THE DISTRIBUTION OF TYPES OF LUMINOUS BLUE VARIABLES

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Abstract: If Luminous Blue Variables (*LBVs*) are not each unique types, three broad groups can be characterized depending on the luminosity and location of *LBVs* in the Hertzsprung-Russell diagram. To assist in defining the evolutionary nature of *LBVs*, connections are made to stars that have similar spectral character with the suggestion that some of these objects that may someday become *LBVs*.

1. Introduction

To be designated a Luminous Blue Variable (*LBV*), a star has to be luminous, blue in color and variable in light and spectrum. The variability typically is a magnitude or so with an accompanying change in spectral type. Since the number of *LBVs* known in any one galaxy can be counted on the fingers of one hand, there is a possibility that each *LBV* is an individual expression of the evolution of massive stars. If *LBVs* are, however, to be better understood, the identification of broad groups of *LBVs* with similar character will provide clearer insight to the origin of the—as yet unknown—physical processes which drive their variability. In order to look at the distribution of types, a rather liberal approach will be taken to group *LBVs* into categories by their luminosity and location in the Hertzsprung-Russell (HR) diagram. We will also seek stars of similar spectroscopic character to *LBVs* which may have the potential to become *LBVs* at some time in the future.

2. The Distribution of *LBVs* in the Hertzsprung-Russell Diagram

The term Luminous Blue Variables was coined by Conti (1984) to include stars which are known by a variety of variable star names—P Cygni, S Doradus, Hubble-Sandage—but that have remarkably similar spectroscopic characteristics and variability. Known *LBVs* are among the brightest stars in a galaxy with spectral types varying in the range between O and A, and with variations in light output of more than 0.2 mag. The best known and most studied of the *LBVs* are P Cygni, AG Carinae and η Carinae in the Galaxy, and HDE 269858 (R 127) and S Doradus in the LMC. Table 1 lists the *LBVs* that are known at this time. References to studies of individual *LBVs* are given by R. Humphreys in this volume.

Lamers (1987) has categorized the different types of spectroscopic and photometric variability exhibited by these most peculiar objects. In general, *LBVs* show evidence for variations that are both large and associated with extensive mass loss; they change their spectroscopic appearance on time scales of years to that of generations of

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astronomers. Spectroscopic changes from as early as type O to as late as type A have been observed in one star. In general, *LBVs* vary at constant bolometric brightness with minimum light at the highest temperatures and maximum light at the coolest, a variation that implies a change in radius. The mass loss rate is greatest at maximum light.

Table 1:
Known Luminous Blue Variables

The Galaxy	P Cyg	AG Car	HR Car	η Car	
LMC (HDE)	S Dor	269582	269858	269006	
M 31	AE And	AF And	Var A-1	Var 15	
M33	Var A	Var B	Var C	Var 2	Var 83
M81	I1	I2	I3		
M101	V1	V2	V3		
NGC 2403	V12	V22	V35	V37	V38

The true nature of Luminous Blue Variables is most often cloaked by a pseudo-photosphere arising from a dense stellar wind. The visible spectrum only crudely reflects the true parameters of the underlying star. In an HR diagram of *LBVs* (Figure 1), most have maximum light conditions that are relatively close to the upper luminosity limit first drawn by Humphreys and Davidson (1979). Minimum light is characterized by a B or late-O type spectrum.

From their luminosity and location in the HR diagram, one can break LBVs into 3 broad groups:

- The most luminous group contains only one star, η Car.
- The second group contains LBVs in the range $-11 > M_{bol} < -9.9$. HDE 269858 (R 127) is the prototype of this group which includes most of the well known LBVs, such as S Dor, P Cyg and AG Car. Var C in M 33 would be near the lower luminosity range of this group.
- The lowest luminosity *LBVs* are found below the Humphreys-Davidson limit and are in a group characterized by HDE 269006 (R 71) in the LMC. M 33 Var A would be at the upper luminosity boundary of this group.

The underlying basis for the differing character of these groups may rest in the available range for radius variation before the star runs into whatever physical process is behind the Humphreys-Davidson limit. η Car has a very limited range in radius before reaching this physical limit and consequently undergoes very large mass ejections with attendant variations in brightness of over 3 mag. in V. The 1837-1860 event, which produced the presently observed extensive nebulosity around η Car, is an example of such a major eruption. The *LBVs* in the second group are able to vary over a wider range in radius with accompanying change in spectral type from mid-B to A or F, or from late O to A. Here the instability usually produces only moderate variations in light, on the order of a mag. or so in V; these are the most commonly observed variations of *LBVs*. For example, S Dor and AG Car have gone through several of these active stages in the past decades (*c.f.* Lamers 1987). The variations are not continuous. Often, there are long times of relative quiescence, for example P Cyg in this century.

The Humphreys-Davidson limit likely maps those conditions at which massive stars return to higher temperatures after post-hydrogen burning expansion due to rapid high mass loss (*e.g.* Maeder 1983). *LBVs* in the two most luminous groups would not then have evolved through a red supergiant phase. While stars in the second group may undergo large eruptions which may leave behind nebulae that are lower in mass than that of η Car, it is not necessary for all LBVs of this group to do so since they can use a number of mass ejections of smaller scale in order to loose sufficient mass and to return to higher temperatures in the HR diagram as Wolf-Rayet stars. By contrast, those *LBVs* in the lowest luminosity group most likely have been red supergiants. HDE 269006, the prototype of the low luminosity group, was characterized as an S Dor variable by Thackeray (1974). This outburst ended in 1977 (*e.g.* Wolf *et al.* 1981). Noteworthy of the probable evolution through a red supergiant phase for this star is the observation of Glass (1984) of a large excess at 10 μm which he interprets as thermal emission from cool dust.

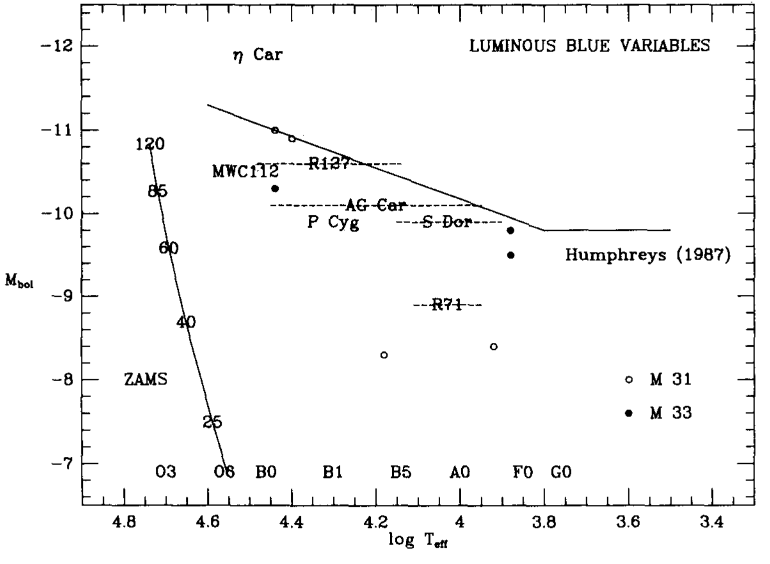

Figure 1. The Distribution of Luminous Blue Variables in the Hertzsprung-Russell Diagram. Temperatures and luminosities for this plot are based upon investigations cited by R. Humphreys in this Colloquium. The luminosity limit is that drawn by Humphreys (1987).

3. The Relationship of LBVs to Other Luminous Emission-line Stars

A clearer understanding of the physical nature of Luminous Blue Variables and of the role that they play in the evolution of massive stars can be gained by finding more *LBVs*, relating *LBVs* to other stars which also characterize the evolution of massive stars, and identifying stars which may become *LBVs* or that perhaps are quiescent *LBVs*.

If this Colloquium had been held before 1982, the number of known *LBVs* would have been one less. In January 1982, Stahl observed that HDE 269858 (R 127) was 0.75 mag. brighter than previously and that its spectrum had undergone a remarkable transformation (Stahl *et al.* 1983). Walborn (1977) had classified this star as OIape extr or alternately as WN9. HDE 269858 had shown essentially the same spectroscopic appearance from the epochs of Feast, Thackeray and Wesselink (1960) to that of Walborn. However, in early 1982 Stahl found that the characteristic Of emission

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features had disappeared and that no He II absorption lines were visible. No photospheric absorption lines were present at all, and the spectrum was dominated by strong P Cygni features of H I, He I, N II, and Fe III. Stahl *et al.* suggest a mid-B type spectral equivalent. Most recently, the spectrum of HDE 269858 has changed to be essentially identical to S Doradus, a prototype *LBV* (Wolf *et al.* 1988). HDE 269858 became an *LBV* while we weren't looking!

Could it be that the Ofpe/WN9 spectrum represents the minimum light stage of many of the second class of Luminous Blue Variables? Recent behavior shown by AG Carinae suggests that this is an idea worth pursuing. During a recent deep light minimum, AG Car exhibited a previously unseen Of-type spectrum that was remarkably similar to three LMC stars that are classified as Ofpe/WN9 (Stahl 1986). If the Ofpe/WN9 classification does represent the minimum light stage of this class of *LBVs*, then the true minimum *LBV* spectrum of P Cyg and S Dor has not yet been observed; these objects have for our lifetimes been in a long-term intermediate state.

Ten stars in the LMC are now designated as Ofpe/WN9 (Bohannan and Walborn 1989). Most have not been observed to vary in light or spectrum; only two are designated as *LBVs*. Besides HDE 269858, HDE 269582 (MWC 112) is a known *LBV*. In this second object, the Of features disappear and the spectrum consists of H I and He I emission lines only; in the simplest terms, a classification of B pe. The variability of HDE 269582 can even include the absence of Hα (Henize 1956). Several other LMC supergiants have similar B pe spectra to HDE 269582; for example, HD 37836 and HDE 268840 in 1983-84. Stahl and Wolf (1987) find that HD 37836 has a surface temperature equivalent to an O-type supergiant. Other LMC stars that they relate to HD 37836 are HDE 269445 and Sk -69° 240, both of which have He II λ4686Å in emission. The infrared observations of LMC supergiants by McGregor, Hillier and Hyland (1989, see also McGregor in this volume) suggest that there is an evolutionary connection between these B pe objects, the Ofpe/WN9 stars, and *LBVs*. For eight supergiants in the LMC, they find that He I λ2.058 μm emission is stronger than H I Brackett-γ, an observation that they link to a surface abundance anomaly arising from stellar evolution. Five of these eight are of the Ofpe/WN9 class, the others are the previously mentioned HD 37836, HDE 268840, and Sk -69° 240.

4. Looking for Potential LBVs

From the discussion above, it appears that a large number of emission-line stars in the LMC seem to be in the post-hydrogen burning stages of stellar evolution, just as has been proposed for *LBVs*. Will some become Luminous Blue Variables? Are some quiescent *LBVs*? What characteristic makes an *LBV* an *LBV* that might point us to potential *LBVs*? *LBVs* are luminous, blue and variable. However, all stars are variable at some level. It is just a question of how hard one wants to look and when one is looking. Recall the situation for HDE 269858. The *LBVs* in M 31 and M 33 were discovered by Hubble and Sandage (1953) in a survey of these galaxies that was very similar in intent to the Harvard program in the Large Magellanic Cloud. Yet, only 2 of the 4 known LMC *LBVs* are Harvard variables, S Dor = HV 90 and HD 269582 = HV 5495. Detected variability may not be the best way to seek potential *LBVs*!

While the famous *LBVs* exhibit a range of spectral character, the common element is the presence of emission lines much stronger than normal for their temperature and luminosity. I will use this characteristic to point to stars that might be considered as *potential LBVs*; not true *LBVs*, but ones that might someday blossom into *LBVs*.

In the Galaxy, the constellation of Carina would be good place to seek potential *LBVs* as 3 of the 4 famous Galactic *LBVs* are found there. Henize and Carlson (1979)

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studied 20 of the southern hemisphere emission-line stars surveyed by Henize (1976); 13 have P Cygni-like or B ep spectra very similar to those shown by the well-known *LBVs*. Moreover, one of these stars, He 3-519, has a ring nebula just like the *LBVs* HDE 269858 and AG Car (Stahl 1987). Is He 3-519 a quiescent *LBV*? A circumstellar shell has also been resolved around the LMC Ofpe/WN9 star Sk -67° 266 (Stahl 1987) and detected spectroscopically for other LMC Ofpe/WN9 stars (Walborn 1982, Stahl and Wolf 1986). Is this just a coincidence or does it strengthen the connection between the Ofpe/WN9 stars first pointed to by HDE 269858 becoming an *LBV* in 1982?

5. The Population of Emission-line Stars in the Magellanic Clouds

By comparison with the Carina region, no *LBVs* are known in Orion or Taurus, also regions of active star formation but with less massive stars present. Perhaps then, one characteristic of an environment in which to find *LBVs* is one with massive stars present in large number. The Magellanic Clouds are rich in massive stars and have a large number of emission-line objects. Some 625 emission-line stars are known in the Large Cloud (Bohannan and Epps 1974) to $M_V = -4.1$ and 231 in the Small Cloud (Bohannan and Doggett 1989) to $M_V = -4.5$. All of these stars have emission-lines much stronger than would be normal for stars of similar luminosity and temperature. The Luminous Blue Variables are very bright, typically brighter than $M_V = -6$. In the LMC, 107 emission-line stars are brighter than $M_V = -6$ compared with 46 in the LMC.

Excluding the Wolf-Rayet stars, the luminous emission-line stars in the Magellanic Cloud can be categorized by the visibility of absorption lines (Bohannan 1986, Doggett and Bohannan 1989):

e Hα and sometimes Hβ in emission with higher Balmer lines possibly weakened by emission. Spectral classification easily assigned by absorption lines.

pe Emission extends to Hβ and possibly to Hγ. Spectral classification assigned with some uncertainty from absorption lines. Different lines may give different subtype.

ex He I λ4471Å in emission as well as other triplet He I lines. Balmer emission stronger than in *e* or *pe*. Classification usually from absorption component of P Cygni features. (P Cygni would be B1 Iex).

extr No or few absorption features present. Types assigned by presence of certain emission lines :
- O — He II 4686Å.
- B — HeI 4471Å strong, no He II 4686Å.
- A — strong Fe II and [Fe II]. (S Dor would be *A extr*)

There are no known *LBVs* in the SMC, although there are several stars with very strong emission lines. The known *LBVs* in the LMC vary over the OBA *extr* categories. Most curiously, there no stars in the B Iex category in which P Cyg is now observed. HDE 269858 was in the O *extr* category when it was a star of the Ofpe/WN9 class before it erupted and it is now evolved to be the A *extr* category. The 13 LMC stars of OBA *extr* categories not known as *LBVs* may yet become *LBVs* and should be frequently monitored so that we can observe the early phases of high mass loss. The distribution of the OBA *extr* stars in temperature and luminosity (Table 2) is essentially the same as that for the known *LBVs*. Note that some are found at relatively low luminosities. Moreover, one of the first stars to be characterized as Ofpe/WN9, BE 381, is at a luminosity well below the limit of this sample of emission-line stars.

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Table 2:
Distribution of Spectral Types of Luminous Emission-line Stars in the Magellanic Clouds

Type	Totals	Number of Stars with M_V =							
		-9.5	-9.0	-8.5	-8.0	-7.5	-7.0	-6.5	-6.0
SMC:	**31**		**1**	**1**	**2**	**5**	**6**	**9**	**7**
O-B *e*	6				1	2	2	1	
> A *e*	12		1	1	1	1	3	4	1
BA *pe*	3							2	1
BA *ex*	0								
O *extr*	0								
B *extr*	1								1
A *extr*	3					1		1	1
WR	4					1	1		2
unknown	2							1	1
LMC:	**107**	**3**	**2**	**10**	**13**	**11**	**21**	**32**	**14**
O-B e	16			1	1		6	5	3
> A e	6	1		3	1			1	
BA pe	26		2	1	7	4	5	6	1
BA ex	0								
O extr	6						3	2	1
B extr	3				1	1		1	
A *extr*	8			2	1	1	2	2	
WR	20	2		1	1	3	3	6	4
unknown	22			2	1	2	3	9	5

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DISCUSSION

Friedjung: After Roberta Humphreys' talk I thought I understood what an LBV is. Now I am not so sure. Can you distinguish what physical mechanism occurs just by looking at the spectrum?

Bohannan: No. To be an LBV a star needs something in addition to a spectrum. Remember that R127 was just an Of/WN star until in 1982 it was seen to brighten and undergo remarkable spectral change. The LMC stars I showed here, beyond the Famous LBV's, are only **potential** LBV's.

Davidson: A good definition of LBV's would concentrate on their unique physical characteristic, eruptions. We could simply say that an LBV is a star, in roughly the right part of the H-R diagram, which has large eruptions. Then maybe there are some LBV's that we don't notice because we're living in the wrong century. But so what? -- the same is true of supernova progenitors and we accept that.

Humphreys: This morning I tried to define an LBV. LBV's are characterized primarily by their instability -- their alternating periods of eruption and quiescence. Spectroscopic similarity does not mean that a star is an LBV! There are many luminous emission-line stars in the Galaxy and Magellanic Clouds. They are not all LBV's.

Maeder: It is certainly interesting to try to extend the group of stars sharing the properties of LBV stars, but we need very clear designations for any new groups. Otherwise we shall enter 10 years of confusion. I strongly recommend that we restrict the term LBV to those stars that are known to have experienced strong outbursts. The new stars that you have found could be called LBV **candidates.**

Lamers: I do not like the extension of the LBV class to "stars with types similar to famous LBV's." This criterion may bring a group of rather different stars within the definition. Since we want to concentrate on "the physics of LBV's," at this colloquium, we should be sure that we talk about genuine LBV's -- even if this results in a small number of stars and very incomplete samples.

Bohannan: It certainly was not my intention to imply that the set of LBV's in the LMC should be expanded to include all of the emission-line stars. Rather I am suggesting that those emission-line stars may represent a parent population of the LMC LBV's, stars that may become LBV's in the future or that are now quiescent LBV's.

De Jager: The main characteristic of LBV's is their episodical eruptions. Hence a search for new examples should go along with that criterion. But there is another criterion, not yet mentioned in the present discussion: photometric monitoring of LBV's over a few years has shown that their brightness variations have larger amplitudes than supergiants. Hence a search based on photometric monitoring could help to discover candidate LBV's.

Bohannan: True, there need to be both spectroscopic characteristics and large-scale photometric variations. My list of suggested candidates may help to guide those making the photometric observations.

Heap: A purely spectroscopic definition of LBV's might include some nuclei of planetary nebulae, such as the central star of He 2-131 (O8 feq).

Bohannan: That's true. However, in the LMC one has a handle on the luminosity and this provides a natural bias against highly evolved low-mass objects.

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Appenzeller: How did you derive the M_{bol} values plotted in your H-R diagram, and how reliable are these values?

Bohannan: Some that have temperatures similar to B supergiants come from UV continuum-fitting with model-atmosphere flux distributions, similar to what the Heidelberg group of Wolf and Stahl employed. I get slightly higher temperatures because I calculate fluxes from a Kurucz atmosphere rather than using the published grid. I assume that the temperatures of Of/WN stars are like O8 I stars. Most of the e and pe star temperatures were derived from a *spectral type vs.* T_{eff} calibration. The value for R 84 comes from the detailed analysis by Schmutz *et al.* described at this colloquium.

Conti: M_V is sufficiently faint for some of the LMC stars that revised bolometric corrections cannot bring them above the red supergiant limit. So they are faint, like R 71.

Shore: Adding to Bohannan's point about catalog incompleteness, Walborn has pointed out that S 83/LMC does not exist; it was MWC 112, but when Henize was constructing his catalog it was not in emission. Perhaps Sk -69° 202, the progenitor of SN 1987A, was like this.

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M.-C. Lortet asking a question. Near her:
van der Hucht, Hearn, Koenigsberger.

Smolinski, Maeder, Hauck, *et al*.

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