R CENTAURI AT MILLENNIUM'S END

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Abstract

We have analyzed ~20,000 visual measures of the double-maximum Mira star R Centauri made by the AAVSO and the RASNZ VSS during the past 72 years. Recently there has been a marked change in the amplitude of variability and the shape of the light curve. The period is also shortening at an increasingly fast rate. *V* and *B-V* measures indicate that the first maximum is comparable to the maximum in normal, single-peaked Mira stars.

1. Introduction

R Centauri is the prototype of a small group of Mira stars which show double maxima. Discovered about 1870, the first three epochs of maximum were measured at Cordoba. Two decades of neglect then saw measures by Roberts beginning in 1894, since which time there is a continuous history of observations.

The dual maxima have caused confusion over epochs. No less a person than Annie Cannon (Cannon 1908) included a secondary maximum amongst primary maxima. In past years the second maximum was the larger and most reviews use this as the primary maximum but there seems to be confusion as to the labeling of maxima and minima—MI and mI, etc. The *General Catalogue of Variable Stars* (GCVS) (Kholopov *et al.* 1985) avoids the issue by using the deep minimum as its epochal marker. We have adopted the second peak as the epoch marker, particularly in studying the period changes, although we show that the first peak is probably more significant. For clarity, we shall describe the deep minimum as m1, the first peak as M1, then m2 and M2.

2. Visual observations

Visual observations during the interval JD 2427000 to JD 2451600 are displayed in Figure 1. They were provided by the American Association of Variable Star Observers (AAVSO) for the interval 1961–2000 (Mattei 2000) and the Royal Astronomical Society of New Zealand (RASNZ VSS) for the interval 1928–1998 (Bateson 1998).

Some changes in behavior are quite noticeable: Maximum2 has declined in brightness from ~5.8 in the 1950s to ~6.5 in the 1990s. Minimum1 has become noticeably shallower over the same interval—from ~11.0 to ~9.5. Maximum1 appears unchanged, although it might have brightened slightly.

During this interval there have been some revisions of comparison sequence values but these have not been sufficient to cause the changes noted. In the context of extreme minimum depths we note that Cannon (1908) quotes Roberts' estimate of m1 as fainter than magnitude 13. This is possibly more reflective of a lack of good comparisons than any major change since the 1890s.

3. Photoelectric observations

Photoelectric *UBV* measures were made at Auckland Observatory in the 1970s and 1980s (Marino 1990) using a 50cm telescope, *UBV* filters, and an EMI 9502 photomultiplier tube. Measures were converted to the standard system. Since then only occasional measures are available (Williams 2000). These coincided with a substantial change in period which is discussed below. We present 115 of these measures in Figure 2. The accuracy is better than 2% but the period and shape of the light curve were varying during the interval shown, hence we have smoothed the data to make it easier to follow. The *U-B* light curve is noisy due to the faintness at minimum and is not shown here.

The *V* light curve is similar to most of the visual curves and needs little comment. The *B-V* color curve is relatively flat, but is bluest just prior to the first maximum and is quite red around the second maximum. This makes clearly defined "blue" and "red" peaks. From this it is clear that the first peak is the true maximum, following close on maximum temperature. In this it differs from another double-maxima Mira star, BH Crucis (Walker and Marino 1991), where *UBV* measures strongly support the idea that M2 is the high temperature peak.

4. Period changes: the O-C view

We have collected all published epochs of maximum and added to these the epochs determined in the present study. For consistency we have used M2 throughout, believing that the amplitude changes to that during the past 20 or so years do not affect its timing significantly. The O-C diagram of these epochs is shown in Figure 3. The light elements (JD(M2) = 2404800.4 + 546.2 E) use the GCVS period but the epochs date from the original discovery epoch.

The period has shortened by almost 10% since its discovery. It does not change continuously but exhibits more abrupt changes at intervals. There was one interval (1945 to 1960) when the period lengthened again. The interval between M1 and M2 is relatively static but it appears to have lengthened as a result of the changes in M2 during the past few cycles.

5. Period changes: the Fourier analysis view

Periodicity of a variable can be also be examined via Fourier Transformation. The AMPSCAN method of Howarth (1991) can be used to further study periodicity by spreading the one-dimensional summed periodicities in a normal Fourier Spectrum over the extra dimension of elapsed time. In this way the period and amplitude behavior of the light curve can be assessed at different intervals (*cf.* Greaves 2000).

The 5-day means from 1946 were subjected to Fourier analysis, which gave only two peaks of any significance. The peaks represent the mean period between occurrences of M2 and the period between the cycle M2–M1–M2, respectively. Consequently, the latter value has a period half of that between successive M2s, and is mostly the result of R Centauri's double-maximum light curve being more distinctly different from a true sinusoid than is the usual case with Miras.

As stated earlier, the period between consecutive occurrences of M2 is presumed to be the main period, and the overall average for the 66-year data set was revealed to be 541.4 days by the Fourier Analysis.

The 5-day means were then analyzed via AMPSCAN at 10-day step intervals using a moving window of 1083 days, twice the period. A filter of 1083 days was also used to reduce the chance of spurious resonance, and overlapping windows with fewer than 20 data points per bin were rejected as being liable to create just noise.

The result is shown in Figure 4. A shallow arc in the phase curve, depicted by the thick line, shows a trend towards declining period from JD 2432000 up to JD 2444000, that is in comparison to a sinusoid based on the average 541.4-day input period. After that point the line steepens somewhat, suggesting an increased rate of decline. A marked decline in amplitude also commences near JD 2444000. Visual inspection of the light curve suggests that this is primarily accounted for by shallowing minima.

The differences between the two period regimes can be highlighted by separating the data into two subsets, one spanning from JD 2432000 to 2444000 and the other from JD 2444000 to 2451000, and submitting them separately to Fourier Analysis. Figure 5 shows the results spanning frequencies equivalent to periods between 200 and 600 days, where the earlier subset is represented by the thick line and the later subset by the thin.

It is helpful in this instance to consider the light curve of R Centauri as being reasonably modeled by the sum of two sine waves, one based on the main period and one based on half that value, and indeed such a summed sine wave emulates the lightcurve quite well. In this light we note the following points.

The thick line, representing the era from JD 2432000 to JD 2444000 shows the peak at the main period to be quite tight and of roughly 1.65 magnitudes semi-amplitude. The half period peak, which will coincide [approximately] with both M1 and M2, is roughly three quarters of this value at 1.25 magnitudes semi-amplitude. For the thin line, representing the era from JD 2444000 to JD 24516000, we find that the magnitude of semi-amplitude has reduced somewhat for the main period to nearly 0.95 magnitude semi-amplitude, but increased at the half period to 1.15 magnitudes semi-amplitude, that is, the half-period peak is now 1.2 times the main-period peak, whereas it was formerly smaller at 0.75 times the main-period peak.

Notice also that each of these peaks is broader in the later data subset compared to the earlier data subset. This is because the power of the peaks is spread out over several frequencies to a greater extent in the later subset, a qualitative indication that

Table 1. O-C derivations for R Centauri.

Starting Epoch	*JD Interval*	*Interval (years)*	*Period (days)*
0	2404535–2414760	1870–1898	568
18	2414760–2423160	1898–1921	560
39	2423160–2431870	1921–1945	542
49	2431870–2437410	1945–1960	554
59	2437406–2445514	1960–1982	540.5
74	2445517–2450260	1982–1996	527

the rate of change of period is greater now (although the fact that the first subset is nearly twice the duration of the second also has some bearing on this, it is somewhat compensated for by the greater change in period in a shorter timespan). This is in agreement with the O-C derivations as shown in Table 1.

These results in some ways are a quantitative assessment of what has already been noted qualitatively from a visual inspection of the light curve. This firmer footing, however, allows the assumption to be made that if the current trend continues, M1 and M2 may well swap places when it comes to prominence within the light curve, and that this may happen in the relatively near future.

6. Conclusions

There are two types of major change taking place in R Centauri. The first affects the amplitude and shape of the light curve, the second constitutes a major change in period. Whether the two are connected, or in any way causal to each other, is impossible to tell from visual light curve data. However, it is noted that in the cases of the Miras R Aql and T UMi, both objects are also simultaneously declining in amplitude and period (*e.g.,* Greaves and Howarth 2000).

Several aspects of the present analysis suggest that a fundamental change in the nature of R Centuari's light curve may be imminently due, and, further, a change that could have significant implications in the light of stellar evolutionary theory. The authors encourage the continued visual monitoring of this fascinating object, and also strongly urge it be added to any *UBV* photometric monitoring programs for variable stars, given that this latter can be used to distinguish the peaks annotated M1 and M2 and any possible variations therein.

7. Acknowledgements

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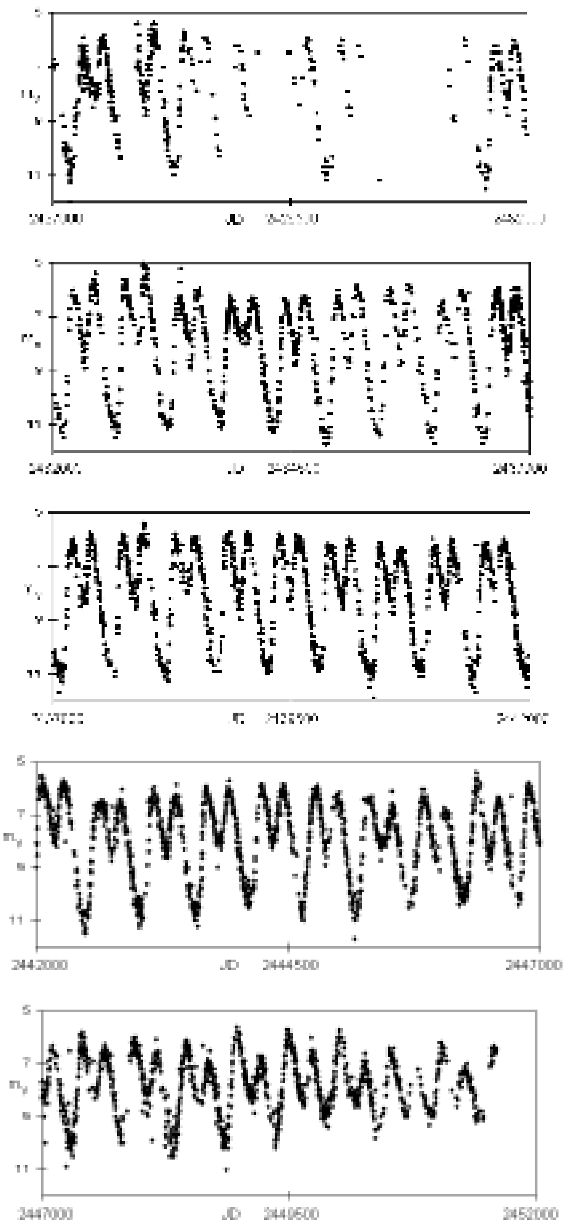

Figure 1. Visual observations during the interval JD 2427000–2451600 (individual measures to JD 2437000, thereafter 2-day means). Note the changes in minimum level and the gradual reduction in brightness of the second peak, M2. (Some earlier measures are not shown.) Data are from AAVSO and RASNZ VSS.

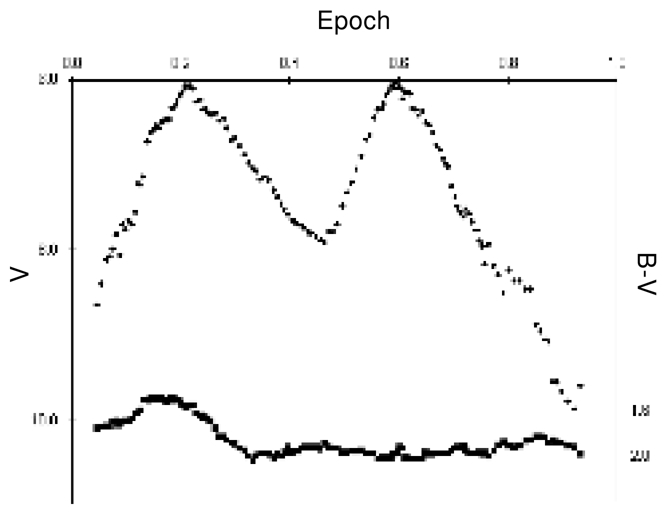

Figure 2. Photoelectric *V* (upper curve), *B-V* (lower curve) measures of R Centauri during the interval JD 2441078–2445893, reduced to the standard *UBV* system. Data are from Auckland Observatory.

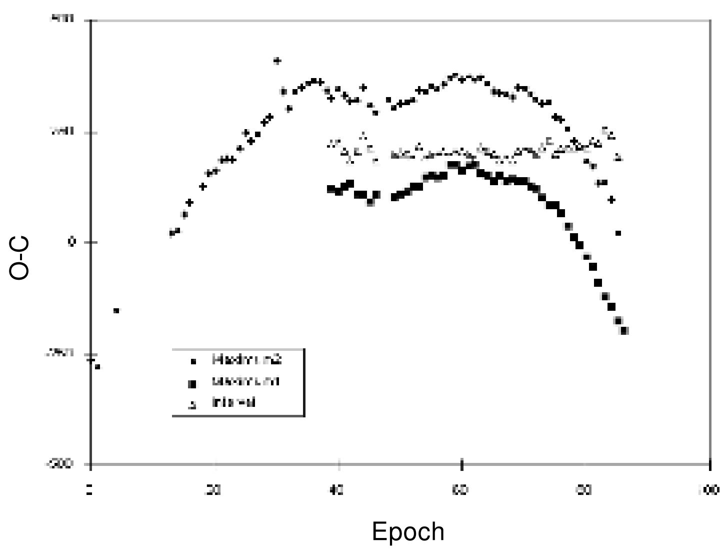

Figure 3. Epochs of R Centauri 1871–2000. The upper curve shows M2, early values of which are from the literature. The lower curve shows M1 since 1934. Intervals between the periods are shown as triangles. JD(M2) = 2404800.4 + 546.2 E.

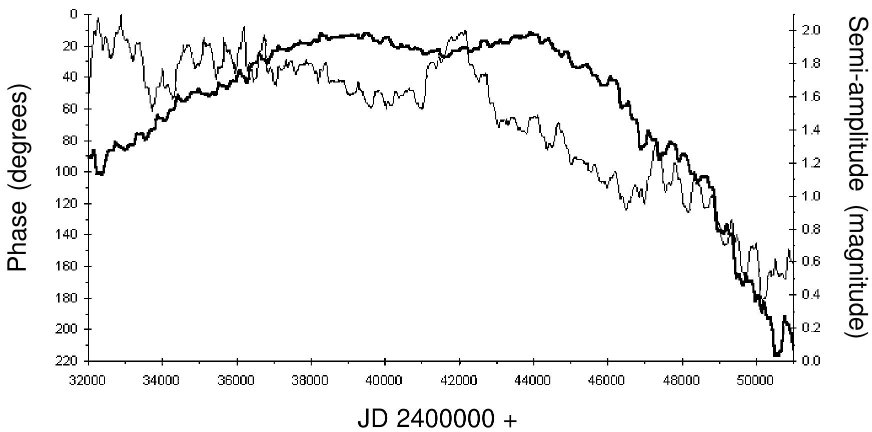

Figure 4. AMPSCAN analysis of the 5-day means for R Centauri from JD 2432000 to JD 2451000 from AAVSO and RASNZ VSS data. The thick line is phase, keyed to the left axis in degrees; the thin line is semi-amplitude, keyed to the right axis in magnitudes.

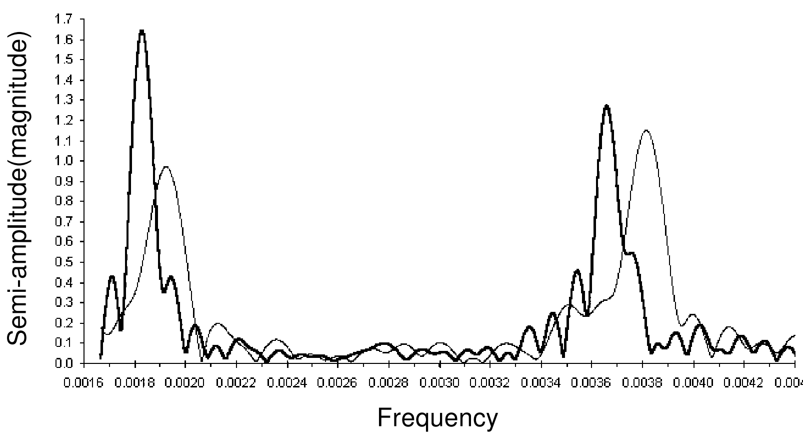

Figure 5. The Fourier analyses of the data separated into two subsets, JD 2432000–2444000 (the thick line) and JD 2444000–2451000 (the thin line), for frequencies equivalent to periods between 200 and 600 days.