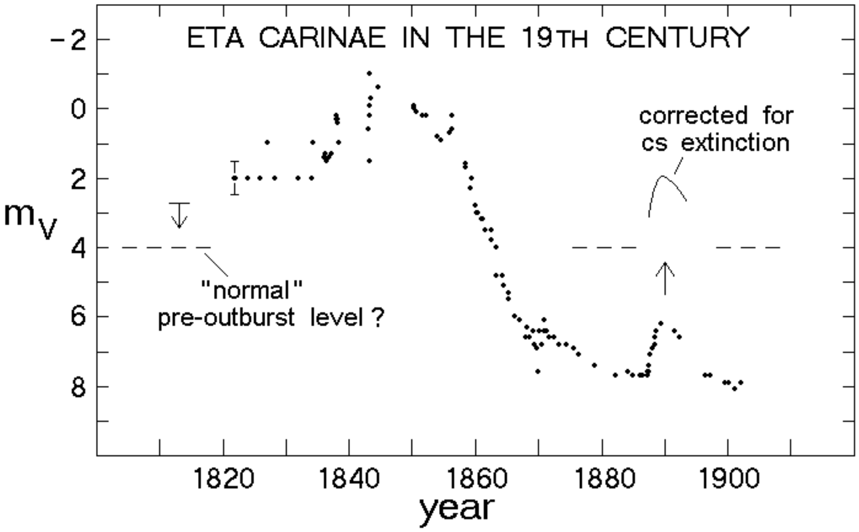

Figure 1. The visual light curve of η Car from 1800 to 1900. The second eruption corrected for circumstellar extinction from two independent estimates (Humphreys, Davidson & Smith (1999)

Afterwards, from $\sim$ 1895 to 1940, the object was quiescent with no recorded photometric or spectroscopic changes until 1941-42 when a rapid brightening began (Figure 2)[1]. In the early 1900's the object developed its now familiar spectrum of hydrogen, Fe II, and [Fe II] emission lines. O'Connell (1956) and de Vaucouleurs & Eggen (1952) summarized its photometric behavior during this time of rapid change, and the latter authors measured an increase of $\sim$ 0.3 mag of the object in only a few weeks in 1952. It was during this time (1944-51) that Gaviola obtained his photographic images of the nebula and spectra (Gaviola 1950, 1953) that showed the first definite record of high excitation lines in the spectrum. He I and other high excitation emission lines had apparently not been observed prior to 1944 (Feast et al 2001, Humphreys, these proceedings, pg).

Since the early 1950's, the object has continued to brighten slowly at a fairly regular rate, but HST/STIS spectra from 1998-99, revealed a rapid brightening of the **central star** of $\sim$ 1 magnitude in only one year (Davidson et al 1999). STIS observations show that the central star has continued to increase in brightness and more rapidly in 2003 during the "spectroscopic event" (Martin & Koppelman 2004). The recent brightening deviates from the long–term trend due to expansion of the dusty ejecta, and raises questions of more rapid dust destruction.

When we look at η Car's historic light curve, it appears that the star undergoes some kind of adjustment or transition approximately every fifty years since the "great eruption" – $\sim$ 1842 to 1887 – 1895 to 1941 – 1952 to now, 1998

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[1] Note that all groundbased estimates and measurements of η Car's apparent brightness after the great eruption refer to the integrated light of the ejected nebulosity and the embedded star.

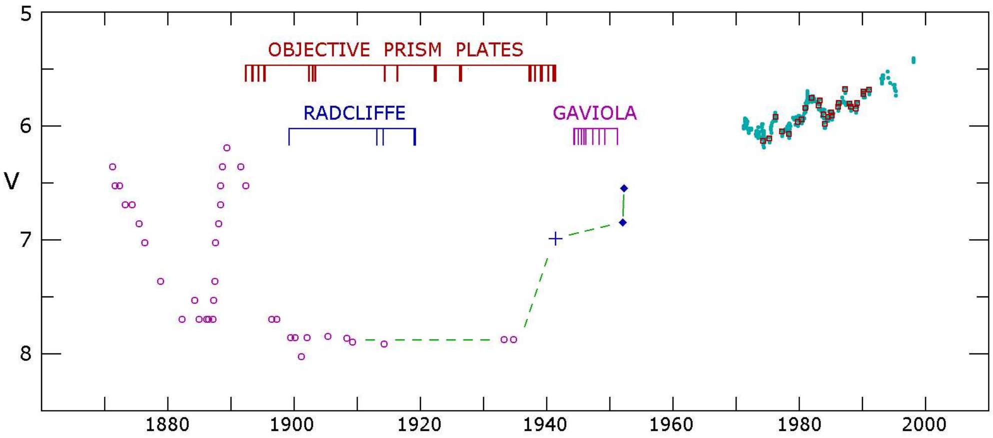

Figure 2. The visual light curve of η Car from its second eruption to the present showing the brightening in the 1940's and beginning in 1998. The tick marks show when the early spectra were obtained.

– 2004. This could be due to some underlying timescale related to the central star's recovery from the "great eruption".

3. Visual Appearance

Today, η Car is famous for its nearly perfect bipolar nebula formed during its "great eruption" and revealed to many astronomers for the first time in the spectacular images from HST (Hester et al, Morse & Davidson et al 1998). However the first optical image that revealed the bipolar lobes and the equatorial debris was obtained in 1985 using speckle imaging although it wasn't published till much later (Duschl et al 1995). But η Car's visual appearance has been changing with time. Images from the early 20th century only showed that it was non-stellar, and some observers described it as multiple. Gaviola's images revealed the extended nebula that he named the "Homunculus" or "little man". It looked very much like the picture by Gehrz and Ney (1972) on the cover of *Sky and Telescope*. And that is what it did look like through a small telescope, sort of like the "Pillsbury dough boy" or the "Michelin man", until recently. The Homunculus of η Car looks quite different now. One can easily see the two faint reflecting lobes and a very bright red–orange arc on the SE lobe where the central star is embedded. This change in appearance is due to brightening of the central star and the contrast between it and the surrounding nebula. Prior to this, the surface brightness of the nebula was more uniform.

4. A Summary of η Car's Measured and Physical Parameters

Distance 2.2 to 2.3 kpc (Allen & Hillier 1993, Davidson & Humphreys 1997, Meaburn 1999, Davidson et al 2001)

Luminosity from the infrared (Westphal & Neugebauer 1969, Cox et al 1995) $L = 5 \times 10^6 L\odot$, $M_{Bol} = -12$ *mag, luminous energy* $\sim 10^{49}$ *ergs* implying a ZAMS mass > 150 $M_\odot$

Current mass ~ 120 $M_\odot$, then the current L/M is within 10-30% of the $\hat{E}$ddington Limit and the expected MS lifetime $\sim$ 3 million yrs

Current mass loss rate $10^{-3} M_\odot$/yr (White et al 1994, Cox et al 1995 Davidson et al 1995, Hillier et al 2001)

Temperature(??) The wind of η Car is optically thick so we do not observe its photosphere. Here we give the apparent temperature of its wind, between 15000° to 30000°K (Hillier et al 2001) corresponding to a radius of 0.4 to 0.9 AU.

Dynamical Timescale $\sim$ 2 weeks

Thermal Timescale $\sim$ 5 to 500 years, depending on the mass fraction considered

Evolutionary State Its ejecta are He and N rich (Davidson et al 1982, 1986, Dufour 1989, Dufour et al 1999) and the nebula is $\sim$ 40% He from the nebular emission. η Car is therefore near or past the end of core H-burning.

5. Highlights from Recent Work

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 from space–based observations and groundbased new technologies.

All groundbased spectroscopy of the central star is contaminated by 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. Fortunately high spatial resolution spectroscopy ($0\farcs05 - 1\farcs0$) possible with HST allows the separation of the star from its nearby ejecta. Observations with HST/FOS and GHRS (Davidson et al 1995, 1997) first showed that the narrow high excitation emission lines that dominate η Car's groundbased spectra, actually arise in compact, dense ejecta $\leq 0\farcs3$ from the central star known as the "Weigelt blobs or knots" (Weigelt & Ebersberger 1986, Hofmann & Weigelt 1988) that were unexpectedly discovered using groundbased speckle interferometry.

It is these high excitation lines that dramatically weaken for a few months leaving only the low excitation emission spectrum during what we now call *"spectroscopic events"*. These events occur regularly every 5.5 years (Damineli 1996). Preceding a "spectroscopic event", the X radiation becomes increasingly unstable or chaotic and then "crashes" to near zero flux (Ishibashi et al 1999, Corcoran, these proceedings). The most common explanation for the X ray light curve is a colliding wind binary model (Pittard et al 1998) , but there is still no realistic orbit based on Doppler velocities or spectroscopic evidence for the proposed companion.

Two independent studies, HST/STIS spectroscopy (Smith et al 2003) and interferometry with the VLT (van Boekel et al 2003) have shown that the wind of η Car is *not spherical.* This discovery may not have come as much of a surprise to many who work on stellar winds, but the spectroscopic results showed that the polar wind is not only faster but denser than the wind at lower latitudes contrary to what most would have expected.

Modern proper motion measurements of the Homunculus (Currie et al 1996, Smith & Gehrz 1998, Morse et al 2001) confirm earlier conclusions that the bipolar lobes expanding at 600 – 700 km s^{-1} were created in the 1840's "great eruption". Proper motions and Doppler velocities (Davidson et al 1997, 2001, Smith & Gehrz 1998) show that the "Weigelt knots" and slow moving ejecta (50 – 100 km s^{-1}) in the equatorial debris date from $\sim$ 1900, and therefore were most likely expelled during the η Car's second eruption. The velocity measurements (Davidson et al 2001) also show that some of the equatorial material was also ejected during the 1840's eruption. A small bipolar velocity structure inside the central region of the Homunculus has been identified by Ishibashi et al (2003). It is nearly symmetric about the star, extending $\pm 2''$ along the major axis, and 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 also 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.

Thus η Car experienced two eruptions only 50 years apart that ejected material along both the polar and equatorial axes and with a wide range of velocities.

Much faster moving material also apparently from the 1840's eruption is found in the outer ejecta, expanding at velocities of 2000 – 3000 km s^{-1} (Dufour 1989, 1994, Weis et al 2004, Smith & Morse 2004). Several long, highly collimated, rope-like structures called "strings" (Meaburn et al 1993, Weis, Duschl & Chu 1999) are observed emanating from the lobes and equatorial plane into the outer ejecta (see Weis, these proceedings pg). There is no satisfactory explanation for these structures.

6. The Great Eruption – Mass Lost and Energetics

During the *great eruption* η Car visually brightened more than four magnitudes above its normal quiescent state or two magnitudes above what it would have been during a normal LBV or S Dor like event. It exceeded $M_{Bol} \sim$ -13 for several years and briefly reached -14!!. It therefore exceeded the *Eddington Limit* for a protracted time.

The first mass loss estimates from the 1840's eruption were based on the mass in the bipolar lobes from visual wavelength scattering (Davidson & Ruiz 1971) and infrared emission from grains which depend on assumption about grain sizes and gas to dust ratios (Hackwell et al 1986, Cox et al 1995, Smith, Gehrz, & Krautter 1998). These yielded conservative estimates of about 3 $M_\odot$. But two recent studies, by Morris et al (1999) based on 2 – 200 μm observations from ISO and measurements at 5 – 25μm by Smith et al (2003) get masses of 10 to 15 $M_\odot$. These results however raise serious questions about where this much mass is located in the ejecta, its composition and resulting extinction.

Depending on how much mass was ejected, η Car's mass loss rate during the "great eruption" was 0.1 to 0.5 $M_\odot$ per year!

Mass loss estimates for the lesser 1890's eruption are more difficult since the material in the equatorial region is mixed. Smith et al (1998) estimated 0.5 $M_\odot$ in the equatorial debris, while Ishibashi et al (2003) obtained ~ 0.1 $M_\odot$ in the "little homunculus". Humphreys et al (2002) derived 0.2 $M_\odot$ assuming that the second eruption was like that of a normal LBV event.

η Car's total luminous energy is well established at $\sim 3 \times 10^{49}$ ergs. Assuming a conservative estimate of 3 $M_\odot$ for the material expelled during the great eruption expanding at 650 km s^{-1}, its kinetic energy was also $\sim 10^{49}$ ergs. The energetics are thus very different from normal LBV's where the luminous energy is much greater than the kinetic. Of course if the total mass lost was closer to 10 to 15 $M_\odot$, then its kinetic energy may have exceeded the luminous energy, like a supernova explosion. For this reason if no other, η Car and objects like it should not be considered typical of normal LBV's.

Not surprisingly, its second eruption was much less energetic, about 6×10^{48} ergs in the outburst and its kinetic energy was much less at $\sim 2 \times 10^{47}$ ergs (Humphreys et al 2002).

7. Outstanding Questions

These observations and results leave us with many intriquing questions:

- How was so much mass ejected from both the polar and equatorial regions of the star in two separate eruptions?

- What is the source of η Car's underlying instability?

- How many times does a very massive star experience a *great eruption*?

- What happens when a star with an initial mass greater than 120 – 150 $M_\odot$ goes supernova?

It is thus appropriate to end with this quote from John Herschel who was at the Cape during the *great eruption*:

" A strange field is opened by this phenomenon ... here we have a star fitfully variable to an astonishing extent, and whose fluctuations are spread over centuries, ... What origin can we ascribe to these sudden flashes and relapses?"
JFW Herschel 1847

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Discussion

Discussion

Hamann: Is the current thinking that the Weigelt blobs were ejected in the 1890's eruption?

Humphreys: Yes. Based on the proper motion and velocity data and other considerations, an ejection during the second eruption is most likely.

Dwarkadas: For many years (decades?) we have been using a value of 2-3 Msun for the mass of the Homunculus nebula. Now you have mentioned 2 papers which cite this mass as 10-15 Msun. What is the reason for this sudden upward revision by a factor of 5? Is it a change in the physics, changes in estimated values, or something else? What are the new error bars on these numbers, and what assumptions are involved?

Humphreys: These are very new results and are based on mid to long infrared observationsthe thermal IR. The results depend on assumptions about the grain size, gas to dust ratio, etc. They will be presented and discussed in Session 6.

Woosley: Does the infrared vary as much as the optical in Eta Car? Could the variables be at least partly due to variations in the bolometric correction?

Humphreys: No. Eta Car does vary in the near-IR (JHK) but not as much as in the optical; however, the variability is correlated. The recent and more long-term brightening is not due to changes in the bolometric correction as far as we know. There is no corresponding change in the spectrum.