

*Clumping in Hot Star Winds*

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# Wind variabilities and asymmetries in Luminous Blue Variables

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Luminous Blue Variables show strong changes in their stellar wind on time scales of typically years to decades when they expand and contract radially at approximately constant luminosity. Micro-variability on shorter time scales and amplitudes can be observed superimposed to the larger scale radial changes. I will show long-term time series of high resolution spectra which we have collected in the past 20 years for many of the well known LBVs together with a few time series of weekly sampling (HR Car, R40, R71, R110, R127, S Dor) covering a time windows of up to a few months.

Wind variability is seen on short and intermediate time scales with the line profiles changing from P Cygni to inverse P Cygni and double peaked profiles sometimes for the same star and spectral line. On longer time scales the ionisation levels for all chemical elements change drastically due to the strong change of the temperature on the stellar surface.

While on the long term the characteristic radial changes may have impact on the over all mass loss rates, the variabilities and asymmetries on short and intermediate time scales may cause false estimates of the mass loss rates when confronting models with the observed line profiles

## 1 Introduction

Luminous Blue Variables (LBVs) play an important role in the evolution of the most massive stars. They at least contribute to the mass loss history of the massive stars if they are not the only link between the early phases of the evolution with very high actual mass and hydrogen rich surface chemistry and the surface hydrogen poor Wolf Rayet stars. With the reduced mass loss rates in the O-star and WR-star phases due to the implementation of clumping in the stellar wind models the importance of the LBV phase has increased and the role of the LBVs should be further investigated.

LBVs show photometric and spectroscopic variability on different time scales and magnitudes, which I will classify as micro-variability, characteristic variability and outburst:

The micro-variability of LBVs appears on time scales of 10 to several 100 days with photometric amplitudes of tenth of magnitudes. These variations appear like semi-periodic pulsation like motions with the time scale  $P$  proportional to the inverse square root of the mean density  $\rho^{-1}$ . Similar variations are observed for all of the most luminous B and A-supergiants.

The characteristic LBV variability occurs on longer time scales of a few years to a few decades. The stars undergo enormous contraction and expansion phases at approximately constant bolometric luminosity. The stars can change from spectral types

WN11 or early B1a at visual minimum light to typically late A-types at visual maximum light. Many of these stars change their parameters continuously and can be rarely found in any stable phase at either minimum or maximum visual phase.

LBV outbursts like for  $\eta$  Car are very rare events. During an outburst an outer shell of 10 solar masses or more can be expelled from the star which will lead to a significant and spontaneous change of the stellar mass and the later stellar evolution of the remaining star.

A massive blue supergiant should be classified as LBV after observing either the characteristic LBV variability or an  $\eta$  Car like outburst. Stars which are spectroscopically very similar to LBVs may be called LBV candidates. Other stars which show LBV nebulae, but no variability like HD 168625 are difficult to classify in this scheme, because the old age of the nebulae and the possibility that the star may never again enter in an active LBV phase.

LBVs overlap in some respect with the parameter space of hydrogen rich Wolf Rayet stars, while for other parameters they can be well separated. The show colder temperatures than WR-stars and the wind momentum transferred to the wind is typically below the single scattering value. The surface abundances of the LBVs show nitrogen enrichment and in some cases like for R71 in the LMC helium appears already significantly enriched (see Lennon et al. 1993).

## 2 Examples

The galactic LBV HR Car together with R 127 and S Dor are here selected from a larger list of stars monitored over the past 20 year with various instruments. For two more stars AG Car and HD 160529 the data was discussed in a comprehensive way by Stahl et al. 2001 and Stahl et al. 2003, respectively. All data reduction has been repeated with the latest version of the data reduction software including a global fit of the wavelength solution over many orders and optimum extraction techniques (CASPEC, HEROS, FEROS).

**HR Car** went through two cycles of characteristic LBV variability in the last 20 years with visual maxima of 7.2 magnitudes in 1991 and 2001 and minima of about 8.2 magnitudes before 1987, in 1992 and after year 2004. Interestingly the star shows rotational broadening of the order of 70km/s during minimum light estimated in Si III and N II line while in the other phases the metal lines have shown P Cygni or more complex profiles which prevented to search for the spin down of the outer stellar photosphere when the star is radially expanding. The later has been observed by Groh et al. 2006 for the galactic LBV AG Car. During most phases the line profiles are rather complex with multiple discrete absorption components. With the circumstellar emission in the forbidden [Fe II] line a reference, the observation appears even more complex since in all phase except of the maximum light the apparent P Cygni-profile appear at an offset red-shifted radial velocity, while at maximum light the Balmer lines appear more like classical P Cygni profiles but blue-shifted in respect to the circumstellar lines. The complexity of the profiles indicate that the velocity fields and wind geometry may deviate significantly from a spherical symmetric stellar wind beyond the observation of clumping in the wind.

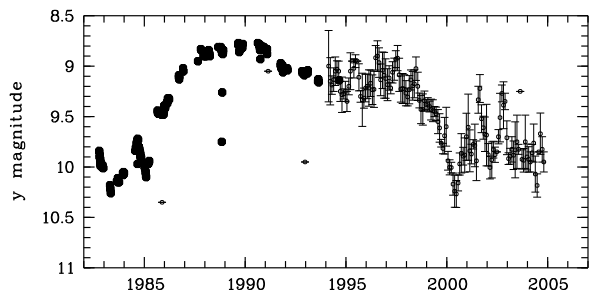


Figure 1: Light curve of the LBV R 127 in the LMC. The data has been collected from the literature (Sterken et al. 1995 and references therein) and from the visual RASNZ observations.

**R 127** located in the Large Magellanic cloud was in the 1970s spectroscopically classified as OF/WN9 star of 11th magnitude. Since then it has radially expanded until 1991 when it has shown a spectrum strongly dominated by singly ionized metal lines (also see Wolf et al. 1988). The star has not undergone another minimum phase during the last two decades. It showed as indicated in Figure 1 a slow decline in visual brightness since 1991 superimposed with a steep but temporary decline in starting in 1999. During this period the emission part of the P Cygni profile has strongly increased. Like for HR Car we take the radial velocity of the circumstellar shell of R 127 as the reference for the system velocity of the star.

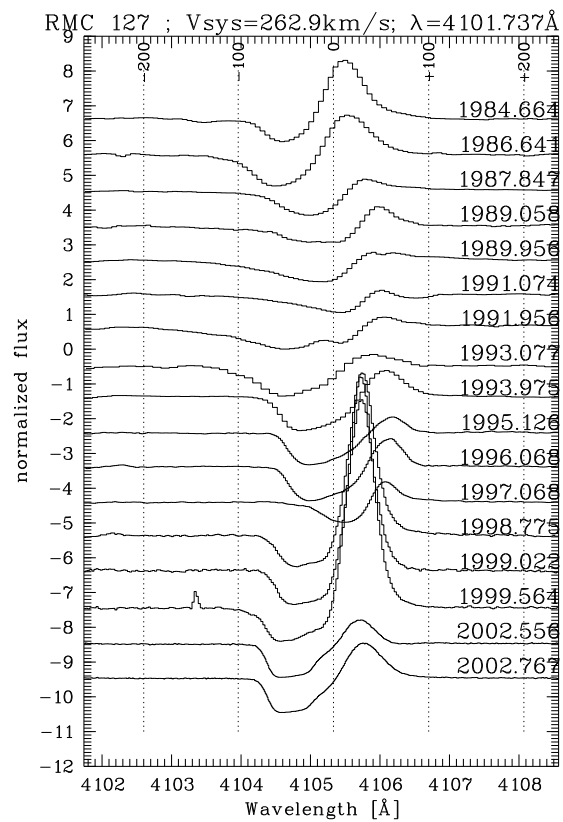


Figure 2: Long-term spectral variation of the H $\delta$ -line of R 127. The indicated velocities are the system velocities in respect to the velocity of the circumstellar shell.

Again I have found that the P Cygni profile do not appear at the radial velocity at which it would be expected following a text book like interpretation of these profiles for an monotonous accelerated radially expanding stellar wind. The strongest red-shift of the profile was found in 1997 when there was no

apparent change in the light curve seen. After reaching the visual maximum in 1991 the star has undergone a phase when inverse P Cygni components were indicating in-falling gas, but at relatively high velocities of 60km/s seen in respect to the circumstellar shell.

In 2002 the star was monitored with higher frequency with UVES in service mode. The spectra show multiple discrete absorption components in the Fe II lines ( $\lambda = 4233\text{\AA}$  can be taken as an example). However unlike for cases of clumps in the wind these components appear not to be accelerated within a period of 80 days covered by the monitoring.

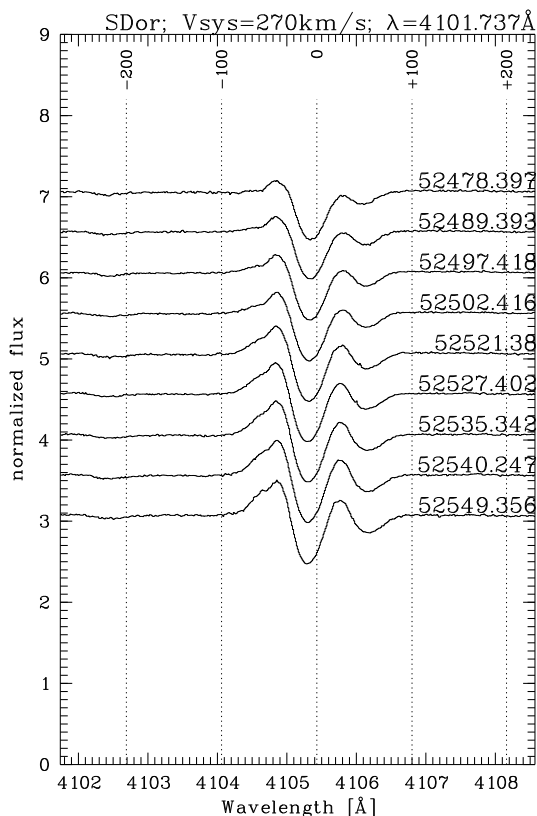


Figure 3: Short-term spectral variation of the H $\delta$ -line of S Dor. The data was obtained in year 2002.

**S Dor** of the LMC has been observed close to maximum visual brightness phase for most of the time since in 1989 and since 1996. During two periods, in 1985 and 1993 it was observed in a phase when it has been 1 magnitude fainter than during the maximum light. The star has been frequently observed with in-

verse P Cygni profiles which appears to persist for a relatively long time (see Wolf & Stahl 1990). A higher level of complexity was reached during 2002 when the star was monitored with higher time resolution (see Figure 3). We find for the Balmer lines (H $\gamma$ , H $\delta$ ) two emission peaks and two absorption peaks at the same time. The absorption minima are at blue- and red-shifted velocities (about -10km/s and +50km/s respectively) while the peak emission were found at -40km/s and +20km/s. The relative intensity of these components have significantly changed during the 80 days monitoring campaign with overall stronger absorption and emission components at the end.

### 3 Discussion

During their extreme radial expansion and contraction episodes the LBVs are very often observed with complex line profiles, which are very puzzling in the sense that even when the lines appear as text book like P Cygni profiles these profiles are shifted in respect to the circumstellar shells taken as a reference for the system velocity. The velocity fields in the stellar wind appear to be very complex even if some of these effect can be explained by unusual radially changing excitation or ionization states. Considering the variability of the profiles it appears more likely that the overall geometry is more complex than the classical radially expanding stellar wind with or without clumps. It is however extremely complicate to derive the geometry of the none stationary LBV winds from the observed time series of line profiles.

The data presented here were taken by the hot star group of the Landesternwarte Heidelberg (Berhard Wolf, Otmar Stahl, Andreas Kaufer, Thomas Rivinius, Franz-Josef Zickgraf and others) at ESO telescopes in La Silla and Paranal. I acknowledge with thanks the variable star observations from the AAVSO International Database and the RASNZ observations.

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**Groh:** The fact that HR Car shows an absolute low value of  $v_{\text{rot}} \sin i$  does not necessarily mean that it is a slow rotator. You have to compare  $v_{\text{rot}} \sin i$  with the value of the critical rotational velocity, which requires the knowledge of  $M$ ,  $L$  and  $R$ .

**Szeifert:** I agree! For reasonable stellar parameter estimates the rotation does not reach critical rotational velocities. The most uncertain parameter in case of HR Car is the distance.

**Weis:** Can you define to me what an LBV outburst is? If you need it as a definition of an LBV none of the objects you showed have been LBVs.

**Szeifert:** This is a misunderstanding: My definition was that LBVs are evolved massive supergiant stars with characteristic variability at approximately constant bolometric luminosities. An LBV outburst like  $\eta$  Car's I have added in a footnote to the class of LBVs even though this outburst will change dramatically the bolometric luminosity.