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PHOTOMETRY OF VARIABLE STARS, AND SYSTEM TRANSFORMABILITY OVER LONG TIME INTERVALS

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Abstract. The fundamental problem of long-term photometric monitoring of variable stars and of multi-wavelength photometric campaigns is the problem of bringing the data to a common standard. Such homogenization can be achieved only when the measurements are made in photometric systems that are truly transformable. This fundamental problem is of a technical nature, and photometric observers, sometimes, are not aware of the problems. This frequently leads to over-interpretation of the data.

Key words: technique: photometric – stars: variables, individual: η Carinae

1. PHOTOMETRY: SYSTEMS AND TRANSFORMATIONS

Astronomical photometry is the use of photometric instruments and techniques to accurately determine the amount of electromagnetic energy (as a function of wavelength) that is received from a celestial object. Magnitudes are *always* determined with respect to a magnitude sequence in a network of standard stars, and the combination of filter and detector response with a set of standard stars defines what is commonly known as a *photometric system*. Note that some photometric systems are not filter-defined: take, for example, the Johnson UBV system, where the U passband is limited by the Earth's atmosphere, or the V band where the red cut-off is only assured by the detector's response, and where U and B have a "red leak". All-sky photometry rarely attains accuracies better then a couple of millimagnitudes. Standardization requirements can be somewhat relaxed in the case of differential photometry, where precisions of a couple of millimagnitudes is standard.

Photometric *transformations* are used to bring to a same scale (preferably the standard system) the measurements that are made with equipment that (slightly) deviates from the original standard equipment. These deviations are either differences of the observing site, the application of other (newer) detectors, and the use of different filters. These transformations, as a rule, are linear (or meant to be linear) and rely on some theoretically founded assumptions, such as, for example, a spectral energy distribution that is continuous, the absence of strong gradients and emission lines, filter transmission functions without steep wings, and, above all, a set of standard stars that is *very well balanced in color, spectral type and luminosity class.* As such, photometric measurements (magnitudes and color indices) can be collected for hundreds of thousands stars with high accuracy, see for example the database at the *General Catalogue of Photometric Data*[1].

2. THE REAL SKY

Evidently, not all stars are unreddened and emission-free main-sequence stars. The most fascinating stars – from an astrophysical viewpoint as well as from the perspective of them being photometric troublemakers – are the Luminous Blue Variables: a couple of dozen mavericks among the multitude of stars that are being observed photometrically. The single most difficult member to measure is η Car (HD 93308) for reasons outlined in Section 2.2.

2.1. LBVs or S Dor stars

S Doradus variables – commonly aliased as LBVs – are evolved massive stars that undergo four major types of intrinsic photometric variability: microvariations, S Dor phases, stochastic variability and eruptions. For an elaborate discussion of these types of variabilities, and for a very complete review of the state of affairs at the end of the second millenium, we refer to van Genderen (2001). These stars were labeled S Dor variables on the basis of behavioral similarities with prototype S Doradus. The Armagh 2000 definition (see de Groot & Sterken 2001) states: *S Doradus variables are hot, luminous stars that show photometric and/or spectroscopic variations like S Doradus and which have undergone – or possibly will undergo – an η Carinae- or P Cygni-type outburst.* η Carinae is the historically best-documented case of eruptive behavior as referred to in this definition:

[1]GCPD, `http://obswww.unige.ch/gcpd/gcpd.html`

it was observed in eruption by John Herschel at the Cape in 1838, and the historical light curve shows a major eruption, followed by a second maximum a few decades later, and then a steady low-gradient brightening during more than a century, see Figure 1.

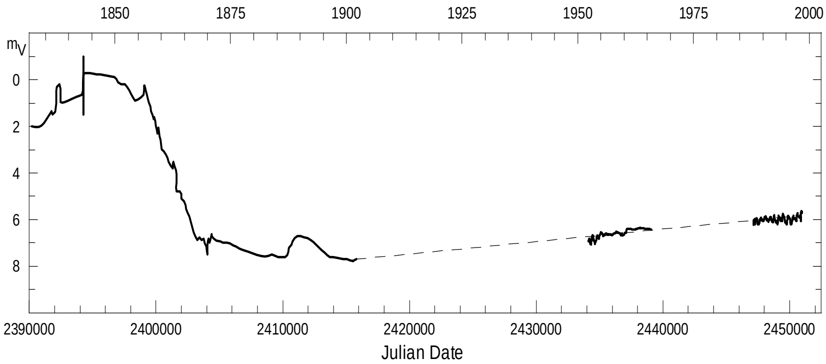

Fig. 1. Visual light curve of η Car since the primary eruption (Sterken 2003).

Van Genderen (2001) gives the following criteria for membership and lists almost 50 members of the class: (1) presence of visible ejecta, caused by single or multiple eruptions (2) high luminosity, coupled to high mass-loss and (3) photometric variability up to 2.5 magnitudes over years to decades, with these stars becoming redder when going brighter while their position in the HR diagram moves to the right.

S Dor stars are distant, their light traverses regions with non- standard reddening, and their irradiance is very much hampered by variable circumstellar extinction of all sorts. The time scales of variability – especially the S Dor phases – are of the order of months to years; the eruptions occur on time scales of decades to centuries. Hence, the photometric study of these stars covers extremely long time baselines, needing data taken by many different observers over many epochs of technological development (mainly in detector technology).

2.2. Eta Carinae

Sterken et al. (1999) presented an elaborate outline of the major problems which photometrists face when performing long-term monitoring of a composite and extended object like η Car. By its appearance as an extended object and by its anomalous spectral nature, this is the single most difficult stellar object to monitor over a long time interval. The problems belong to several levels:

1. Gaps in the data record: seasonal and logistic

This element concerns the classical problem of seasonal gaps, or even intervals of longer duration during which no data have been obtained. Sometimes observers will 'stretch' the observing season by observing at much higher air masses than is normally permitted, with the unavoidable consequence that severe color effects are introduced – color effects that can lead to spurious periodicities, as was illustrated by Jones & Sterken (1997).

2. A suitable light collector

The prime requirement – the availability of a modest-size telescope with suitable photometric instrumentation – becomes increasingly difficult to fulfill. This is illustrated in Figure 2 of Sterken et al. (1999), which shows the cumulative number of photometric measurements that was obtained over more than five years. The reason for this situation is not lack of interest or shortage of manpower: the only cause is the progressive decommissioning of small and intermediate-size photometric telescopes.

3. Bright stars and photomultiplier photometry

Because of its extreme brightness, η Car (and thus also its local comparison stars) is sometimes observed with a neutral-density filter, and if color equations are not routinely maintained for these filters in the photometer, the resulting data cannot be guaranteed to be accurately tied to the standards.

4. Bright stars and CCD photometry

Photomultiplier photometry requires excellent atmospheric conditions which can somewhat be released by using a suitable nearby comparison star. CCD photometry can be considered as less prone to poor sky conditions, but the differential method imposes the most stringent requirement that the comparison star must be found within a couple of arcminutes from the variable. The best choice for η Car is HD 303308, which, unfortunately, is fainter by almost three magnitudes, and half a magnitude bluer in $B-V$. The magnitude difference represents ratios up to a factor of five in the y count-rates, which are to be kept well below saturation level.

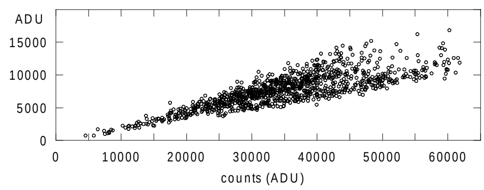

Fig. 2. Maximum count rates for η Car (X-axis) and HD 303308 (Y-axis). Source: Sterken et al. (2001).

Figure 2 shows the count rates for η Car versus HD 303308. An optimal situation from the viewpoint of a photometrist would allow for a cloud of points in the upper right corner, or a small range of dots along the bisectrix. For the η Car field, however, the situation is awkward due to the fact that observers sometimes acquire data during periods of mediocre atmospheric quality, entailing very low count rates for the comparison star. When performing differential photometry, the noise on both magnitudes is combined, leading to very pessimistic error estimates amounting to 0.03–0.04 mag for those frames which were not too well exposed.

5. A label does not make a passband

Figure 3 of Sterken et al. (1999) shows the passbands of three photometric systems that were used for measuring η Car. Non-specialists often do not realize that ultraviolet-blue color indices (like u–v, for example) cannot be compared or transformed to homologous counterparts (such as Johnson U–B) because of the fact that the location of the Balmer jump – but also the presence of strong emission lines – drastically influences the related spectral energy gradient.

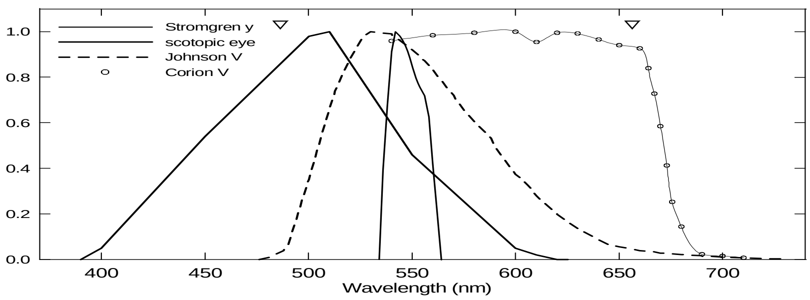

Fig. 3. y, V and Corion normalized transmissions. ∇: Hβ and Hα.

The three photometric systems that we applied do allow a comparison, though not necessarily a transformation of ultraviolet color indices. This is very well illustrated in Figure 7 of van Genderen et al. (1999) which shows a combination of ultraviolet color-index curves of η Car in the Walraven, Strömgren and Geneva photometric systems: though the respective color indices are not transformable from one basis to the other, the color curve's maxima reveal the existence of an ultraviolet-variable source. The effect completely disappears when color indices are used that are somewhat contaminated by the Balmer discontinuity, such as Johnson's U.

6. The V-band, a harmful generic concept

But even a matter as simple as the so-called *V-band* leads to immense problems of standardization when discussing accurate photom-

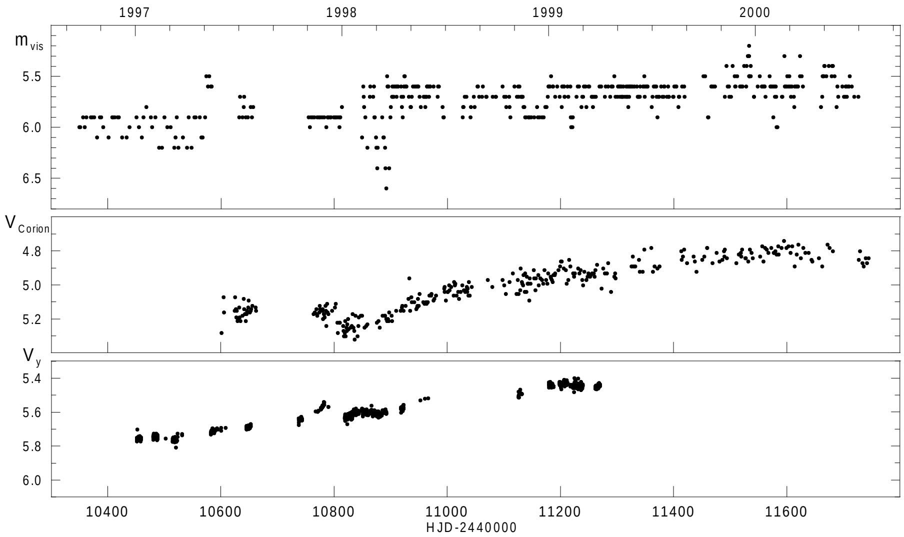

Fig. 4. Top: visual magnitude estimates of η Car, middle: CCD photometry with Corion NR-400 V filter, bottom: y-CCD photometry (23$''$.0 aperture). Source: Sterken et al. (2001).

etry of S Dor variables. See, as an example, Figure 3, which shows the transmission curves of three so-called V passbands: y, Johnson-V, and a Corion NR-400 broad-band filter. The full line gives the response of the human eye in night vision, and the triangles indicate the position of Hβ and Hα (lines with variable emission).

Figure 4 shows three light curves roughly obtained during the same time span. The visual magnitudes $m_{\rm vis}$ display a long-term brightness increase of an average 0.12 magnitudes per year. The middle panel gives the light curve in the $V_{\rm Corion}$ magnitude scale. Note the strong zero-point difference between the magnitude scales of both plots. The lower graph is the photomultiplier-based y photometry for the same period of time. It is evident that it is very difficult to combine sections of one of these graphs with parts of another. Besides some limited information on gradients and trends, these three light curves are simply incompatible.

7. The V-scale zero-point and the transformation from y to V

HD 303308, the basic comparison star, is widely used as the primary key for bringing differential photometry of η Car to one scale. The difference between the V-magnitude listed in the GCPD, $V_{\rm GCPD}$, and $y_{\rm V}$ based on LTPV data[2] is less than 0.01 mag, and perfectly acceptable in view of the observational precision of 0.006–0.008 mag.

[2]Long-Term Photometry of Variables, see Sterken (1983, 1994).

However, this standard star has also been measured in closely-resembling setups, such as the *UBVRI* Kron-Cousins system, and there is much more confusion than one would like to admit.

8. The diaphragm matters

Classical photometers use a set of fixed diaphragms which, typically, have sizes of 10 to 30 arcsec. Figure 5 in Sterken et al. (1999) illustrates the effect for the three diaphragms that were used during our photometric monitoring. It is evident that each instrument measures a different area of the η Car region: whereas one configuration barely encompasses the far wings, the other aperture includes two nearby stars, and a much larger nebular area. Figure 5 shows the CCD-field of η Car with calibration star HD 303308 (with $13''.3$ aperture). The apertures surrounding η Car measure $13''.3, 23''.0$ and $33''.6$.

A circular aperture with diameter $13''.3$ was used for calculating aperture photometry of the central core with some contributed light of the surrounding Homunculus (smallest aperture shown in Figure 5). We also repeated our calculations for two larger apertures (diameters $23''.0$ and $33''.6$) including a larger section of the Homunculus region. The aperture used for the comparison star magnitudes was $13''.3$. Figure 6 illustrates the effect caused by the selection of the aperture size. The average y-magnitude difference between the $13''.3$ and the $23''.0$ aperture amounts to 0.05 mag, and for the difference with the largest aperture ($33''.6$) the discrepancy amounts to 0.07 mag. Note that these offsets are *not constant*: sporadic excursions up to almost 0.1 mag appear, and sometimes there are night-to-night differences of several hundredths of a magnitude. It is not possible to separate instrumental effects (focus) and atmospheric effects (seeing). We conclude that – though it is possible to establish an overall correction factor to accommodate magnitudes of η Car obtained with other apertures – the correction of a single isolated measurement remains prone to random errors of the order of 0.005–0.015 mag.

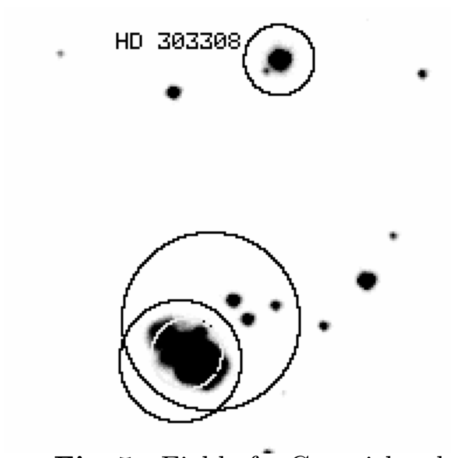

Fig. 5. Field of η Car with calibration star HD 303308 (see text).

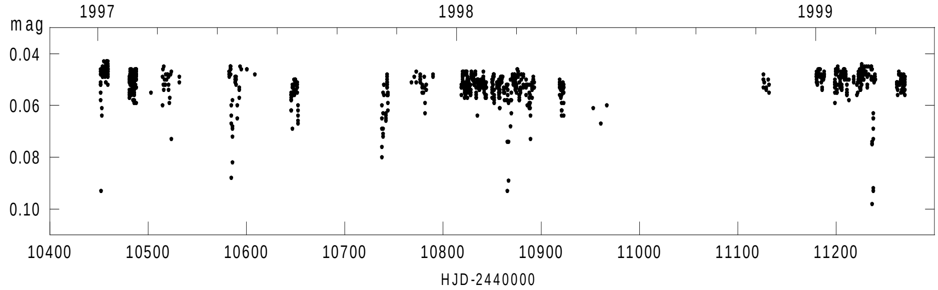

Fig. 6. y magnitude differences between 13″.3 and the 23″.0 apertures (Sterken et al. 2001).

9. The effect of spectral features: Hα and other emission lines. The Balmer jump is not the only quasi-discontinuous spectral feature: η Car, from time to time, has strong emission lines in the spectrum, and the presence of such lines in one or more passbands will modify the color indices in an uncontrollable way. In the right panel of Figure 5 of Sterken et al. (2001), several off-liers appear: they are all peculiar stars or binaries with "underestimated" V magnitudes. Thus, "underestimated" V magnitudes based on y filter photometry of a peculiar star like η Car are not to be considered a suspicious characteristic of intermediate-band photometry, but as an inherent element of the photometric approach of discussing V magnitudes on the basis of data obtained with a Strömgren y filter.

3. CONCLUSIONS

Those transformation problems are less disturbing in the visual passbands, but still render any comparison of isolated photometric magnitudes and color indices very difficult: the combination of non-overlapping data taken with different detectors, different diaphragm sizes and different filter systems (even seemingly-close UBV systems) is, to say the least, hazardous. From our previous experience, we estimate that such systematic effects may easily reach 0.1–0.2 mag. As such, when comparing η Car V magnitudes from one database with isolated Johnson's V measurements, great care must be taken because the unavoidable differences between photometric systems may result in very severe discrepancies. After all, V_{Johnson} is what is measured with a photometer using Johnson's V filter, while other V are magnitudes constructed from y, V_{Walraven}, V_{Geneva}, etc.

Any useful photometric monitoring of this most enigmatic star must satisfy the conditions of (1) being in a suitable multicolor photometric system, (2) delivering a vast amount of data (sparse and isolated data sets in mutually incompatible filter systems are inadequate) and (3) yielding data that overlap in time in order to assure contiguous and homogeneous blending of adjacent light curves.

Whether the multicolor photometry is carried out in an established standard system is not an absolutely necessary condition, as long as the internal homogeneity of the data is guaranteed.

REFERENCES

van Genderen A. M., Sterken C. et al. 1999, A&A, 343, 847

van Genderen A. M. 2001, A&A, 366, 508

de Groot M., Sterken C. 2001, *P Cygni 2000: 400 Years of Progress*, eds. M. de Grrot & C. Sterken, ASP Conf. Ser., 233, 289

Jones A., Sterken C. 1997, Journal Astron. Data, 3, 3

Sterken C. 1983, The ESO Messenger, 33, 10

Sterken C. 1994, in *The Impact of Long-Term Monitoring on Variable-Star Research*, eds. C. Sterken & M. de Groot, NATO ASI Ser. C, 436, 1

Sterken C., van Genderen A. M., de Groot M., Burki G. 1999, in *Eta Carinae at the Millennium*, eds. J. A. Morse, R. M. Humphreys & A. Damineli, ASP Conf. Ser., 179, 200

Sterken C., Freyhammer L. M., Arentoft T., van Genderen A. M. 2001, in *P Cygni 2000: 400 Years of Progress*, eds. M. de Groot & C. Sterken, ASP Conf. Ser., 233, 39

Sterken C. 2003, in *Interplay of Periodic, Cyclic and Stochastic Variability in Selected Areas of the HR Diagram*, ASP Conf. Ser., 292, 437