An analysis of the small amplitude variations in the light curves of the R Corone Borealis variables, S Apodis and UW Centauri

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Summary. The small amplitude variations in the light curves of the R CrB stars, S Aps and UW Cen, are examined. The periodicity of these variations appears to be changing rapidly in S Aps and slowly, if at all, in UW Cen. The evolutionary consequences of these effects are discussed.

1 Introduction

The R CrB variable stars are probably a subset of the small group of known hydrogen-deficient carbon stars (HdC stars) which have hydrogen underabundant by factors of up to $10^5$ and carbon overabundant by factors of 3 to 10 (Warner 1967). Feast (1975) has given a review of the basic properties of R CrB variables; they are generally late F- or G-type supergiants which occasionally undergo drops in brightness of up to 8 or 9 mag. Much of the interest in the R CrB stars has centred on these spectacular changes, and it is generally supposed that they are due to obscuration by material ejected from the star and condensing into particles, probably of carbon.

In addition to the irregular ‘obscuralional’ minima, a few R CrB stars show rather more regular variations of a much smaller amplitude, usually less than 0.5 mag. Of the well-observed stars, RYSgr has the most pronounced and most regular small-scale variations, though even in RYSgr these can vary markedly in amplitude. Alexander et al. (1972) showed that the small-scale variations in RYSgr are due to stellar pulsation, but no comparable studies have been made of the other R CrB stars which exhibit the phenomenon. Fernie, Sherwood & Du Puy (1972) have tentatively suggested that the small-amplitude variations in R CrB itself may be due to pulsation.

Theoretical work on R CrB star pulsations has been recently reviewed by King (1980) who indicated the difficulties in understanding the possible pulsation modes in the extended, non-adiabatic envelopes of these stars and notes that pulsations are possible over a wide range of temperatures, corresponding to the R CrB stars and the (probably related) hot hydrogen-deficient or ‘helium’ stars.

Kilkenny & Lynas-Gray (1982) found a decreasing period for BD+13° 3224, the only hot hydrogen-deficient star definitely known to pulsate and Pugach (1977) discovered that the pulsation period of RYSgr varied and probably decreased. Subsequently, Kilkenny (1982) has shown that the occurrence of pulsational minima in RYSgr can be
represented by an ephemeris with a linearly decreasing period. The decrease rate agrees very well with Schönberner’s (1977) model for a 1 $M_\odot$, $T_{\text{eff}} = 6900$ K star evolving rapidly from red giant to white dwarf.

It is clearly of some importance to establish a changing period for a rapidly evolving, pulsating star because the increase or decrease in the period shows whether the star is expanding or contracting and the rate of change enables tests of evolutionary models to be made. In this paper we have examined the available data for S Aps and UW Cen and find that the times of the small-scale minima can also be represented by ephemerides with changing periods, although with less certainty than for RY Sgr. It is not known if the low-amplitude variations in S Aps and UW Cen are caused by pulsation (analogy with RY Sgr suggests they are) and so we do not, for the present, refer to them as ‘pulsational’ minima.

2 Observations

Waters (1966) collected visual observations of S Aps covering the period 1922–60. We have re-examined much of this material and find substantial agreement with Waters’ smooth curve interpretation of the data; in particular we agreed with his positioning of the small-amplitude minima.

For UW Cen, times of minima derived from visual observations were taken from Bateson & Jones (1972) and Bateson (1974, 1975, 1978). These data covered the interval 1954–77.

3 Analysis

The method outlined by Kilkenny (1982) was followed; an identification or ‘cycle’ number, $n$, was assigned to each minimum, based on an ‘instantaneous’ period calculated from several cycles near the epoch under consideration. Because the variations in both S Aps and UW Cen are more irregular than in RY Sgr, the risk of ‘aliasing’ is much greater. In addition, both stars are near 10th magnitude at maximum and so tend to be too faint to be observed visually in the ‘obscuratational’ minima. The occurrence of these deep minima therefore increases the chance of aliasing faults.

Both authors independently carried out the process of identifying minima and the results are discussed below.

3.1 S Aps

For S Aps, our independent solutions were slightly different. However, both results indicated that a surprisingly large quadratic term was present. If we follow the Kilkenny & Lynas-Gray (1982) notation and write:

$$JD_{\text{min}} = T_0 + nP_0 + n^2k$$

then we obtained values of $k = -0.18$ and $-0.21$ day. In other words, it is highly likely that the period of the small-amplitude variations in S Aps is decreasing but, with the available data, we cannot derive an unequivocal value for the decrease rate. In an attempt to test for the effect of the aliasing problem, we have computed many ephemerides solutions for S Aps by identifying points at which aliasing errors might have occurred and then deriving ephemerides in which minima subsequent to the gap are re-named $n = n + 1$ and $n = n - 1$. Using our two initial solutions as starting points, we found all ‘derived’ solutions to have values of $k$ between $-0.06$ and $-0.23$ day. The ‘best’ solution (i.e. with least rms scatter
in the residuals) was

\[ T_0 = 2423 \, 505 \, \text{day} \pm 10 \]
\[ P_0 = 131.8 \, \text{day} \pm 0.4 \]
\[ k = -0.194 \, \text{day} \pm 0.003 \]

for 62 minima covering a total of 114 cycles. Fig. 1(a) shows the (O–C) residuals from an ephemeris with a constant (mean) period \( \bar{P} = (\text{epoch of last minimum} - \text{epoch of first minimum})/114 \). The need for a second-order term is evident. Fig. 1(b) is a plot of the residuals for the above ‘best’ ephemeris with a linearly decreasing period.

We have so far found no satisfactory ephemeris with a constant or increasing period or with a decreasing period significantly smaller than \( k = -0.06 \). In fact, we observe interesting effects in some of our solutions with rather larger period decrease rates. Fig. 2(a) is a plot of the residuals for one of our ‘initial’ solutions with a mean period \( \bar{P} = 118.4 \, \text{day} \); Fig. 2(b) shows the residuals after the quadratic least-squares solution:

\[ T_0 = 2423 \, 493 \, \text{day} \pm 23 \]
\[ P_0 = 138.7 \, \text{day} \pm 0.9 \]
\[ k = -0.184 \, \text{day} \pm 0.007 \]

The residuals are clearly not random but exhibit a smooth variation similar to that seen for RY Sgr in fig. 2(a) of Kilkenny (1982) and attributed to non-adiabatic effects. For S Aps, we cannot say whether this is a real effect or simply caused by the aliasing problem.

**Figure 1.** (O–C) residuals from the ‘best’ solution for S Aps (a) with a mean period, \( \bar{P} = 107.8 \, \text{day} \); (b) with the ephemeris given in Section 3 and represented by the solid line in (a).
Figure 2. (O–C) residuals for an ‘initial’ solution for S Apsids (a) with a mean period, $\bar{P} = 118.4$ day; (b) with the ephemeris given in Section 3 (see text for discussion) and represented by the solid line in (a).

3.2 UW Cen

A similar procedure was followed to that described for S Aps. In the case of UW Cen, however, the situation is less clear. We have found several solutions with comparable scatter in the range $+0.003 \geq k \geq -0.006$, so the period could be constant or increasing/decreasing at a relatively slow rate. Our ‘best’ solution is:

$$T_0 = 2435.279 \text{ day} \pm 3.6$$

$$P_0 = 42.82 \text{ day} \pm 0.09$$

$$k = +0.0030 \text{ day} \pm 0.0004$$

which is illustrated in Fig. 3.

4 Discussion

RY Sgr has $k = -0.0005$ (Kilkenny 1982), a value which is close to that expected from Schönberner’s (1977) evolutionary models for hydrogen-deficient stars evolving from the asymptotic giant branch to white dwarf. Comparison can be made because a fine analysis has been carried out for RY Sgr, enabling it to be located in the log $g$, $T_{\text{eff}}$ plane (Schönberner 1975). For S Aps and UW Cen we can find no such data in the literature. Feast
& Glass (1973) have compared JKL photometry of R CrB stars with models derived from a combination of blackbody radiators at 4000 + 900 K and 6000 + 800 K (star + cool circumstellar shell). These models suggest stellar temperatures of $\sim 5000$ K for S Aps and $\sim 6000$ K for UW Cen, somewhat high for stars of spectral type R3 and K respectively (e.g. Feast & Glass 1973) but still rather cool for comparison with existing models.

Adopting $T_{\text{eff}} = 6000$ K for UW Cen and using Schönberner's (1977) $1 M_\odot$ model to estimate log g and the rate of change of log g (and assuming that the small-scale variations are caused by pulsation) we should expect $k$ to have a value of $\sim -10^{-4}$; certainly it should be more positive than the $k = -0.0005$ observed for RYSgr. These rough estimates are consistent with our range of solutions in Section 3.

We conclude that UW Cen is probably similar to RYSgr. If UW Cen has an increasing period, this could mean that it has not yet reached the top of the asymptotic giant branch. Röser's (1975) models for stars with $X = 0.1$, $M = 1 M_\odot$ and $2 M_\odot$, reach $T_{\text{eff}} \sim 3.8$ ($T_{\text{eff}} \sim 6000$ K) at the tops of the giant and asymptotic giant branches.

S Aps is much more difficult to explain in terms of a decreasing pulsation rate. We can find no model for evolution of hydrogen-deficient stars which allows such a rapid change of period on a nuclear time-scale. Röser's (1975) models exhibit radius changes by factors of up to 100 in $\sim 10^5$ yr (giant-branch to horizontal-branch evolution), allowing an average $k$ value of $\sim -0.0006$ day. This is comparable with rates derived from Schönberner's (1977) models (asymptotic giant-branch to white dwarf) but is still a factor of $\geq 100$ too small.
One possibility is that S Aps is a low mass star in which helium-burning has never started. Schönberner (1977) has noted that in his models, stars with masses less than $0.65 \, M_\odot$ 'collapse within a gravitational time-scale, i.e. a few hundred years, from low to high temperatures ($\log T_{\text{eff}} > 4.5$'). Such a time-scale would be compatible with our derived values of $-0.06 \leq \zeta \leq -0.23$ for S Aps.

Another possibility is suggested by Schönberner’s (1979) models for asymptotic giant branch evolution with steady mass loss. In these models, helium shell flashes occur at low temperature ($T_{\text{eff}} \sim 4000$ K) and can cause extensive blue loops in time-scales of $\sim 10^3$ yr. The rapid temperature change at constant luminosity is equivalent to a radius change by a factor of $\sim 250$. Such a change in 10$^3$ yr would result in $\zeta \approx -0.04$ which is comparable with the lower limit of our range of results for S Aps. Schönberner’s (1979) models start with envelopes of normal composition ($X = 0.74$) at the onset of helium burning and would have to lose the hydrogen-rich envelope to be comparable with the R CrB stars. The mechanism by which this could occur is not known.

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References


