The Long-Term Variability of Luminous Blue Variables

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Abstract. The stars known as Luminous Blue Variables include two very distinctive subgroups - the S Dor-type variables which basically define what we call an LBV and the much rarer 'giant eruption' LBV's which include famous stars like η Car and P Cyg. The distinctive characteristics and long term variability of these two groups is reviewed. The lesser 1890 eruption of η Car is shown to have been much more significant than previously believed and resembles the second peak seen in the historic light curve of P Cyg. Because so many, if not all, stars in certain parts of the HR diagram appear to be luminous, blue, and variable, I suggest returning to our previous designation - S Dor variables and η Car variables for these two important groups of stars.

1 Introductory Remarks

Throughout this meeting every star or class of stars that has been discussed is luminous, blue, and variable!

So the first question is what is a Luminous Blue Variable or LBV?

The most important point to remember about the definition or description of any class of objects is that we must be talking about the same physics. In previous reviews, we (Humphreys 1989, Humphreys and Davidson 1994) have described LBV's in terms of their behavior i.e. 'luminous, hot stars that exhibit a particular type of instability' whose defining characteristic is the irregular eruption or outburst. During this eruption the star brightens 1 to 2 magnitudes in the visual; the duration is measured in years, and the star maintains nearly constant bolometric luminosity with corresponding changes in its spectrum and apparent temperature. This is a description of the normal or classical LBV's typified by stars like S Dor and AG Car.

A second group of stars also called LBV's are the giant eruption LBV's; stars like η Car and P Cyg which actually increased their luminosity during the eruption. There are only four probable members of this group and they are also included in this review.

The second question is what is meant by 'long-term'? A normal LBV eruption typically lasts a few years followed by a period of quiescence or additional outbursts. So for the purpose of this paper, long-term will refer to a photometric record lasting a decade or more.

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2 The Normal or Classical LBV's

On timescales of 10 years or more, the light curves of the normal or S Dor-type variables show a wide range of variability, but all vary by 1 to 2 magnitudes during the eruption. Some have an eruption and then are relatively quiescent for many years. Examples are R71 in the LMC (see Sterken et al 1997), M33 Var.C (Hubble and Sandage 1953, Humphreys et al 1988, Szeifert et al 1996) and M33 Var.2 (Hubble and Sandage 1953). While others appear to repeat in an almost semi-regular way such as M33 Var.B (Hubble and Sandage 1953, Szeifert et al 1996), AG Car, and the proto-type S Dor (see de Koter 1993 for recent variability). Humphreys and Davidson (1994), van Genderen et al (1997), and Sterken et al (1997) have pointed out the quasi-periodic variability seen in some LBV's.

2.1 The S Doradus Instability Strip

When we look at the upper HR diagram (see Figure 9 in Humphreys and Davidson 1994) we notice a very important property of the S Dor-type variables; their temperature at quiescence or visual minimum is luminosity dependent. Wolf (1989 a,b) was the first to recognize that the S Dor variables at quiescence all lie along an inclined strip in the HR diagram. This locus combined with the constant luminosity and the cool temperature limit near 8000K at visual maximum shows that the amplitude of the variability depends on the luminosity. The more luminous the S Dor variable, the higher the amplitude (Wolf 1989a,b). This is a very important characteristic of the S Dor-type variables. It must be providing an important clue to the origin of the instability in these evolved stars ranging in initial mass from $\approx$30 to $100M_{\odot}$.

So what do these stars have in common? Most likely, their L/M ratio. All of them are overluminous for their current mass; consequently, they are near the Eddington limit for their mass. The less luminous variable have most likely shed a lot of mass as red supergiants while the more luminous ones may have undergone giant eruptions like P Cyg or η Car plus repetitive S Dor-type outbursts.

3 Giant Eruption LBV's

The giant eruption LBV's or η Car-like variables actually experience a significant increase in their total energy during their eruption. The four historical members of this group are η Car (1840's), P Cyg (1600's), V12 in NGC2403 (SN54J) in 1954, and SN61V in NGC1058 (1961). The properties of these very rare stars are summarized in Table 1. The recently discovered variable, V1 in NGC2363 (Drissen et al 1997), is a possible member of this group.

Eta Car is famous for what is often called the 'great eruption' around 1840 that lasted more than 20 years during which it briefly became the second brightest star in the sky. Although its famous bipolar lobes were created during the great eruption, measurements of the proper motions of the Weigelt knots within 0.2 arcsec of the central star (Weigelt et al 1995) and the velocities of the same knots (Davidson et al 1997) show that they are in the equatorial ejecta and have an age of 100 years, the time of the lesser eruption in 1890. Smith and Gehrz (1998a) have measured motions of several identifiable features in the equatorial ejecta with a 50 year baseline and also derive an 1890 date.

Table 1. Properties of Giant Eruption LBV's

	ΔM_v (mags)	ΔM_{bol} (mags)	M_{bolmax} (mags)	Total energy released (ergs)
η Car	3-5	~ 2	-14	$10^{49.5}$
P Cyg	~ 3	1-2	-11 to -12	$10^{48.4} - 10^{48.8}$
SN61V	~ 5.5	$\sim$3.5	-17	$10^{49.5}$
V12	4	~ 2	$\leq$-11.6	$\geq 10^{47.3}$

The second or lesser eruption in 1890 doesn't look very impressive on the historic light curve (see Figure 1), but Smith et al(1998b), using the measured motions and their estimate of the mass in the lobes and equatorial ejecta from their infrared images, find that the kinetic energy is $10^{48.4}$ergs and $10^{48.1}$ergs for the 1840 and 1890 eruptions, respectively, compared to $10^{49.5}$ergs total energy in the great eruption (Davidson and Humphreys 1997). Given that the kinetic energy in the two eruptions is comparable, it is worth taking a second look at the 1890 one.

We now know that η Car formed dust after the 1840 eruption and its extreme faintness near 8th magnitude, $\approx$ 4 magnitudes below its pre-eruption brightness, was due to circumstellar dust. The 1890 eruption lasted 7 years with a maximum in 1889 at 6.2 apparent visual magnitude. A spectrum from 1893 shows an early F supergiant absorption spectrum with hydrogen emission like an S Dor-type variable at maximum. Assuming that the luminosity remained constant ($M_{bol} \approx$ -12mag) as in a normal S Dor-type eruption, then its m_v would have been $\approx$ 1.5 mag (Figure 1) minus the CS extinction and the total energy was $\approx 10^{48.4}$ergs.

A second and independent estimate can be made from the probable amount of circumstellar extinction in 1890. From its current energy distribution and assuming that η Car is 20,000 to 25,000K, the CS extinction is presently 2 to

3 mags. But Eta has brightened about two magnitudes since the late 1940's. So in 1890, it was probably suffering 4 to 5 magnitudes of extinction and its m_v was actually 1.2 to 2.2 mag during the lesser eruption.

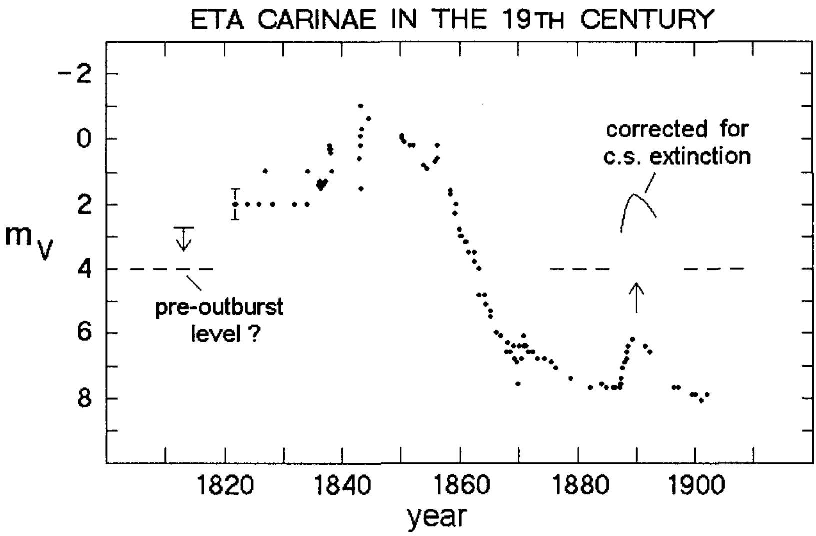

Fig. 1. The light curve of η Car showing the great eruption and the lesser eruption in 1890 corrected for circumstellar extinction.

A similar second peak or eruption has been observed for P Cyg (de Groot 1988 , Lamers and de Groot 1992) and in the light curve for SN61V (Doggett and Branch 1985). It is uncertain whether V12 has had a second peak because of infrequent measurements since 1955. The light curves of P Cyg, SN61V, and V12 in NGC2403 also show a post-eruption plateau or shoulder at or near the pre-outburst magnitude. Eta Car may also have had a brief plateau in 1860 - 1862. Circumstellar dust is also present around η Car, SN61V (Shields and Filipenko 1997) and V12. P Cyg does not have any evidence for CS dust now, but it has been 400 years since its primary eruption. This raises an important question. Why and how do these giant eruptions end? Does the eruption end and then dust forms or does the dust form first, bringing the eruption to an end? The short plateau in the light curves of these stars may be relevant to this question, especially since it occcurs at or near the pre-outburst magnitude.

4 Final Thoughts

Within the general class of stars we now call LBV's, there are two clearly recognizable groups - the S Dor variables and the η Car-like variables. These two groups are undoubtedly related; some of the η Car-like variables have shown S Dor-like variability, but the physics of their distinctive behavior and what we observe is very different.

In addition, there are now numerous candidate LBV's with some shared properties with these two groups. These stars are often called LBV's in the literature. We also have stars like HD5980 (Barba et al 1995, and see paper by Koenigsberger this volume) and the 'pistol star' (Figer et al 1997). Are they LBV's? HD 5980, like many massive stars is luminous, blue and variable, but I do not think it is an S Dor-type variable.

When it was first introduced the term LBV served a useful purpose by helping us recognize the similarities between groups of stars that were variously known as S Dor variables, P Cygni stars, η Car stars, Hubble-Sandage variables etc. But I think it is increasingly clear that use of the term LBV has become confusing. Remember, if are ever going to understand any group of stars we must be confident that its members share the same physics. Therefore I suggest we return to our former terminology:[1]

- *S Dor variables* with their characteristic light and spectral changes at nearly constant luminosity; and
- η *Car-like variables* with a significant increase in luminosity during the eruption; other characteristics may include a brief plateau, obscuration by circumstellar dust, and a second, lesser eruption.

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[1] The term P Cygni should be reserved for the line profile.

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Discussion

R. Ignace: Paczynski has coined the term "hypernova" for gamma-ray burst afterglows, because their light curves closely resemble the light curves of other classes of novae. In a purely phenomenological sense, do the light curves of LBV outbursts fit nicely into this scheme or are they radically different?
S. Shore: In answer to you question, one could say that DQ Her and η Car show analogous behaviour during dust formation. But remember that if you put enough Fe absorption lines in the way and shroud the cental source with dust, all of these objects will look alike. This is unfortunate because you then don't have a unique explanation for many of the observational effects.

I. Appenzeller: Since η Car has been established to be a binary, could the "giant eruptions" be connected to binarity?
R. Humphreys: Tidal interactions with a close companion star are probably not the explanation for the giant eruption (e.g., in 1840). The kinetic energy associated with the expanding debris is a significant fraction of the total gravitational binding energy of the proposed binary system. Therefore, the large mass ejections in η Car are related to the star's instability.

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