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Strömgren *uvby* photometry of σ Scorpii I. 1972–1974

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Abstract

This paper presents and discusses information about the observations and data reductions of a time series of photometric measurements of σ Sco that has been collected in 1972 and 1974. Nearly two thousand standardised *uvby* magnitude differences σ Sco *minus* τ Sco, together with unpublished instrumental differential magnitudes, are herewith supplied. This extended dataset will enhance the applicability of these more than four decades old measurements when used in studies based on data obtained with modern-day techniques such as robotic and space telescopes.

Keywords: technique: photometric – stars: individual: σ Sco, τ Sco, AG Car – variable stars: β Cephei stars, S Doradus stars

1 Introduction

σ Sco (HD 147165 = HR 6084) is a high-mass ($18.4 \pm 5.4\,M_\odot$, North et al. 2007) binary with a β Cephei-type pulsating variable primary component. Selga (1918) was the first to obtain a large number of spectrograms (191 plates in 1914–1915) from which he derived a period of $0.^{d}246829$ – the second shortest period thus far found.

Van Hoof (1966) was the first to carry out a systematic photometric monitoring of σ Sco: Pretorius, Van Hoof, Haffner, Briers and Bester obtained photometry during 74 nights in 1962–1965 with the 60″ Rockefeller telescope of the Boyden Observatory in South Africa. From these data, Van Hoof (1966) derived a main pulsation period $P_0 = 0.^{d}2468406$ and a secondary period $P' = 0.^{d}2396710$ yielding a beat period $P_b = 8.^{d}256$ that is nearly exactly $\frac{1}{4}$ of the value of the orbital period $P_{\rm orb} = 33.^{d}008$ that he derived. He noted that P_0 is on the decrease since 1955, and that little is left of the earlier suggested secular increase of 2.3 sec/century that was believed to have an evolutionary significance.

Van Hoof's work on the main period and its variation inspired the author to undertake an observing run of 52 contiguous nights in 1972 supplemented by another 3 nights in 1974.

The resulting photoelectric data were first used by Sterken (1975) for a study of the variation of P_0 that concluded that the main period was again on the increase. The 4-colour data were consequently used by Jerzykiewicz & Sterken (1984), who found two additional low-amplitude components with periods $0\overset{\mathrm{d}}{.}16745$ and $0\overset{\mathrm{d}}{.}15595$. The partial dataset of differential magnitudes, transformed to the standard *uvby* system, was published by Sterken (1984).

In the present paper we offer the same data combined with the unpublished instrumental magnitudes, supplemented by a more substantial description of observational and instrumental information, and with a more detailed account of the data-reduction procedures. The reasons for doing so are the following:

1. first and foremost, σ Sco has been proposed as a target for the BRITE mission[1] (Handler 2012),
2. the data reported by Sterken (1984) are not machine-readable,
3. the sixth page of Table 1 of that publication was omitted during the printing process, and thus the published dataset is incomplete,
4. the differential magnitudes were given on a standard *uvby* system, and no instrumental magnitudes were provided,
5. when combining these more than 40 year old ground-based measurements with data obtained with modern-day techniques (such as data obtained from space), a more detailed description of the instrumental setup is required for a proper assessment of the technical limitations of these vintage data.

2 Telescope, photometer and data acquisition

2.1 The telescope and the four-colour photometer

The observations were carried out at the European Southern Observatory (ESO La Silla Observatory) from 29 April to 19 June 1972, and on 3 nights in early May 1974. The Danish National 50-cm Cassegrain $f/13.6$ Dall–Kirkham reflector[2] had been relocated from Brorfelde Observatory to La Silla one year before the bulk of our data were collected. A vintage photograph of the telescope and of its dome building is reproduced in Figs. 1 and 2.

The simultaneous four-colour photometer was described by Grønbech et al. (1976). The instrument basically is a grating spectrograph (see Fig. 3) in which slots isolate four wavelength windows that contain the u, v, b and y filter transmissions. This set of four interference filters was one of a batch of filter sets acquired from the Kitt Peak National Observatory, and the transmission curves match fairly closely those of the filters used in the original *uvby* photometric system. The passbands of the Danish photometer are entirely

[1] www.univie.ac.at/brite-constellation/index.html

[2] The telescope had been designed and built by Poul Bechmann at the mechanical shop of Copenhagen Observatory.

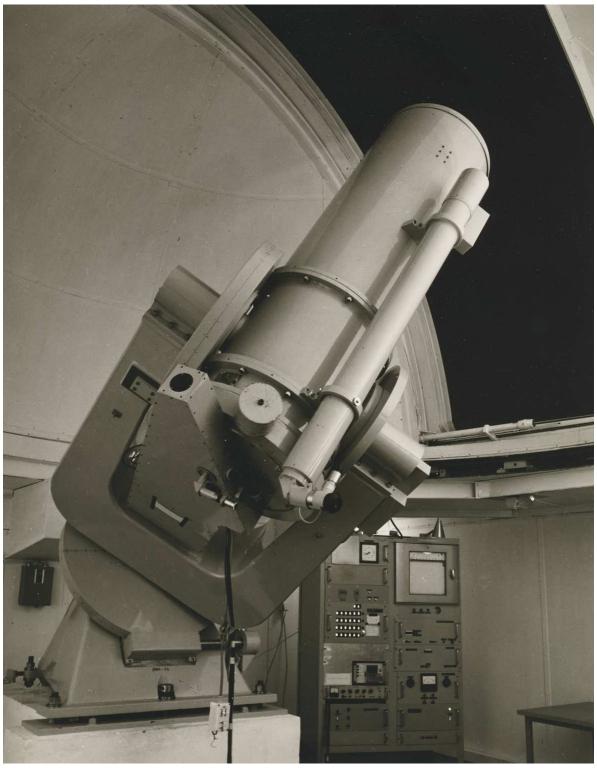

Figure 1: The Danish 50-cm telescope equipped with the original *uvby* photometer. The electronic rack in the background houses a printer, and has four 6-digit Nixie tube displays that give the total number of counts. Photo courtesy ESO.

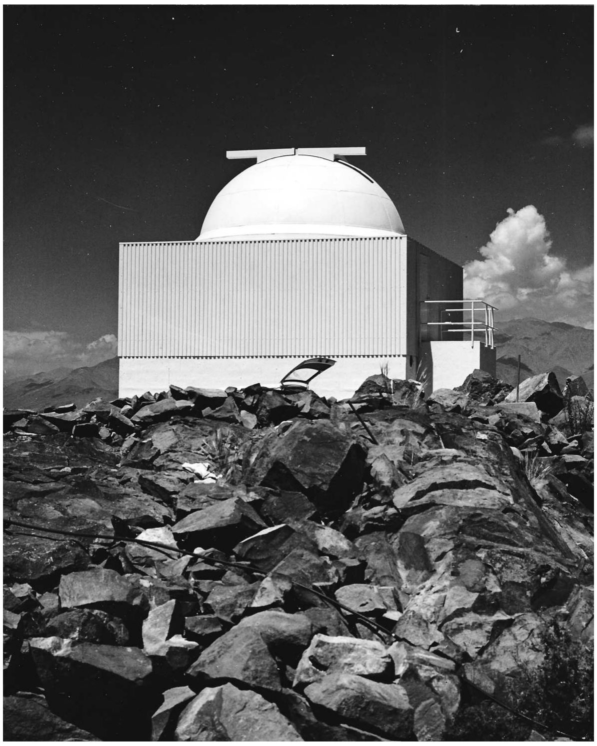

Figure 2: The Danish 50-cm dome in the early 1970s. The black cable on the foreground is part of the ground loop of the earthing system of the Danish 50-cm and Bochum 60-cm telescopes. Photo courtesy ESO.

defined by the slots and by the filters placed in front of the four uncooled EMI 6256SA photomultipliers. The normalised sensitivity functions – obtained by multiplying the filter transmission with the product of the photomultiplier sensitivity, the zenith transmission, the mirror reflectivities and the grating modulation function – as given in Table 2 of Grønbech et al. (1976) are shown in Fig. 6.

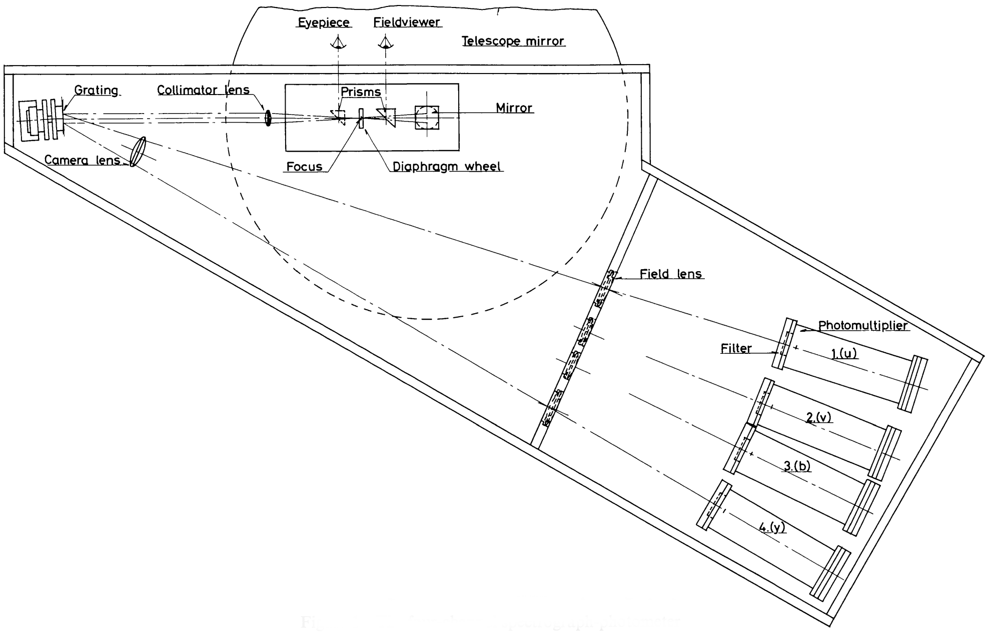

Figure 3: The Danish *uvby* photometer. Source: Grønbech et al. (1976).

2.2 The data acquisition

Stellar irradiance was measured by "pulse counting", i.e., a pulse height discriminator was used in standard fashion. The dead-time of the system is 70 nanoseconds. Data recording in the dome consisted of a printout on a simple drum printer with a fixed font numerical character set engraved onto the periphery of 8 print wheels (the printer is located just below the fluorescent tube displays in Fig. 1) producing long 6-cm wide paper ribbons that record the sum of counts in each channel, the integration time and the object identifier (both set by toggle switches), and the sidereal time. The electronic rack in the dome also had four 6-digit Nixie tube[3] displays that showed the total number of counts.

[3]A Nixie tube is a glass tube that contains a wire anode and multiple cathodes, shaped like numerals.

3 The observations

τ Sco (HD 149438 = HR 6165, B0.2V), the comparison star used by Van Hoof (1966), was used as the only comparison star. Our entire dataset, thus, rests on the assumption that the comparison star is constant. One measurement consisted of the sequence $\tau\ s\ \sigma$, where τ and σ represent four to five four-second integrations of the comparison and the program star respectively, and s stands for two to three integrations of the sky background.

Due to technical problems causing difficulties in pointing the telescope during some nights, the observer decided to collect consecutive integrations of σ Sco in blocks of about three minutes. In between those intervals, four integrations of the comparison star were taken each time.

The 1972 observing run was severely hampered by a number of technical problems, viz.,

1. The motorised dome movement broke down early in the observing mission, but since the declination of both stars (-25° to -28°) nicely coincides with the observing site's geographical latitude of $-29^\circ 15'$, several hours of observing were possible with the dome slit pointing East or West, so that each night only one manual movement of the heavy dome was needed.

2. The aforementioned limited sky coverage due to a stationary dome slit severely restricted the selection of standard stars.

3. The synchronisation of one of the printer wheels broke down, so that the second column of digits (i.e., each digit standing for 10 000 counts) had to be recorded by hand for each printed line.

4. As the telescope tracking was not optimal – a fact that did not hamper the measurements of the comparison star – this defect, from time to time, must have interfered with the measurements of σ Sco because of its $19\farcs95$ nearby companion σ Sco B ($V = 8.3$) drifting on the edge of the $30''$ diaphragm.

5. Since σ and τ Sco are too bright for photometry with a 50-cm telescope, a ring-shaped diaphragm was installed on top of the telescope tube. This diaphragm had to be mounted when preparing the telescope for the night, and was removed when closing down each morning. This ring diaphragm decreased the f-ratio of the telescope optics, and may have introduced some diffraction effects in the 1972 as well as in the 1974 data.

4 Data reduction

Data reduction in the early 1970s merely was a labor-intensive manual job. The numbers on the print ribbons were transferred to tabular paper, together with the corrections for the defective printer wheel. Counts were then keyed in on a HP 9100A programmable desktop scientific calculator (see Fig. 4) of which one machine was available at La Silla, and another one at the ESO Headquarters in Santiago. According to the HP Computer Museum (`www.hpmuseum.net`), the term "personal computer" was first documented in a 1968 Science magazine[4] advertisement[5] for the Hewlett-Packard 9100A. This US$ 5000 PC, weighing over 18 kilograms, could handle trigonometric and logarithmic functions and used a 3-level *Reverse Polish Notation* (RPN, a system for representing mathematical expressions without the use of parentheses). This machine had the great advantage of having a magnetic card reader/writer. The HP 5000-5884 Calculator Program Card had two tracks that could store 196 steps each, just enough for programming the sequence $-2.5 \times \log(\mathrm{star} - \mathrm{sky}) +$ constant as well as Hardie's equation for air mass (Hardie 1962).

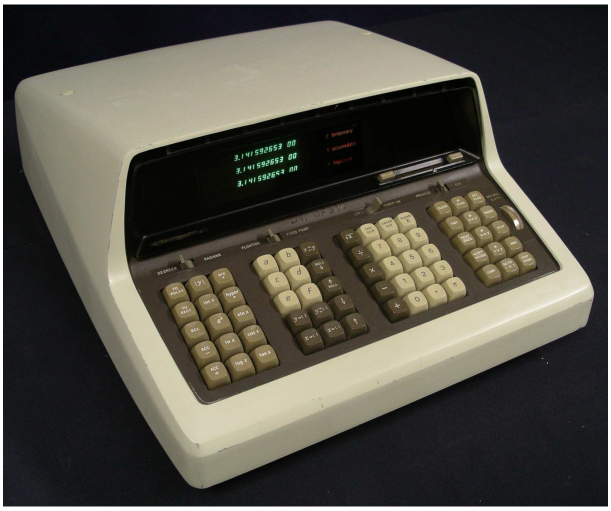

Figure 4: HP 9100A desktop computer. Courtesy HP Computer Museum, `www.hpmuseum.net`.

4.1 Atmospheric extinction

Atmospheric extinction was determined with the graphical Bouguer method applied to the visual instrumental magnitudes y, and to the colour indices $y-b, b-v$ and $v-u$ of τ Sco. Figure 5 shows an example of the original plots. The extinction coefficients were derived by linear least-squares fits (with the HP 9100A). The resulting nightly coefficients were published by Sterken & Jerzykiewicz (1977), and are also given for each passband in Table 1.

4.2 Transformations to the standard *uvby* system

The nightly transformation equations to the standard system of Crawford & Barnes (1970) were derived graphically in the same way as the Bouguer lines were determined (for a sample, see Fig. 5).

The transformation from raw counts to extinction-corrected instrumental magnitudes took several months. These magnitudes were finally transferred to IBM 80-column punched

[4] Science, October 4, 1968.

[5] `www.hp.com/hpinfo/abouthp/histnfacts/museum/personalsystems/0021/other/0021ad.pdf`

Table 1: Extinction coefficients *k*.

ddmmyy	JD	k_y	k_b	k_v	k_u
280472	1436.6	0.142	0.184	0.303	0.580
290472	1437.6	0.123	0.180	0.290	0.571
300472	1438.6	0.124	0.169	0.283	0.564
010572	1439.6	0.128	0.179	0.289	0.566
020572	1440.6	0.119	0.167	0.275	0.551
030572	1441.6	0.161	0.181	0.289	0.571
040572	1442.6	0.060	0.174	0.290	0.582
090572	1447.7	0.103	0.166	0.266	0.549
100572	1448.7	0.120	0.180	0.294	0.602
110572	1449.6	0.116	0.154	0.263	0.531
120572	1450.6	0.114	0.175	0.287	0.560
140572	1452.6	0.143	0.190	0.299	0.573
150572	1453.6	0.115	0.163	0.271	0.539
160572	1454.6	0.047	0.147	0.271	0.575
180572	1456.7	0.090	0.166	0.279	0.576
250572	1463.5	0.126	0.165	0.275	0.542
300572	1468.5	0.139	0.184	0.286	0.549
310572	1469.5	0.125	0.179	0.291	0.566
140672	1483.7	0.101	0.178	0.293	0.602
150672	1484.5	0.116	0.169	0.277	0.556
160672	1485.5	0.074	0.157	0.271	0.529
170672	1486.5	0.091	0.162	0.272	0.535
180672	1487.5	0.114	0.170	0.287	0.589
080574	2176.6	0.119	0.166	0.288	0.564
100574	2178.6	0.125	0.175	0.299	0.577
110574	2179.5	0.119	0.175	0.289	0.567

cards, after which all magnitudes were transformed to standard values using the IBM System/360 Model 30 mainframe computer at the University of Ghent (Belgium) in 1973.

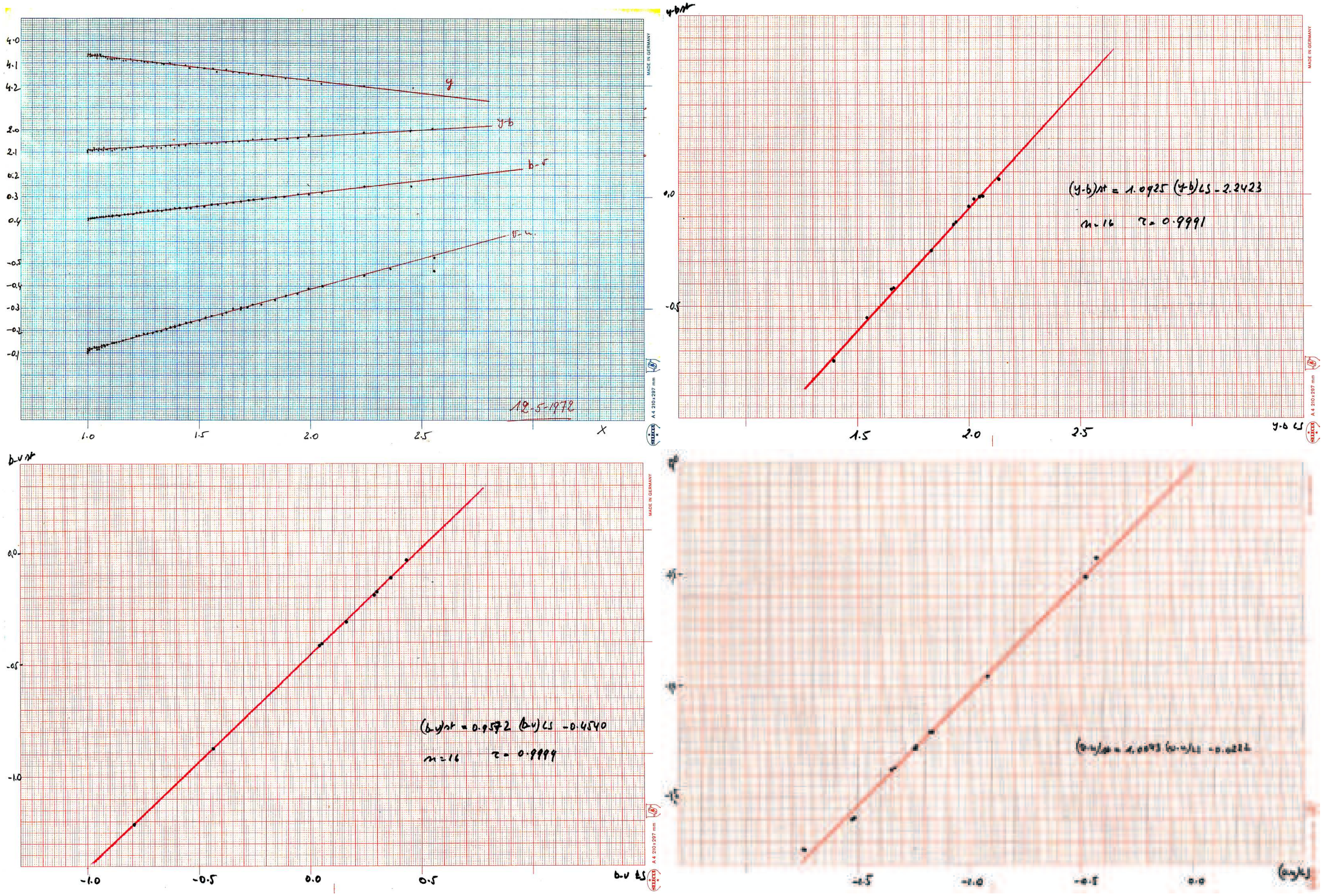

Figure 5: Bouguer extinction curves for May 12, 1972 (Top left) and linear transformations in the $y-b$, $b-v$ and $v-u$ colour indices for the same date.

5 The magnitude data

The dataset consists of 1946 standardised *uvby* magnitude differences σ Sco *minus* τ Sco, together with the associated magnitude differences in the instrumental system. Table 2 shows the first couple of lines of the ASCII-file `uvby.dat`.

Table 2: Heliocentric Julian Date, differential magnitudes y_s, b_s, v_s, u_s in the standard system, and instrumental differential magnitudes y_i, b_i, v_i, u_i (first 8 datalines of `uvby.dat`).

HJD−2440000	y_s	b_s	v_s	u_s	y_i	b_i	v_i	u_i
1436.6381	0.065	0.331	0.532	0.801	0.067	0.307	0.517	0.787
1436.6531	0.061	0.321	0.519	0.782	0.063	0.298	0.504	0.768
1436.6567	0.039	0.317	0.516	0.783	0.040	0.291	0.499	0.767
1436.6601	0.047	0.316	0.517	0.783	0.049	0.291	0.501	0.768
1436.6754	0.050	0.322	0.523	0.786	0.052	0.297	0.507	0.771
1436.6807	0.061	0.317	0.521	0.785	0.063	0.294	0.507	0.772
1436.6881	0.049	0.325	0.528	0.797	0.051	0.300	0.511	0.782
1436.6911	0.054	0.320	0.524	0.791	0.056	0.296	0.508	0.777

6 Intricacies of photometric transformations

Manfroid & Sterken (1992) discussed the fact that the transformation of photometric data between two different systems (thus also between an instrumental and a standard system) introduces errors of two kinds, viz., *conformity errors* and *reduction errors*. Conformity errors arise from the very fact that the passbands of both systems are just too different to allow for the construction of reliable transformation equations. Reduction errors, on the other hand, are of a purely methodological nature, and are due to the limited range of stellar spectral types and the distribution of colour indices used in the determination of the transformation equations.

Our data set should be free of conformity errors, since we have used one and the same instrumental setup. When combining our data with another *uvby* instrumental system, however, such errors can become substantial, and combining these data with magnitudes and colour indices in a totally different photometric system can be quite hazardous. Take, for example, the photometric system in use on the BRITE satellites: Fig. 6 shows the BRITE instruments BLUE and RED filter transmission curves, and CCD QE response together with the sensitivity curves of the *uvby* system that was used for observing σ Sco in 1972–1974. The RED passband is much wider (150 nm) than the visual passband y, and only covers its red wing, while the BLUE passband covers v but in addition contains H_γ.

For what concerns the second type of errors, two aspects should be taken into account for this specific case of observations of σ Sco:

1. A proper selection of standard stars all over the sky was not possible for technical

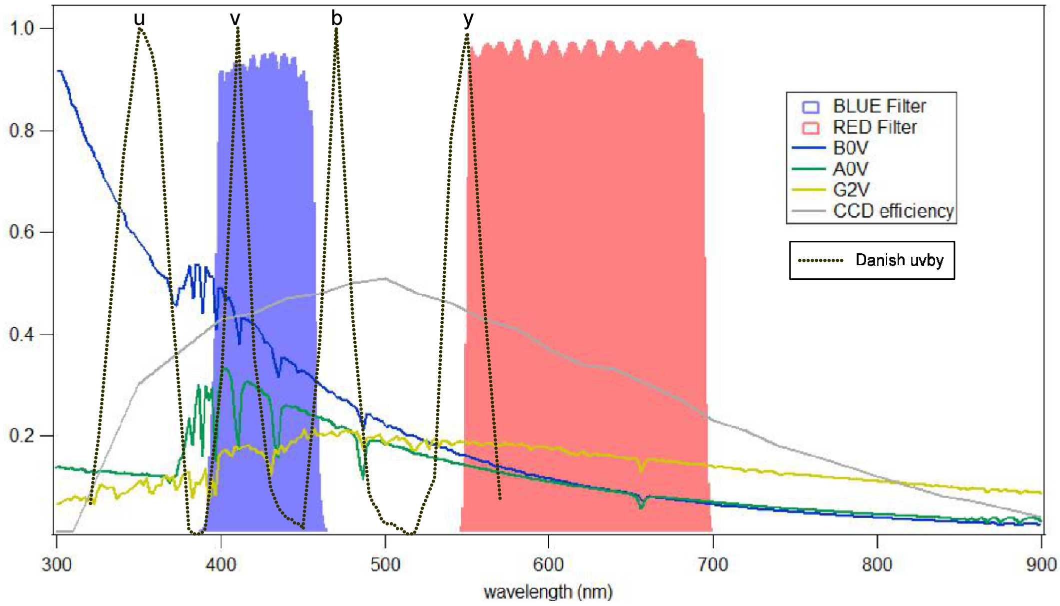

Figure 6: BRITE instruments BLUE and RED filter transmission curves, and CCD quantum-efficiency response compared to stellar flux spectra (source: `http://www.univie.ac.at/brite-constellation/html/filters.html`) together with the sensitivity curves of the *uvby* system (see text).

reasons (see Sec. 3), so the standards were necessarily restricted to stars in the vicinity of the declination circle at 30° south.

2. Because of the very basic computing facilities during the early stages of data reduction (extinction and standardisation), advanced computer methods such as the multi-night approach or the all-sky extinction determination (Sterken & Manfroid 1992, Chapter 10) could not be applied. Hence, the transformation equations were applied on a night-to-night basis, instead of a multi-night approach.

On a more general scale, there is a third source of problems, viz., those caused by the presence of strong emission lines in the stellar spectrum. A most instructive example of combining decade-old Johnson V magnitudes with more recent Strömgren y magnitudes for a star with an extreme spectrum was presented by Sterken (2012). Arlo Landolt observed the S Doradus star AG Carinae (HD 94910) in 1967 in the UBV system and Bond & Landolt (1970) found that "AG Car slowly varied in V over a range of $0\overset{m}{.}16$", see Fig. 7. These authors clearly specified the standardisation procedure:

> *A standard set of UBV filters, a refrigerated 1P21 photomultiplier, and observations of numerous UBV standards each night permitted the transfer of all data onto the UBV photometric system.*

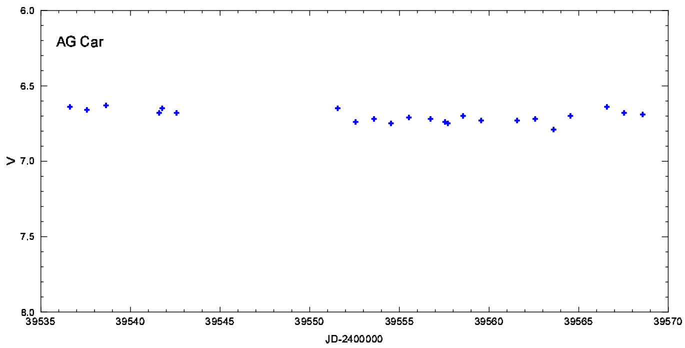

Figure 7: The variations of AG Car in 1967, based on the data in Table 1 of Bond & Landolt (1970).

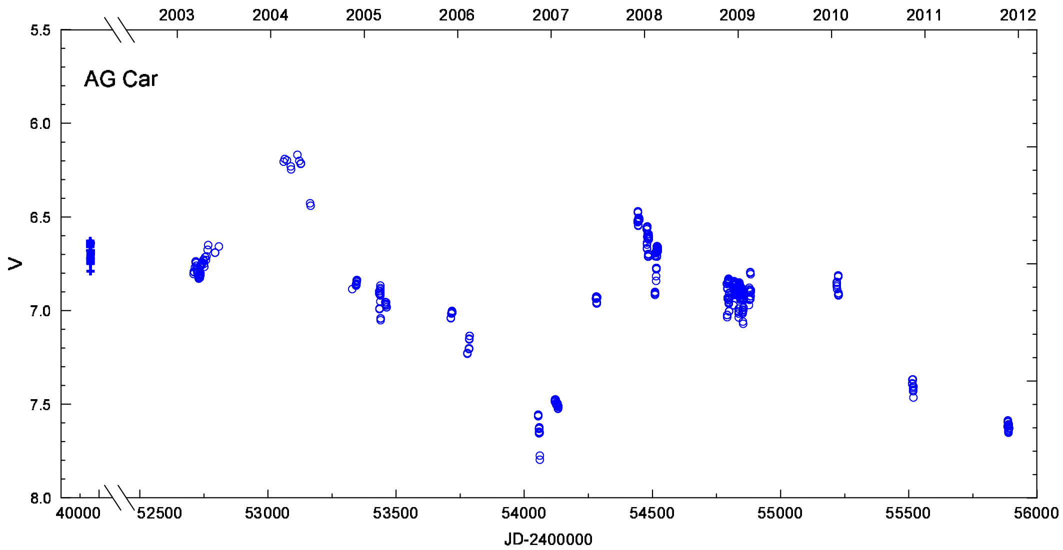

Figure 8: The variability of AG Car on a time scale of one decade. +: Bond & Landolt (1970), ○: based on data of the *Long-Term Photometry of Variables* project, see text.

When combining Landolt's 1967 V magnitudes with Strömgren y magnitudes obtained with the same Danish 50-cm telescope but with the next-generation 4-colour photometer (data collected in the framework of the *Long-Term Photometry of Variables* project, Sterken 1983) we get a totally different picture: whereas the star appeared to be in a relatively quiescent state in the mid-1960s (short-term variability on the 4–5 σ level), its long-term behaviour in 2003–2012 shows that the object undergoes quasi-cyclic variations with an amplitude exceeding 1 magnitude (Fig. 8). These observations were taken in a later variant of the Strömgren system, and the combination of the V and y magnitudes can still be done with a fair amount of reliability because the y-band does not contain any strong emission features (such as the higher Balmer lines, see Fig. 9). However, there is no way to combine the y and V datasets and still achieve the same level of accuracy as described by Bond & Landolt (1970).

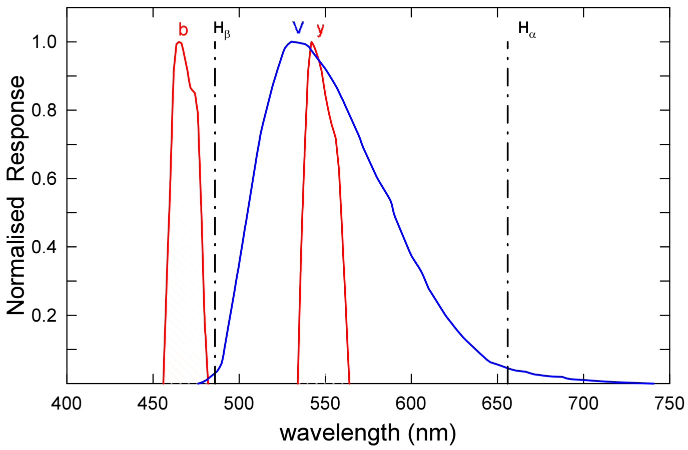

Figure 9: Response curves for the Johnson V and Strömgren y passbands together with the position of the Balmer lines Hα and Hβ.

7 Conclusions

This outline of information about the observations and data reductions should enable any user of this dataset to properly assess the precision of the time series. There are four important aspects that are irrevocably linked to these data, and that cannot be changed:

1. The spectral window of the data, i.e., the distribution of the observing windows – see Figs. 1 and 2 in Jerzykiewicz & Sterken (1984),
2. the accuracy of the sidereal time clock – an unknown parameter, though of utmost importance in $O-C$ studies,
3. the hardware limitations of the photometric system's passbands, and
4. the underlying assumption of the observational approach – that is, the photometric constancy of τ Sco.

Landolt (2012) summarised the pitfalls of standardisation: standards must include reddened and unreddened stars, as well as stars of each spectral class and luminosity type, and last but not least one single set of reduction procedures should be applied. Besides this, he also mentioned "problems of environment, filters, detectors, and cantankerous troubles". Unfortunately, not many photometrists have life-long access to an open, stable and well-calibrated photometric system, and many have no other choice than to use whatever photometer that is made available. As such, all photometry of stellar objects carries a time stamp – and even the standards carry a time stamp as well.

Successful research depends on the understanding of that time stamp; unfortunately that stamp is very seldomly explicated in detail.

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Acknowledgments

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