Southern Horizons in Time-Domain Astronomy
Proceedings IAU Symposium No. 339, 2019
E. Griffin, ed.

doi:10.1017/S1743921318002284

Photometric Variability of Luminous Blue Variable Stars on Different Time-Scales

G. Gantchev and P. Nedialkov

Department of Astronomy, University of Sofia, Bulgaria
email: g_gantchev@phys.uni-sofia.bg

Abstract. We have compiled historical observations, spanning ∼100 years, for a dozen of the best-studied LBVs in the Local Group. We described how we prepared structure functions for their light-curves and calculated two parameters (the structure function slope and the characteristic time-scale) to describe the behaviour of the LBVs. The sensitivity of those parameters to the variability behaviour of the stars was tested with a number of photometric data sets. The slope of the structure function may anticorrelate with the time-scale. These types of variable stellar objects are crucial to studies of stellar variability and the final stages of stellar evolution.

Keywords. Luminous Blue Variables, structure function, time-scale

1. Introduction

Luminous blue variables (LBVs) are rare, massive hot stars that are undergoing violent sporadic eruptions and mass-loss events on time-scales of years or decades (Humphreys & Davidson 1994). They are bright (typically $M_{bol} \leqslant -9.6$ mag), and their masses are $\geqslant 50 M_\odot$; the most luminous ones are found close to the Eddington limit. LBVs represent a short phase of about 40 000 yr in the evolution of massive stars, one that is characterised by a strong mass loss of $\dot{M} \sim 0.3$–$0.5\, M_\odot\, \mathrm{yr}^{-1}$ during an eruption. LBVs are considered to be objects in transition from early O-type stars towards Wolf-Rayet stars (Meynet Eggenberger & Maeder 2011). However, recent theoretical work (Groh *et al.* 2013) has shown that less massive rotating stars (20–25 $M_\odot$) can also undergo an LBV phase after the red supergiant stage, before exploding as a supernova.

During a major eruption (which occurs once in a few centuries) an LBV can increase in brightness by more than 3 magnitudes. The ejected mass exceeds 1 $M_\odot$ and may be as much as 10 $M_\odot$, as estimated for η Car and P Cyg. Smaller ('normal') eruptions, observed in the well-known cases of S Dor and AG Car, cause variations of 1–2 mag on time-scales of a few years up to a few decades. The effective temperatures at minimum light, or the quiescent stage, are T_{eff}=10 000–30 000 K. This state usually lasts several years, and is followed by visual brightening of the star within a few months. At that time an optically thick 'pseudo-photosphere' that is slowly expanding by 100–200 km s^{-1} is formed. The object reddens and reaches the Humphreys-Davidson limit while its mass loss accelerates.

The brightness variations of an LBV provide important constraints on the final evolutionary stages of a massive star during its instability phase. The first known objects of this class in the Milky Way (η Car and P Cyg) have been observed since the 17$^{\mathrm{th}}$ century and possibly earlier, but they were not recognised as objects belonging the same class until the mid-1960s. Actually, Hubble & Sandage (1953) identified five LBVs in M 31 and M 33 on archived plates 40 years ago while looking for photometric variability.

Studies of LBVs meet certain obstacles. (1) The short duration of the LBV phase limits their discoverability, and (2) the lack of large photometric variations on reasonably short time-scales of the kind that could easily be covered by homogeneous observations complicates the discovery of new LBVs.

2. Overview

We mention first the relevance of structure functions. A structure function describes the tendency of a source to change its observables as a function of the time between two measurements. A structure function analysis tends to be less sensitive to the homogeneity of the observational coverage, and for that reason it is often used to study the variability of quasars where the time-scales are extremely long and can easily exceed years (e.g. Hughes *et al.* 1992). Following the original work of Hughes *et al.*, Ovcharov *et al.* (2008) have defined the structure function of a photometric time-sequence as:

$$S(\tau) = \langle [m(t) - m(t+\tau)]^2 \rangle. \tag{2.1}$$

Where $m(t)$ is the magnitude at a time t and τ is the time interval or 'lag' between the two measurements. The time lags are binned, and the angle brackets express the average over measurements within the same time-lag bin. The structure function is usually parametrised in term of its slope:

$$b \;=\; d\;log\,S\;/\;d\;log\,\tau. \tag{2.2}$$

The photometric variability of LBVs, caused by changes in mass-loss rate during brightness minima and maxima, might be another process suitable to be studied via a structure function analysis. To test that possibility, we selected a sample of 10 Local-Group LBVs with well known photometric light-curves covering time-spans from a dozen to hundreds of years. Since most of the observations were carried out before the CCD era, and in order to minimise calibration problems, only historical light-curves were considered.

3. First Results

We calculated structure functions for our targets using the expression given in Eq. 2.1, with the logarithmic time-lag bin equal to 0.25 dex. That value is larger by a factor of five for our sample than the one used by Hughes *et al.* (1992). However, it is appropriate for this case because we have on average the same number of data-points as did Hughes *et al.*, but we are attempting to obtain comparable results for all LBVs, especially those with really poor coverage.

The structure functions of the LBVs in M 31 are shown in Fig. 1. Slopes have been derived for AE And because of the hint of a plateau at intermediate time lags. The result might be interpreted as a signature of two distinct processes driving the stellar variability (Hughes *et al.* 1992). Notably, AE And is the only LBV in M 31 that exhibits plateaux at relatively small time-scales of ∼1 yr, with amplitudes ∼1 mag corresponding to the so called 'normal' variations rather than the sporadic mass-loss events. The characteristic time, however, can be derived only for AF And, because among the remaining LBVs in M 31 only V 15 displays a hint of a plateau at long time lags. In those cases we set only a lower limit for that parameter. The structure function for the LBVs in M 33 and the Milky Way one (Fig. 2) have a shape similar to the expected one, thus allowing a straightforward derivation of their time-scales and slopes, except for Var 2 for which only the minimum time-scale is determined. Like AE And, S Dor starts to exhibit a plateau at time-scales of ∼1 yr. Because the high plateau is ill-defined with only a single possible point, η Car – for which the time lag shows correlated behaviour – it is much better fitted with two different slopes than with one.

https://doi.org/10.1017/S1743921318002284 Published online by Cambridge University Press

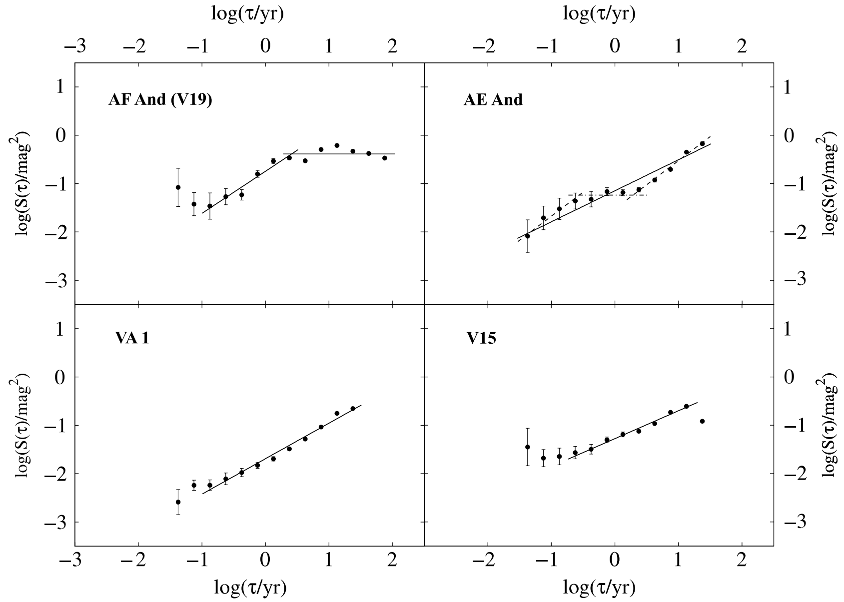

Figure 1. Structure functions for 4 LBVs in M 31. For each variable, the slopes of structure functions are derived from the inclined lines. In the case of AF And (upper left panel), the higher plateau is represented by a horizontal line. (*Modified version of originals by Gantchev et al. 2017*).

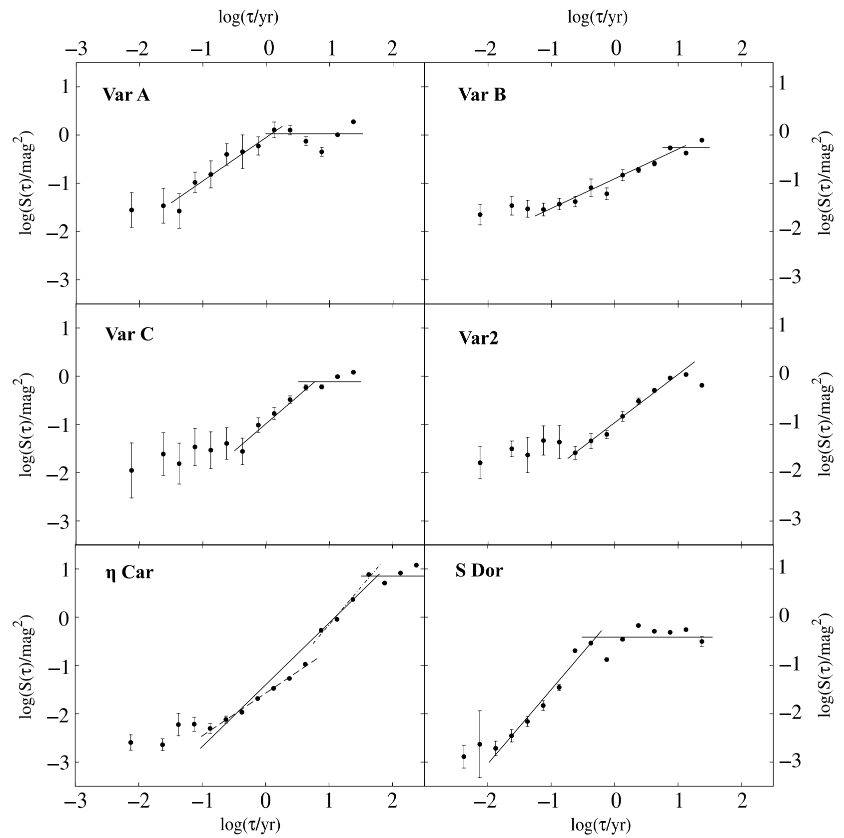

Figure 2. The same as Fig 1, but for the 4 LBVs in M 33, plus η Car and S Dor. (*Modified version of originals by Gantchev et al. 2017*).

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The results outlined in this report suggest that the structure function analysis can be a useful tool for interpreting the variability of LBVs in the Local Group on various times-scales – in fact, from several days to nearly a century. In many cases we were able to recover from historical data the expected typical shape of the structure function: two plateaux at the shortest and at the longest time lags, and a power-law portion in between.

The structure functions of some LBVs in our sample deviate from the 'universal' shape: AE And, which has a plateaux at middle-range time lags, Var A and S Dor, which have a prominent minimum after the longest correlation time-scale, and η Car, for which the correlation range is best fitted with two different power-law slopes. In some cases the monthly variations of an LBV may influence the structure function at the corresponding short time-lags.

We also used a well-studied long-period Cepheid (S Vul) to demonstrate that the structure function of a periodical variable shows a series of minima at long time-scales, corresponding to the multiples of its period. The superposition of those minima can result in a flattening of the structure function.

Most importantly, it seems that if the characteristic time-scales of LBVs derived via structure function analyses are used instead of the regular Cepheid periods, then the LBVs can be placed on an extension to the period–luminosity relation. That has the potential to turn the LBVs into useful extragalactic distance indicators – a possibility that needs revisiting with better and newer data sets.

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