New Light Elements for the High Amplitude δ Scuti Star BS Aquarii

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Abstract DSLR photometry of the monoperiodic, high amplitude δ Scuti star BS Aquarii yielded five times of maximum in September and October 2013. These data were analyzed with twenty-two times of maximum obtained by other observers from 1973 to 1995. New light elements were calculated, revealing a period of 0.197822765 day ($\pm$0.000000010) at HJD 2456543.0250 ($\pm$0.0005). These light elements represent a linear ephemeris, with no significant change in the period of the star from 1973 to 2013. The data do not support the previous suggestion in the literature of an unseen companion affecting the O–C diagram.

1. Introduction

BS Aqr is a 9th magnitude high-amplitude monoperiodic δ Scuti star with a period of 4.75 hours and an amplitude of 0.45 magnitude in V. Its variability was first identified by Hoffmeister (1931), and Andrews (1936) identified it as a pulsating variable star. Fifty-six times of maximum obtained by various observers between 1935 to 1995 have been reported in earlier literature. Examination of O–C diagrams of those data reveal that the period decreased between the 1930s and 1973, after which it increased.

Yang *et al.* (1993) fitted a quadratic function to the O–C data calculated from times of maximum up until 1984, but inspection reveals that the fit is not good. Fu *et al.* (1997) added a single time of maximum from observations in 1995, and applied a quadratic function with additional trigonometric terms, which resulted in a curve providing a better fit than the quadratic function alone. These authors suggested that the results could be explained by the effects of an unseen companion to BS Aqr.

The most recent data in the literature are those of Rodriguez *et al.* (1998), who added six times of maximum obtained between 1992 and 1995. The present paper reports five new times of maximum obtained in September and October 2013, presents O–C diagrams of the new data and previous times of maximum from the literature, and calculates a new linear ephemeris based on times of maximum obtained from 1973 to 2013.

2. Observations

DSLR photometry was performed on RAW images taken with a Canon EOS 500D DSLR camera imaging through a refracting telescope with an aperture of 80mm at f/7.5, mounted on a Losmandy GM8 German equatorial mount. Photometric data reduction from instrumental magnitudes utilized the software package AIP4WIN (Berry and Burnell 2011). The comparison and check stars were HD 223049 and HD 223293, respectively. Transformed magnitudes in V were calculated using transformation coefficients for the blue and green channels of the DSLR sensor, obtained from images of standard stars in the E regions (Menzies *et al.* 1989).

Transformation coefficients were obtained from DSLR images of a field containing E region stars E408, E417, E426, E432, E433, and E434. The catalogue B–V color indices of these stars ranged from –0.018 to 0.984. Transformation coefficients represented the slopes of the plots of b–v (y axis) against B–V, and B–b (y axis) against B–V, where b and v are the instrumental magnitudes for signals from the blue and green channels, respectively, of the DSLR sensor, and B–V is the catalogue color index of each star.

The time of maximum of each light curve was taken as the time in Julian days of the maximum value of a sixth-order polynomial function fitted to each light curve by the period analysis software PERANSO (Vanmunster 2013), and converted to HJD prior to the plotting of O–C diagrams.

3. Analysis

Figure 1 is an example of a light curve from one night's observations with a sixth-order polynomial expression fitted to the central part of the data by the software program PERANSO, for the determination of the time of maximum. The light curve has the typical pattern of a high-amplitude δ Scuti star, characterized by a fast rise to maximum light, and a slower fall toward the minimum. Table 1 lists the times of maximum light of BS Aqr in Julian days (JD) for each of the five light curves obtained by the author in 2013, calculated using PERANSO, and showing the confidence limits assigned by that program. Those confidence limits cover a range of ± 2.3 minutes to ± 3.2 minutes.

All published times of maximum from the literature and from our observations are shown in Table 2, together with O–C values based on the period determined by Fu *et al.* (1997) of 0.197822612 day, and with T_0 being the first time of maximum determined by us (maximum 57 in Table 2). The O–C diagram plotted from all of those observations is shown in Figure 2, upper plot. The earlier data are somewhat scattered. Then, there was a decrease in the period of the star to 1973 (the letter "A" on the diagram is placed beneath the group of 1973 observations), after which the period increased. Because of the patterns revealed by visual inspection of this O–C diagram, it was decided to analyze the

Table 1. Times of maximum (TOM) in Julian days (JD) of BS Aqr determined by the author during 2013.

TOM (JD)	Confidence Limits
2456543.020917	0.00157
2456544.997666	0.00186
2456561.020382	0.00215
2456570.123946	0.00223
2456592.080070	0.00158

Table 2. Times of maximum (TOM) of BS Aqr from 1935 to 2013 in heliocentric Julian days (HJD), calculated O–C (observed minus computed) values, and the list of publications representing the source of the data.

Max	TOM (HJD)	Cycles	O–C	Primary Source*
1	2428095.3380	−143804	−0.00572	1
2	2429111.7450	−138666	−0.01130	2
3	2429899.2660	−134685	−0.02212	3
4	2430187.3040	−133229	−0.01385	3
5	2433027.4460	−118872	−0.01109	3
6	2433862.4600	−114651	−0.00633	3
7	2433888.3650	−114520	−0.01609	3
8	2434211.4220	−112887	−0.00342	3
9	2434400.3350	−111932	−0.01101	3
10	2434961.3660	−109096	−0.00494	3
11	2435631.3920	−105709	−0.00413	3
12	2435696.4720	−105380	−0.00777	3
13	2436040.0771	−103643	−0.02054	4
14	2436300.4260	−102327	−0.00620	3
15	2436458.0904	−101530	−0.00642	5
16	2436460.8540	−101516	−0.01234	5
17	2436461.8475	−101511	−0.00795	5
18	2436874.1120	−99427	−0.00578	4
19	2437561.3491	−95953	−0.00443	6
20	2437561.5445	−95952	−0.00685	6
21	2437562.5345	−95947	−0.00597	6
22	2437563.5242	−95942	−0.00538	6
23	2437564.5156	−95937	−0.00309	6
24	2437582.5180	−95846	−0.00255	6
25	2437583.3105	−95842	−0.00134	6
26	2437584.2934	−95837	−0.00755	6

Table continued on next page

Table 2. Times of maximum (TOM) of BS Aqr from 1935 to 2013, cont.

Max	TOM (HJD)	Cycles	O–C	Primary Source*
27	2437584.4924	−95836	−0.00638	6
28	2437911.4916	−94183	−0.00795	6
29	2437932.4617	−94077	−0.00705	6
30	2437933.4552	−94072	−0.00266	6
31	2437934.4383	−94067	−0.00868	6
32	2437946.3083	−94007	−0.00803	6
33	2437947.2960	−94002	−0.00945	6
34	2439087.1561	−88240	−0.00324	7
35	2441946.6714	−73785	−0.01379	8
36	2441946.8693	−73784	−0.01372	8
37	2441947.6620	−73780	−0.01231	8
38	2441947.8603	−73779	−0.01183	8
39	2441948.6500	−73775	−0.01342	8
40	2441948.8489	−73774	−0.01234	8
41	2441949.6400	−73770	−0.01253	8
42	2441950.6300	−73765	−0.01165	8
43	2441950.8295	−73764	−0.00997	8
44	2445612.7240	−55253	−0.00984	9
45	2445620.6380	−55213	−0.00874	9
46	2445625.5830	−55188	−0.00931	9
47	2445637.6470	−55127	−0.01249	9
48	2445644.5720	−55092	−0.01128	9
49	2445997.0920	−53310	−0.01117	10
50	2450072.0441	−32711	−0.00706	11
51	2448912.8046	−38571	−0.00605	12
52	2449606.7644	−35063	−0.00798	12
53	2449606.9621	−35062	−0.00810	12
54	2449607.9513	−35057	−0.00801	12
55	2449956.5150	−33295	−0.00775	12
56	2449957.5048	−33290	−0.00707	12
57	2456543.0266	0	0.00000	13
58	2456545.0034	10	−0.00146	13
59	2456561.0261	91	−0.00241	13
60	2456570.1294	137	0.00110	13
61	2456592.0845	248	−0.00213	13

Primary sources: 1. Andrews (1936); 2. Ashbrook (1943); 3. Satanova (1961); 4. Kinman (1961); 5. Spinrad (1959); 6. Tremko and Sajtak (1964); 7. Harding and Penston (1966); 8. Elst (1976); 9. Meylan et al. (1986); 1 10. Yang et al. (1993); 11. Fu et al. (1997); 12. Rodriguez et al.(1998); 13. Present paper.
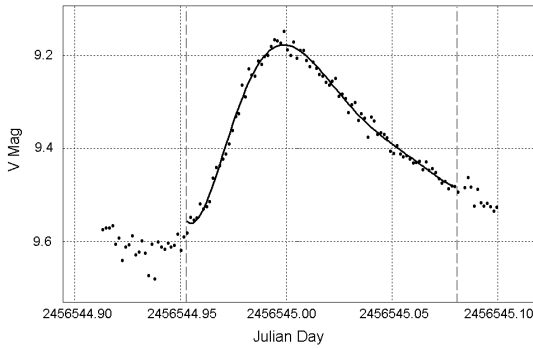
Figure 1. An example of a light curve of BS Aqr from a single night's observations, with a fitted sixth-order polynomial expression using the sofware program PERANSO (Vanmunster 2013), from which the time of maximum is calculated.
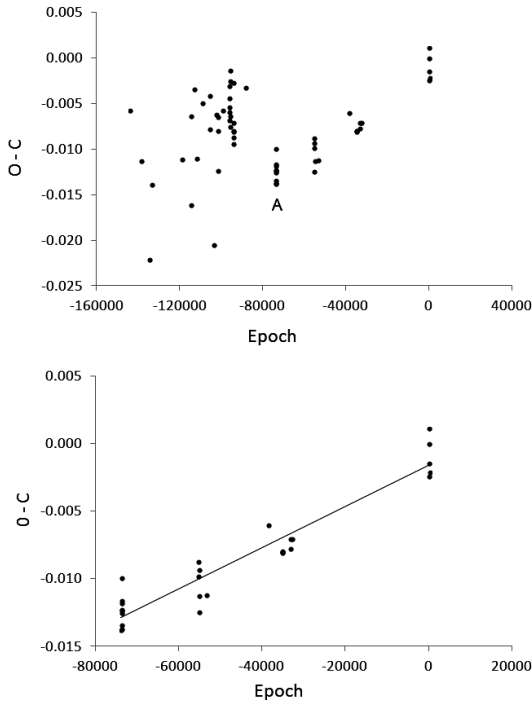

Figure 2. Upper plot: O–C diagram of all times of maximum of BS Aqr from the literature and obtained by the present author, spanning the period 1935 to 2013. The group of observations immediately above the letter "A" were made in 1973. Lower plot: O–C diagram of times of maximum of BS Aqr obtained between 1973 and 2013. Twenty-two times of maximum were obtained from the literature for observations between 1973 and 1995, and five times of maximum were obtained by the author in 2013. The straight line fitted to the data represents a least squares linear expression.

data from 1973 to 2013 separately, which yielded the O–C diagram in Figure 2, lower plot. This diagram represents a plot of the data for maxima 35 to 61 from Table 2, and includes a line which is the least squares linear fit to the data. Although a curve representing a quadratic function was initially plotted (instead of a linear function), the 95% confidence limit of the quadratic term was almost identical to the quadratic term itself, implying that the higher order term could be disregarded as insignificant. If a linear fit is accepted for the data from 1973 to 2013, this result implies that the period of the star has been constant over this time.

The generic formula for the linear function shown in Figure 2, lower plot, is:

$$\text{O–C} = aE + c \tag{1}$$

where E is the epoch (cycle number), a is the slope of the line, and c is a constant.

The values for this formula from the data upon which Figure 2, lower plot, is based, are as follows, with 95% confidence limits in brackets:

$$a = 0.0000001526 \,(\pm\, 0.0000000096) \tag{2}$$

$$c = 0.00158 \,(\pm\, 0.00051) \tag{3}$$

The light elements of the star are determined by a plot of times of maximum (y axis) against epoch (x axis). The values for the epochs are scaled so that the earliest of our personal observations (maximum 57 near the end of Table 2) represents T_0.

A linear function fitted to this plot represents the light elements of the star, and has the general formula:

$$T_{max} = aE + T_0 \tag{4}$$

where T_{max} is the time of maximum light, E is the epoch number, T_0 is the time of maximum light when E is zero, and the slope a is the period (in days) of the star. The values are as follows, with 95% confidence limits in brackets:

$$a = 0.197822765 \,(\pm\, 0.000000010) \tag{5}$$

$$T_0 = 2456543.0250 \,(\pm\, 0.0005) \tag{6}$$

4. Conclusions

Observations of the times of maximum of BS Aqr span 78 years, from 1935 to 2013, with a gap of 18 years between the most recently published previous data obtained in1995 and the data obtained by us in 2013. It is therefore timely to report an update of the behavior of this star. The observations and analysis reported in this paper indicate that there has been no significant change in the period from 1973 to 2013. Fu *et al.* (1997) suggested that the O–C diagram calculated by them could be explained by the light time effect of an as-yet undiscovered companion to BS Aqr, and inspection of their Figure 1(b) illustrates that possibility. However, the data obtained by us do not support that suggestion.

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