Self-Correlation Analysis of R Coronae Borealis Stars: A Pilot Project

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Abstract R. Coronae Borealis (RCB) stars are peculiar yellow supergiant stars which suddenly and unpredictably decrease in brightness by up to several magnitudes, then slowly return to normal. Most (perhaps all) RCB stars also pulsate, and the pulsations may be related to the ejection of the dust clouds which produce the fadings. As a pilot project, we have applied self-correlation analysis to two datasets: long-term photometry of R CrB itself by J. D. Fernie, and long-term photometry of several southern RCB stars by P. L. Cottrell, L. Skuljan, and their colleagues. Self-correlation is a simple form of time series analysis which displays the cycle-to-cycle behavior of a variable star, averaged over a dataset. It is especially useful for semiregular variables. Generally, the seasonal pulsation time scales and amplitudes which we derive are in agreement with Fourier analysis of the same datasets. In the case of R CrB, we confirm that there is apparent mode-switching from season to season.

1. What are RCB stars?

R Coronae Borealis (RCB) stars are low-mass, carbon-rich, hydrogen-poor, yellow supergiants in an advanced stage of evolution: they may be merged white dwarfs, or undergoing a final helium flash (a "burp" in their nuclear fusion processes) in the course of changing from an asymptotic giant branch star to a white dwarf. They are also variable stars: most famously, they undergo sudden, unpredictable, irregular, rapid (weeks) fadings of up to 10 magnitudes, then slow (months) returns to normal. They also undergo small-amplitude semiregular variability, with periods of tens of days, due to radial pulsation. Only a few dozen are known; there may be hundreds more waiting to be discovered and studied in our galaxy. See Clayton (1996) and Skuljan and Cottrell (2004) for recent reviews. There are many unsolved questions about RCB stars. What is the evolutionary state: merged white dwarfs, or final helium flash? What causes the fadings? Probably ejected clouds of carbon dust (soot), but why do the fadings occur when they do, i.e., what triggers the formation of the dust cloud, and how? What role, if any, does pulsation play? Is it the trigger?

2. What's known about RCB pulsation?

The most detailed studies of RCB pulsation have been carried out by P. L. Cottrell and his colleagues at the University of Canterbury in New Zealand, using the facilities of the Mount John University Observatory, and by J. D. Fernie and his colleagues at the University of Toronto, using the facilities of the David Dunlap Observatory, and of the Automatic Telescope Service. In both cases, these facilities allow for the collection of long sets of high-quality photometric data. These show that all RCB stars show Cepheid-like pulsation with small amplitude—usually less than 0.1 magnitude—and periods of tens of days. R CrB itself occasionally changes its pulsation period, possibly as a result of a change of pulsation mode (e.g. Fernie and Lawson 1993). But because of the semiregularity of these stars, and the complications of the fadings, it is not always straightforward to analyze the photometry of the stars at maximum light.

3. Purpose of this project

Previous studies of RCB stars at maximum have used both visual inspection of light curves and Fourier analysis to determine the period. Fourier analysis, however, assumes that the period is constant through the dataset, and these stars may occasionally change mode and period from season to season. We therefore decided to use an alternative method of time-series analysis—self-correlation—to see whether it would be a useful adjunct to the other two methods. Self-correlation has proven to be useful in analyzing other types of semiregular variable stars (e.g. Percy and Mohammed 2004).

4. Self-correlation

Self-correlation analysis is a simple method of time-series analysis which measures the cycle-to-cycle behavior of the star, averaged over all the data. It is related to variogram analysis (Eyer and Genton 1999). It is suitable for semiregular variables, and those with seasonal gaps in the data, and has been found to be a useful adjunct to Fourier analysis. See the recent paper in this *Journal* by Percy and Mohammed (2004) for a more complete description of the method.

The self-correlation diagram plots the average magnitude difference, Δm, against the difference between the times of observation, Δt. The useful features of the self-correlation diagram are as follows: (i) there are minima at multiples of the period (if any); (ii) the minima will gradually disappear with increasing Δt if the variability is not strictly periodic; (iii) the value of Δ m, as Δt approaches zero, is the average observational error; (iv) the difference between the height of maximum and minimum is approximately 0.9 times the average amplitude (or half-range) of variability.

5. Data

Data for R CrB were those accumulated by J. D. Fernie (2003) and are available on-line. Data for S Aps and RS Tel were taken from Lawson *et al.* (1990). Data for other stars were provided by P. L. Cottrell, and were obtained at the Mount John University Observatory.

6. Results

The results are contained in Table 1, which lists the period, *P*, and the amplitude, ΔV, for each star, for each season. Individual seasons of data were analyzed for most of the stars, as well as the total data for each star. Figures 1–4 show sample seasonal self-correlation diagrams for two stars. Note that if a self-correlation diagram is calculated for Δt up to a maximum value of T, then the diagram utilizes pairs of measurements which are up to T days apart, not more.

For R CrB, the data were generally dense enough so that the self-correlation diagram was well-defined, and showed two or more minima. If that was not the case, there is a colon after the derived time scale in Table 1. For the other stars, the data were sparser, so the derived time scales are more often uncertain. The statistical properties of self-correlation analysis have not been determined, and it would probably be difficult to do so.

7. Discussion

The probable errors of the seasonal periods are estimated to be typically ± 3 days, except for the values marked with a colon, which are less certain. Ideally, the self-correlation method requires datasets which are several times longer than the periods being sought, and sampled as often as possible. Although the University of Canterbury's Mount John University Observatory is ideally suited for long-term photometric monitoring, in terms of facilities, weather, and staff, our datasets were not always as long and dense as would have been ideal. The R CrB data were obtained mostly with a robotic telescope, and sampled as often as nightly, but there were seasonal gaps, due both to the sun and to the Arizona monsoon season.

8. Conclusions

For each star, there is a useful estimate for the period (or more properly the time scale) and amplitude for each season, and for the overall data. There is definite evidence for mode switching in R CrB—something which was previously known from light curve and Fourier analysis. There is marginal evidence for mode switching in RZ Nor and RT Nor. We conclude that self-correlation analysis can be useful, in some cases, for interpreting the behavior of complex semiregular variable stars such as RCB stars, especially when used in combination with light curve and Fourier analysis.

9. Acknowledgement

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Table 1. Seasonal time scales and amplitudes for several RCB stars, determined by self-correlation analysis.

Star	*Seasons*	*P(d)*	*ΔV*	*Star*	*Seasons*	*P(d)*	*ΔV*
R CrB	1967–1970	50	0.05:	RT Nor	1988–1989	55	0.05
R CrB	1978–1980	23	0.02:	RT Nor	1992–1994	48	0.09
R CrB	1985	46	0.13	RT Nor	1994–1996	40	0.04:
R CrB	1987	45:	0.07	RT Nor	1996–1998	40:	0.02:
R CrB	1988	60	0.04	RT Nor	all	50±6	—
R CrB	1989	45:	0.09				
R CrB	1990	45	0.07	RS Tel	1971–1976	42:	0.08:
R CrB	1991	58	0.06	RS Tel	1986–1989	38	0.04
R CrB	1992–1994	40	0.05	RS Tel	1988–1989	40	0.03
R CrB	1994	44	0.05	RS Tel	all	40±6	—
R CrB	1997	39:	0.04				
				S Aps	1971–1972	45:	0.02
R CrB	1997–1998	40	0.03	S Aps	1986–1989	43:	0.02
				S Aps	1991–1993	40:	0.02
RZ Nor	1973–1976	45:	0.10:	S Aps	all	44±3	—
RZ Nor	1989–1990	51:	0.04				
RZ Nor	1990–1994	44:	0.04	U Aqr	1986–1989	40	0.10
RZ Nor	1998	35	0.05	V CrA	1986–1988	106:	0.03
RZ Nor	all	38±3	—	Y Mus	1986–1989	100:	0.01:

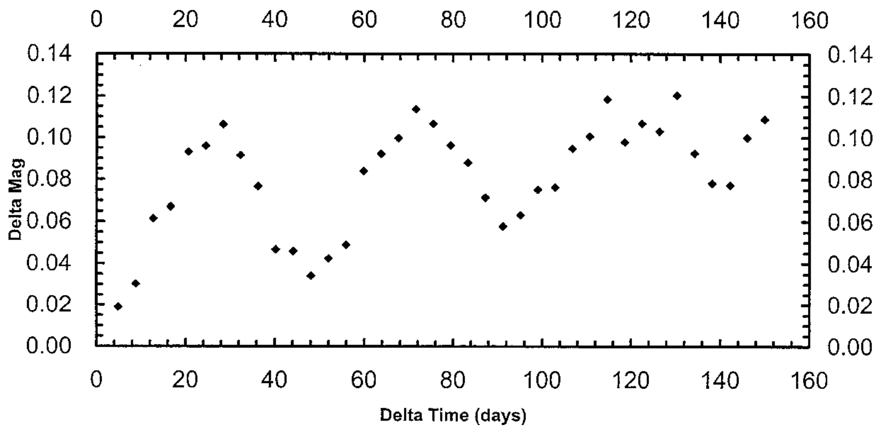

Figure 1. Self-correlation diagram for R CrB for JD 2446822–2446976. Minima occur at multiples of 47 days.

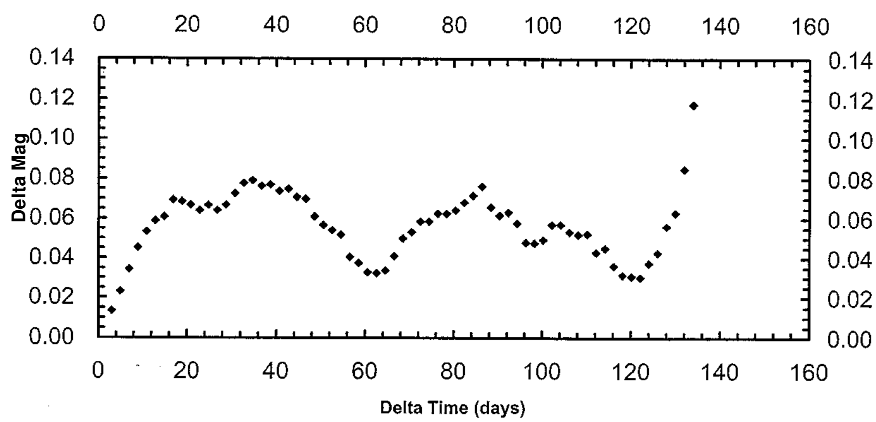

Figure 2. Self-correlation diagram for R CrB for JD 2447175–2447329. Minima occur at multiples of 60 days.

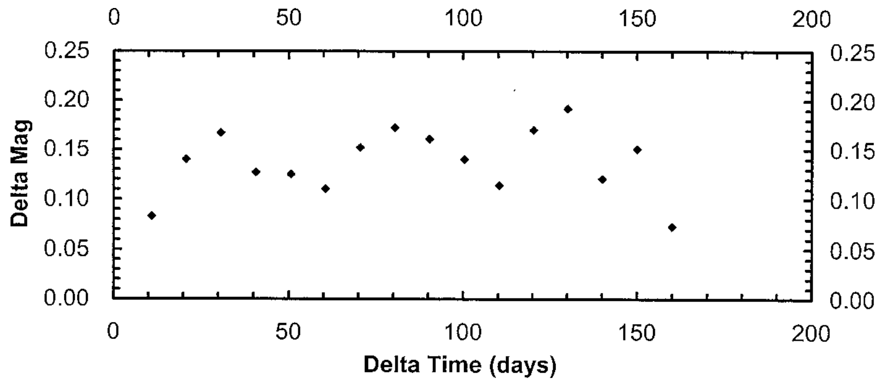

Figure 3. Self-correlation diagram for RT Nor for JD 2447281–2447832. Minima occur at multiples of slightly more than 50 days. The data are somewhat sparser than for R. CrB, so the minima are not as well defined.

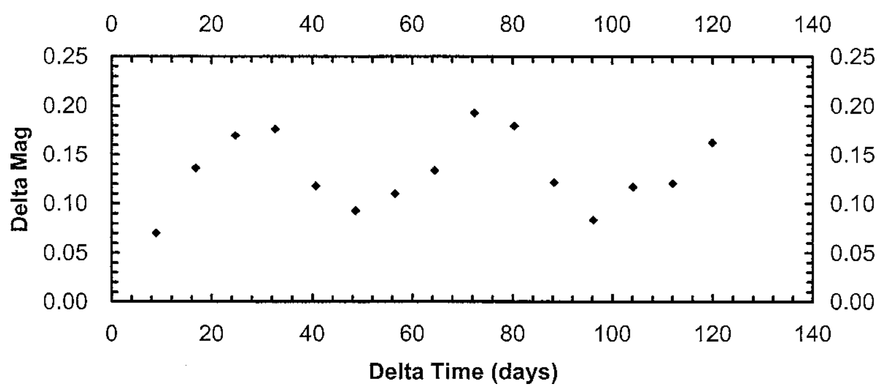

Figure 4. Self-correlation diagram for RT Nor for JD 2448694–2449504. Minima occur at multiples of slightly less than 50 days, which is not inconsistent with Figure 3.