Studies of R CrB Star Pulsation Using ASAS-SN Photometry

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Abstract R Coronae Borealis (RCB) stars are low-mass, carbon-rich, hydrogen-poor stars which suddenly and unpredictably fade by up to eight magnitudes or more in visual brightness, then slowly return to maximum. They may also undergo small-amplitude variations, on time scales of weeks, due to pulsation. The present study uses data from the All-Sky Automated Search for Supernovae (ASAS-SN), along with light curve analysis and time-series analysis, to study pulsational variations in 23 stars which were classed as RCB stars in both the *ASAS-SN Variable Star Catalog* and the *General Catalogue of Variable Stars*. All show irregular or semiregular variability on time scales of 20 to 100+ days, with semi-amplitudes of 0.05 to 0.3 magnitudes. For 14, some estimate of the period could be derived; the periods cluster between 30 and 50 days and are, on average, about half those of low-mass yellow supergiants with similar luminosity but more normal composition.

1. Introduction

R Coronae Borealis (RCB) stars are rare, low-mass yellow supergiant stars with bizarre chemical compositions. They can spend years or decades at normal maximum brightness, then suddenly and unpredictably fade by up to eight magnitudes or more in the course of a few days or weeks, then slowly return to maximum. See Clayton (2012) for an excellent review.

Unlike "normal" stars which are about 3/4 hydrogen, 1/4 helium, and 2 percent everything else, by mass, RCB stars are about 9/10 helium, 1/10 carbon, and less than one percent hydrogen, by mass. There are two main models for the formation of these stars, neither of which is entirely satisfactory—the merger of two white dwarfs, or a final helium flash.

The fadings are due to the obscuring effect of clouds of carbon-rich dust ("soot"), ejected randomly from the star in time and direction. If the cloud lies between the observer and the photosphere of the star, then a fading is seen. The cloud, being warm, can be detected at infra-red wavelengths. As the dust disperses, the star slowly returns to normal maximum brightness.

Some and perhaps all RCB stars show another form of variability—pulsation. This is not surprising; normal low-mass yellow supergiants pulsate as RV Tauri or SRd variables. In the RCB stars, this pulsation may have some role in ejecting matter from the star, perhaps leading to a fading. A very comprehensive study of the pulsation of RCB stars was carried out by Lawson *et al.* (1990). Percy *et al.* (2004) carried out self-correlation time-series analysis of the Lawson *et al.* data and of other data. The results, for the stars in the present sample, are included in Table 1.

The brightest RCB stars are RY Sgr and R CrB itself. RY Sgr has a normal visual magnitude of 6.5 and a pulsation period of 38.6 days, and a range of 0.5 in V. R CrB has a normal visual magnitude of 5.8 and a pulsation period of about 41 days and a range of 0.1 or more, but its pulsational variability is semiregular at best; some observers have suggested that it also has a 67-day period, and is bimodal. Figure 1 shows recent AAVSO V observations of R CrB as it came out of a deep minimum (Kafka 2022). In the first half of the dataset, a 42-day variability can be clearly seen. The variability then becomes semiregular. The 42-day signal reappears at the end.

There is evidence that, in a few stars, the onset of fadings may be linked to the phase in the pulsation cycle (Pugach 1977; Lawson *et al.* 1992; Crause *et al.* 2007; Percy and Dembski 2018), but the sample sizes were not large enough to tell whether this link is statistically significant.

The photometric observations in the All-Sky Automated Survey for Supernovae (ASAS-SN) database are a potentially useful tool for studying RCB star pulsation. That is the purpose of the present paper.

2. Data and analysis

The ASAS-SN variable star website and catalog (Shappee *et al.* 2014; Jayasinghe *et al.* 2018, 2019), contains 93 stars which the catalog classifies as RCB stars. For many of these, there was no evidence of a fading in the ASAS-SN data.

Table 1. Period and amplitude analysis of ASAS-SN observations of RCB stars.

Name	*GCVS Range*	*P(d) / A (mag)*	*Other Periods*
UX And	8.2–9.9	54/0.03	—
U Aqr	10.6–15.9	30/0.22	40,80 L, 40 PY
V943 Ara	10.8–17.2	55/0.05:	—
UW Cen	8.89–17.9	41:/0.05, 68:/0.05	42.8 L
DY Cen	12.0–<16.4	18:/0.02	—
V742 Lyr	11.5–<17.5	48.6/0.16	—
W Men	13.4–<18.3	32/0.03, 47/0.03	—
Y Mus	10.5–12.1	38/0.05	107, 227 L, 100 ± PY
RT Nor	10.6–16.3	40/0.07, 60/0.07	43 L, 50 ± 6 PY
RZ Nor	10.63–<13.	50:/0.05:	—
V409 Nor	11.8–19.	49.9/0.05, 70/0.07	—
VZ Sgr	10.8–15.0	126/0.06	40–50 L
GU Sgr	11.33–15.0	—	37.8 L
V3795 Sgr	11.5–<15.5	35	—
FH Sct	13.4–16.8	47/0.08	—
RS Tel	9.0–15.34	100/0.07	40 L, 40 ± 6 PY

Note: In the last column of other period determinations, L denotes Lawson et al. *(1990), and PY denotes Percy* et al. *(2004).*

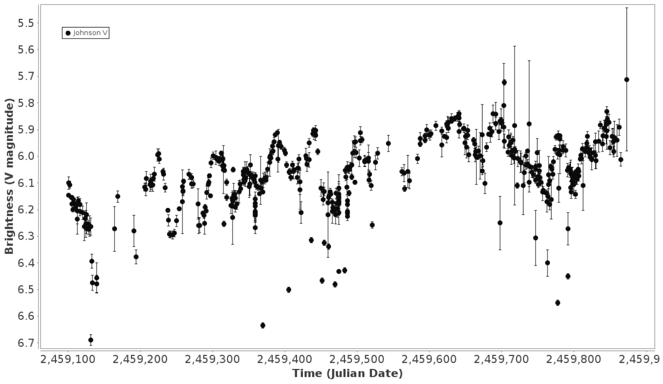

Figure 1. A 1000-day light curve of R CrB, based on AAVSO V photometry, showing the semiregular variability due to pulsation.

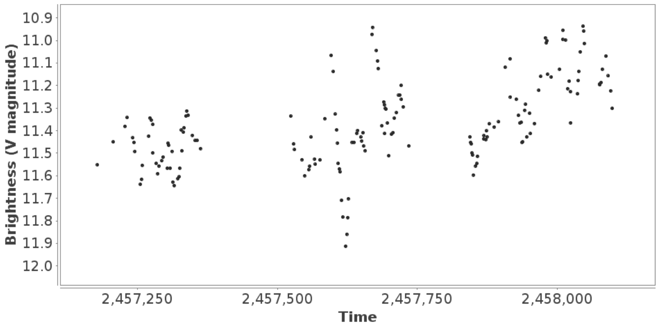

Figure 2. The light curve of U Aqr, based on ASAS-SN V photometry, showing short-term semiregular variability due to pulsation.

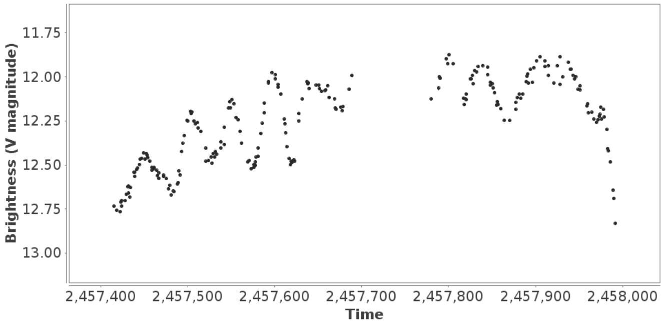

Figure 3. The light curve of V742 Lyr, based on ASAS-SN V photometry, showing relatively regular 48.6-day variability due to pulsation.

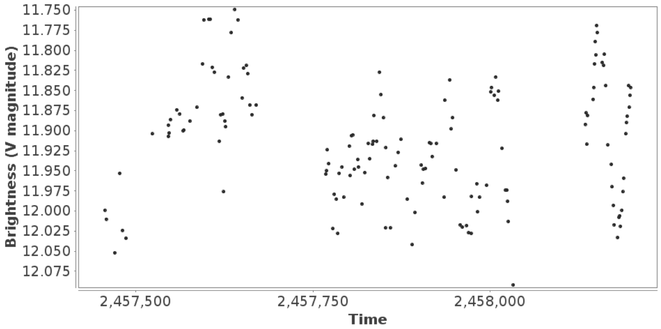

Figure 4. The light curve of V409 Nor, based on ASAS-SN V photometry, showing 49.9-day variability due to pulsation.

The present study included only stars which are also classified as RCB stars in the *General Catalogue of Variable Stars* (Samus *et al.* 2017). Some of these stars were in the process of entering or leaving a fading, and were unsuited for study of the small-amplitude pulsation. A few others were either too bright or too faint for study. In the end, the present study included the 16 stars in Table 1, plus those seven mentioned at the end of section 3.

The ASAS-SN data and light curves are freely available online (asas-sn.osu.edu/variables). The error bars on the ASAS-SN observations are 0.02 mag, and this is also the noise level in our Fourier analyses.

In addition to very careful analysis of the light curves, the Fourier analysis routine in the American Association of Variable Star Observers (AAVSO) time-series package VSTAR (Benn 2013) was used. Note that the amplitudes which are given in this paper, including in the tables, are actually semi-amplitudes—the coefficient of the sine curve with the given period—and not the full amplitude or range.

3. Results

The results are summarized in Table 1, which includes the range as given in the *General Catalogue of Variable Stars*, as well as the period(s) and amplitude(s), and comparisons with other determinations. A colon (:) denotes uncertainty. Notes on individual stars are given below. A few typical light curves are shown.

UX Ant A 54±4-day period is clearly visible in the light curve though, in the wavelet analysis, it is possible that there are separate 47- and 57-day periods. The amplitude seems to decrease as a fading approaches.

U Aqr There is a strong signal, with a period of 30±3 days and an amplitude of 0.22, but reaching as high as 0.5 (!). There is an even stronger 80-day period in the last 3/4 of the dataset, as the star begins a fading (Figure 2).

V943 Ara The light curve is dominated by fading and recovery, but there is a strong 50–60-day period in one season of the light curve.

UW Cen There is very weak evidence for periods of about 41 and 68 days; the amplitude is less than 0.05 and the periodicity is not convincing.

DY Cen There is a very weak signal at a period of 18 days.

V742 Lyr There is a very strong (amplitude 0.16) signal at a period of 48.6 days in the data between two fadings; it is also visible before the first of the two fadings (Figure 3). The light curve shows some degree of regularity.

W Men The pulsation amplitude seems to increase as a fading approaches, and is greatest at the end of the dataset. The dominant period switches from 32 to 47 days.

Y Mus There is a 38-day signal which, though weak, becomes more noticeable as a fading approaches at the end of the dataset.

RT Nor There are strong semiregular variations with periods of 40 and 60 days, with amplitudes of 0.07. There is also a signal in the Fourier spectrum at 180 days, with amplitude 0.09, but it is not visible in the light curve.

RZ Nor The light curve is dominated by recovery from a fading, but there is a hint of a 50-day period in one season of the light curve.

V409 Nor There is a period of 49.9 days, with an amplitude of 0.05, and a slightly weaker signal at 70 days. The amplitude of the 49.9-day period increases to 0.10 or more at the end of the dataset (Figure 4).

VZ Sgr There are large, irregular variations on time scales greater than 100 days. A period of 126 days (amplitude 0.06) is present in the Fourier spectrum.

GU Sgr Although there are no signals in the Fourier spectrum with amplitude greater than 0.03, there is one very large cycle with amplitude of 0.3 just before the fading at the end of the dataset.

V3795 Sgr There are complex variations in the period range of 30-40 days, which are clearly visible in the light curve.

FH Sct There is a strong 47 ± 10-day signal, with an amplitude of 0.08, including just before a fading.

RS Tel There is a strong 100-day period, with amplitude 0.07, which is visible especially in the last 2/3 of the dataset.

For the following stars, there was small-amplitude, short-term variability, but no obvious period in the Fourier spectrum or in the light curve: S Aps, UV Cas, V854 Cen, V2552 Oph, MV Sgr, SV Sge, V482 Cyg. RY Sgr and R CrB are normally too bright for ASAS-SN photometry.

4. Discussion

All of the stars in Table 1 show small-amplitude (typically 0.05 to 0.30) variations on time scales of 20 to 100 days (but clustering between 30 and 50 days), presumably due to pulsation.

Determining precise periods and amplitudes is a challenge. In some stars, the amplitude is only slightly larger than the nominal error in the data, namely 0.02 magnitude. There are seasonal gaps in the data, which may introduce alias periods in the Fourier spectra. In some stars, the pulsations are superimposed on slow variations due to changes in dust obscuration. The variations are semiregular at best. This can be seen in the figures, including Figure 1. Only V742 Lyr (Figure 3) showed reasonable regularity. Some stars may be bimodal.

It is known that low-mass yellow supergiants with normal composition show semiregular pulsation. For instance, Percy (2022) examined a sample of yellow semiregular (SRd) variables, and found that 34/38 were semiregular primarily because their pulsation amplitudes varied by factors of up to 10 on time scales of 20–30 pulsation periods. This may be because the mode lifetimes are only 20–30 pulsation periods, unless the modes are continuously driven. Other causes of semiregularity were long secondary periods, multiple pulsation periods, period switch, or "wandering."

This is one possible reason why the periods, determined in this study, differ in some cases from those in the literature (Table 1, last column). The length, distribution, and accuracy of the ASAS-SN data differ from those of the photoelectric data, which were used by both Lawson *et al.* (1990) and Percy *et al.* (2004). Different modes may dominate at different times. In Figure 1, for instance, the behavior of R CrB changes between the first half of the data and the second half. Also, Percy *et al.* 2004) used a different method of time-series analysis—self-correlation—than Lawson *et al.* 1990). This method tends to identify a single dominant period in the data, rather than multiple periods.

There are six stars for which absolute visual magnitudes M_V can be crudely estimated from their mean normal V magnitude, because their GAIA distances (taken from the ASAS-SN catalogue) are reasonably accurate, and their interstellar reddening and extinction are small. They are: UX Ant, –2.92; U Aqr, –4.08; V742 Lyr, –5.08; RS Tel, –4.71; R CrB, –4.31; and RY Sgr, –5.50. These are consistent with previous estimates of the M_V of RCB stars, namely –3 to –5 (Clayton 2012). There is no obvious period-luminosity relation in these six stars.

The pulsation periods of RCB stars are generally 20 to 100 days, but clustering between 30 and 50 days. Comparing the M_V and log P values with the period-luminosity relation for RV Tauri stars—which are also low-mass yellow supergiants, but of normal composition—indicates that their periods are about half what would be expected from the RV Tauri P–L relation (Bodi and Kiss 2019). This could indicate that the periods are high overtones, but it is more likely because the composition, structure, and previous evolution of the RCB stars are much different from those of the RV Tauri stars.

In section 3.1, a few stars have been noted as having a pulsation amplitude which seems to increase before a fading, but the sample size is too small to tell whether this trend is significant.

5. Conclusions

This study strengthens the conclusion that most, if not all, RCB stars vary semiregularly or irregularly on a time scale of weeks, with small amplitude, due to pulsation. The periods cluster between 30 and 50 days, and are about half those of normal low-mass yellow supergiants of similar luminosity.

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