PHOTOMETRIC VARIABILITY OF LUMINOUS BLUE VARIABLES IN QUIESCENT STATE

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ABSTRACT. This paper reviews the major new facts on microvariability of LBV's of the last few years, and discusses some observational requirements for the future.

1. INTRODUCTION

LBV's are photometrically variable with a large range of amplitudes (hundreths of a magnitude to several magnitudes) and with a vast range of timescales (hours to several decades). The amplitudes of the variations seem to increase with the timescales at which they occur. Lamers (1987) reviewed the three types of variations, viz. the large variations (which are associated with the eruptions, and which are seen in some, but not in all LBV's, and which occur on timescales of centuries), the moderate variations (seen on timescales of decades, and which occur at irregular intervals), and the small-scale photometric variations, also called microvariations, which have been found in all LBV's which have been observed sufficiently accurately, and which are also known to be present in the case of normal supergiants.

2. THE CHARACTER OF THE SMALL-SCALE PHOTOMETRIC VARIATIONS

The variability of Ia supergiants was discovered by Maeder and Rufener (1972). No lightcurves were available at that time, but the semi-periodical variations seen in the spectroscopically studied supergiants seemed to support the picture that there is a linear relation between the characteristic times of the spectroscopic variations and the luminosities of the stars, in the sense that the brightest stars have also the longest semi-periods. These relations depend on the spectral types of the stars.

During the following years, several investigators systematically monitored supergiants (for a review, see de Jager 1980, chapter 8.2). All well-studied supergiants show light fluctuations on timescales

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of days to years with amplitudes of hundreths of a magnitude to several tenths. The variations are strongest in hypergiants.

These variations are not strictly periodic, and the characteristic period is not always unambiguously visible. Van Gent and Lamers (1985), for instance, reanalysed available data on photometric variations of P Cygni, and concluded that the range of timescales goes from 25 days to 60 days. These timescales are not constant in length.

The variations reported in the 1970's have one common aspect: with a few exceptions, <u>the observations cover in time only a couple of months, and they are all distributed over one or two observing seasons</u>. A more complete picture however emerged from a few cases of long time-baseline photometry of LBV's and some less luminous supergiants. These investigations were mainly the work of van Genderen and his collaborators at the University of Leiden, and by Wolf and his team at the Landessternwarte in Heidelberg.

Van Genderen, during the early seventies, started a systematic high-precision VBLUW photometric study of several very luminous LMC supergiants. Due to this intense observing, long series of homogeneous photometric data are now available for analysis.

In the case of R71 the microvariations are characterised by regular and smooth ups and downs with an amplitude of about 0.1 mag, and with a semi-period of about 23 days for the 1983-1985 period, and of about 14 days for the 1986-1987 period (van Genderen et al. 1985, 1988a). This clearly illustrates that this star, in quiescent state, changes its period of light variation. It would be interesting to know if these cycle length variations have any relation with an eventual outburst which might build up during the next five to seven years. The colours vary too, but the amplitudes of variation are a few orders of magnitude smaller than the light amplitudes. The colour curves are usually in phase with the lightcures, and the light amplitudes tend to increase with decreasing wavelength.

A star similar to R71 for what concerns its variability, is AG Car. Van Genderen et al.(1988a) give an extensive discussion of its variability. The time interval between successive eruptions is of the order of 5 years, and the brightness rises seem to be characterised by a very steep rising branch (about 0.01 mag/day in V), and a descending branch which gradient is about 0.002 mag/day (this is still two times as large as the great descend in light seen in η Carinae between 1856 and 1868!). The microvariations in quiescent state have a characteristic time of about 14 days, and there seem to be large cycle-to-cycle shifts in the mean light level present. This was not the case for R71. Whether this is a signature of activity which is related to the higher gradients of rise and descend as is seen in R71 is not clear. The colour variations of AG Car on the other side are very alike those seen in R71.

Van Genderen and Thé (1987) report new photometry of η Carinae for the years 1983-1986, and show that a new light maximum was present in 1986. This maximum has a similar height as the maximum seen in 1981-1982. The problem of these data is that the time resolution is only sufficient to reveal the occurence of such maxima, but gives little information about the microvariations.

S Doradus received a lot of attention by the Leiden and Heidelberg observers (van Genderen 1979, 1982; Stahl and Wolf 1982, Leitherer et al. 1985). In 1983 Leitherer et al. reported that S Dor reached a maximum brightness of V=9.2, the highest value ever measured. This maximum was followed by a typical fast decline. In 1985 there is evidence for a second maximum, but it is not clear whether this is a maximum, or just a wiggle as was seen in 1965 and 1968. If this is a regular microvariability, it may well have a characteristic time of about 100 days.

Another LBV in the LMC, R127, is now under continuous monitoring since Stahl et al. (1983) discovered that this star had become an S Dor star in 1982. No data are available in quiescent state, but observations obtained in 1986 showed it in outburst (0.001 mag/day).

The highlight in LBV monitoring undoubtedly is the discovery that R81 is an eclipsing binary (Stahl et al. 1987). From data collected by 20 different observers during more than 600 allotted nights of telescope time, they saw that dips in the lightcurve with a depth of 0.4 mag occurred at regular intervals. Appenzeller (1972) had observed a similar brightness decrease in 1972, and his observations were fully compatible with the data used by Stahl et al. The resulting period is 74.59 ± 0.01 days. There is no secondary minimum visible, but there is a pre-eclipse dip at phase 0.8. The lightcurve indicates a contact system with complicated mass motions. Strangely, the irregular intrinsic variations of R81 itself are unusually small for a supergiant.

Van Genderen et al. (1988b) discuss two other interesting cases of microvariations which may have a causal connection with the geometric configuration: HD57060 and HD167971. HD57060 = UWCMa is a binary consisting of an O8 supergiant star and an O or B type main sequence star in synchronous revolution with a period of 4.39 days. According to the authors the system shows abnormally strong microvariations which may be connected with the strong distortion of the star filling its Roche lobe, and the intensity of the mechanism causing the microvariations. HD167971 is an interacting binary consisting of two main-sequence O stars, with extra light from a third O8 supergiant which may or may not be a member of the system. This system was studied in detail by Leitherer et al. (1987) who determined the period P=3.32 days. This system shows (according to van Genderen et al. 1988b) normal microvariations.

3. THE AMPLITUDES AND THE PERIODS OF THE MICROVARIATIONS

Van Genderen (1988) discusses the maximum light amplitude (MLA) of the microvariations of nearly 100 massive stars with spectral types O3-F8. The data are taken from visual lightcurves from the literature and from his own unpublished material. All involved stars are more massive than 15 Mo. He did not use the six massive B[e] stars in the LMC (Zickgraf et al. 1986) because they are fast rotators with peculiar stellar wind properties. Also η Carinae was ommitted for various reasons, as well as the distorted massive stars in close binary systems. Van Genderen sees a clear separation between normal α Cygni variables and the S Dor stars and those suspected as such (with, as exceptions, HR Car and R81): the light amplitudes are systematically much larger for the latter than for the former. There are also two types of oscillation: variations of S Dor stars are smooth, while those for normal α Cyg variables often are more bumpy. From this he concludes that there is a marked difference between the outer layers of S Dor (QS) variables and the other blue super-and hypergiants.

If we plot the positions of the well-observed LBV's in the Mv/Sp diagram of Burki (1978) we see that the positions agree well with the Sp/Mv/P relation given by him. In other words: α Cyg variables and S Dor variables are not separated in the Sp/Mv plane: the periods agree with the lines for calculated periods given by Burki.

How then the amplitudes deviate, and not the periods? One explanation simply can be that the order of magnitude of the semi-period, even in the case of the S Dor variables, can be accurately determined, while the determination of the amplitude is more dependent on the frequency at which observations were taken. Take for example R81, with a period of 2.5 months, which is almost a full observing season. One week of interruption around the time of minimum (due to bad weather, or due to the observing schedule) would be sufficient for an eclipse to go undetected, and to suggest that the star has microvariations with an amplitude of not more than 0.1 mag. This would move the star outside the region indicated in figure 1 of van Genderen (1988). Stars with higher amplitudes could be undetected binaries. Especially interacting binaries, like HD167971 and HD57060 with periods of a couple of days may, when observed at too low frequency, give the impression of microvariability. But the reverse is also true: the gradients of decline during the eclipse of R81 are alike those which are measured at the occasion of ingress or egress from an eruptive phase of an LBV, so a poorly defined lightcurve with suppressed microvariability might suggest an eruptive phase instead of an eclipse. After all, the orbital period of R81 is of the same order of length as the semi-periods present in the light variations of some of the not so well observed Ia supergiants.

4. THE CAUSES OF THE MICROVARIABILITY

The modulation of the lightcurves, and the radial velocity variations, are often interpreted as evidence for oscillations in the photosphere (Leitherer et al. 1985, Wolf 1986, Lamers 1987, van Genderen 1988). These speculations are supported by the presence of a P/L/C relation and the rough constancy of the pulsation constant Q. Van Genderen (1988) believes that the microvariations are caused by an oscillation mechanism which is only confined to the surface layers of super-and hypergiants. But Harmanec (1987) argues whether the existence of a PLC relation necessarily implies the presence of some kind of pulsation. He tested the possibilities that the variations may be caused by rotation of a spotted star, or by orbital motion, and he concludes that both alternative interpretations give rise to a similar PLC relation, but that the spotted star hypothesis is untenable.

The binary hypothesis seems to be as plausible as the possibility of pulsation: Harmanec points out the large uncertainties in deriving the PLC relation, such as the estimate of the semi-period, the mass, effective temperature and radius.

Direct observational support of the binary thesis are the small radial velocity variations (up to 20 km/s), the shallow eclipses, the small orbital light variations due to ellipticity effects, and the cycle-to-cycle variations of light- and velocity curves caused by mass transfer variations.

But there are evenly simple observational arguments which would, in spite of the large scatter in the PLC relation, support the pulsational viewpoint. For example the interesting point of a causal connection between the strength of the microvariations (oscillations) and the binary nature of the star. Van Genderen et al.(1988b) observed that the primary of HD57060 shows abnormally strong microvariations, which are either due to the supergiant, or to the comparison, or to both. This is in apparent contradiction with the case of R81, where the microvariations are abnormally small. It is tempting to look at the interrelation between pulsation and binary nature in the much less luminous pulsating B stars. Fitch (1967) showed that in the ß Cephei star σ Sco the long-period modulation observed in the light variations appears to originate in disturbances of the normal pulsation mode by tidal deformation produced in the outer layers by a faint companion. Waelkens and Rufener (1983) investigated the photometric variability of close binary stars, and they concluded that the presence of a close companion prevents a star in the ß Cephei instability region from pulsating with a large amplitude. This result would support the effect seen in R81, but it contradicts van Genderen's conclusions for HD57060.

Extrapolating the positions of Burki's lines of equal period towards periods of a couple of hours approximately brings us down to the main sequence, where we know that there are several groups of stars which exhibit pulsational variations, such as ß Cephei stars, 53 Per stars, etc. This region corresponds to the locus of very small amplitude variability in van Genderen's MLA/Teff diagram. If pulsation is the cause of the microvariability in LBV's and supergiants, it would suggest that in the PLC or P/M/Teff space there exists a continuous smooth surface which links the characteristic parameters, and which goes down right to the main sequence with shorter and shorter periods of pulsation. Indeed, some of the observed phenomena in pulsating B stars are remarkably similar to some of the properties of microvariations seen in super- and hypergiants, such as

- progressions in radial velocity
- increasing light amplitude with decreasing wavelength
- modulated lightcurves
- in some specific cases the light amplitudes stand out amidst other stars of the same class of variability (e.g. BW Vul)
- there are changes of the period (which, in some cases, are sudden)
- the origin of the pulsations is in the atmospheres
- the amplitudes are variable (Spica, 16 Lac)
- the pulsation mechanisms remain unknown

5. WHICH OBSERVATIONS ARE CRUCIAL?

Almost every paper on LBV's ends with an explicit plea for more observations of a specific kind. But it is obvious that the breakthrough in this research could only occur after an enormous amount of painstaking systematic observations over long periods of time had been collected. It is now clear that this kind of approach must be continued and even extended on a larger scale. Two fundamental subjects must be tackled:

i. A search for new LBVs

One should compile a list of LBV candidates from an inspection of observational HR diagrams and from a search of archive plates and catalogues for photometric anomalies. These candidates should be monitored photometrically in one stable photometric system for several years. The time resolution for the monitoring should not be lower than 2 to 3 days. This monitoring should be supplemented by spectrographic (ground-based and space) backup in order to permit the discrimination between eruptions, pulsational variations, and changes caused by orbital motion in a binary system. One should focus on short-period ellipsoidal and eclipsing binaries, solve the light curves and study the residual microvariations. Special attention should be given to the detection of multiple periods, and to period changes.

ii. Determination of the stellar parameters

Masses must be derived from eclipsing binary studies, and also luminosities and distances. Accurate knowledge of distances is imperative, because this yields clear information on the existence of period-luminosity relations, and the usefulness of these stars as distance indicators. Therefore, systematic research on extragalactic LBVs is the best choice. It is clear that the best place to work is the LMC (and eventually the SMC). The LMC as a laboratory is optimal because of its advantageous declination which allows most favourable seasonal coverage using high-technology instruments which are available at different locations in the southern hemisphere.

The search phase of this project could be accomplished in less than three years, while the monitoring part would need at least ten years of intensive observations.

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DISCUSSION

Moffat: One could take your comparison between variations in supergiants and in β Cephei stars further by including polarization. This leads to problems if one claims non-radial pulsations (NRP) in both. Some β Cep stars show $\Delta m \approx 0\overset{m}{.}1$ and $\Delta P \approx 0.01\%$ (Watson 1983, *Astrophs. Sp. Sci.* **92**, 293). Some supergiants show $\Delta m \approx 0\overset{m}{.}1$ **but** $\Delta P \approx 0.5\%$ (!) for stars like P Cyg showing micro-variations (see work by Hayes; Lupie & Nordsieck). Even if a different density-temperature combination prevails in each kind of star, one might expect $\Delta m/\Delta P \approx$ constant with NRP. Thus I have difficulty assigning NRP to blue supergiants/LBV's.

Sterken: There are no polarization measurements of LBV's on the micro-variation timescale. Concerning β Cep stars, theoretical considerations make one expect polarization variations but the observational evidence so far is insufficient.

Moffat: Hayes has studied short-timescale polarimetric variations of P Cyg (1985, *Astrophys. J.* **289**, 726).

Friedjung: As far as I am aware the cause of the instability of β Cep stars is not known. Therefore aren't you putting together two badly-known phenomena?

Sterken: I realize that the two groups of stars are very different and that the observed phenomena are poorly known. My talk illustrated the observational similarities, which support the interpretation of pulsation in LBV atmospheres. Whether the excitation mechanism is the same for both groups is another problem, which can be solved only after we know more about the excitation mechanism in β Cep stars.

Maeder: Supergiants having a characteristic pulsation time longer than average in view of the standard *P-L-C* relation should also exhibit significant nitrogen enhancements, provided that the pulsation mode is the same for stars on the blueward and redward tracks.

De Groot: With respect to Maeder's remark, remember that the time-scale of variations that we see in P Cyg is at least twice as long as expected for a normal blue supergiant. On other grounds we already concluded that P Cyg is moving to the left in the H-R diagram (*Astr. Astrophys.* **128**, 299). So here is a clear example.

Gallagher: Could there be a difference in micro-variability characteristics between two kinds of binaries, those where the extended envelope is contained within the system (as in R 81, where eclipses occur) *vs.* those where both components are buried within an extended envelope (common-envelope systems)? How would this affect the interpretation of micro-variability?

Sterken: Micro-variability might be influenced by the binary configuration even if it is caused by pulsation. I do not know what would be seen in the case of a common envelope.

Lamers: Could the smaller micro-variations in binaries be explained by the fact that two stars are in the photometer aperture? If only one star in a pair is variable, the relative amplitude will then be smaller than for the varying star by itself.

Sterken: In R 81 the secondary component does not contribute much to the light (the secondary minimum is not visible). So there is no doubt in that case.

Walborn: UW CMa (= HD 57060) is a peculiar interacting binary with gas streams which may be the source of the variations, rather than the stars themselves.

Sterken: Mass exchange may cause additional variability, as Van Genderen has pointed out.