Bull. Astr. Soc. India (1982) **10**, 234-243

Analysis of the light variations of BS Aquarii

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Received 1982 June 21; accepted 1982 July 20

Abstract. An analysis of *UBV* light variations of BS Aqr is presented. Intrinsic ($U-B$) and ($B-V$) values are used to derive the temperature and surface gravity. The mean values are $T_{eff} = 7600 \pm 100$ K and $\log g_{eff} = 3.8 \pm 0.1$. These values suggest that BS Aqr is a normal population I pulsating star and a member of δ-Scuti group.

Key words : variable star—photometry—pulsation—dwarf Cepheid

1. Introduction

The variability of BD $-8°6194$ = HD 223338 (BS Aqr) was discovered by Hoffmeister (1931), who classified it as an irregular variable. Florija (1932) classified this star as a member of the W UMa group and obtained a period greater than $0^d.26$ and an amplitude of $0^m.4$. Andrews (1936) classified it as a cluster type RRc variable, a classification which was later confirmed by Ashbrook (1943). Spinrad (1959) classified this star as an ultra-short variable, along with YZ Boo, DH Peg and SX Phe, on the basis of his photoelectric observations. Tremko & Sajtak (1964) determined from their photoelectric observations of BS Aqr that the height of the maximum, the depth of the minimum, the asymmetry, amplitude and form of the light curve are subject to changes. In view of these divergent opinions about the nature of BS Aqr and with the availability of new data (Elst 1976), the following analysis were undertaken with a view to understanding its classification and intrinsic properties more closely.

2. Observations and period determination

Recent *UBV* photoelectric observations of BS Aqr obtained with the 50-cm reflector at ESO have been published by Elst (1976). His observations are given on the standard *UBV* system and the comparison star was CE (1973) : $\alpha = 23^h42^m.7$; $\delta = -8° 36'.8$. He adopted the following values for the comparison star : $V = 8.21$, $B - V = 0.33$ and $U - B = 0.12$. No analysis of these observations has been given in the literature so far.

In the present analysis, the observations are best fitted by the following expression for times of maximum brightness :

$$\text{Max.} = \text{JD (Hel.)}\ 2437544.5333 + 0.19782236\,E$$
$$\pm 0.00000005 \qquad \ldots(1)$$

The period has been determined from the times of maxima in the ten cycles in Elst's data, the time of maximum as determined in the Rocznik Astr. Obser. Yearbook (1971) and an elapsed number of cycles were assumed on the basis of the previously determined period. The standard deviation quoted above represents the internal agreement among these ten maxima.

Table 1 gives the mean brightness of BS Aqr in U, B and V, along with a standard deviation for each phase interval, computed on the basis of above period for the observational data given by Elst from JD 2441946 through JD 2441950. The table also gives the mean brightness for each phase interval after omitting the observational data of JD 2441946. The reason for omitting these data is that BS Aqr is somewhat brighter and fainter at maximum and minimum during that cycle, compared to the other four nights of observations. The standard deviations given in table 1 exhibit more scatter in the computation of mean values when all data are included. It is not clear from the published observations whether this behavior of BS Aqr on the night of JD 2441946 is real or not. Omitting the effects of the unusual light curve on that night do not significantly affect the physical parameters discussed below.

Figure 1 shows a typical light curve of BS Aqr in U, B and V. Figure 2 gives the mean light variation in V, $B-V$ and $U-B$ plotted in the sense variable *minus* comparison, for the last four nights of observations. Because of the short period, the mean values given in figure 2 are averages of from five to nine data points, depending on the phase in question.

3. Interstellar reddening

The mean colour indices computed over a pulsation cycle for BS Aqr are : $\langle (B-V) \rangle = 0.34$ and $\langle (U-B) \rangle = 0.14$. The interstellar reddening correction for BS Aqr has been obtained by two independent techniques. First, the spectral type-intrinsic colour calibration given by Fitzgerald (1970) was used. Preston (1959) classified the star as F1 at the time of minimum brightness and $\Delta s = 0$, where Δs is the difference between metallic and hydrogen spectral types, an indication of metal deficiency in the outer layers of the star. Kinman (1961) showed that BS Aqr varies from A8 to F4 during the cycle and remains fairly stationary at F0 for a large fraction of the period. Assuming a mean spectral type of F0 and a luminosity classification IV–V, one obtains a colour excess, $E(B-V) = 0.04$.

Secondly, the interstellar reddening arising from the galactic disk can be estimated from the Parenago formula (Parenago 1945), a cosecant extinction relation, without recourse to observations of BS Aqr itself. The relation is

$$A_V = \alpha_0 \beta \csc |b| \left[1 - \exp \frac{(-r \sin |b|)}{\beta} \right] \qquad \ldots(2)$$

where A_V is the visual absorption in magnitudes, α_0 the absorption in mag kpc^{-1} in a line parallel to the galactic plane, β the scale height, r the distance to the star in

Table 1. Mean magnitude of BS Aqr from JD 2441946 to JD 2441950, both inclusive

Passband & Std. Dev.	Phase 0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Mean
Visual	9.138(10)*	9.206(7)	9.298(7)	9.383(7)	9.439(8)	9.482(9)	9.543(9)	9.582(9)	9.513(9)	9.304(10)	9.389(10)
	.007	.005	.006	.009	.010	.008	.007	.012	.013	.009	
Blue	9.381(10)	9.477(6)	9.589(7)	9.711(7)	9.793(8)	9.851(9)	9.928(9)	9.974(9)	9.884(9)	9.596(10)	9.718(10)
	.019	0.18	.028	.019	.018	.015	.022	.026	.016	.026	
Ultraviolet	9.529(10)	9.634(8)	9.730(7)	9.841(7)	9.922(8)	9.976(9)	10.051(9)	10.142(9)	9.991(9)	9.718(10)	9.853(10)
	.043	.037	.045	.044	.039	.038	.039	.066	.039	.044	
Mean magnitude of BS Aqr from JD 2441947 to JD 2441950 excluding JD 2441946											
Visual	9.136(8)	9.205(6)	9.296(5)	9.378(5)	9 435(6)	9.481(7)	9.544(7)	9.584(7)	9.514(7)	9.303(8)	9.388(10)
	.006	.003	.005	.003	.006	.005	.005	.011	.011	.005	
Blue	9.389(8)	9.483(5)	9.605(5)	9.722(5)	9.802(6)	9.857(7)	9.939(7)	9.985(7)	9.891(7)	9.606(8)	9.728(10)
	.008	.011	.006	.006	.009	.010	.012	.016	.008	.007	
Ultraviolet	9.549(8)	9.646(7)	9.756(5)	9.867(5)	9.943(6)	9.995(7)	10.070(7)	10.111(7)	10.009(7)	9.738(8)	9.868(10)
	.013	.015	.011	.008	.007	.009	.004	.006	.017	.010	

*No. of data points from mean light curves,

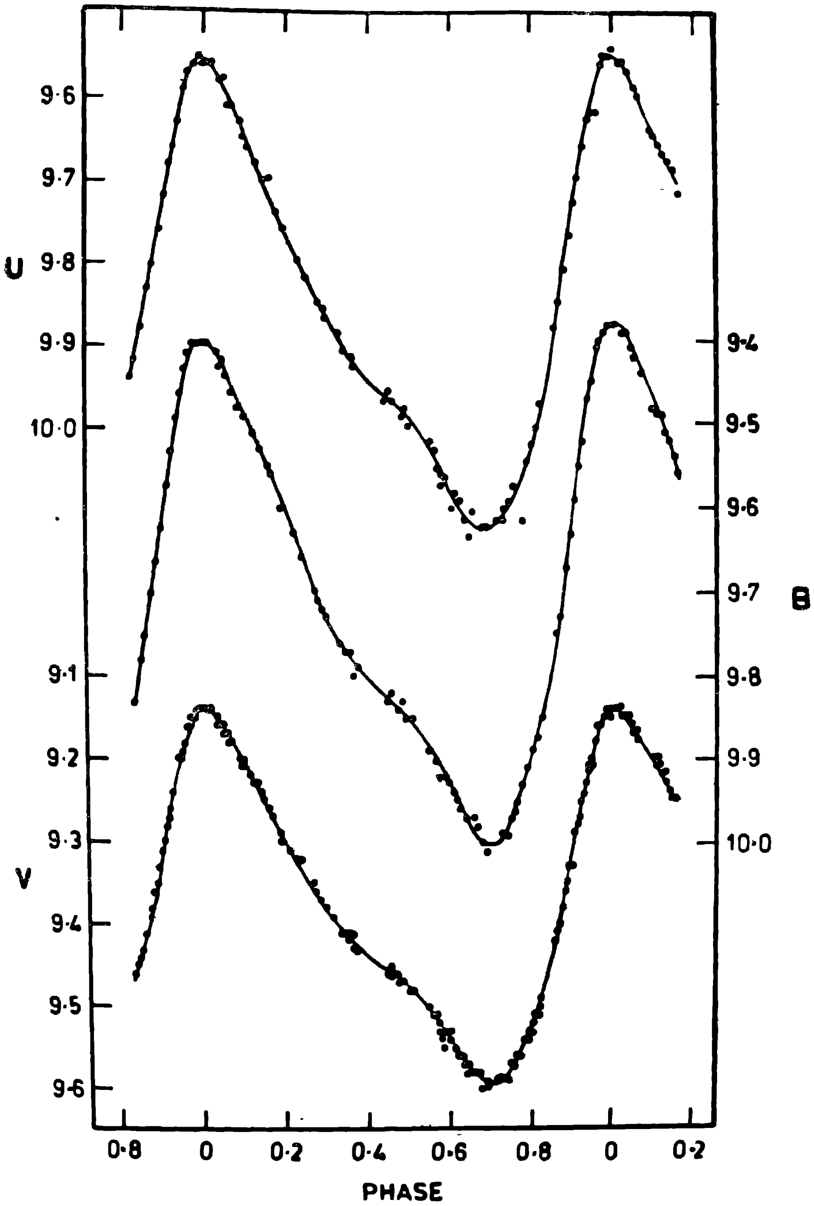

Figure 1. Light variations of BS Aqr in U, B and V on JD (Hel.) 2441950.

parsecs and b the galactic latitude. The parameters α_0 and β have been obtained by Sharov (1964), using distant OB stars; $\alpha_0 = 1^m.6$ kpc^{-1} and $\beta = 114$ pc are appropriate for the position of BS Aqr. Obviously, the distance to BS Aqr is not known and several absolute magnitudes were assumed to see if the resulting reddening is very sensitive to the absolute magnitude at this latitude. The results are : $A_V = 0.20$, 0.18 and 0.16 mag for the assumed absolute magnitudes of $M_V = +1$, $+2$ and $+3$, respectively. As may be seen, the absorption at this latitude ($b = -66°$) depends only weakly on our knowledge of the distance to the star. Colour excess is then $E(B-V) = 0.06$, 0.03 and 0.05, if we take $R = 3.3$. These two methods were given weights of 3 for the spectral type-intrinsic colour method, and weights of 1 for each of the assumed absolute magnitude results in the Parenago method. This yields $E(B-V) = 0.05 \pm 0.01$ (standard deviation). For $E(U-B)/E(B-V) = 0.72$, one

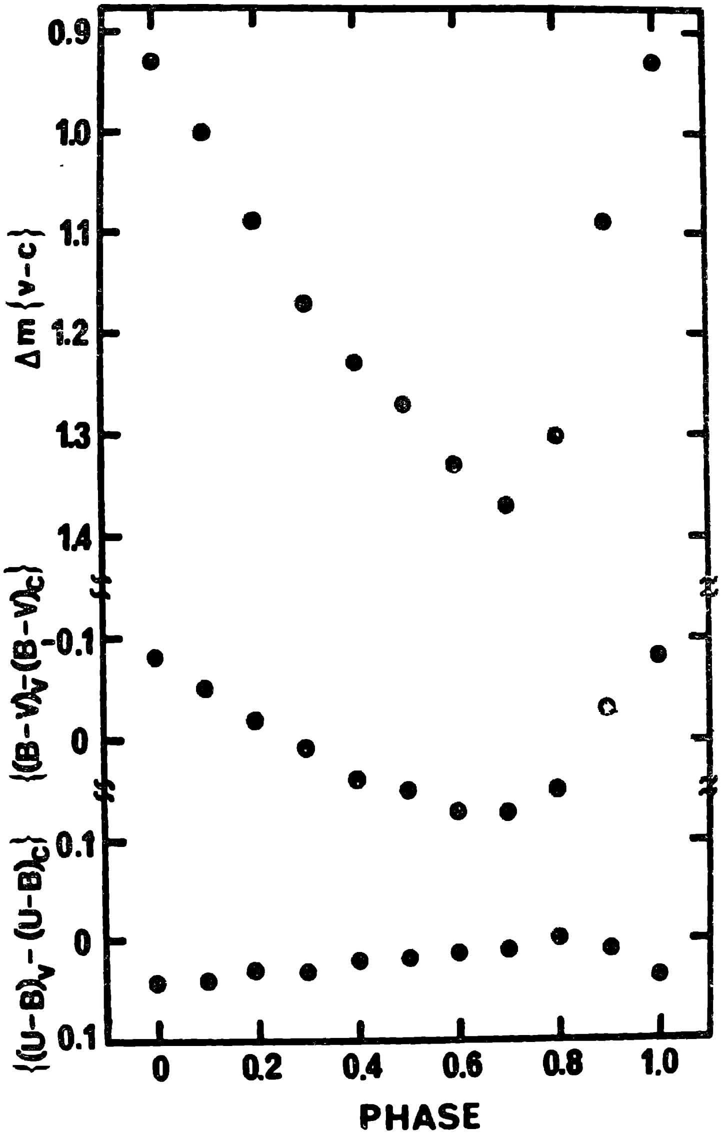

Figure 2. Mean light and colour variations of BS Aqr plotted in the sense variable *minus* comparison, versus phase for observations from JD 2441947 through 2441950.

obtains $E(U-B) = 0.03$. The standard deviation of $\pm 0^{m}.01$ quoted represents *only* the internal agreement among above methods. As a check, McNamara's (1965) relation of

$$(B-V)_0 = +0.23 \log P + 0.473$$

for short period, large amplitude variables is used and a value of $(B-V)_0 = +0.31$ is obtained for BS Aqr. This gives a colour excess of $E(B-V) = 0.03$. Even though McNamara's relation is based on very few stars, the colour excess derived agrees satisfactorily with the other methods. The small amount of reddening derived here supports the assumption made by Oosterhoff & Walraven (1966) that BS Aqr is unreddened in their analysis. The following discussion is based on $E(B-V) = +0.05$ and $E(U-B) = +0.04$.

4. Discussion

Figure 3 gives the mean colour-colour relation for BS Aqr (the dashed line is the relation for main-sequence), with colours corrected for interstellar absorption. The 'loop' is clearly seen, and it is similar to those observed in other pulsating stars with the direction 'of rotation in the loop' being counter-clockwise. At phases corresponding to the ascending portion of the light curve, the star radiates more strongly in the short wavelength region than on the descending portion. The position of BS Aqr in the two-colour plane lies below the normal main sequence line. The position of a star in the two-colour plane is influenced by effective temperature, line blanketing and surface gravity. If the star has a composition similar to the Hyades stars, the blanketing effects will be similar and Preston's classification for BS Aqr ($\Delta s = 0$), suggests that there are no abnormal line blanketing effects. This leads to a conclusion that the ultraviolet deficiency of BS Aqr in figure 3 will be predominantly caused by its lower surface gravity. The lower surface gravity could be responsible for the observed ultraviolet deficiency noted through the spectral type-intrinsic colour calibration also.

Figure 3 also shows the theoretical intrinsic colour calibration in terms of effective temperature and surface gravity as given by Bell (1971) for F and G dwarfs with Solar composition. Bell concluded that his computations showed that the effective temperature and $(B - V)$ colour indices of the models agreed with the observational relations derived by Johnson (1963), but the $(U - B)$ colour indices of the models are systematically bluer than those of Johnson. He attributed this difference to the

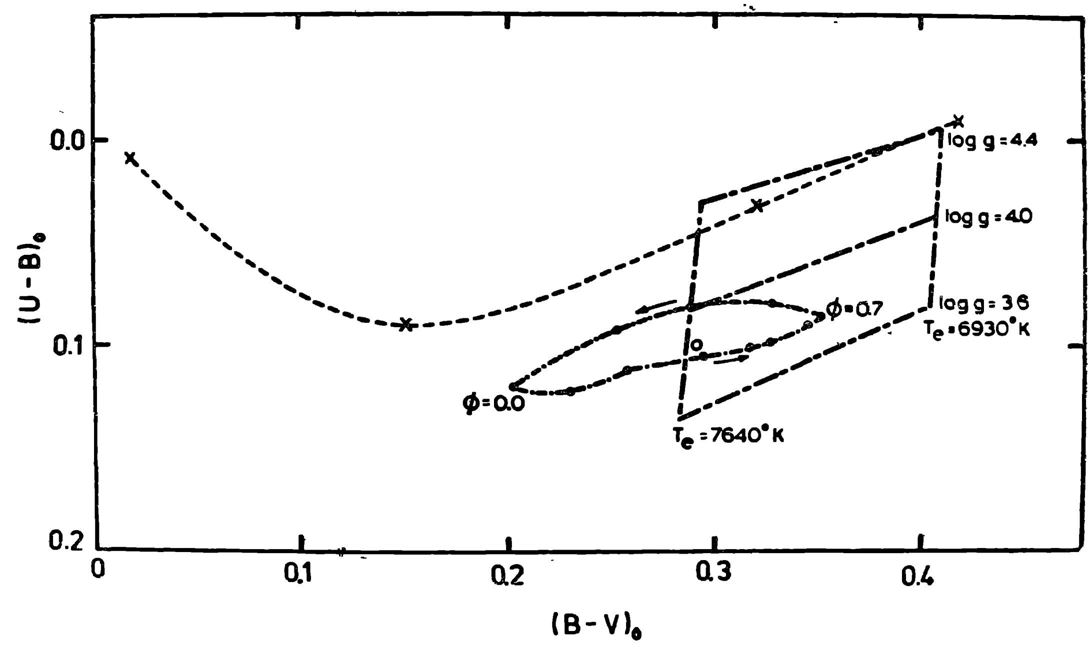

Figure 3. Two-colour diagram with mean colour indices, corrected for interstellar absorption. The loop is the observed path of variations of the colour indices through one cycle by BS Aqr. The open circle represent the mean unreddened position of the star. The dashed line represents the locus of points for main-sequence stars. The gravity (log g) and effective temperature lines are from Bell's (1971) models relating $(U - B)_0$ and $(B - V)_0$ to T_{eff} and g.

procedure adopted for zero-point calibration. A comparison of the effective temperature-colour relations indicates that Bell's computed $(U-B)$ colour indices are systematically bluer by $0^m.04$. The $(U-B)$ values used in figure 3, for a given $T_{\rm eff}$ and $\log g$ are the new values obtained after applying a correction of $0^m.04$. No correction has been applied for $(B-V)$ values. In addition, Johnson's calibration is based on an effective temperature of A0 type stars of 10,800 K while the recent calibration by Morton & Adams (1968) is based on an effective temperature of A0 type stars of 9600°K. For the mean color index here, the effective temperature obtained from Morton & Adam's calibration is slightly higher than from Johnson's calibration, by +300 K. This scaling correction has been applied to the constant temperature contours in figure 3.

The mean effective gravity as derived from figure 3 is $\langle \log g_{\rm eff} \rangle = 3.8 \pm 0.1$. At light maximum $\log g$ reaches a value of 3.85, while the maximum value of 4.00 occurs at phase 0.85. The mean effective gravity derived from the two-colour plane is sensitive to the interstellar reddening, however, the incorporation of the internal error associated with the derivation of interstellar reddening into the colour indices does not alter the value of $\log g$ by even ± 0.1. The intrinsic $(B-V)$ index versus effective temperature scale given by Morton & Adams for A and F spectral types leads to $T_{\rm eff}$ (median) = 7600 K, with maximum and minimum temperatures of 8150 K and 7250 K. The standard errors in these temperatures are $\simeq$ 100 K.

Figure 4 shows the $\log g$ *versus* effective temperature relation for RR Lyrae stars, types a, b and c and δ-Scuti stars as given by McMillan *et al.* (1976). The position for BS Aqr is shown by the symbol ●. The mean parameters derived for BS Aqr in this analysis classifies this star as population I δ-Scuti star on this diagram. The equation for mass/luminosity ratio in solar units is (McMillan *et al.* 1976):

$$\log \mathcal{M}/L = \log g - 4 \log T_{\rm eff} + 10.61. \qquad \ldots(3)$$

Using the mean values for BS Aqr, we obtain

$$\log \mathcal{M}/L = -1.1 \pm 0.1.$$

From equation (3) and the period-density relation, $Q = P\sqrt{\rho/\rho_\odot}$ (McMillan *et al.*) :

$$\log Q - 0.1\, M_{\rm bol} = -6.454 + \log P_f + 0.5 \log g + \log T_{\rm eff} \qquad \ldots(4)$$

where Q and P_f are in days. This yields a value of $(\log Q - 0.1\, M_{\rm bol}) = -1.38 \pm 0.1$. This value of -1.38 obtained for BS Aqr is slightly larger than the average values derived for high velocity dwarf pulsators by McMillan *et al.* and for δ-Scuti stars with $T_{\rm eff} \leqslant 7800$ K derived by Breger & Bregman (1975), but agrees with the average values obtained for RR Lyrae a, b and c types by Jones (1973) within the error limits. This unexpected coincidence of the $(\log Q - 0.1\, M_{\rm bol})$ index obtained for BS Aqr with that of RR Lyrae variable's average value is difficult to reconcile, compared to the classification obtained for BS Aqr on the basis of $\log g - T_{\rm eff}$ diagram. (A similar discrepancy is also noted in the case δ-Scuti itself from the published $T_{\rm eff}$ and $\log g$ values). One can visualize the difficulty by considering the parameters associated in deducing this index. The three parameters associated with this index are the surface gravity, the effective temperature and the period of pulsation. The effective temperature and colour index calibration are well established so that the

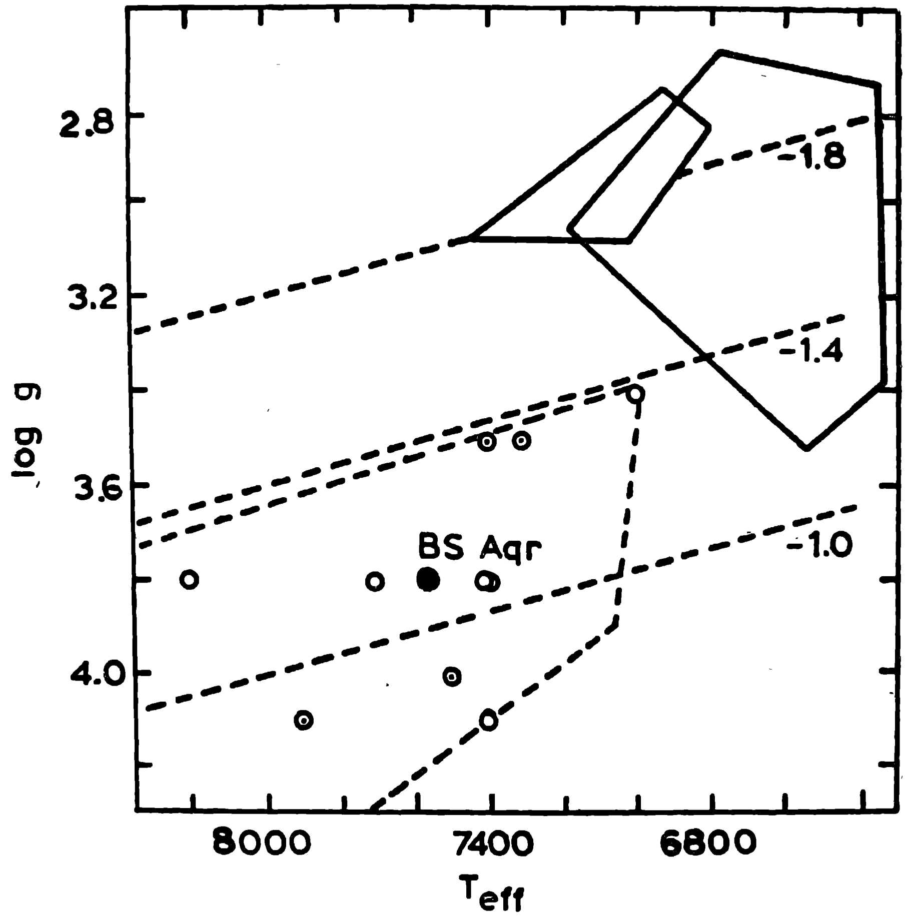

Figure 4. Log (surface gravity) vs effective temperature from McMillan *et al.* (1976). ○ = small amplitude variables, ⊙ = known RRs stars. Large solid lined polygon : RRab stars; small solid lined polygon : RRc stars; dashed-line polygon : Population I δ-Scuti stars. The three parallel curves correspond to log $(\mathfrak{M}/L)$ = − 1.0, − 1.4 and − 1.8 as indicated.

errors in $T_{\rm eff}$ can introduce negligible error in this index. If one assumes an error of 0.2 in log g, the discrepancy still exists. Hence, we suggest that the longer period of pulsation is the main cause for the discrepancy in the classification through the (log $g - T_{\rm eff}$) plane and the (log $Q - 0.1\, M_{\rm bol}$) index. An almost 33 per cent reduction in the fundamental period would be required to obtain agreement between these two methods, but of course, the period is stable and well-determined. This suggests that the relations are possibly not applicable for normal population I pulsating stars with longer periods. This is rather an unexpected remarkable conclusion since equations (3) and (4) follow directly from the definition of Q, $T_{\rm eff}$ and g and to change the constants in equations (3) or (4) requires changing at least one of the accepted values of G, $M_\odot$, $R_\odot$, $T_{\rm eff\odot}$ or $M_{\rm bol\odot}$.

Unfortunately, one had to conclude that the derivation of physical parameters through broad band *UBV* photometric analysis with the presently available theoretical calibrations are not satisfactory and the need for detailed calibration which agrees with observations are very essential. A summary of the physical parameters of BS Aqr are presented in table 2. The standard errors are internal estimates.

Table 2. Physical parameters of BS Aqr

Parameter		Value	σ
ΔV		$0^{m}.44$	± 0.01
$< (B-V)_{0\ \mathrm{med}} >$		0.29	± 0.01
$< (B-V)_{0\ \mathrm{max}} >$		0.20	± 0.01
$< (B-V)_{0\ \mathrm{min}} >$		0.35	± 0.01
$< T_{\mathrm{eff}} >$		7600 K	$\pm$ 100 K
$< \log g_{\mathrm{eff}} >$		3.8	± 0.1
$\log \mathcal{M}/L$	=	-1.1	± 0.1
$(\log Q - 0.1\ M_{\mathrm{bol}})$	=	-1.38	± 0.1

The so-called "dwarf cepheid", BS Aqr, seems to be a normal population I star based on its position on the ($\log g - T_{\mathrm{eff}}$) plane and is indistinguishable from the other δ-Scuti variables, except for its larger pulsation amplitude and slightly longer period. In addition, the well-determined period of pulsation and the derived $\log g$ places this star in the domain of normal mass, large amplitude, cool δ-Scuti variables and high-mass dwarf cepheids on the ($\log g$ — Period) plane given by Breger & Bregman (1975). Even if one arbitrarily assumes that BS Aqr is a metal-poor star, (which we cannot, because of Preston's observation of $\Delta s = 0$), and arbitrarily reduce the value of gravity by 0.4, the period and the resultant gravity place this star still among normal-mass, cool, large amplitude δ-Scuti variables and high-mass dwarf cepheids. Thus, BS Aqr appears to be a member of the δ-Scuti group and undergoing similar evolution as other δ-Scuti stars, as suggested by Breger (1975, 1977).

Acknowledgements

The author would like to thank Dr John Percy of the University of Toronto and Dr David L. DuPuy of Saint Mary's University for their helpful comments. Special thanks are due to Mr Randall Brooks for preparation of the diagrams. This work was supported by the National Research Council of Canada through an Operating Grant for Dr David L. DuPuy and a regional development grant to Saint Mary's University.

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