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# Strömgren photometric study of BS Aqr

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**Abstract.** Simultaneous *uvby* photometric observations of the high amplitude $\delta$ Sct star BS Aqr have been collected and new times of light maxima were obtained. Additionally, some $H_\beta$ observations are also presented. The light curves have been analysed and the physical parameters of this star are determined. The results indicate that BS Aqr is an evolved monoperiodic $\delta$ Sct star, with solar abundances, pulsating radially in the fundamental mode.

**Key words:** $\delta$ Scu – stars: individual: BS Aqr – stars: oscillations – techniques: photometric

## 1. Introduction

BS Aqr (HD 223338) is one of the high amplitude $\delta$ Sct stars with longer periods known (V=9.$^m$39, $\Delta$V=0.$^m$44, P=0.$^d$1978, Rodríguez et al. 1994). Its variability was discovered by Hoffmeister (1931), who classified it as an irregular variable. During the following two decades, some authors observed this star, but their results led to very different interpretations about the nature of its variability. Finally, Spinrad (1959) classified BS Aqr as an ultra short period variable ($\delta$ Sct type) on the basis of his photoelectric observations. Since that date several authors have made new observations of BS Aqr using mainly the Johnson photometric system. Only a few data, collected in 1965 by Langford (1976), were obtained using Strömgren photometry. From these works BS Aqr seems to be a monoperiodic pulsator, at least no marked distortions are apparent in its light curves. Moreover, different interpretations are given in the bibliography on the period change for this star: the period is continuously decreasing (e.g., Elst 1986; Yang et al. 1993) or the period is actually decreasing due to both the intrinsic continuous decreasing combined with the light-time effect caused as part of a binary system (Fu et al. 1997). The main aim of the present work is to achieve a detailed photometric study of this star using new and simultaneous measurements in Strömgren photometry.

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## 2. Observations

Simultaneous photometric *uvby* observations were carried out through the years from 1992 to 1995 at the observatories of San Pedro Mártir, México (1.5 m telescope) and Sierra Nevada, Spain (0.9 m telescope). Additionally, some $H_\beta$ data were collected during 1997 using the latter telescope. Both telescopes are equipped with identical six-channel *uvby*$\beta$ spectrograph photometers for simultaneous measurements in *uvby* or in the narrow and wide $H_\beta$ channels, respectively, using uncooled EMI photomultipliers type 9789 QA (Nielsen, 1983).

Throughout HD 222465 (V=7.$^m$2, F8) was used as the main comparison star with HD 223216 (V=7.$^m$6, F8) and HD 224093 (V=6.$^m$7, F0) as check stars. During the observations reported here, neither of the comparison stars showed any sign of variability. The standard deviations of C2-C1 were found to be of 0.$^m$0092, 0.$^m$0059, 0.$^m$0051, 0.$^m$0054, 0.$^m$0029, 0.$^m$0095 and 0.$^m$0054 for *u*, *v*, *b*, *y*, b-y, $c_1$ and $\beta$, respectively. In the case of C3-C1, the values obtained for the standard deviations are of 10.3, 5.3, 4.8, 4.5, 2.9 and 12.2 mmag, respectively. Please note that $\beta$ values were not collected for C3. To transform our data into the standard system we have used the same procedure described in Rodríguez et al. (1997). The data obtained, as magnitude differences variable minus C1=HD 222645 in the standard system versus Heliocentric Julian Day, have been deposited in the Commission 27 IAU Archives of Unpublished Observations, file 335E, and can also be requested from the authors.

## 3. Results

### 3.1. Periods

Firstly, analysis of frequencies was carried out on our data in the *v* filter using the Discrete Fourier Transform method, as described in López de Coca et al. (1984), using a Fourier sine fitting formula. The periodograms showed a principal peak at $\nu$=5.0550 cd$^{-1}$, agreeing with the period P=0.$^d$19782 derived by earlier authors. After prewhitening for this frequency and its harmonics, the resulting periodograms did not show any trace of another peak, suggesting the monoperiodic nature of this star. The same analysis was performed on all the other three *uby* filters and the results were consistent among them. Frequency

**Table 1.** New times of maxima of BS Aqr

| i | $T_i$(HJD) 2400000.+ |
|---|---|
| 1 | 48912.8046 |
| 2 | 49606.7644 |
| 3 | 49606.9621 |
| 4 | 49607.9513 |
| 5 | 49956.5150 |
| 6 | 49957.5048 |

analysis was also carried out on the different data sets available from earlier authors, especially on the five best ones, i.e. to the 1961-62 V data of Tremko & Sajtak (1964), the 1973 B and V data of Elst (1976) and the 1983 B and V data of Meylan et al. (1986). In all the cases we find similar results to those found with our data. Therefore, we conclude that there are no remaining periodicities in the light variation of BS Aqr.

Using the new data, six new times of light maxima were obtained (they are listed in Table 1) between 1992 to 1995 by using the method described in Rodríguez et al. (1990), where each light maximum was derived as an average over the three *vby* bands. The *u* band was not considered for the averages since the time of maximum for this filter is shifted with respect to the other three by about 0.015 cycles (see Table 2), as with other $\delta$ Sct type pulsators (Rodríguez et al. 1993 and references therein). These times of maxima were used to obtain a linear ephemeris to describe our data. $T_0$=2449606.$^d$7644 (our second light maximum) was adopted as the initial epoch and $P_0$=0.$^d$197822612 (from Fu et al. 1997) as the initial period. The corresponding least-squares fit leads to a linear ephemeris with the following elements: T=2449606.$^d$7649 ($\pm$0.0002) and P=0.$^d$1978224 ($\pm$0.0000001). The residuals are very small and the standard deviation of the fit is of only 0.$^d$0006. Thus, this ephemeris seems to describe well the pulsation of BS Aqr for our *uvby* data from 1992 to 1995. Unfortunately, we have not precision enough to calculate times of maxima in $\beta$ using the data collected in 1997 and, therefore, to make a further O–C analysis with a longer baseline.

### 3.2. Photometry

The phases of all individual observations were calculated according to the above derived linear ephemeris. Fig. 1 shows the resulting light and colour index variations of BS Aqr along the cycle of pulsation. In agreement with other high amplitude $\delta$ Sct pulsators, the dispersion showed in the $\beta$ curve is much larger than in the other ones because the intensity in the narrow and wide $H_\beta$ channels is much smaller than in all the other bands. Nevertheless, in the case of BS Aqr, the dispersion showed in the $\beta$ curve seems to be too large. In fact, the residuals are of 0.$^m$0167. This high scatter might be produced by systematic errors in the $\beta$ measurements (as due to errors in subtracting the sky; the sky is very critical for the $\beta$ measurements of BS Aqr) or to a possible complexity of the $\beta$ curve (additional to the intrinsic pulsation).

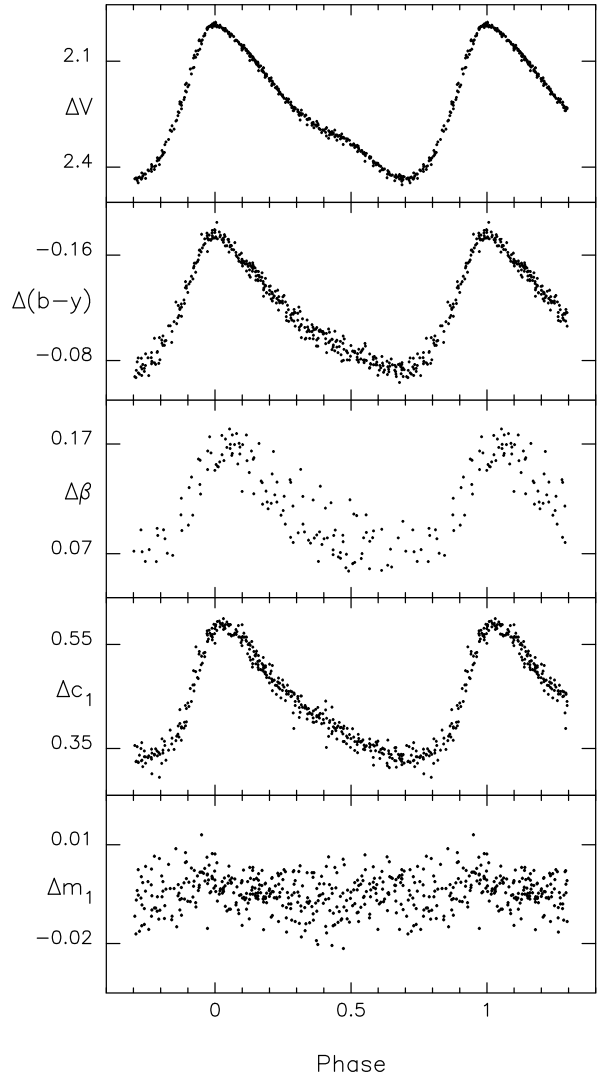


**Fig. 1.** Light curve and colour index variations of BS Aqr along the pulsation cycle

Table 2 lists the results of the Fourier decomposition, up to 6 terms, applied to the *uvby* data, with amplitudes, phases, mean values and residuals calculated for all the four *uvby* filters together with the b–y and $c_1$ indices. The initial time, $T_{or}$, corresponds to the phase 0.0. The residuals listed in this table are in good agreement with those listed in Sect. 2 for the comparison stars, taking into account that these objects are substantially brighter than the variable. On the other hand, the results listed in Table 2, for the V band, are in very good agreement with those obtained by Antonello et al. (1986) using the V data from Tremko & Sajtak (1964): the corresponding amplitude ratios and phase differences between harmonics are consistent with the results summarized in Table 3 of Antonello et al. (1986) who used a Fourier cosine fitting formula instead of our sine fit.

Fig. 1 shows that the b–y curve is phased with the V curve while the maximum in the $c_1$ index occurs some hundredths of a

**Table 2.** Results from Fourier fitting

| | *u* | | *v* | | *b* | | V | | b–y | | $c_1$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H | A (mag) | $\varphi$ (rad) | A (mag) | $\varphi$ (rad) | A (mag) | $\varphi$ (rad) | A (mag) | $\varphi$ (rad) | A (mag) | $\varphi$ (rad) | A (mag) | $\varphi$ (rad) |
| $\nu$ | 0.2054 | 4.240 | 0.2710 | 4.157 | 0.2279 | 4.147 | 0.1838 | 4.126 | 0.0443 | 4.238 | 0.1105 | 0.878 |
| | 8 | 4 | 6 | 2 | 5 | 2 | 5 | 3 | 4 | 8 | 10 | 9 |
| $2\nu$ | 0.0786 | 4.905 | 0.1012 | 4.683 | 0.0866 | 4.679 | 0.0710 | 4.683 | 0.0155 | 4.660 | 0.0427 | 1.134 |
| | 8 | 11 | 6 | 6 | 5 | 6 | 5 | 7 | 4 | 22 | 10 | 24 |
| $3\nu$ | 0.0205 | 5.957 | 0.0250 | 5.310 | 0.0216 | 5.360 | 0.0169 | 5.400 | 0.0048 | 5.221 | 0.0181 | 1.329 |
| | 8 | 40 | 6 | 24 | 5 | 23 | 5 | 30 | 4 | 71 | 10 | 56 |
| $4\nu$ | 0.0093 | 5.743 | 0.0138 | 5.443 | 0.0118 | 5.481 | 0.0094 | 5.488 | 0.0023 | 5.455 | 0.0076 | 1.869 |
| | 8 | 88 | 6 | 44 | 5 | 42 | 5 | 54 | 4 | 144 | 10 | 133 |
| $5\nu$ | 0.0037 | 5.869 | 0.0065 | 5.700 | 0.0056 | 5.757 | 0.0043 | 5.900 | 0.0014 | 5.316 | 0.0038 | 2.307 |
| | 8 | 219 | 6 | 93 | 5 | 89 | 5 | 117 | 4 | 234 | 10 | 265 |
| $6\nu$ | 0.0029 | 5.079 | 0.0035 | 5.791 | 0.0033 | 5.788 | 0.0027 | 5.755 | ... | ... | 0.0024 | 3.567 |
| | 8 | 278 | 6 | 175 | 5 | 154 | 5 | 187 | | | 10 | 422 |
| mean value (mag) | 2.3228 | | 2.0115 | | 2.1297 | | 2.2434 | | –0.1136 | | 0.4296 | |
| | 6 | | 4 | | 4 | | 4 | | 2 | | 7 | |
| residuals (mag) | 0.0118 | | 0.0080 | | 0.0066 | | 0.0068 | | 0.0045 | | 0.0135 | |
| $T_{or}$(Phase) | 0.0 | | | | | | | | | | | |

cycle after the maximum in V due to the temperature and gravity variations along the pulsation (Garrido & Rodríguez 1990). In addition, the $m_1$ index curve of BS Aqr shows only a very small variation in the same sense as the light curve. This suggests that BS Aqr is a star with metal content similar to the solar one (Rodríguez et al. 1991).

On the other hand, Table 2 shows that the light maximum in the V band occurs after both maxima in the *v* and *b* filters. Also, the maximum in b–y occurs before that corresponding to the V band. In particular, for the first harmonic, we obtain $\phi_v$–$\phi_V$=1.°8 (±0.3), $\phi_b$–$\phi_V$=1.°2 (±0.3) and $\phi_{b-y}$–$\phi_V$=6.°4 (±0.6). Similar results are obtained when our *vby* data collected in 1994 or 1995 are analysed independently (the data obtained in 1992 or 1993 are not enough for a Fourier fitting). These values agree very well with those obtained for the same star by Rodríguez et al. (1996) from earlier authors using Johnson photometry. These effects indicate radial pulsation for BS Aqr agreeing with the results obtained by these authors for a large sample of high amplitude $\delta$ Sct stars using Strömgren and Johnson photometry.

In order to discuss the variation of the physical parameters of BS Aqr, the individual observations were sorted by phase into twenty equally spaced bins throughout the cycle. Mean points for the magnitudes and colour indices were calculated for the midpoint phase of each bin. These normal points are listed in Table 3. The standard errors for the normal points in V, b–y, $m_1$, $c_1$ and $\beta$ are typically of 0.$^m$004, 0.$^m$001, 0.$^m$001, 0.$^m$004 and 0.$^m$007, respectively. Next, the standard magnitude differences of BS Aqr minus C1=HD 222465 were transformed to apparent magnitudes of the variable assuming the following values for C1: V=7.$^m$157, b–y=0.$^m$312, $m_1$=0.$^m$159, $c_1$=0.430 and $\beta$=2.$^m$629 (Olsen 1983, Hauck & Mermilliod 1990). The reddening can be derived by comparing the intrinsic and observed b–y indices at normal points along the pulsation cycle. This leads to a mean colour excess of $E_{b-y}$=0.$^m$008 (±0.007) using the reference lines of Philip & Egret (1980) with the appropriate corrections for gravity and metallicity (Crawford 1975a, Philip

**Table 3.** Photometry (normal points) of BS Aqr

| Phase | V | b–y | $m_1$ | $c_1$ | $\beta$ |
|---|---|---|---|---|---|
| 0.00 | 9.161 | 0.137 | 0.158 | 1.007 | 2.785 |
| 0.05 | 9.182 | 0.145 | 0.156 | 1.016 | 2.796 |
| 0.10 | 9.218 | 0.155 | 0.155 | 0.987 | 2.788 |
| 0.15 | 9.261 | 0.166 | 0.155 | 0.955 | 2.774 |
| 0.20 | 9.308 | 0.179 | 0.154 | 0.923 | 2.758 |
| 0.25 | 9.354 | 0.190 | 0.154 | 0.895 | 2.746 |
| 0.30 | 9.394 | 0.200 | 0.153 | 0.870 | 2.737 |
| 0.35 | 9.426 | 0.208 | 0.152 | 0.850 | 2.726 |
| 0.40 | 9.451 | 0.214 | 0.152 | 0.835 | 2.717 |
| 0.45 | 9.470 | 0.220 | 0.152 | 0.818 | 2.712 |
| 0.50 | 9.492 | 0.225 | 0.153 | 0.801 | 2.709 |
| 0.55 | 9.520 | 0.230 | 0.154 | 0.788 | 2.708 |
| 0.60 | 9.552 | 0.234 | 0.155 | 0.778 | 2.706 |
| 0.65 | 9.576 | 0.237 | 0.155 | 0.768 | 2.704 |
| 0.70 | 9.587 | 0.237 | 0.154 | 0.764 | 2.706 |
| 0.75 | 9.565 | 0.232 | 0.153 | 0.766 | 2.708 |
| 0.80 | 9.514 | 0.220 | 0.153 | 0.778 | 2.710 |
| 0.85 | 9.427 | 0.200 | 0.155 | 0.810 | 2.723 |
| 0.90 | 9.319 | 0.176 | 0.157 | 0.868 | 2.743 |
| 0.95 | 9.219 | 0.152 | 0.158 | 0.946 | 2.769 |

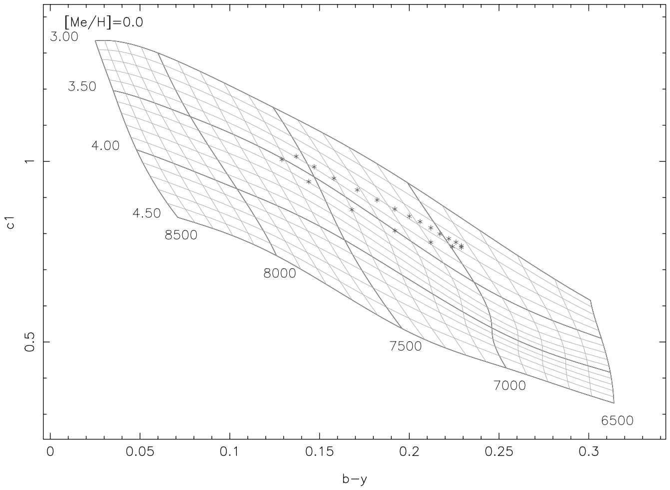


**Fig. 2.** Observed loop of BS Aqr in the ($c_1$, b–y) diagram. $T_e$ and log g lines are from Lester et al. (1986) for [Me/H]=0.0

et al. 1976). This value for the reddening obtained in Strömgren photometry is in good agreement with that of $0.^m007$ derived by Lub (1979) using the Walraven photometric system. Using $E_{c_1}$=0.2$E_{b-y}$ and $E_{m_1}$=–0.32$E_{b-y}$ (Crawford 1975b), very small corrections of $0.^m002$ and $-0.^m003$ must be applied to the $c_1$ and $m_1$ observed indices to obtain the corresponding intrinsic values of BS Aqr. This way, mean values along the cycle for the deviations from the ZAMS's values of $<\delta c_1>=0.^m230$ and $<\delta m_1>=0.^m025$ are found. These results indicate that BS Aqr is an evolved $\delta$ Sct star with nearly solar abundances.

In Fig. 2, $(b–y)_0$ and $c_0$ values, corresponding to normal points, are plotted in a (log g,$T_e$) grid from Lester et al. (1986) for [Me/H]=0.0. The effective temperature of BS Aqr varies from $T_e$=7780 K at light maximum to $T_e$=6820 K at light minimum while the effective surface gravity varies from log g=3.74 to log g=3.44. The mean values obtained along the cycle are $<T_e>$=7190 K and $<\log g>$=3.52. In addition, the log g-log P relation derived by Claret et al. (1990) for a large sample of Population I high amplitude $\delta$ Sct stars was used and a value of log g=3.53 can be obtained for BS Aqr in good agreement with the mean value found above for log g, suggesting pulsation in the fundamental radial mode.

We can also calculate the metal content from the $\delta m_1$ parameter at minimum light (phases from 0.6 to 0.8), when the metal lines are strongest and $m_1$ is most sensitive to abundance differences. By using the Nissen's (1988) calibration for metal abundances with $\delta m_{1min}=0.^m017$ it is found that [Me/H]=–0.13. From a comparison with the ($\Delta m_1^*$,$\beta$) grids from Rodríguez et al. (1991), a small $m_1$ index variation of about $0.^m005$, in the same sense as that of the V light curve, must be expected over the full cycle of pulsation of BS Aqr agreeing well with the observed $m_1$ index variation shown in Fig. 1.

In order to calculate the mass, luminosity and age of this star, the evolutionary tracks from Schaller et al. (1992) have been used for Z=0.020. Assuming mean values of $T_e$=7190 K and log g=3.52, a mass of 2.13($\pm$0.1) $M_\odot$ was obtained in a post-main sequence stage of evolution. The age corresponding to the position of this star in the log g-log $T_e$ diagram is of 1.0($\pm$0.2) $10^9$ years and $M_{bol}=0.^m7(\pm0.2)$. Finally, a value of $Q=0.^d034$ ($\pm$0.005) (Breger 1990) is found for the pulsation constant using the relation by Petersen & Jørgensen (1972), indicating pulsation in the fundamental mode.

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