Expansion and Reinterpretation of the O–C Diagram of the High Amplitude δ Scuti Star RS Gruis

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Abstract Photometry obtained with a digital single lens reflex (DSLR) camera and a CMOS astronomical camera from 2016 to 2020 expands the O–C diagram of RS Gru to cover a span of nearly 68 years. Analysis of the data reveals that a previous report of a constant rate of increase of the period between October 2003 and July 2013 may not be correct. Instead, evidence is presented that there was a constant rate of increase of the period from October 2003 to October 2010 followed by a constant but slower rate of increase from July 2011 to July 2020, with the latter described by the expression $dP/dt = 2.99\ (0.96) \times 10^{-8}\ d\ yr^{-1}$ or $dP/Pdt = 2.04\ (0.65) \times 10^{-7}\ yr^{-1}$. A new quadratic ephemeris derived from the 2011 to 2020 observations is TOM (HJD) = 2459045.1247 (0.0002) + 0.14701221 (0.00000004) E + 6.0X10^{-12} (1.9×10^{-12}) E2 for which zero time occurred on 14 July 2020 UTC.

1. Introduction

RS Gru (HD 206379) is a high amplitude δ Scuti star with a period of 0.147 d (3.53 h), and a magnitude range of 7.9 to 8.5 approximately in V. Its variability was first reported by Hoffmeister (1956). Rodriguez *et al.* (1995) reported times of maximum from observations taken by them and others between 1952 and 1988, and determined that the period was 0.147010864 d (0.000000022) at HJD 2447464.7095 (0.004). They fitted a quadratic function to the data and from this calculated that the period had decreased at a constant rate of $dP/dt = –1.56\ (0.12) \times 10^{-8}\ d\ yr^{-1}$, or $dP/Pdt = –10.6\ (0.8) \times 10^{-8}\ yr^{-1}$.

Garcia (2012) reported a dataset expanded by observations taken over the years 2003 to 2010 comprising personal observations and data from the AAVSO International Database. He fitted a cubic model to 37 times of maximum from 1952 to 2010, although examination of his Figure 5 shows a fit which is not optimal. He found a period of 0.14705874 d from Fourier analysis of observations in international databases.

Axelsen (2014) reported personal photoelectric and DSLR photometric observations, and analyzed the resulting enlarged dataset of 50 times of maximum to 2013. He reproduced Garcia's (2012) analysis, applied a cubic fit to the entire 1952 to 2013 dataset, and confirmed that it was not optimal. A quadratic fit was calculated for a subset of the data, comprising 28 times of maximum from 2003 to 2013, which was interpreted to indicate that the period was increasing at a constant rate of $dP/Pdt = 84.95\ (15.74) \times 10^{-8}\ yr^{-1}$, considered by the author to be the highest rate of increase reported for a Population I high amplitude δ Scuti star with radial pulsation. However, inspection of Axelsen's (2014) Figure 3 suggests that a period jump occurred prior to the last three groups of observations followed by a new trend. This paper investigates the latter suggestion and reports the results of the analysis of that data and subsequent observations. A new ephemeris for RS Gru is calculated.

2. Methods

Images for photometry were taken for several hours each night through an 80-mm refractor at f/7.5 on an autoguided mount. The images were taken with a Canon EOS 500D camera in 2016, 2017, and 2018, and a ZWO ASI1600MM Pro CMOS astronomical camera with a Johnson V filter in 2019 and 2020. Images were calibrated with dark, flat, and bias frames (DSLR images) or dark and flat frames (ZWO images). Transformed V magnitudes, using standard stars from the E Regions (Menzies *et al.* 1989), were calculated from measurements of the DSLR images, and non-transformed V magnitudes were derived from the images taken with the ZWO camera. Table 1 lists the comparison and check stars.

RAW DSLR images were processed in AIP4WIN (Berry and Burnell 2011). Images captured in the FITS format by the ZWO camera were processed in ASTROIMAGEJ (Collins *et al.* 2017). Light curves were drawn and times of maximum determined for each peak using either PERANSO (Vanmunster 2013) or VSTAR (Benn 2012). The times of maximum were taken to be the times of the maximum values of polynomial expressions fitted to the peaks and the adjacent ascending and descending limbs of the light curves. Five times of maximum were obtained in July and August 2016, 5 in May 2018, 6 in August and September 2018, 4 in August 2019, and 7 in July 2020, making a total of 32. The fitting of linear and quadratic functions to O–C data was performed using regression analysis in Microsoft EXCEL and in MINITAB (https://www.minitab.com/en-us/).

Table 1. Comparison and check stars.

Star	*Star Name*	*V*	*B–V*
Comparison	HD 206442	8.485	0.490
Check star, DSLR camera	HD 206344	9.171	0.641
Check star, ZWO camera	HD 206584	8.451	0.950

3. Results

Figures 1 and 2 show the light curve of RS Gru and the check star obtained during one night with the DSLR and ZWO cameras, respectively. It is evident that the precision is better with the ZWO camera.

Table 2 presents all times of maximum, epochs, and O–C (observed minus computed) values for observations between November 1952 and July 2020, a time span of 67 years and 8 months. The calculations of the O–C values are based on zero epoch at HJD 2459045.12400, the time of maximum of the first light curve peak obtained by the author in July 2020, and a period of 0.147011369 d from the linear ephemeris calculated by Axelsen (2014). The O–C diagram drawn from values in this table is shown in Figure 3. The first part of the diagram, between epochs –168149 and –78718, is drawn from observations made between 1952 and 1988 which were published by Rodriguez *et al.* (1995), who interpreted the data to indicate that the period was decreasing at a constant rate.

Figure 4 shows a part of the O–C diagram of RS Gru drawn from observations published by Axelsen (2014), who fitted a quadratic model to the data, and interpreted the diagram to indicate that the period was increasing at a constant rate of $dP/Pdt = 84.95\,(15.74) \times 10^{-8}\,yr^{-1}$. However, careful inspection of this figure leads to the observation that the rate of change in the period between epochs –41664 and –24233 may be different from that between epochs –22305 and –17326. Furthermore, a period jump may have occurred between these two epoch ranges. There is one discrepant data point, O–C –0.02343 at epoch –24239.

Figure 5 shows the O–C diagram of RS Gru from October 2003 to October 2010, in which the dashed line represents a fitted quadratic model. The solitary discrepant data point shown as a filled square is not included in the model. From the times of maximum and the epochs, it is calculated that the period of RS Gru was increasing at a constant rate of $dP/dt = 7.8\,(3.1) \times 10^{-8}\,d\,yr^{-1}$ or $dP/Pdt = 2.3\,(2.1) \times 10^{-7}\,yr^{-1}$.

Figure 6 shows the O–C diagram of RS Gru from July 2011 to July 2020, between epochs –22305 and 35. Inspection suggests that a linear model may fit the data, but examination of the plots of residuals versus epochs from linear and quadratic models (Figures 7 and 8, top right panels) reveals that the latter yields a better fit. In addition, the quadratic model also reveals a better result for the normal probability plot (more data points on the line), and plots of the residuals versus fits, residuals versus order of observations and the histogram of the residuals (Figures 9 and 10). A quadratic ephemeris is therefore preferred, and is given by the following formula, derived from the times of maxima and the epochs:

$$TOM\,(HJD) = 2459045.1247\,(0.0002) + 0.14701221\,(0.00000004)\,E + 6.0 \times 10^{-12}\,(1.9 \times 10^{-12})\,E2. \quad (1)$$

The period was thus 0.14701221 (0.00000004) d at zero time, very close to the time of the first peak of the light curve captured on 14 July 2020 UTC.

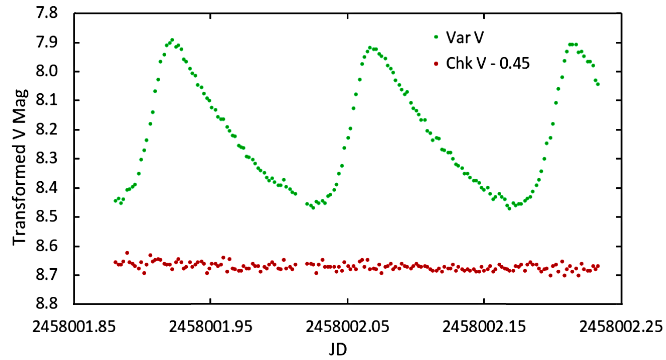

Figure 1. Light curve of RS Gru and check star from data taken during one night with the Canon EOS 500D DSLR camera. The check star data are shifted for optimal viewing.

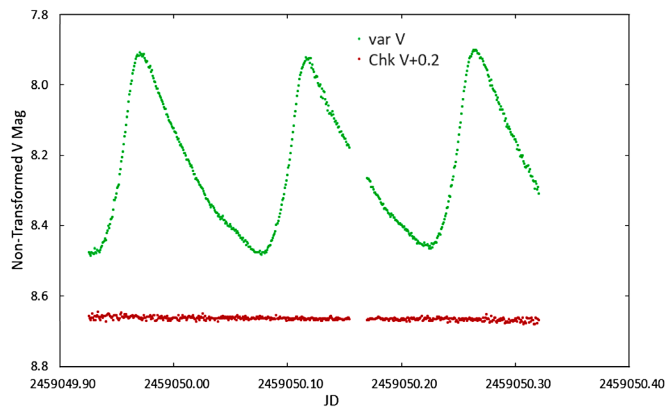

Figure 2. Light curve of RS Gru taken during one night with the ZWO ASI1600MM Pro camera. The check star data are shifted for optimal viewing.

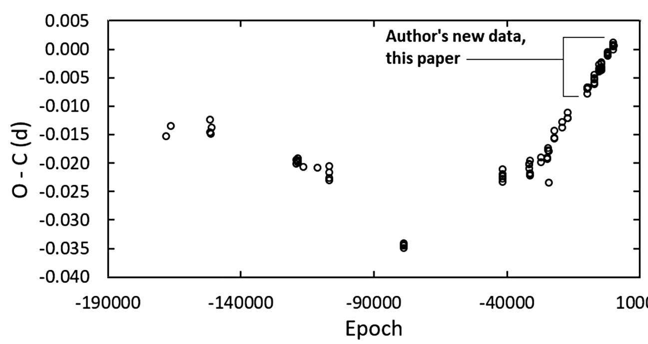

Figure 3. O–C (observed minus computed) diagram of RS Gru, November 1952–July 2020, drawn from the data in Table 2. The calculations of O–C values are based on zero epoch at HJD 2459045.12400, the time of maximum of the first light curve peak obtained in July 2020, and a period of 0.147011369 d, the linear ephemeris calculated by Axelsen (2014).

4. Discussion

Sterken (2005) discusses uncertainties in the interpretation of O–C diagrams. Specifically, he states “It is rather difficult to decide whether an O–C curve should be represented by a continuous curve (second degree polynomial) or by a sequence of short linear segments. The latter approach leads to the interpretation that the period of the star undergoes sudden changes.” Even though one model may yield smaller residuals than another and would therefore be the preferred one, doubt may still exist as to the physical reality of the behavior of the star.

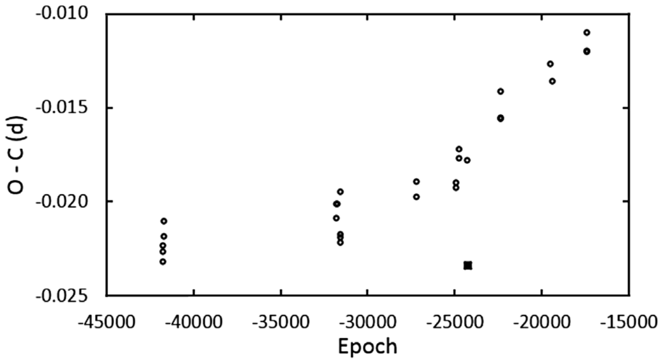

Figure 4. Part of the O–C diagram of RS Gru, Octiber 2003–July 2013 corresponding to Figure 3 of Axelsen (2014). The single discrepant data point is represented by a filled black square. Note that the scales of the two axes are different from those in the original paper because the original periods and epochs for calculating the O–C tables differ. The basis for the calculations of the O–C values is given in the legends for Table 2 and Figure 3.

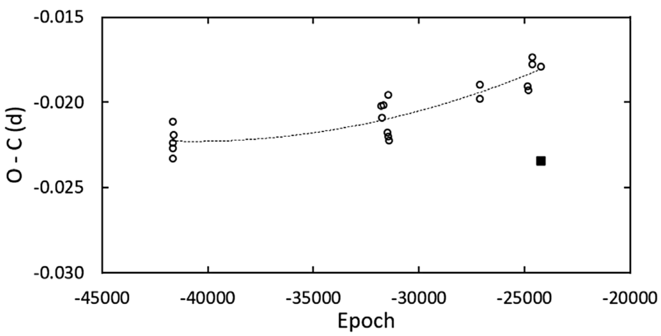

Figure 5. O–C diagram of RS Gru, October 2003–October 2010. A quadratic function is fitted to the data, after excluding the discrepant data point (the filled black square). The basis for the calculations of the O–C values is given in the legends for Table 2 and Figure 3.

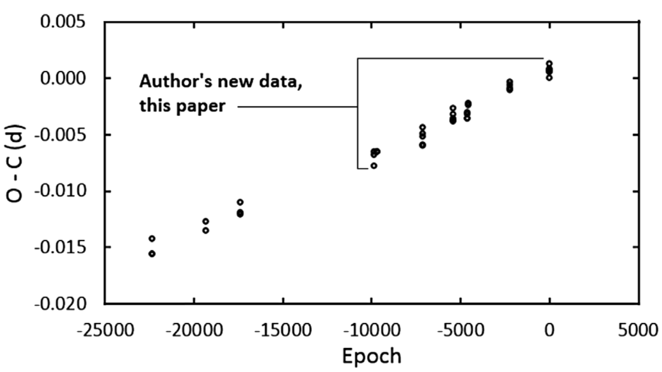

Figure 6. O–C diagram of RS Gru, July 2011–July 2020. The author's new observations, reported in this paper, are represented by the data between epochs –10000 and zero approximately, i. e., the last six groups of data in this figure. The basis for the calculations of the O–C values is given in the legends for Table 2 and Figure 3.

The other point Sterken (2005) makes is that "piecewise linear segments can only point out the occurrence of a period jump, but cannot reveal exactly when such events do occur—unless a series of contiguous cycles has been observed."

Rodriguez *et al.* (1995) interpreted the O–C diagram of RS Gru from data taken between 1952 and 1988 to be represented by a quadratic model, a smooth continuous curve which implied a decreasing period at a constant rate. On the other hand, Garcia's (2012) Figure 5 shows some of the groups of data points from the Rodriguez (1995) O–C diagram joined by straight lines, which on face value suggests that the author considered that there may have been times during which the period was constant, between which period jumps occurred. Despite these aspects of Garcia's Figure 5, he describes the fitting of a cubic function (a smooth curve) to all of the RS Gru data he reported.

There is, however, another piece of evidence supporting the occurrence of period jumps in RS Gru. Figure 3 of Laney *et al.* (2003), which is reproduced with permission as Figure 11 in the present paper, is an O–C diagram of this star which graphs the data of Rodriguez *et al.* (1995) from epoch -100,000 to zero epoch and additional data between zero epoch and epoch 40,000, but Laney *et al.* do not tabulate the numerical values underlying the additional data. Most of it would appear to fit into the gap in the O–C diagram in Figure 3 of the present paper, between epoch –78,718 and epoch –41,651. There are two period jumps in Figure 3 of Laney *et al.* (2003), one of them after zero epoch and the other after epoch 20,000.

Figure 4 of the present paper provides evidence of another period jump. The figure represents the data published initially by Axelsen (2014), who interpreted the plot to indicate that the period of RS Gru was increasing at a constant rate, since a quadratic model could be applied to the data. However, careful inspection of the figure suggests the alternative interpretation that the period was increasing at a constant rate between epochs –41664 and –24233, after which a period jump may have occurred. The remaining data in the plot, from epoch –22305 to epoch –17326, could conceivably represent the development of a new trend.

Support for the latter interpretation is provided by Figure 6, in which the O–C diagram between epochs –22305 and 35 shows what could be a linear trend. However, as demonstrated in Figures 7 and 8, a quadratic function provides a better fit, indicating that the period of RS Gru is slowly increasing at a constant rate during the time over which these observations were made.

What causes period changes in δ Scuti stars? Attempted answers to this question involve consideration of complex astrophysical processes, which are discussed by Breger and Pamyatnykh (1998). Their discussion is paraphrased selectively in what follows. It has been determined that the rates of observed period changes in δ Scuti variables are greater than rates predicted from theoretical evolutionary models by about a factor of 10. The causes of non-evolutionary period changes are not known. However, for δ Scuti stars with more than one mode of pulsation, it has been suggested that period changes, including period jumps, may be caused by non-linear mode interactions, but this could not apply to RS Gru, a radially pulsating Population I star. Stars such as RS Gru with known period changes are high amplitude stars that occur in the central part of the instability strip, near the theoretical Blue Edge of the fundamental radial mode in a $\log g - \log T_{eff}$ diagram (Figure 3 of Breger and Pamyatnykh 1998). These authors note that the clustering may, however, be accidental because this is the most populated part of the central instability strip. However, fundamental radial mode instability appears or disappears at this line,

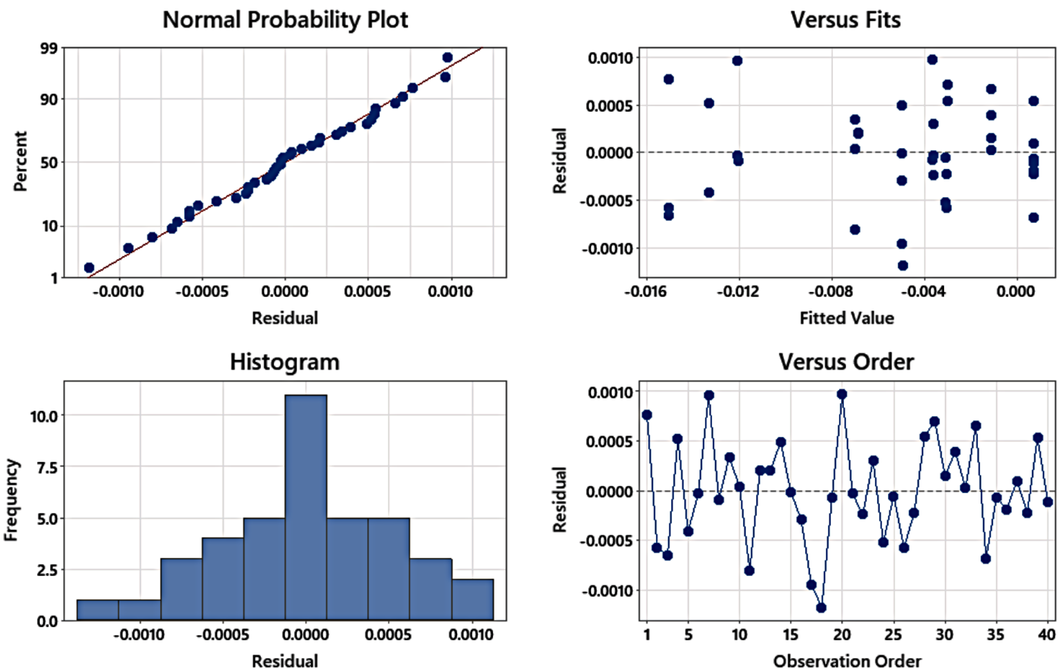

Figure 7. Analysis of the residuals from the quadratic fit to the O–C data. Compare each of the four panels in the above figure to the corresponding panel in Figure 8 below. For each panel, the behavior of the residuals is better in Figure 7, indicating that the second order model is preferred.

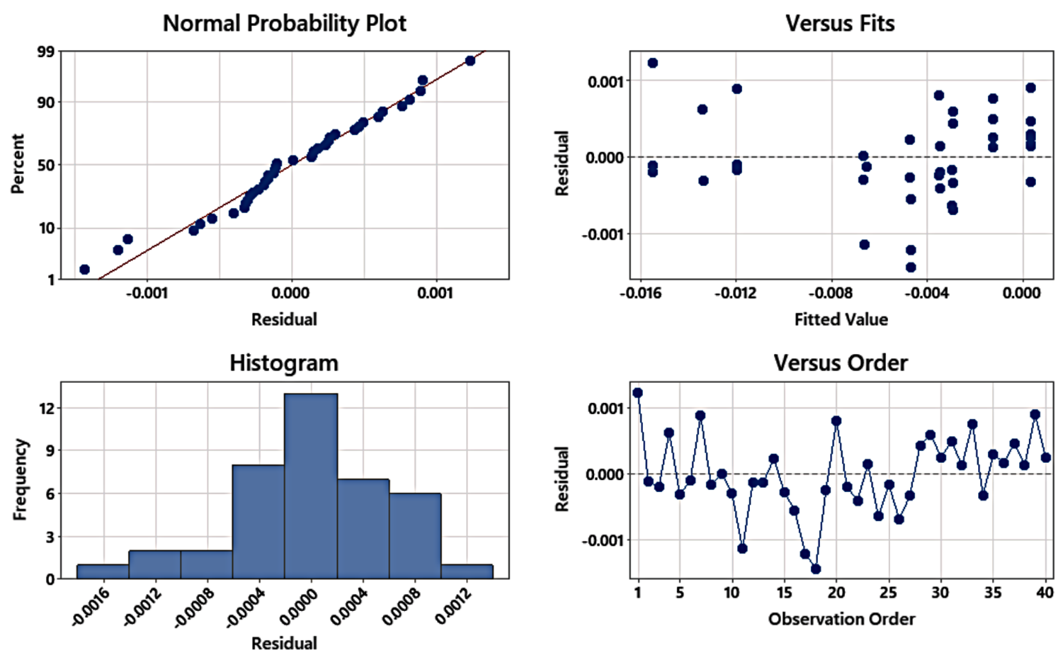

Figure 8. Analysis of the residuals from the linear fit to the O–C data. As indicated in the legend to Figure 7, the residuals from the linear model do not fit the data as well as the residuals from the second order model. In particular, the non-linear behavior of the residuals vs the fitted values indicates a model imperfection which is eliminated by moving to a quadratic model (Figure 7).

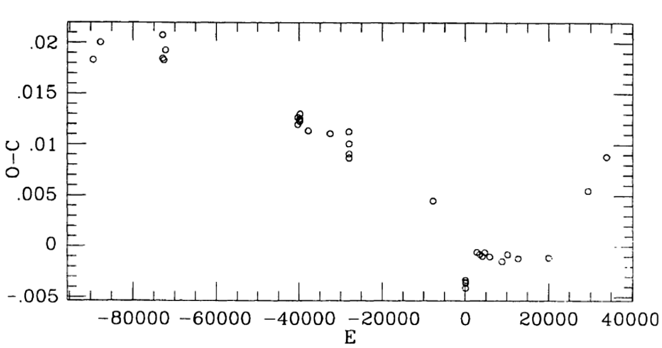

Figure 9. This is a reproduction (with permission) of Figure 3 of Laney *et al.* (2003). The O–C diagram implies period jumps after zero epoch and after epoch 20,000.

Table 2. O-C data for RS Gru.

Maximum	TOM (HJD)	Epoch	O–C (d)	Primary Source	Maximum	TOM (HJD)	Epoch	O–C (d)	Primary Source
1	2434325.2940	–168149	–0.01531	1	42	2455482.5796	–24233	–0.01790	11
2	2434573.4510	–166461	–0.01350	1	43	2455766.0212	–22305	–0.01426	9
3	2436756.5710	–151611	–0.01233	2	44	2455767.0489	–22298	–0.01560	9
4	2436760.5380	–151584	–0.01464	2	45	2455768.0779	–22291	–0.01567	9
5	2436801.5540	–151305	–0.01481	3	46	2456196.9130	–19374	–0.01279	9
6	2436853.3030	–150953	–0.01382	3	47	2456205.8798	–19313	–0.01368	9
7	2441538.4027	–119084	–0.01943	4	48	2456496.9639	–17333	–0.01207	9
8	2441538.5490	–119083	–0.02015	4	49	2456497.1119	–17332	–0.01108	9
9	2441610.4379	–118594	–0.01980	4	50	2456497.9929	–17326	–0.01213	9
10	2441611.3200	–118588	–0.01977	4	51	2457598.9665	–9837	–0.00664	12
11	2441611.4677	–118587	–0.01908	4	52	2457599.1132	–9836	–0.00694	12
12	2441612.3493	–118581	–0.01955	4	53	2457599.9945	–9830	–0.00778	12
13	2441915.4856	–116519	–0.02070	4	54	2457626.0166	–9653	–0.00665	12
14	2442687.5892	–111267	–0.02081	5	55	2457627.0457	–9646	–0.00664	12
15	2443355.4610	–106724	–0.02165	6	56	2458001.9269	–7096	–0.00448	13
16	2443355.6092	–106723	–0.02047	6	57	2458002.0734	–7095	–0.00498	13
17	2443360.4584	–106690	–0.02264	6	58	2458002.9552	–7089	–0.00526	13
18	2443360.6050	–106689	–0.02305	6	59	2458003.1015	–7088	–0.00591	13
19	2447464.7095	–78772	–0.03494	7	60	2458003.9834	–7082	–0.00613	13
20	2447468.5324	–78746	–0.03434	7	61	2458250.2298	–5407	–0.00375	14
21	2447468.6793	–78745	–0.03445	7	62	2458251.2599	–5400	–0.00270	14
22	2447472.6489	–78718	–0.03416	7	63	2458257.1394	–5360	–0.00367	14
23	2452920.0196	–41664	–0.02272	8	64	2458257.2862	–5359	–0.00388	14
24	2452921.9311	–41651	–0.02237	8	65	2458258.1688	–5353	–0.00333	14
25	2452922.0772	–41650	–0.02328	8	66	2458360.0474	–4660	–0.00362	15
26	2452923.9905	–41637	–0.02113	8	67	2458360.1949	–4659	–0.00315	15
27	2452925.0188	–41630	–0.02191	8	68	2458370.9263	–4586	–0.00361	15
28	2454373.9645	–31774	–0.02023	9	69	2458371.0736	–4585	–0.00326	15
29	2454374.9929	–31767	–0.02091	9	70	2458371.9565	–4579	–0.00249	15
30	2454387.9307	–31679	–0.02018	9	71	2458372.1036	–4578	–0.00233	15
31	2454417.0373	–31481	–0.02179	10	72	2458719.05179	–2218	–0.00099	16
32	2454417.9191	–31475	–0.02202	9	73	2458719.19904	–2217	–0.00075	16
33	2454417.9216	–31475	–0.01956	10	74	2458720.08075	–2211	–0.00111	16
34	2454423.9464	–31434	–0.02223	10	75	2458720.22839	–2210	–0.00048	16
35	2455059.0379	–27114	–0.01981	9	76	2459045.12400	0	0.00000	17
36	2455059.9208	–27108	–0.01898	9	77	2459045.27163	1	0.00062	17
37	2455391.7254	–24851	–0.01907	11	78	2459046.00657	6	0.00050	17
38	2455394.6654	–24831	–0.01930	11	79	2459046.30088	8	0.00079	17
39	2455422.0115	–24645	–0.01734	9	80	2459047.03562	13	0.00047	17
40	2455423.0401	–24638	–0.01775	9	81	2459049.97662	33	0.00124	17
41	2455481.6920	–24239	–0.02343	11	82	2459050.27000	35	0.00060	17

Note: Observations were made between November 1952 and July 2020. The calculations of O–C values are based on zero epoch at HJD 2459045.12400, the time of maximum of the first light curve peak obtained in July 2020, and a period of 0.147011369 d, the linear ephemeris calculated by Axelsen (2014).

Primary sources: 1. Hoffmeister (1956), November 1952 and July 1953 observations; 2. Oosterhoff and Walraven (1966), July 1959 observations; 3. Kinman (1961), August and October 1959 observations; 4. Dean et al. *(1977), August 1972 to August 1973 observations; 5. McNamara and Feltz (1976), October 1975 observations; 6. Balona and Martin (1978), July and August 1977 observations; 7. Rodriguez* et al. *(1995), October and November 1988 observations; 8. Derekas* et al. *(2009), October 2003 observations; 9. Axelsen (2014), including personal observations from September 2007 to July 2013; 10. Mattei (2013), observer DSI, November 2007 observations; 11. Garcia (2012), July and October 2010 observations; 12. This paper, author's data, August 2016 observations; 13. This paper, author's data, September 2017 observations; 14. This paper, author's data, May 2018 observations; 15. This paper,author's data, August and September 2018 observations; 16. This paper, author's data, August 2019 observations; 17. This paper, author's data, July 2020 observations.*

depending on the direction of stellar evolution, and the authors suggest that this may have a role in future period change interpretations. With respect to the direction of period change, it is seen that the expected theoretical prediction of increasing period with increasing evolutionary status is not borne out in practice, since the numbers of stars with increasing and decreasing periods are about equal.

5. Conclusion

RS Gru has long been known as a high amplitude δ Scuti star which exhibits period changes. At various times, the period has decreased at a constant rate, remained apparently constant between period jumps, and most recently, after yet another apparent period jump, has increased at a constant rate of $dP/dt = 7.8(3.1) \times 10^{-8}\,d\,yr^{-1}$ or $dP/Pdt = 2.3(2.1) \times 10^{-7}\,yr^{-1}$. The period on 14 July 2020 UTC was 0.14701221 (0.00000004) d.

6. Acknowledgements

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