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# R Centauri: An Unusual Mira Variable in a He-Shell Flash

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**ABSTRACT.** We present an analysis of AAVSO visual observations of the Mira variable R Cen from 1918 to 2000. The period of the dominant mode has been steadily decreasing from 550 days at JD 2,434,000 (1951) to its present value of 505–510 days. In the same interval, the pulsational amplitude has decreased by 3 mag, from 5.5–11.8 *V* to 6.3–9.1 *V*. We suggest that both are caused by a He-shell flash, as the period decrease is similar to that of other He-shell flash stars such as R Hya, R Aql, and T UMi. The period change is consistent with the luminosity drop expected immediately after the flash, as predicted by He-shell flash models for stars of 2–3 $M_\odot$ or less.

The light curve shows the familiar pattern of alternating deep and shallow minima, giving the appearance of double maxima. While the amplitude of the main mode has decreased 3 mag in the last 50 years, the amplitude of the secondary mode near 274 days has remained almost constant, so that the double maxima have nearly vanished from the light curve in recent years. The power spectrum between 1930 and 1966 shows harmonics up to 8 times the main frequency at 1/548 cycle day$^{-1}$. The most likely explanation for the double-peaked light curve is a resonance between two modes.

## 1. INTRODUCTION

R Centauri (R Cen) is an oxygen-rich Mira variable ($\alpha = 14^h16^m35^s.6$, $\delta = -59°54'43''$; J2000) with a period of 546 days, range of variation of 5.3–11.8 mag at *V*, and spectral type of M4e–M8 IIe as listed in the General Catalogue of Variable Stars (Kholopov 1985). Distance estimates range from 229 pc (Celis 1995) to 640 ± 300 pc (Hipparcos Catalogue: ESA 1997). The light curve shows some unusual properties: it alternates between deep and shallow minima, giving the appearance of double maxima, and the period and amplitude of the 546 day mode have been steadily decreasing over the last 50 years. In this paper we present AAVSO visual observations of R Cen from 1918 to the present and discuss the recent decline in period and pulsational amplitude in terms of a He-shell flash.

Mira variables with double maxima are rare. Jacchia (1933) called attention to the first of these, R Cen (546 days), R Nor (490 days), and U CMi (410 days), and Campbell (1955) also included RZ Cyg and RU Cyg in this group. Among these stars, R Cen has the most persistent and stable double maxima. For the others, the second maximum is often weak, and the light curve sometimes reverts to that of a normal Mira. The double-peaked Miras could be considered an extreme case of the more common Mira variables with bumps on either the ascending or descending part of the light curve. Keenan, Garrison, & Deutsch (1974) show that the 546 day period of R Cen is anomalously long for its M4.5 spectral type at maximum compared to other Miras and suggest the 274 day mode as the true period.

Jacchia (1933) pointed out the similarity in the light curve of R Cen to the RV Tauri variables. The double maxima may be caused by a resonance between modes in a manner similar to that proposed for RV Tauri stars by Takeuti & Petersen (1983) and thought to be operating in the bump Cepheids (Buchler, Moskalik, & Kovács 1990). The resonance hypothesis is attractive as it could naturally explain why Miras with double maxima are rare if an extremely close resonance match is required between two prominent modes to produce a double-peaked light curve. Alternately, the double-peaked Miras may simply be a very short lived phenomenon in the life of a red giant.

The period of a Mira variable is an important indicator of the mass, age, metallicity, and pulsational mode of the star (Feast 1989; Wood 1990). Period changes may result from a detonating flash in the He burning shell, and so they are important in understanding the evolutionary state of these stars. For the past several hundred years, the Mira variables R Hya and R Aql have been observed to have periods that are decreasing steadily by about 1 day year$^{-1}$ (Plakidis 1932; Sterne & Campbell 1937). Wood & Zarro (1981) showed that this rate is consistent with the luminosity drop expected from a He-shell flash in an asymptotic giant branch (AGB) star. Recently, the star T UMi has been found with a very large continuous period decrease of 2.5 day yr$^{-1}$ from 1979 to the present (Mattei & Foster 1995; Gál & Szatmáry 1995), and S Sex has been proposed to be in a He-shell flash due to a period change (Merchán Benítez & Jurado Vargas 2000). From the relative amount of

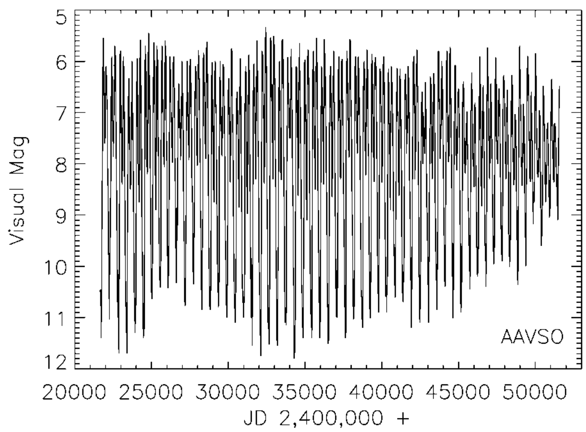


FIG. 1.—AAVSO light curve of R Cen, 1918–2000. Ten day averages of the data have been connected by a solid line for visual clarity.

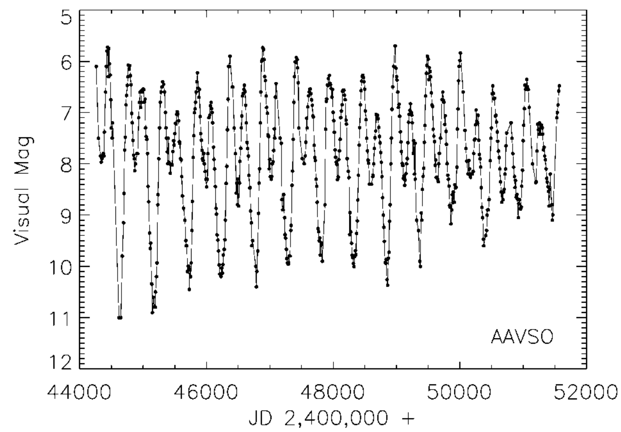


FIG. 2.—AAVSO light curve of R Cen, 1980–2000. The dots are 10 day averages of the data. The solid line is a visual aid and has no other significance.

time that a 1 $M_{\odot}$ star spends in the part of its thermal pulse cycle when the period changes are greatest, we would expect to catch at most only a few percent of AGB stars in a He-shell flash (Percy & Au 1999; Wood & Zarro 1981).

## 2. OBSERVATIONS

Figure 1 shows the light curve of R Cen from 1918 to 2000 taken from the AAVSO International Database. This light curve is composed of 13,857 individual observations from 308 observers worldwide. Figure 2 shows a section of the light curve from 1980 to 2000. The familiar pattern of double maxima can be seen as the light curve alternates between deep, then shallow minima. The maximum that follows the deep minimum is usually stronger, but the second maximum is always present. In the last decade this pattern has begun to change as the minima are becoming progressively similar.

An unusual aspect of the light curve is a gradual decline in overall amplitude during the last 50 years. This is not typical for a Mira variable, although a few other Miras are known with similar behavior. In 1988 Y Per rather abruptly dropped in amplitude from 2.5 to below 1 mag in about 800 days, or less than 2 pulsational cycles (Kiss et al. 2000). Other stars such as V Boo (Szatmáry, Gál, & Kiss 1996) and RU Cyg (Kiss et al. 1999) have behaved more like R Cen, with a gradual decline in amplitude. Some Cepheid variables have also been known to drastically decrease in overall amplitude, almost turning off their variability at times, including the well-known case of Polaris. In addition to the overall decline in amplitude in the light curve in the past 50 years, R Cen also shows some long-term variations in the depth of the minima around 1925–1940.

## 3. POWER SPECTRUM

Although the AAVSO data extend from 1918 to the present, a wavelet analysis showed that the dominant period around 550 days has been steadily getting shorter in the past 50 years and is now around 505–510 days. Therefore, in analyzing the power spectrum of R Cen, we used only a subset of the data where the main 550 day period was most stable, from JD 2,426,000 to JD 2,439,295 (1930–1966). A total of 6444 data points randomly spaced in time were averaged into 1279 points in 10 day bins prior to the spectral analysis.

For the spectral analysis, we use the date-compensated discrete Fourier transform (DCDFT) of Ferraz-Mello (1981) and the CLEANEST algorithm as described by Foster (1995). The traditional Fourier transform can give good results for evenly sampled data of infinite or very long length, but these conditions are almost never met for variable star observations. A finite or small data length can produce large sidelobes in the spectrum, and data with large gaps and irregular sampling can generate false peaks in the spectrum. The false peaks can even be larger than the true signal peaks in the case of data with large gaps or pathological sampling, such as data gaps at intervals similar to the signal period. In these cases the DCDFT and CLEANEST algorithms give better estimates of the true signal peaks and their frequencies and amplitudes.

The CLEANEST algorithm is an attempt to find the true signal peaks in the spectrum by getting rid of the false peaks caused by the window function. It does this by subtracting each signal peak from the spectrum one at a time, along with its attendant sidelobes. This is done in an iterative process where the amplitudes of the signal peaks are adjusted and more signal peaks are subtracted with each successive iteration, until there is no more signal in the spectrum. The final CLEANEST spectrum is then a composite spectrum of the Fourier transform of the residual data after subtracting all signal, with all of the CLEANEST signal components added back to the spectrum as delta functions with their correct amplitudes, minus their window function sidelobes.

Figure 3 shows the power spectrum of R Cen from an anal-

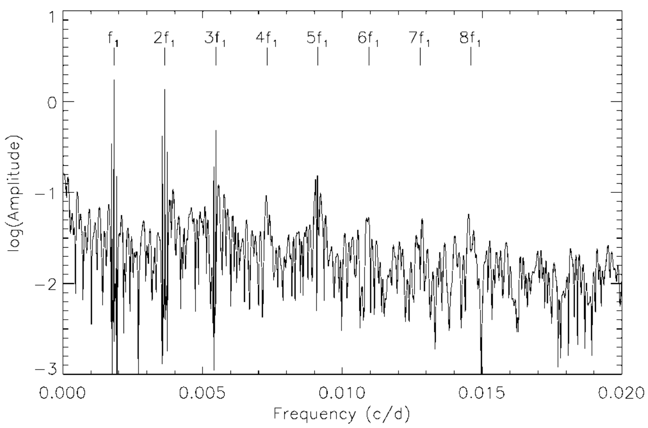


FIG. 3.—Power spectrum of R Cen in frequency range 0–0.02 cycle day$^{-1}$. Harmonics of the main mode at $f_1 = 1/548$ cycle day$^{-1}$ are shown.

ysis using the CLEANEST algorithm as described above. The strongest peak is at 548 days, or $f_1 = 0.001825$ cycle day$^{-1}$, which is the long period in the light curve between successive deep minima. In addition, the spectrum contains a series of harmonics up to 8 times the frequency of the main peak. Many Mira variables show higher harmonics in their power spectra (Barthès et al. 1998); *o* Ceti has up to five harmonics in its power spectrum (Barthès & Mattei 1997). This usually indicates an asymmetrical light curve deviating from a pure sinusoid, but for R Cen the second harmonic is an unusually high fraction of the main peak, resulting in the double-peaked light curve.

Table 1 lists all the peaks with significant power above the local background in the power spectrum of R Cen. All of these are either harmonics of the main 548 day mode or satellite frequencies near the main mode or its harmonics. These satellite peaks result from the slowly changing periods of the main peak and harmonics during the span of the data. There was no significant peak at frequencies above 0.02 cycle day$^{-1}$.

TABLE 1
POWER SPECTRUM OF R CEN

| Frequency (cycle day$^{-1}$) | Period (day) | Amplitude | Associated |
|---|---|---|---|
| 0.001750 ...... | 571.5 | 0.35 | |
| 0.001825 ...... | 548.0 | 1.77 | $f_1$ |
| 0.001925 ...... | 519.5 | 0.15 | |
| 0.003559 ...... | 281.0 | 0.42 | |
| 0.003644 ...... | 274.4 | 1.37 | $2f_1$ |
| 0.003737 ...... | 267.6 | 0.28 | |
| 0.005394 ...... | 185.4 | 0.19 | |
| 0.005467 ...... | 182.9 | 0.49 | $3f_1$ |
| 0.007277 ...... | 137.4 | 0.09 | $4f_1$ |
| 0.009037 ...... | 110.7 | 0.14 | |
| 0.009109 ...... | 109.8 | 0.15 | $5f_1$ |
| 0.009208 ...... | 108.6 | 0.09 | |
| 0.010857 ...... | 92.1 | 0.053 | |
| 0.010932 ...... | 91.5 | 0.054 | $6f_1$ |
| 0.012651 ...... | 79.1 | 0.034 | |
| 0.012858 ...... | 77.8 | 0.053 | $7f_1$ |
| 0.014520 ...... | 68.9 | 0.059 | $8f_1$ |
| 0.014690 ...... | 68.1 | 0.039 | |

## 4. WAVELET ANALYSIS

Because the period and amplitude of R Cen are changing over time, we sought analysis methods which could reveal, and quantify, that time evolution. Essentially we want to do a *time-frequency* analysis; put in these terms, the most natural choice would be a wavelet analysis. Unfortunately, most wavelet methods are very poorly suited to studying time series which are not evenly spaced in time; even a mildly irregular time sampling can wreak havoc.

Fortunately, an exception is the *weighted wavelet Z-transform*, or WWZ (Foster 1996), which is specifically designed to study the time evolution of period and amplitude for periodic and pseudoperiodic time series with uneven time sampling (in fact, it was created at AAVSO with long-period variable light curves in mind).

At any given moment of time $\tau$, and for any given test frequency $\omega$, we compute constants $\mu$, $A$, and $B$ by a weighted least-squares fit of the data to the function

$$f(t) = \mu + A\cos(\omega t) + B\sin(\omega t).$$

If all the data are weighted equally, this is simply a Fourier analysis, of the type known as the *date-compensated discrete Fourier transform* (Ferraz-Mello 1981). It becomes a wavelet analysis when data weights are chosen as a Gaussian function of the time

$$W(t) = e^{-c\omega^2(t-\tau)^2}.$$

The term $W(t)$ localizes the signal to time near $\tau$, and the constant $c$ defines the width of the Gaussian. We use $c = 0.0125$, which is a good compromise between higher frequency resolution (lower $c$) or higher time resolution (higher $c$). We can then compute a test statistic for the fit, the WWZ, as well as the peak frequency (presumably the signal frequency) and its amplitude. Further details of our wavelet analysis procedure are given in Foster (1996).

Another way to study changes in R Cen over time is to Fourier analyze small time segments. We applied the CLEANEST spectrum to each 2000 day section of the data from JD 2,421,609 to JD 2,451,500 (1918–2000). This gives estimates of period and amplitude for that time section, along with errors. The true errors in period and amplitude are likely to be twice that of our theoretical estimates, which are based on a classical formula which assumes as its null hypothesis that the data are a pure multiperiodic signal plus random noise.

The wavelet analysis of the R Cen data from 1918 to 2000 is presented in Figures 4*a*, 4*b*, 5*a*, and 5*b*. Results are shown

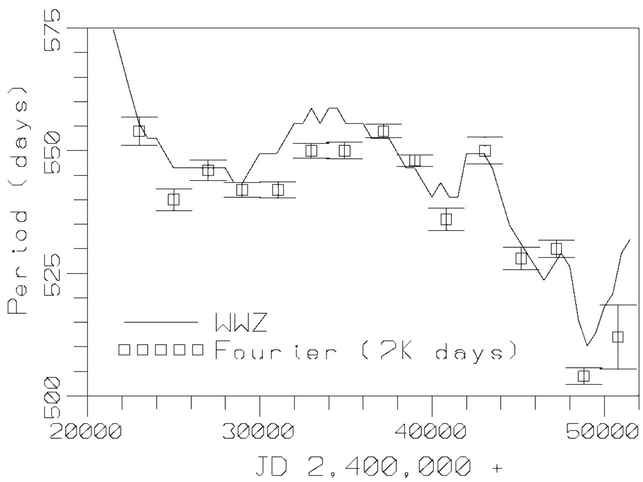


FIG. 4*a*

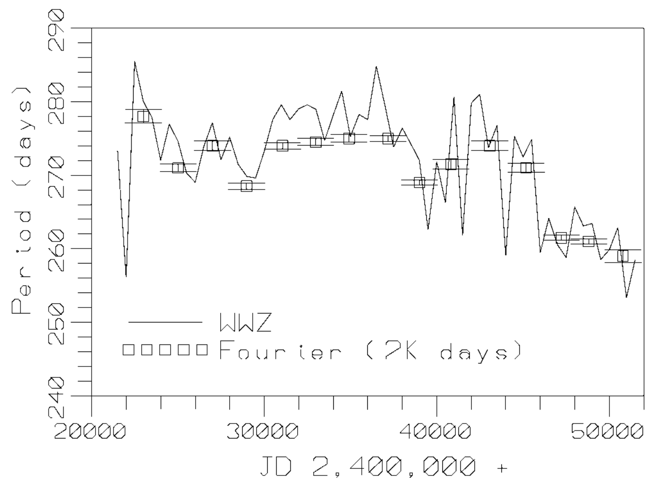


FIG. 4*b*

FIG. 4.—Wavelet plot (*solid line*) showing the period change in the (*a*) primary and (*b*) secondary modes from 1918 to 2000. The squares show a Fourier analysis of the data in 2000 day segments.

only for the primary and secondary modes near 550 and 275 days, respectively, as the other harmonics were too noisy for a useful wavelet analysis. Figures 4*a* and 4*b* show that the periods of both the primary and secondary modes have been decreasing dramatically since JD 2,434,000 (1951) to the present. During this change, the primary has maintained a constant 2:1 period ratio with the secondary to within 1%. The figures also show the same period changes from a Fourier analysis of the same data divided into 2000 day segments.

Figures 5*a* and 5*b* show that the amplitudes of the primary and secondary modes have also been changing dramatically over the length of the data. Whereas the primary mode was dominant over most of the time range, it has recently dropped below the level of the secondary.

## 5. DISCUSSION

Figure 4 shows that the period of the dominant mode in R Cen has been steadily decreasing from 550 days at JD 2,434,000 (1951) to its present value of 505–510 days. This change of $3 \times 10^{-3}$ day day$^{-1}$, or 1 day yr$^{-1}$, rules out eclipses of a red giant pair as a cause of the alternating deep and shallow

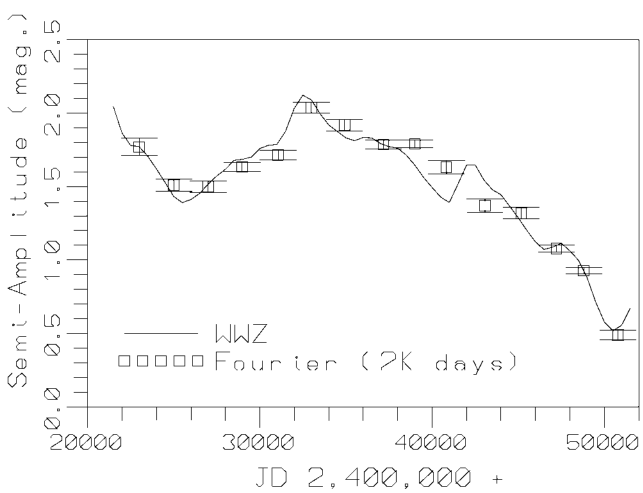


FIG. 5*a*

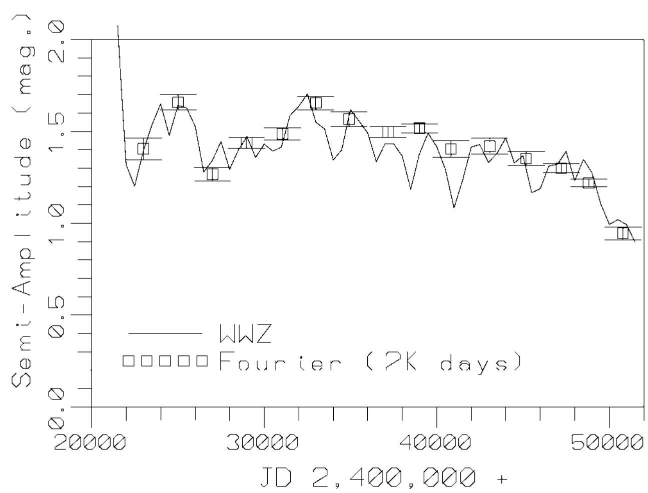


FIG. 5*b*

FIG. 5.—Wavelet analysis showing the change in amplitude of the (*a*) primary and (*b*) secondary modes from 1918 to 2000. The squares show a Fourier analysis of the data in 2000 day segments.

minima of R Cen. Most Mira variables show random period changes from one cycle to the next that do not follow any long-term pattern. Large, consistent period changes in pulsating AGB stars are usually interpreted in terms of a He-shell flash in the stellar interior.

A star experiencing a He-shell flash may show a period change lasting only a few tens of years if it is caught right after the flash begins, as indicated between points A and B in Figure 1 of Wood & Zarro (1981, hereafter WZ). The period drop could also last a few hundred to a few thousand years if it appears after the luminosity of the He-shell flash reaches the surface, between points C and E of the same figure. During both of these episodes the surface luminosity is expected to drop by less than a magnitude, and thus a period change is easier to measure and compare to He-shell flash calculations over a long time span. From the period change and using equation (10) of WZ, we compared the luminosity change of R Cen to that of He-shell flash models for stars of different masses as in their Figure 3. We used the same parameter values in equation (10) of WZ as adopted by those authors, namely $\alpha = 62.5$, $\beta = 16.67$, $b = 2$, and $C = 5.75 \times 10^{-3}$ (days). The luminosity drop is determined mainly by the rate of period change and is not very sensitive to $\beta$, the slope of a star in the HR diagram along a thermal pulse track.

The period and luminosity change for R Cen is steeper than for R Hya, although it has occurred over a much shorter time span. The data fit best if R Cen is in the period right after the beginning of a He-shell flash, between points A and B in Figure 1 of WZ, but only for lower mass stars with core mass $\leq 0.65\ M_{\odot}$, or total mass $\leq 2$–$3\ M_{\odot}$. For higher mass stars, the initial luminosity drop is too steep. R Cen could also be between C and D in Figure 1 of WZ, the point after the luminosity of the He-shell flash reaches the surface. If this is the case, then a much larger range of stellar mass would be allowed, although probably only for core masses $\geq 0.6\ M_{\odot}$. Although of luminosity class II, R Cen could be either a low- or high-mass supergiant, and an independent mass determination would provide a further constraint for He-shell flash models.

Further observations of R Cen are needed to better determine its true place on the thermal pulse cycle. Some Mira variables show abrupt period changes of the same magnitude expected for He-shell flashes, lasting 10 years or longer, only to reverse direction in $\dot{P}$ for a similar magnitude and timescale. S Her and T Cep are good examples (WZ). These short-term changes can mimic and mask the effect of He-shell flashes and other long-term evolutionary changes, so WZ stress the need for long-term observations when identifying the effects of He-shell flashes.

Since the decline in pulsational amplitude and period decrease of the main mode began around the same time (1950), both are probably related to a He-shell flash. The decline in pulsational amplitude may be caused by additional convection, brought on by the shell flash. It is thought that strong convection can either partially or totally damp pulsations, e.g., as in the models of convectively damped pulsations of RV Tauri variables by Deupree & Hodson (1976) or the nearly total damping of the pulsations of Y Per in 1988 (Kiss et al. 2000). Along with a period decrease, the He-shell flash star T UMi also shows a recent decrease in pulsational amplitude (as can be seen in the AAVSO International Database), although the drop is not as large as for R Cen.

An alternate explanation for the pulsational decline in R Cen may be that it is changing from a Mira to a semiregular variable by switching pulsational modes, probably from the fundamental to an overtone. The wavelet analysis in Figure 5 shows that the amplitude of the primary mode at 510–550 days has been gradually declining in the past 50 years and is now damped below the level of the 274 day mode.

Will R Cen become like RU Cam, a former Cepheid that has now nearly ceased to pulsate (Demers & Fernie 1966)? In the microlensing study of millions of stars in the Large Magellanic Cloud by the MACHO Collaboration, all stars in the AGB section of the HR diagram are variable, except for the expected number of reddened foreground stars in our own galaxy (D. Alves 2000, private communication). Thus we would not expect R Cen to stop pulsating entirely, at least not for a long period of time. It should instead behave similar to the Mira variables Y Per and RV Cen, which declined in pulsational amplitude for a few years but then rebounded (Mattei 1997). This is one more reason R Cen should be monitored well in the future.

## 6. CONCLUSIONS

Since 1950, the period of R Cen has been steadily decreasing from 550 days to its present value of 505–510 days. R Cen is probably experiencing a He-shell flash, as the period decrease of 1 day $\mathrm{yr}^{-1}$ is of the same order of magnitude as other He-shell flash stars such as R Hya, R Aql, and T UMi. Since the pulsational amplitude decreased by 3 mag in the same interval, we suggest that it is also a result of a He-shell flash.

While the amplitude of the main mode decreased by 3 mag since 1950, the amplitude of the secondary mode at 274 days has remained nearly constant, so that the double maxima have nearly disappeared from the light curve in recent years. The most likely cause of the double maxima is a resonance between two modes.

We gratefully acknowledge the dedicated observations of hundreds of variable star observers since 1918 that made this study possible.

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