A Study of Pulsation and Fadings in some R Coronae Borealis (RCB) Stars

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Received, September 10, 2018; revised October 16 2018; accepted November 5, 2018

Abstract We have measured the times of onset of recent fadings in four R Coronae Borealis (RCB) stars—V854 Cen, RY Sgr, R CrB, and S Aps. These times continue to be locked to the stars' pulsation periods, though with some scatter. In RY Sgr, the onsets of fading tend to occur at or a few days after pulsation maximum. We have studied the pulsation properties of RY Sgr through its recent long maximum using (O–C) analysis and wavelet analysis. The period "wanders" by a few percent. This wandering can be modelled by random cycle-to–cycle period fluctuations, as in some other types of pulsating stars. The pulsation amplitude varies between 0.05 and 0.25 in visual light, non-periodically but on a time scale of about 20 pulsation periods.

1. Introduction

R Coronae Borealis (RCB) stars are rare carbon-rich, hydrogen-poor, highly-evolved yellow supergiants which undergo fadings of up to 10 magnitudes, then slowly return to normal (maximum) brightness; see Clayton (2012) for an excellent review. Most or all RCB stars also undergo small-amplitude pulsations with periods of a few weeks. Although it was once considered that the fadings were random, it is now known that, in at least some RCB stars, the fadings are locked to the pulsation period, i. e., the onsets of the fadings occur at about the same phase of the pulsation cycle (Pugach 1977; Lawson *et al.* 1992; Crause *et al.* 2007, hereinafter CLH). This suggests a causal connection: e. g., the pulsation ejects a cloud of gas and dust; when this cools, the carbon condenses into soot; if the cloud lies between the observer and the star, the star appears to fade; it slowly reappears as the cloud disperses. It is also possible that temperature and density fluctuations in the stellar atmosphere, during the pulsations, lead to dust condensation (e. g., Woitke *et al.* 1996). Either case implies that the ejection is not radially symmetric; a cloud is ejected, not a shell.

Our interest in these stars was sparked by a somewhat-accidental encounter with the RCB star Z UMi (Percy and Qiu 2018). We had been studying Mira stars, and Z UMi had been misclassified as a Mira star in the *General Catalogue of Variable Stars* (GCVS; Samus *et al.* 2017) and in VSX (Watson *et al.* 2014), even though it had been identified as an RCB star by Benson *et al.* 1994). This star did not have a definitive pulsation period, but we measured the times of onset of its fadings, and we found that they were "locked" to a period of 41. 98 days, a typical pulsation period for an RCB star.

2. Data and analysis

We used visual observations from the AAVSO International Database (AID; Kafka 2018), the AAVSO VSTAR time-series analysis package (Benn 2013) which includes Fourier analysis, wavelet analysis, and polynomial fitting routines, and (O–C) analysis to study the five RCB stars previously studied by CLH, and to study the pulsation of RY Sgr in more detail.

3. Results

3.1. Pulsation-fading relationships in RCB stars

CLH showed that, in five RCB stars, the times of onset of fadings were locked to their pulsation periods. The five stars, and their pulsation periods in days, were: V854 Cen (43. 25), RY Sgr (37. 79), UW Cen (42. 79), R CrB (42. 97), and S Aps (42. 99).

In the first part of this project, we determined the times of onset of fadings of these five stars since the work of CLH. The determination of these times was non-trivial. The visual observations had a typical uncertainty of 0.2 magnitude. Sometimes the data were sparse, and the exact time of onset was not well covered by the observations. This is especially true if the onsets fell within the seasonal gaps in the stars' observations. Some onsets could therefore not be measured. To determine the times, we experimented with fitting horizontal lines to the light curves preceding fadings, and sloping lines to the light curves following the onset of fadings, as well as using "by-eye" judgment.

We first determined, independently, the times published by CLH. Our times differed on average by ± 4 days, which is the typical uncertainty of our determinations and CLH's. The differences averaged only ± 3 days for R CrB, presumably the most densely-observed star. On average, our times were +1 day later than CLH's, which is not significantly different from zero. Our times are given in Table 1. The ephemerides are the same as used by CLH. UW Cen did not have any recent fadings whose times could be determined. The first time listed for each star is our redetermination of the time of onset of the last fading observed by CLH. This is followed by the CLH determination. This provides an indication of the difference and uncertainty in the timings. Times are labelled with a colon (:) if there was some scatter and/or sparseness in the data, or with a double colon (::) if there was much scatter and/or sparseness.

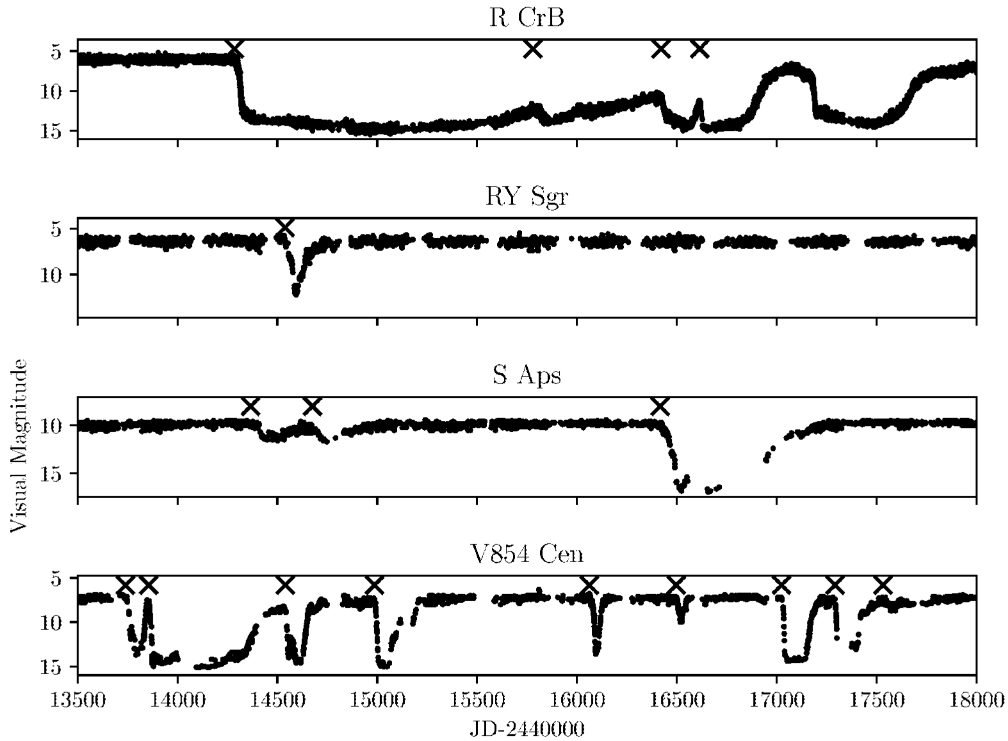

Figure 1. The recent AAVSO visual light curves of R CrB, RY Sgr, S Aps, and V854 Cen. The times of fadings (Table 1), as measured by us, are marked with an ×.

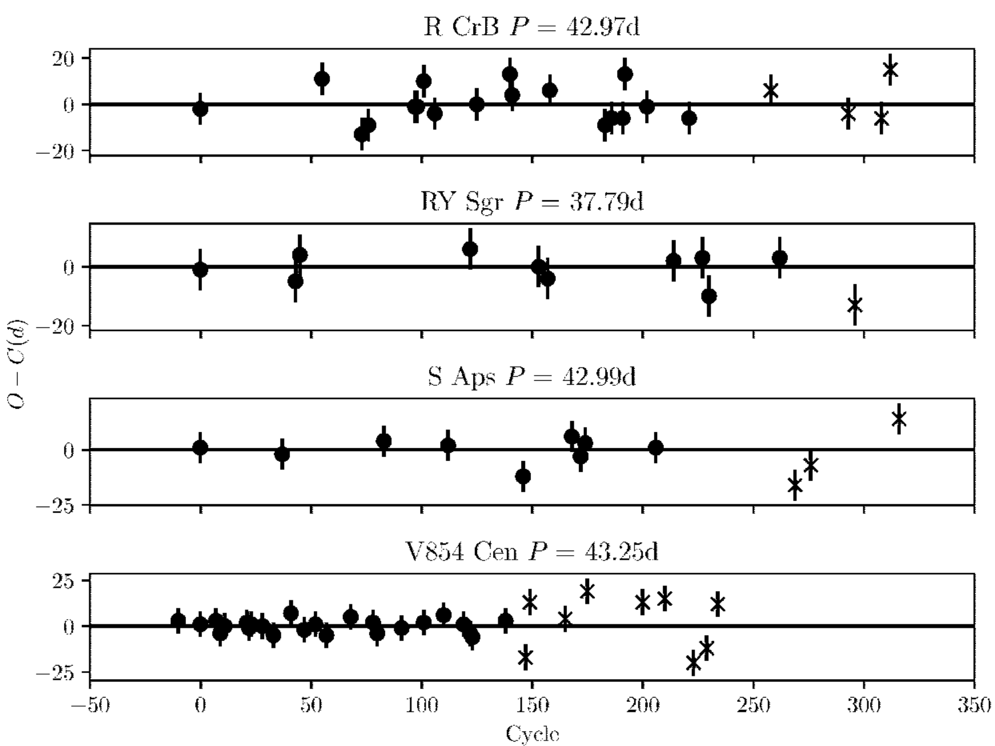

Figure 2. The (O–C) diagrams for the times of onsets of fadings in R CrB, RY Sgr, S Aps, and V854 Cen, using the periods given in section 3.1, and the observed times and cycle numbers listed in Table 1. The filled circles are the (O–C)s published by CLH.

Figure 1 shows the light curves, using the same format as CLH. The times of onset of fadings are indicated with an ×. Figure 2 shows the (O–C)s between our times of onset of fadings, and the pulsation ephemerides used by CLH. The average (O–C) for our times is almost twice that for CLH's times. This will be discussed in section 4.

3.2. Times of pulsation maximum in RY Sgr

RY Sgr has the largest pulsation amplitude of any known RCB star, though it is only about 0.15 in V. Several groups have observed or discussed the pulsation of RY Sgr for the purpose of determining and interpreting its apparent period change: Kilkenny (1982), Lawson and Cottrell (1990), Lombard and Koen (1993), Menzies and Feast (1997), among others.

RY Sgr has been at maximum since JD 2454900. In order to investigate the pulsation period, we have determined the times of 58 pulsation maxima between JD 2455031 and JD 2458243. They are listed in Table 2. They were determined independently by both of us, using low-order polynomial fitting (KHD, JRP) and phase-curve fitting (JRP), and then appropriately averaged.

3.3. Pulsation period variations in RY Sgr

The authors who were mentioned in section 3.2 determined the apparent period change in RY Sgr, and suggested various interpretations, including smoothly-varying period changes, and abrupt period changes. We have used two methods to investigate the period change: (O–C) analysis, and wavelet analysis, and applied them to the times in Table 2.

Figure 3 shows the (O–C) diagram for RY Sgr, using the times of maximum listed in Table 2, and a period of 37. 91 days. The scatter is consistent with the uncertainties in the times of maximum. Figure 4 (top) shows the period variation determined by wavelet analysis, using the WWZ routine in VSTAR. Both figures show that the period "wanders" between values of 37.0 and 38.5 days, with the period being approximately constant in the first third of the interval, increasing to a higher value in the second third, and decreasing to a lower value in the final third. The variation is not periodic, but its time scale is about 20 pulsation periods. In Mira stars, the time scale averages about 40 pulsation periods (Percy and Qiu 2018).

3.4. Are the period variations due to random cycle-to-cycle fluctuations?

The "wandering" pulsation periods of large-amplitude pulsating red giant stars (Mira stars) have been modelled by random cycle-to-cycle period fluctuations (Eddington and Plakidis 1929; Percy and Colivas 1999). We have investigated whether the period variations in RY Sgr can be modelled in this way by applying the Eddington-Plakidis formalism to the times of pulsation maximum given in Table 2. For this, we used a program written by one of us (KHD) in Python. We first tested it (successfully) on times of maximum of Mira, for comparison with Figure 1 in Percy and Colivas (1999).

In Figure 3, we showed the (O–C) values for RY Sgr, using a period of 37.91 days. Then, following Eddington and Plakidis (1929): let a(r) be the (O–C) of the rth maximum, and let ux(r) = a(r + x) – a(r), and $\overline{ux}^2$ be the average value, without regard to sign, of ux(r) for as many values of r as the observational material admits, then $\overline{ux}^2 = 2a^2 + xe^2$ where a is the average observational error in determining the time of maximum, and e the average fluctuation in period, per cycle. A graph of $\overline{ux}^2$ versus x (the "Eddington-Plakidis diagram") should be a straight line if random cycle-to-cycle fluctuations occur. Figure 5 shows the $\overline{ux}^2$ versus x graph for RY Sgr, using the times listed in Table 2. The graph is approximately linear, with scatter which is not unexpected, given the limitations of the data. The value of a = 2.7 days is consistent with the errors in the measured times of maximum.

We also generated a $\overline{ux}^2$ versus x graph for RY Sgr, using the times of pulsation maximum published by Lawson and Cottrell (1990). They extend from JD 2441753 to 2447642. The graph is shown in Figure 6. The graph is approximately linear. The slope is comparable with that in Figure 5, and the value of a = 3.1 days is consistent with the expected errors in the

Table 1. New times of onset of fadings in four RCB stars.

Star	*Cycle (n)*	*JD (obs)*	*JD (calc)*	*O–C (d)*	*Note*
S Aps	206	2451670	2451674	–4	PD
—	206	2451675	2451674	1	CLH
—	269	2454366::	2454382	–16	—
—	276	2454676:	2454683	–7	—
—	316	2456417	2456403	14	—
RY Sgr	262	2453273	2453266	7	PD
—	262	2453269	2453266	3	CLH
—	296	2454538:	2454551	–13	—
V854 Cen	138	2453376	2453368	8	PD
—	138	2453371	2453368	3	CLH
—	147	2453740::	2453757	–17	—
—	149	2453856	2453843	13	—
—	165	2454540:	2454536	4	—
—	175	2454987	2454968	19	—
—	200	2456062	2456049	13	—
—	210	2456497	2456482	15	—
—	223	2457024	2457044	–20	—
—	229	2457292:	2457304	–12	—
—	234	2457532	2457520	12	—
R CrB	221	2452678	2452689	–11	PD
—	221	2452683	2452689	–6	CLH
—	258	2454285	2454279	6	—
—	293	2455779	2455783	–4	—
—	308	2456421	2456427	–6	—
—	312	2456615	2456599	15	—

Table 2. Times of pulsation maximum in RY Sgr (JD – 2400000).

JD (max)	*JD (max)*	*JD (max)*	*JD (max)*
55031	55740	56466	57274
55064	55787	56509	57309
55104	55823	56548	57600
55143	55863	56582	57653
55258	56018	56618	57683
55301	56046	56774	57721
55332	56085	56812	57906
55367	56125	56847	57940
55409	56167	56891	57984
55448	56197	56924	58018
55486	56239	56958	58055
55520	56268	57113	58205
55629	56349	57155	58243
55673	56394	57193	
55714	56427	57231	

measured times of maximum. The slopes e are 0.9 and 1.0 day for our data and Lawson and Cottrell's, respectively.

3.5. Pulsation amplitude variations in RY Sgr

Most of the famous Cepheid pulsating variables have constant pulsation amplitudes, but this is not true of other types, especially low-gravity stars: pulsating red giants (Percy and Abachi 2013), pulsating red supergiants (Percy and Khatu 2014), and some pulsating yellow supergiants (Percy and Kim 2014). The amplitudes of these stars vary by up to a factor of ten, on time scales of 20–30 pulsation periods.

We have used wavelet analysis to determine the variation in pulsation amplitude in RY Sgr, during the last 3,000 days when the star was at maximum (JD 2455000 to JD 2458250). The results are shown in the lower panel in Figure 4. The visual amplitude varies between 0.05 and 0.25. The amplitude variations can be confirmed by Fourier analysis of subsets of the data. The variation is not periodic, but occurs on a time scale of about 20 pulsation periods. This time scale is comparable to that found in the pulsating star types mentioned above. There is no strong consistency to the direction of the changes, though there is a slight tendency for the amplitude to be relatively medium-to-high at the beginning of a maximum, and relatively medium-to-low at the end.

We used the same method to study the amplitude variations during several shorter intervals when the star was at maximum. The results are given in Table 3. During these intervals, the visual amplitude also varies between 0.05 and 0.25. The median time scale of visual amplitude variation is about 30 (range 15 to 55) pulsation periods.

3.6. At what pulsation phase does the onset of fading occur?

CLH stated "...the absolute phase of the decline onsets could not be determined from the AAVSO data...." We have attempted to make this determination for RY Sgr, as follows. For each of the times of onset of fading determined by CLH, we have examined the previous 50–60 days of data, and measured the times of pulsation maximum using the same methods as in section 3.2. The results are listed in Table 4. The times of onset of fadings are the predicted times, given by CLH. There is considerable scatter, as there was in measuring the times of maximum in Table 2. Before some fadings, the data were too sparse to measure the pulsation maximum.

On average, the onsets of fading occur 7 days after pulsation maximum. According to Pugach (1977), the onset of fadings occurs at pulsation maximum, and the same is true for V854 Cen (Lawson *et al.* 1992). These conclusions depend, to some extent, on the definition of when the onset occurs, and may not be in conflict.

4. Discussion

The times of onset of fadings that we have measured (Table 1, Figure 1) seem to continue to be locked to the pulsation periods (Figure 2), though with a scatter ± 11 days which is twice that obtained by CLH, even though our measured times are consistent with theirs. There are several possible explanations: (1) our times are actually less accurate than theirs;

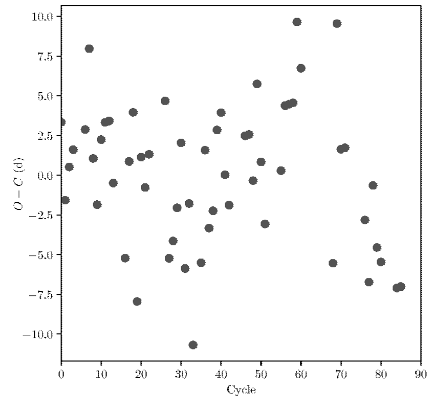

Figure 3. The (O–C) diagram for the times of pulsation maximum of RY Sgr listed in Table 2, using a period of 37.91 days. The period is approximately constant through cycles 0–25, slightly larger than average (upward slope) through cycles 25–60, and slightly smaller than average (downward slope) through cycles 60–90.

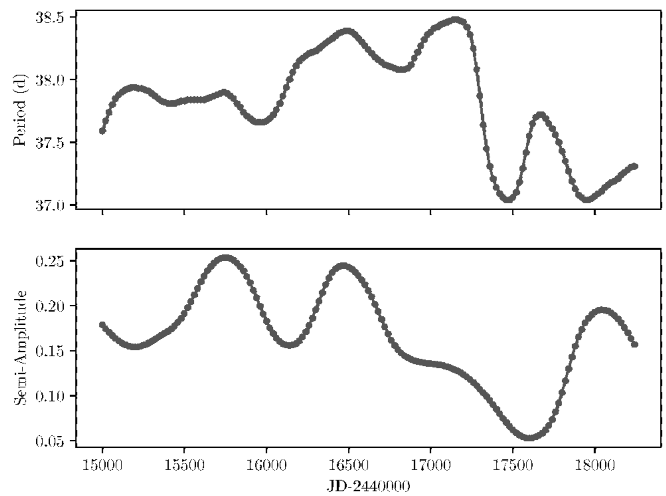

Figure 4. The variation in the pulsation period (top) and amplitude (bottom) of RY Sgr versus time, determined using the WWZ wavelet routine in VSTAR, and AAVSO visual observations.

Table 3. Pulsation amplitude variations in RY Sgr.

JD Range	*Amplitude Range*
2432950–2435437	0.06–0.20
2436597–2438054	0.14–0.20
2438303–2439653	0.07–0.23
2442095–2443300	0.17–0.11
2445739–2447949	0.07–0.20
2449886–2451403	0.10–0.24
2452078–2453227	0.04–0.15

Table 4. Times of onset of fading and of pulsation maximum in RY Sgr.

Onset of Fading F	*Pulsation Maximum M*	*F–M (d)*
2443366	2443357	+9
2444990	2444970	+20
2445066	2445064	+2
2447976	2447977	–1
2449147	2449133	+14
2441452	2441458	–6
2452057	2452046	+11
2453266	2453260	+6

(2) the "wandering" period (Figures 3 and 4) causes some scatter; (3) the fadings are not exactly locked to the pulsation; there are random factors in the pulsation, mass ejection, and onset of fadings which add to the scatter; (4) the differences are a statistical anomaly. We recognize that it is challenging to determine times of onset of fadings, or times of pulsation maxima, using visual data. This is where the density of the visual data can often help.

The interpretation and misinterpretation of period changes, especially as determined from (O–C) diagrams, has a long history, and a whole conference was devoted to this topic (Sterken 2005). If the (O–C) diagram has the appearance of a broken straight line, even with much scatter, it is often interpreted as an abrupt period change, e. g., Lawson and Cottrell (1990). If the (O–C) diagram is curved, even with much scatter, it is often interpreted as a smooth evolutionary change, e.g., Kilkenny (1982). Hundreds of (O–C) diagrams of Mira stars show these and other appearances, and can be modelled as due to random, cycle-to-cycle period fluctuations (Eddington and Plakidis 1929; Percy and Colivas 1999).

Our results (the linearity of Figures 5 and 6) suggest that the period variations in RY Sgr can be modelled, at least in part, by random cycle-to-cycle variations, as in Mira stars, rather than solely by a smooth evolutionary variation, or an abrupt variation. We cannot rule out the presence of a small smooth or abrupt variation but, if so, it is buried in the random period-fluctuation noise. The cause of the fluctuations is not known, but may be connected with the presence of large convective cells in the outer layers of the stars. The fact that the star ejects clouds, rather than shells, suggests that the outer layers of the star are not radially symmetric.

The discovery of a variable pulsation amplitude in RY Sgr (Figure 4) is an interesting but not-unexpected result, given the presence of amplitude variations in other low-gravity pulsating stars. Fernie (1989) and Lawson (1991) both pointed out that the pulsation amplitude of R CrB varied from cycle to cycle, but did not investigate the time scale of this phenomenon. We note that, when the pulsation amplitude is at its lowest, it is even more difficult to measure the times of pulsation maximum.

There is also the possibility that some RCB stars have two or more pulsation periods, either simultaneously or sequentially. Both Fernie (1989) and Lawson (1991) found a variety of periods in R CrB: Fernie (1989) found only 43.8 ± 0.1 days in 1985–1987, but 26.8, 44.4, and 73.7 days (possibly an alias) in 1972; Lawson (1991) found 51.8 and possibly 56.2 days in 1986–1989. Fernie (1989) considered that 26.8 and 44.4 days could possibly be the first overtone and fundamental periods, but 51.8 and 56.2 days are too close together to be radial overtones.

There are, unfortunately, many problems in determining these periods. The precision dP/P of periods P, determined from a single season of data, is limited to P/L, where L is the length of the dataset; see Figure 1 in Lawson (1991). If the period "wanders," the Fourier peaks will be further broadened. If the amplitude of the pulsation is changing, then Fourier analysis will give more than one period, whether or not these periods are real. If periods are determined from two or more seasons of data, then there will be alias periods; see Figure 2 in Fernie (1989). There may be undetected variability due to minor dust obscuration, or other low-amplitude processes. For all these reasons, it is difficult to draw firm conclusions about multiple or variable pulsation periods.

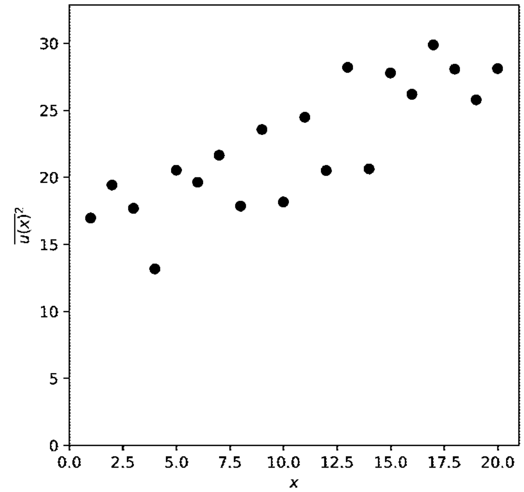

Figure 5. The Eddington-Plakidis diagram for RY Sgr, using the times of pulsation maximum in Table 2, and a period of 37.91 days.

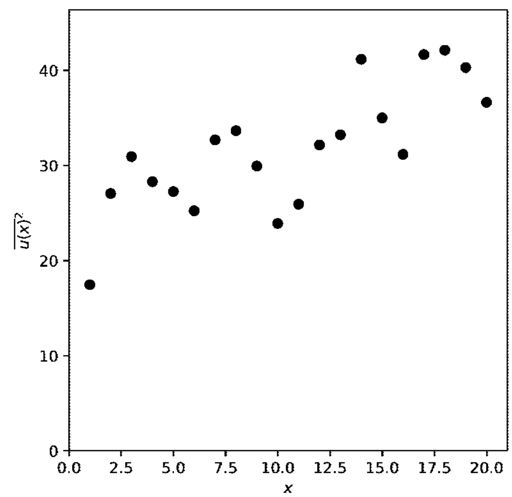

Figure 6. The Eddington-Plakidis diagram for RY Sgr, using the times of pulsation maximum given by Lawson and Cottrell (1990) between JD 2441753 and 2447642, and a period of 38.56 days.

There are other RCB stars which are known or suspected to pulsate. Rao and Lambert (2015) list 29. Most if not all of them have pulsation amplitudes which are even smaller than that of RY Sgr, so it will be almost impossible to study their pulsation with visual data. At least one of the 29 stars has an incorrect period: Z UMi is listed as having a period of 130 days, but Percy and Qiu (2018) were not able to fit AAVSO data to that period but, as mentioned in the Introduction, using the observed times of onset of fadings, they suggested a period of 41.98 days instead. It may be possible to determine times of onset of fadings of some of the 29 stars, and see if there is a period to which they are locked, as Percy and Qiu (2018) did for Z UMi.

In the future, most of these stars will be monitored through facilities such as LSST (the Large Synoptic Survey Telescope), but the century of archival AAVSO data will remain unique.

5. Conclusions

We have derived new information about the pulsation of the RCB star RY Sgr, especially about the variation of its period and amplitude. We have also strengthened the connection between the pulsation and the fadings in this star. We have used long-term archival visual data but, since the pulsation amplitudes of other RCB stars are even smaller than that of RY Sgr, future studies like ours will have to use long-term precision photoelectric or CCD observations.

6. Acknowledgements

We thank the AAVSO observers who made the observations on which this project is based, the AAVSO staff who archived them and made them publicly available, and the developers of the VSTAR package which we used for analysis. Coauthor KHD was a participant in the University of Toronto Work-Study Program, which we thank for administrative and financial support.

This project made use of the SIMBAD database, maintained in Strasbourg, France. The Dunlap Institute is funded through an endowment established by the David Dunlap family and the University of Toronto.

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