New Light Elements for the High Amplitude δ Scuti Star RS Gruis

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Abstract

Photoelectric and DSLR photometry of the monoperiodic high amplitude δ Scuti star RS Gruis yielded 16 times of maximum determined by the author from 2007 to 2013. These data are combined with historical observations obtained from 1952 to 1988 and more recent observations by others from 2003 to 2010. This combined dataset, comprising 50 times of maximum spanning 61 years, was subjected to O–C analysis, which revealed an obvious change in the period of the star between 1988 and 2003. Separate O–C analysis of the data from 2003 to 2013, comprising 28 times of maximum, yielded a quadratic fit, with the pulsational period increasing at the rate of dP/Pdt = 84.95 (15.74) × 10^{-8} yr^{-1}. To our knowledge, this rate of increase in period is the highest ever reported for a Population I high amplitude δ Scuti star with radial pulsation. From a quadratic (second order polynomial) ephemeris, the period was calculated to be 0.14701118 (0.00000011) d at HJD 2452920 (in October 2003) and 0.14701241 (0.00000012) d at HJD 2456497 (in July 2013).

1. Introduction

RS Gru (HD 206379) is a pulsating variable star of high amplitude δ Scuti type, with a period of 0.147 d (3.5 h), and an amplitude of 0.6 magnitude in V, with maximum and minimum magnitudes of approximately 7.9 and 8.5, respectively. The star was first recognized to be variable by Hoffmeister (1956), and Oosterhoff and Walraven (1966) reported that it had a stable light curve. Radial velocity studies were undertaken by Kinman (1961), McNamara and Feltz (1976), and van Citters (1976). Balona and Martin (1978) found that RS Gru was a spectroscopic binary, with a period probably longer than one week, and Joner and Laney (2004) found an orbital period of about two weeks. Derekas *et al.* (2009) finally determined the orbital period of the binary system to be 11.5 days.

Rodríguez *et al.* (1995) fitted a quadratic function to the times of maximum obtained from 1952 to 1988, calculated the period to be 0.147010864 d (0.000000022) at HJD 2447464.7095 (0.004), and determined that the pulsational period of RS Gru had decreased at a rate of dP/dt = –1.56 (0.12) × 10^{-8} d yr^{-1}, or dP/Pdt = –10.6 (0.8) × 10^{-8} yr^{-1}.

García (2012) analyzed an enlarged dataset of times of maximum, comprising the historical data studied by Rodríguez (1995) and additional observations covering the years 2003 to 2010 sourced from the AAVSO International Database (AID) and from personal measurements. He performed O–C analysis, determined that the period of RS Gru had increased between 1988 and 2010, and fitted a new cubic regression to the pulsational behavior of the star across the dataset of 37 times of maximum from 1952 to 2010. He also performed Fourier analysis on over 4,000 observations from international databases and from personal measurements, and found a period for the pulsational behavior of the star of 0.14705874 d.

2. Observations

Observations were made by photoelectric photometry from 2007 to 2010, and by DSLR photometry from 2011 to 2013. Two different photoelectric photometers were used, both supplied by Optec Inc, Lowell, Michigan. The data from 2007 was obtained with an SSP-3 model instrument, and in 2009 and 2010 an SSP-5 model instrument with a Hamamatsu R6358 multialkali photomultiplier tube was used. Both photometers were fitted with Johnson V and B photometric filters from Optec Inc, and measurements were taken through a Celestron C9.25 Schmidt-Cassegrain telescope, on a Losmandy GM8 German equatorial mount.

DSLR photometry was performed with a Canon EOS 500D camera imaging through a refracting telescope with an aperture of 80 mm at f/7.5, mounted on a Losmandy GM8 German equatorial mount.

For photoelectric photometry, non-transformed data in V were obtained, since the color indices of the comparison and check stars (HD 206025 and HD 206442 respectively) were similar to that of the variable. For DSLR photometry, RAW images were processed in AIP4WIN (Berry and Burnell 2011) to obtain instrumental magnitudes of the variable, comparison, and check stars. Transformed magnitudes in V were then determined from 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).

A standard method was required for determining the time of maximum light for each night's partial (or complete) light curve. For photoelectric photometry, the numbers of observations before or after the time of maximum were sometimes small, as was the total number of observations on a few nights. As a consequence, it was not possible to obtain a polynomial fit for all observation sets. Therefore, for each observation set that yielded a time of maximum, a center-moving average of each three consecutive observations was plotted against JD, and the time of maximum for each observation set was estimated visually. The time of maximum was then converted to HJD. All 50 times of maximum in HJD from our observations and those in the literature from 1952 to 2013 were tabulated.

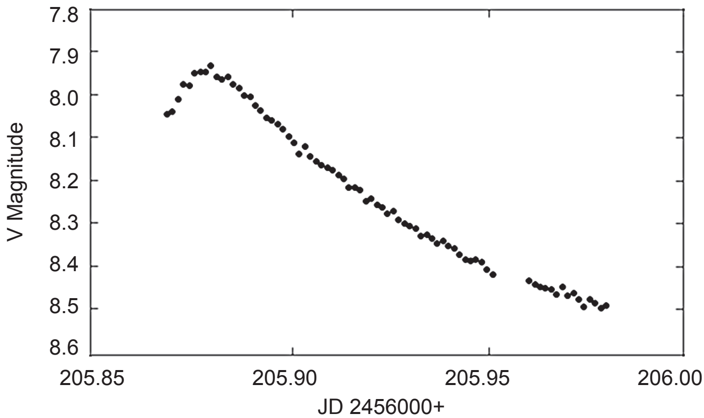

Figure 1. Sample light curve of RS Gru, one night's DSLR photometry data.

Table 1. Times of maximum (TOM) of RS Gru from 1952 to 2013, epochs, and O–C values.

Max	*TOM (HJD)*	*Epoch*	*(O–C)*	*(O–C)c*	*Primary Source**
1	2434325.2940	–89377	–0.026108	0.002786	1
2	2434573.4510	–87689	–0.023447	0.004807	1
3	2436756.5710	–72839	–0.014777	0.007849	2
4	2436760.5380	–72812	–0.017070	0.005545	2
5	2436801.5540	–72533	–0.017101	0.005409	3
6	2436853.3030	–72181	–0.015926	0.006451	3
7	2441538.4027	–40312	–0.005450	0.004848	4
8	2441538.5490	–40311	–0.006161	0.004137	4
9	2441610.4379	–39822	–0.005574	0.004539	4
10	2441611.3200	–39816	–0.005539	0.004571	4
11	2441611.4677	–39815	–0.004850	0.005260	4
12	2441612.3493	–39809	–0.005315	0.004793	4
13	2441915.4856	–37747	–0.005417	0.003910	4
14	2442687.5892	–32495	–0.002874	0.004461	5
15	2443355.4610	–27952	–0.001429	0.004184	6
16	2443355.6092	–27951	–0.000240	0.005373	6
17	2443360.4584	–27918	–0.002399	0.003202	6
18	2443360.6050	–27917	–0.002810	0.002791	6
19	2447464.7095	0	–0.000600	–0.005580	7
20	2447468.5324	26	0.000018	–0.004972	7
21	2447468.6793	27	–0.000093	–0.005084	7
22	2447472.6489	54	0.000213	–0.004787	7
23	2452920.0196	37108	0.030359	0.011315	8

Table continued on next page

Table 1. Times of maximum (TOM) of RS Gru from 1952 to 2013, epochs, and O–C values, cont.

Max	*TOM (HJD)*	*Epoch*	*(O–C)*	*(O–C)c*	*Primary Source**
24	2452921.9311	37121	0.030717	0.011669	8
25	2452922.0772	37122	0.029807	0.010757	8
26	2452923.9905	37135	0.031965	0.012911	8
27	2452925.0188	37142	0.031189	0.012132	8
28	2454373.9645	46998	0.037844	0.015051	9
29	2454374.9929	47005	0.037168	0.014373	9
30	2454387.9307	47093	0.037942	0.015113	9
31	2454417.0373	47291	0.036431	0.013527	10
32	2454417.9191	47297	0.036205	0.013300	9
33	2454417.9216	47297	0.038665	0.015760	10
34	2454423.9464	47338	0.036020	0.013099	10
35	2455059.0379	51658	0.040617	0.016059	9
36	2455059.9208	51664	0.041452	0.016892	9
37	2455391.7254	53921	0.042502	0.017086	11
38	2455394.6654	53941	0.042285	0.016861	11
39	2455422.0115	54127	0.044334	0.018840	9
40	2455423.0401	54134	0.043928	0.018431	9
41	2455481.6920	54533	0.038453	0.012805	11
42	2455482.5796	54539	0.043988	0.018338	11
43	2455766.0212	56467	0.048593	0.022212	9
44	2455767.0489	56474	0.047256	0.020873	9
45	2455768.0779	56481	0.047190	0.020804	9
46	2456196.9130	59398	0.051550	0.024058	9
47	2456205.8798	59459	0.050687	0.023172	9
48	2456496.9639	61439	0.053297	0.025031	9
49	2456497.1119	61440	0.054286	0.026020	9
50	2456497.9929	61446	0.053241	0.024973	9

** Primary Source: 1. Hoffmeister (1956); 2. Oosterhoff and Walraven (1966); 3. Kinman (1961); 4. Dean* et al. *(1977); 5. McNamara and Feltz (1976); 6. Balona and Martin (1978); 7. Rodríguez* et al. *(1995); 8. Derekas* et al. *(2009); 9. Present paper; 10. AAVSO (2013), observer DSI; 11. García (2012).*

Notes: The epochs in the third column and the O–C value in the fourth column were calculated using the quadratic ephemeris of Rodríguez et al. (1995), T_1 *= HJD 2447464.7101, and* P_1 *= 0.147010864 d. The* $(O–C)_c$ *values in column 5 were calculated using the elements from the cubic ephemeris in Equation 1 in the present paper, T = HJD 2447464.71508 and P = 0.147011243 d. Actual (O–C) values are displayed, not residuals from the regression analysis.*

In this paper, each numerical result from our observations and calculations is followed by the standard error in brackets, recognizing that the standard error is half the 95% confidence limits.

3. Analysis

Two analyses were performed. The first involved 50 times of maximum spanning the years 1952 to 2013, and followed as closely as possible the procedures employed by García (2012). In view of the results, a second analysis was performed, using only the data from 2003 to 2013.

A sample light curve of RS Gru obtained during one night by DSLR photometry is shown in Figure 1. Fifty times of maximum from the literature and from our observations are shown in the second column of Table 1. Three of the times of maximum in the paper by García (2012) represent data submitted by us to the AAVSO International Database. They appear as maxima 28, 29, and 30 in Table 2 in García's paper and in Table 1 in the present paper, where the times of maximum shown are those determined by us, so that a consistent method for determining times of maxima was used for all of our own data. Subsequent new times of maximum by us in Table 1 were not previously submitted to the AAVSO International Database. The epochs in the third column and the O–C values in the fourth column of Table 1 were calculated from the ephemeris of Rodríguez *et al.* (1995), namely $T_1 = 2447464.7101$ d and $P_1 = 0.147010864$ d.

Using the times of maximum and the epochs listed in Table 1, we then performed a linear least squares fit, which yielded an ephemeris with the new elements $T_0 = 2447464.7247$ (0.0008) HJD and $P_0 = 0.147011369$ (0.000000016) d. These results are close to those of García (2012). Using the new elements, a cubic (third order polynomial) regression was calculated, from the times of maximum in column two and the epochs in column three of Table 1, yielding the following ephemeris:

$$T_{max} = \text{HJD } 2447464.71508\ (0.00074) + 0.147011243\ (0.000000020)E + 4.220\ (0.298) \times 10^{-12}E^2 + 4.130\ (0.534) \times 10^{-17}E^3 \quad (1)$$

The fifth column in Table 1 contains the O–C values based upon the elements from Equation 1 above (that is, T = 2447464.71508 and P = 0.147011243) and the O–C diagram graphing those values is shown in Figure 2, where the superimposed curve represents a cubic (third order polynomial) expression. The O–C diagram and the superimposed cubic fit are generally similar to the plot in Figure 5 of García (2012). However, examination of García's Figure 5 and our Figure 2 reveals that the cubic expression is not an ideal fit. In view of this, and since our data extend the O–C diagram significantly for recent observation years, it was decided to analyze the more recent (2003 to 2013) data separately.

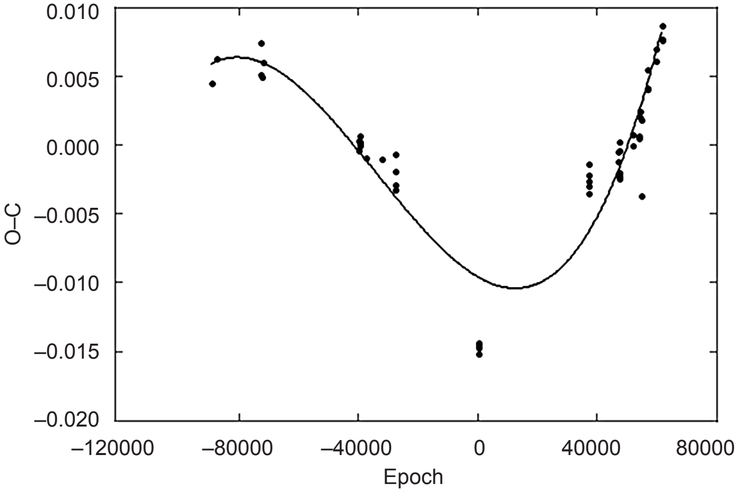

Figure 2. O–C diagram of RS Gru, representing all of the data in Table 1, from observations made between 1952 and 2013. The diagram is based on the elements of Rodriguez *et al.* (1995) T_0 = 2447464.7101 d and P_0 = 0.147010864 d.

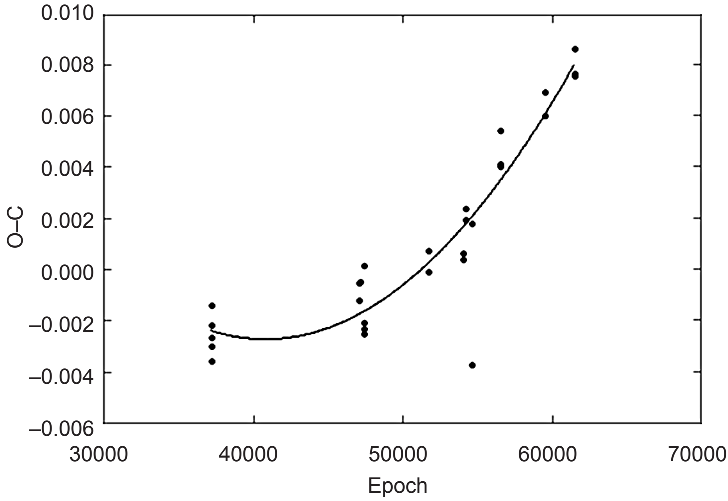

Figure 3. O–C diagram of RS Gru, representing maxima 23–50 of the data in Table 1, from 2003 to 2013. The diagram is based on the same elements as those used for Figure 2. The fitted curve is a quadratic function, the shape of the which (concave up) indicates that the period of RS Gru has been increasing during the years of these observations.

To this end the O–C diagram shown in Figure 3 was plotted, representing the epochs and O–C values in the fourth column of Table 1, for maxima 23 to 50. The curve represents a quadratic (second order polynomial) fit, which we consider to be a better fit to these recent data than that seen in Figure 2. A quadratic ephemeris in the form $T_{max} = T_0 + PE + AE^2$ is given by the following equation, based on an initial epoch of HJD 2452920.0196:

$$T_{max} = \text{HJD } 2452920.02019\ (0.00064) + 0.14701118\ (0.000\,000\,11)E + 2.513\ (0.466) \times 10^{-11}E^2 \quad (2)$$

From the coefficient of the second order term in Equation (2) above, the pulsation period of RS Gru is calculated to be increasing at the rate of dP/dt = 12.29 (2.31) × 10^{-8} d yr^{-1}, or dP/Pdt = 84.95 (14.74) × 10^{-8} yr^{-1}.

The first order term and the constant term (T_0) of Equation (2) indicate that the pulsation period of RS Gru was 0.14701118 (0.00000011) d at HJD 2452920 (7 October 2003). By rescaling the epochs and recalculating the ephemeris, it can also be shown that the pulsation period of RS Gru was 0.14701241 (0.00000012) d at HJD 2456497 (23 July 2013).

4. Conclusions

The present paper confirms the work of others that the pulsational period of RS Gru has increased since the 1988 studies of Rodríguez *et al.*, published in 1995. Furthermore, the O–C diagram of the entire dataset of results from 1952 to 2013, and in particular the separately analyzed results from 2003 to 2013, show that the pulsation period of the star is continually increasing.

In the first of our analyses of O–C values and ephemerides, which attempted to follow as closely as possible the methods of García (2012), the results for the cubic ephemeris seen above in Equation (1) are very close to the results seen in García's Equation (2).

However, the O–C diagrams in García's (2012) Figure 5 and our Figure 2 both show that the pulsational period of RS Gru underwent a change after the studies of Rodríguez (1995), whose data are represented by the lowest points on both O–C diagrams. In view of this, and in view of the fact that the cubic function shown on both of these O–C diagrams does not appear to represent an ideal fit, we decided that separate O–C analysis of the recent data from 2003 to 2013 might prove useful.

The results indicate that the pulsational period of RS Gru has been increasing continuously during those years. From the quadratic ephemeris, the period of RS Gru in at HJD 2456497 (23 July 2013) was calculated to be 0.14701241 (0.00000012) d. This figure differs significantly (by approximately 4 seconds) from the period of 0.14705874 d derived by García (2012) from Fourier analysis of more than 4,000 observations from various databases and personal observations made between HJD 2447880 (December 1989) and HJD 2455525 (November 2010). A similar difference is also found if the pulsational period of RS Gru is calculated from the first derivative of the cubic ephemeris during the time span from which the observations for the Fourier analysis were made.

Previous studies by others have shown both increasing and decreasing periods in high amplitude δ Scuti stars (Breger and Pamyatnykh 1998). However, the rate of increase in the period of RS Gru calculated by us for the years 2003 to 2013, dP/Pdt = 84.95 (15.74) × 10^{-8} yr^{-1}, is substantially greater than that published for any other Population I high amplitude δ Scuti star with radial pulsation, with the next largest figure being dP/Pdt = 15 × 10^{-8} yr^{-1} for AI Vel, according to Breger and Patmyatnykh (1998).

In view of this unusually high rate of change of the period of RS Gru, and because the data from 2003 to 2013 represent the most concentrated longitudinal series of the times of maximum of this star since it was found to be variable some 60 years ago, continued monitoring of its light curve each season will undoubtedly prove to be valuable.

5. Acknowledgements

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