R CrB: PHOTOMETRIC EVIDENCE REGARDING THE NATURE OF ITS PULSATION, AND A PUTATIVE CONNECTION BETWEEN PULSATION AND DEEP DECLINES

J. D. FERNIE
David Dunlap Observatory, University of Toronto
Richmond Hill, ON Canada

Abstract. It is shown that the historical lightcurve of R CrB contains features that argue against the deep declines being caused by pulsation. As well, recent photoelectric photometry does not show the onset of deep declines occurring at a specific phase of pulsation. The photometry suggests that only one period is present at any time, although this period can drift and/or be replaced by another period. The evidence is strong that the pulsation is radial and obeys relationships found among classical Cepheids.

1. Introduction

R CrB is the prototype of a small class of variable supergiants defined as having atmospheres rich in carbon and extremely deficient in hydrogen. Almost all of them show low-amplitude variability of a few tenths of a magnitude in V with unstable periods in the range of $\sim$35 to 55 days. The class is renowned for the deep declines of up to 8 magnitudes in visible light which occur at apparently random times and which may last for months.

The canonical explanation of this behaviour is that the pulsation generates shock waves that produce mass loss. The material, however, is not emitted as a shell, but rather as a localized puff. This puff, rich in carbon, condenses into dust at some distance from the star, and if the puff was in a direction near our line of sight, the expanding dust cloud will veil the star and cause it to appear much fainter. The slowly expanding cloud eventually dissipates and the star appears restored to its former glory.

The question then arises as to whether puffs are emitted in every pulsation cycle, and if so, at what phase of the cycle. A second question is

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whether the instability of the period implies that more than one period is present at any given time, and if so, what are the individual periods and how do they relate to the phasing of the puffs. A third question is whether the pulsation is radial or non-radial.

In what follows I review these questions through the use of the historical light curve of R CrB and a database of modern photoelectric photometry of the star. This database is available on the World Wide Web at the URL http://ddo.astro.utoronto.ca/rcrb.html

2. The Historical Light Curve

The light curve of R CrB for the 152 years between 1843 and 1995 has been compiled by Mattei et al. (1991, 1996). It contains several features of interest. The first is the consistency with which the star sinks 8 mag to 14th magnitude in a deep decline, but never goes below that level. The latter is probably set by the emission lines that appear in the spectrum at this stage, coupled with a complete veiling of the photosphere by carbon dust. The second feature of interest is the relative frequency of deep and shallow declines. If we define a deep decline as one in which the visual magnitude becomes fainter by 6–8 mag, and a shallow decline as one of 1–2 mag, then the record shows that deep declines outnumber shallow ones by nearly 2:1. (There are, of course, intermediate declines as well.) That this is not due to observational selection is shown by the record of the last 30 years or so, when R CrB has been under almost constant scrutiny by dozens of amateur astronomers whose precision of observation is of order 0.1 mag. A drop of 1–2 mag would not have been missed, yet again there are nearly twice as many deep declines as shallow ones.

This is rather surprising. One would think that deep declines would require puff ejection close to the line-of-sight, and thus be less frequent than the shallow declines which come from puffs ejected at larger angles. Presumably this is an argument for the dust forming rather close to the star and expanding considerably, so that its initial direction is less important. However, the point of interest here is the implication that almost any puffing on the hemisphere of the star facing us will result in a detected decline.

With that in mind we turn to another feature of the historical light curve. Between the years 1924.9 and 1934.9 no declines at all were seen. This interval corresponds to ~100 pulsation cycles, none of which apparently resulted in puffs from the hemisphere facing us. Could they all have happened on the far side of the star? (And rotation, low though it must be, must in the course of 10 years have brought most of the surface of the star into view.) The probability of this happening would be tantamount to the probability of tossing a coin 100 times and having it come down heads every time. Could a way out be found by postulating that the star's pulsation died away during those 10 years, something analogous to the Maunder minimum of sunspots? The answer is no. By coincidence, it was in the middle of this period that Jacchia discovered the low-amplitude pulsations (Jacchia 1933), announcing that the star was pulsating with a visual amplitude of 0.4 mag and period 44 days. Although the difference is hardly significant, this means that, if anything, the star had an even larger amplitude then than it does now (0.25 mag).

Another feature of the historical light curve shows almost the opposite situation. Between 1863.8 and 1873.8 – again an interval of 10 years – R CrB was in a state of almost perpetual veiling. Only once in that interval, and then only very briefly, did it return to its normal maximum brightness. Again it seems improbable that this could happen on the basis of randomly directed puffs.

3. Modern Photometry

For the past several decades I have obtained, or had obtained for me, photoelectric photometry of R CrB. These data through 1993 have been published (Fernie & Seager 1994, and references therein); later data are unpublished, but all the data are available at the Web site given above.

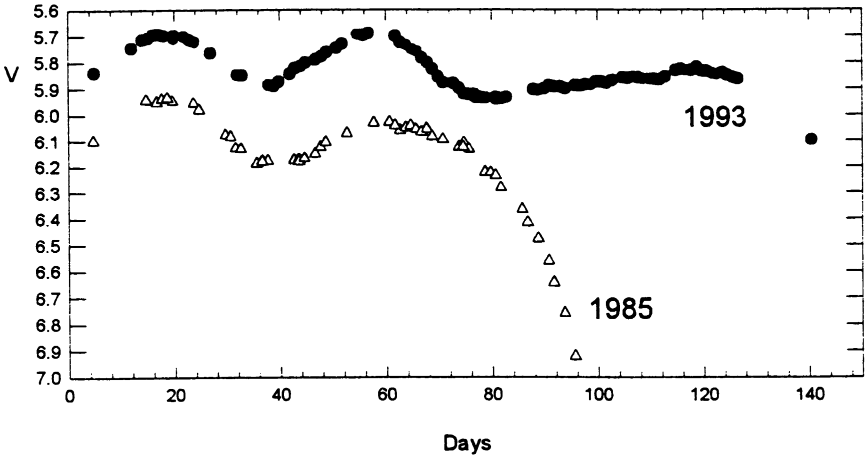

Figure 1. The start of two well-observed deep declines. It seems unlikely that they both started at the same phase of the pulsation cycle.

Figure 1 shows two well-documented beginnings of deep declines present in the above photometry. It is difficult to assess precisely when a deep decline begins, but it seems fair to say that the start occurred at different phases of the pulsation in these two cases. In the 1985 case it seems to have started near maximum light, whereas in 1993 the start must have been closer to minimum light. Of course, the delay between the eruption of material through the photosphere and its later condensation into dust is not known; nor is it known whether that delay is the same in all cases, so it is difficult to draw firm conclusions from Fig. 1, but at least it offers no support for the view that puffs are related to the pulsation. Asplund et al. (1997) and Asplund (2000) offer an alternative mechanism for producing the puffs.

3.1. NATURE OF THE PULSATION

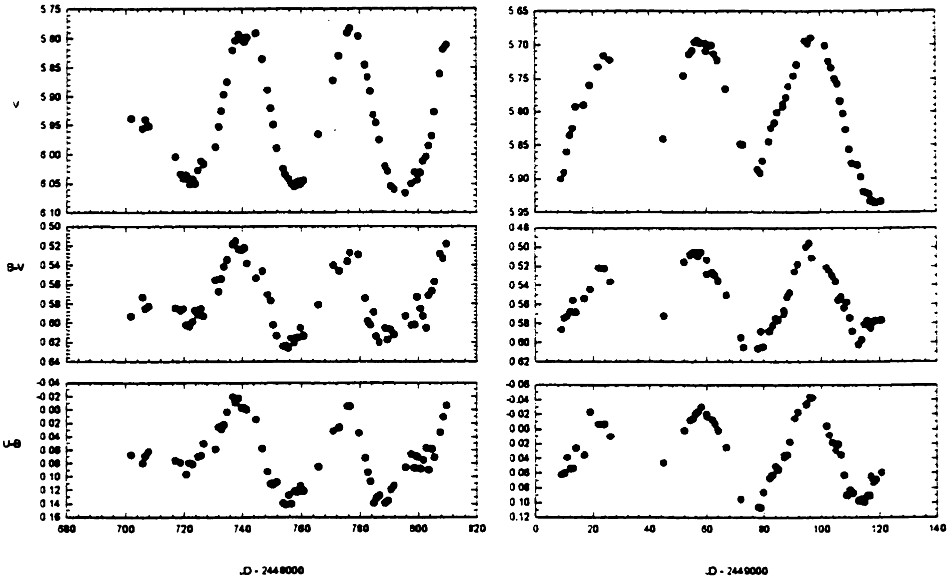

Figure 2. Photometry of R CrB in 1992 (*left*) and 1993 (*right*). There is no suggestion of more than one period being present, and times of maximum can be fitted with a simple ephemeris.

Figure 2 shows the *UBV* photometry of R CrB obtained in 1992 (on the left) and in 1993 (on the right). There is no suggestion in this figure (or in Fig. 1) of there being more than one period present. Not only are the light curves smooth and repeating, but one can fit a simple ephemeris linking the times of maximum across these ten cycles. An even more convincing case was reported in Fernie (1989) where it is shown that a single period of 43.8 days fits all observed times of maxima over 16 cycles in 1985, 1986, and 1987. Moreover, during this interval the star suffered a deep decline and

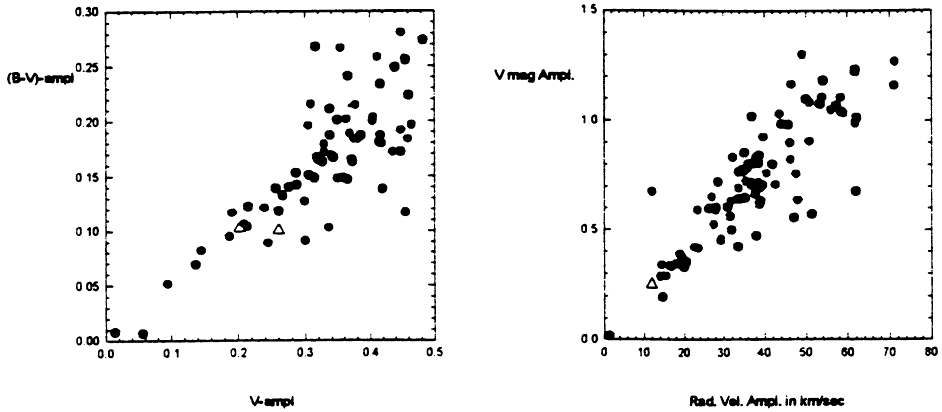

Figure 3. The colour/light amplitude relation (*left*) and light/radial velocity amplitude relation (*right*) for classical Cepheids (*circles*) and R CrB (*triangles*). Clearly, R CrB follows the Cepheid relations, implying radial pulsation.

recovery, so that the maintenance of the pulsational phasing strengthens the view that the star itself is not affected by such declines.

It is probably the majority view that the pulsation is radial, but since Stanford et al. (1988) suggested non-radial pulsation it is worth examining the photometric evidence. Figure 2 shows first that the B–V and U–B colour curves are definitely in phase with the V curve, which is a strong indicator of radial pulsation. Secondly, it shows that the colour amplitudes are a substantial fraction of the V amplitude, again strongly favouring radial pulsation. In fact, the left panel of Figure 3 shows the relation of B–V amplitude and V amplitude for classical Cepheids (circles) and for R CrB (triangles) on two occasions, and it is clear that R CrB obeys the Cepheid relation. Fernie & Lawson (1993) have discussed the radial velocities of R CrB, and the right panel of Fig. 3 shows the V amplitude versus the radial velocity amplitude for classical Cepheids (circles) and R CrB (triangle). Again the latter seems to be in accord with Cepheid pulsation. The conclusion must be that R CrB is a radial pulsator.

However, it would be a mistake to believe that R CrB behaves like a Cepheid in all respects. In particular, the period is quite unstable. The well-behaved light curve of 1992 in Fig. 2 has a period near 36 days, which rises to 39 days in 1993, although a linear drift with time easily fits the data. This is significantly different from the constant 43.8 ±0.1 day period of the 16 cycles in 1985–87. The left panel of Figure 4 (the 1994 data) shows how great the period instability can be; the interval between the first two maxima is 52 days, while it is 45 days between the second and third maxima,

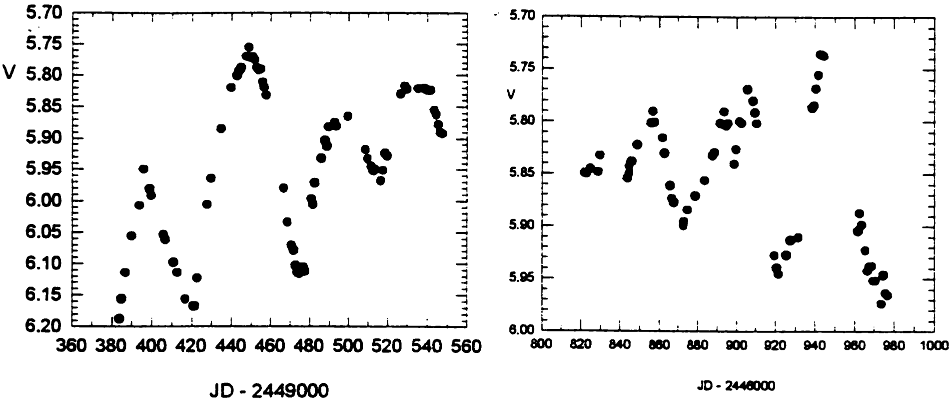

Figure 4. Examples of period instability (*left*) and amplitude instability (*right*), showing that some aspects of R CrB's behaviour are decidedly non-Cepheid-like.

and 39 days between the third and fourth peaks. Moreover, not only can there be frequency modulation, but also amplitude modulation. The right panel of Fig. 4 (1987 data) shows a series of cycles with a constant period of 44 days, but with rapidly increasing amplitude. This is probably the signature of strongly non-adiabatic behaviour. It might be thought that partial veiling could be the cause of these various apparent instabilities rather than the star itself, but this is unlikely. The colours continue to follow the *V* magnitude in just the same way as they do when no modulation is present, and it is improbable that random veiling would produce an apparent period in Fig. 4 (right) that is constant and the same as it had been in the two previous seasons. Finally, given that radial velocities should be unaffected by veiling, one may examine the data of Gorynya et al. (1992). In 1991 they found a well-defined velocity curve with a period of 43.0 days, but, despite the use of the same equipment and procedures, the following season produced only a very ill-defined velocity curve with a period of 34.0 days.

4. Conclusions

The historical photometric evidence suggests that a connection between pulsation and mass loss in the form of puffs is unlikely. The fact that deep declines (6–8 mag) in the light outnumber shallow declines (1–2 mag) by nearly a factor of 2 implies that condensation of a puff into dust must happen quite close to the star and expand to veil almost all the photosphere if the puff occurred on the hemisphere facing us, i.e. we should detect almost every puff on that hemisphere. Yet between 1924 and 1934 no declines at all were seen, despite the fact that the star was pulsating at its full amplitude during that time. The probability that all puffs during that decade ($\sim$100 pulsation cycles) happened on the far hemisphere is negligibly small. During another decade between 1864 and 1874 the star was veiled almost constantly, again an improbable event if puffs occur randomly.

Recent photoelectric photometry shows that in the two cases observed, the deep decline began once near pulsational maximum light and once near minimum light, suggesting that declines are not associated with any particular phase of pulsation. The photometry also shows that only one period is present at a time, and that this may remain stable for at least sixteen cycles. At other times, both period and amplitude can drift significantly from one cycle to the next. The B–V and U–B curves are closely in phase with the V light curve, and the ratios of colour amplitude to light amplitude and radial velocity amplitude to light amplitude are the same as those for Cepheids. This strongly suggests that the pulsation is radial, as one would expect.

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Discussion

Cannon: You pointed out the remarkable constancy of the depth of the deep minima, with apparently a very stable lower luminosity limit. Is there a simple physical explanation for this?

Fernie: The most likely explanation is that it is the spectral emission lines that set the level of the deepest minima, although this begs the question of why they, in turn, are so consistent.

Asplund: Even though the modelling by Sedlmayr, Woitke, and collaborators is very promising, the pulsation-induced dust condensation often invoked to explain the declines of RCB stars has some clear problems: not all RCB stars pulsate, and other similar stars pulsate but still do not show any light declines.

Fernie: I'm not sure that there are non-pulsating RCB stars; in some cases there is not much data.

Sedlmayr: Do you find any noticeable changes in the normal small variations in the quiet state just before a decline event, e.g. amplitudes, frequencies, etc.?

Fernie: No, although the data are rather limited.

Asplund: The similarity between UU Her and RCB stars only exists for the semi-regular pulsations and not for the light declines and H-deficiency. Therefore I do not expect a relation between these two classes.

Fernie: My remark about their similarity referred in fact to the semi-regular pulsations, plus their rarity and galactic distribution. I certainly agree, however, that the pulsation-emission connection is somewhat doubtful.

Green: Is there any evidence for increased dust formation above starspots, and could that explain the long gaps without declines as starspot minima and the changes in period as starspot latitude changes?

Fernie: Not that I know of. I'm not sure what observational evidence one could expect for this.

Hrivnak: You showed a graph of V magnitude vs. time, in which the V amplitude appeared to build up, starting with very low amplitude. At the same time, the low V amplitude corresponds to a large variation in $U - B$. Can you comment on this?

Fernie: On reviewing the graph, I think it is more likely observational noise. The APT is only a 25-cm telescope, and the U filter gives the weakest signal.

Bakker: If R CrB experiences reddening due to dust ejected in the line of sight, one would also expect dust to be ejected on the other side of the star. In that case blue light is scattered and I would expect an increase in magnitude. Do you observe this?

Fernie: No, this is not observed. I don't have a certain explanation for that, but would guess that the dust on the far side is too far away and too thin for backscattering to be detectable.