Period Change in the Semiregular Variable RU Vulpeculae

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Received September 4, 2007; revised November 30, 2007, accepted January 10, 2008

Abstract

The well-observed semiregular variable RU Vulpeculae has undergone a substantial change in period over the past fifty-five years. The discovery period of ~155 days has undergone a continuous change to its current value of 108 days. The amplitude and stability of the light curve have changed as well; the pulsations are much less regular and have a lower amplitude now than at the time of RU Vul's discovery and classification. The character of the period change is quantitatively similar to that of the well-studied Mira variable T Ursae Minoris, and we argue that RU Vul may be a semiregular analog of Mira variables undergoing dramatic period changes. We place RU Vul in the context of other AGB stars exhibiting similar behavior, and discuss possible explanations for its period change.

1. Introduction

The Templeton *et al.* (2005) study of 547 well-observed Mira variables found that about 1.5 percent of Mira stars exhibit large, easily detectable changes in pulsation period. One possible explanation for these changes is that they are due to *thermal pulses*, which are rapid, helium-shell burning events predicted to occur in asymptotic giant branch (AGB) stars. These pulses and their aftereffects last for a few thousand years, and their occurrence is confirmed observationally by the presence of the short-lived isotope technetium in the spectra of many AGB stars. The energy generated in these pulses would act to change the equilibrium structure of the star, resulting in a substantial change in pulsation period detectable on observable timescales. The fraction of stars with large period changes is consistent with the ratio of the durations of thermal pulses (around 10^3 y) to the time between pulses (around 10^5 y) predicted by stellar evolution models. However, it is unclear whether thermal pulses are responsible for any or all of the observed cases of period changes in Miras, and whether such changes are potentially observable in all pulsating AGB stars, including the semiregular variables.

Formally, the Mira and semiregular variables differ in amplitude (Miras have amplitudes above 2.5 magnitudes by definition; semiregulars, below 2.5) and period (Miras have periods above 100 days; semiregulars can have a range of periods up to and beyond 100 days). However, there is substantial overlap between the two classes, with some Miras exhibiting striking irregularities, and some semiregulars appearing quite regular in comparison to others in the same class. Wood *et al.* (1999) showed that the LMC Miras and semiregulars are concentrated on separate parallel tracks on the period-luminosity diagram; this implies that they are physically similar objects pulsating in different radial modes. The fact that some semiregular stars lie on the period-luminosity relation for Mira variables in the solar neighborhood (Bedding and Zijlstra 1998) suggests some overlap between the two. This and other observational information point to Miras as fundamental mode pulsators, while the semiregulars are predominantly overtone pulsators with a few being fundamental mode pulsators. Whether there is an evolutionary progression from one to the other isn't clear, but it is a reasonable assumption that as stars slowly increase in luminosity, progressively lower-order modes become excited, until they become Miras pulsating in the fundamental mode (see Marigo and Girardi 2007). One major difference between Miras and semiregulars is known to be the mechanism of driving. Christensen-Dalsgaard *et al.* (2001) and Bedding *et al.* (2005) showed that there are spectral signatures of stochastic behavior in the semiregular stars, whereas Miras are comparatively more stable. Recent work by Kiss *et al.* (2006) on the supergiant semiregulars shows similar behavior, along with the presence of low-frequency *red noise*—another signature of stochastic behavior. Many semiregular stars are known to be multiperiodic, with more than one pulsation mode excited at a given time. This could explain the irregularity observed in some but not all of these objects. Semiregulars in general appear to be less chemically evolved than Miras. Lebzelter and Hron (2003) found that most semiregulars lack Technetium, but many Mira stars also lack Technetium.

It is a given that as a star moves through the AGB instability strip, pulsation modes will become excited or damped, and pulsations may become regular or irregular. Miras themselves show significant cycle-to-cycle variations, and the semiregular phenomenon may simply be an extreme example of this behavior. Or, conversely, the Miras (or fundamental mode pulsators generally) may be driven to such high limiting amplitudes that they overcome the instability inherent in the semiregular variables of higher overtone. Individual stars may transition from one type to the other during their AGB lifetimes, and such transitions may be especially rapid during thermal pulses.

RU Vul (AAVSO 2034+22A, HIP 101888; R.A. $20^{h}\,30^{m}\,52.69^{s}$, Dec. +23° 15' 31.2", J2000) is an M3e oxygen-rich semiregular variable. Its distance (and hence absolute magnitude) is unknown (Perryman *et al.* 1997), but RU Vul is believed to be a part of the thick disk population of the Milky Way (Mennessier *et al.* 2001). The changing period of RU Vul has been known for some time, and four different period epochs are noted in the *General Catalogue of Variable Stars* (GCVS) fourth edition (Kholopov *et al.* 1985). Percy and Au (1999) described these variations in terms of a linear period change, while Kiss *et al.* (1999) explained them with multiperiodicity. Later, Zijlstra and Bedding (2002) used a time-frequency analysis to show that the period variation is best described in terms of a *continuous period change*, from about 155 days at the time of its discovery to about 108 days currently.

In this paper, we analyze the most current available data to quantify the rate of period change, and attempt to place RU Vul in context of the Mira variables exhibiting similar behavior.

2. Data and results

We used the 6,230 visual observations of RU Vul taken from the AAVSO International Database, spanning JD 2427820.6–2454312.6 (1935 January 18–2007 July 31). These data were averaged into ten-day wide bins, yielding 1,788 averaged data points (Figure 1). These were then analyzed for time evolution of the pulsation period using the *weighted wavelet Z-transform WWZ* (WWZ) developed by Foster (1996). The WWZ algorithm is analogous to a discrete Fourier transform using a Gaussian weighting function for the data. The time center and width of the Gaussian window are adjustable, and may be moved along a given set of data to measure the time evolution of the variability. We used the procedure outlined in Templeton *et al.* (2005) to measure the time-frequency behavior of RU Vul. The dominant signal's period, amplitude, and mean magnitude as functions of time are shown in Figure 2.

The period of RU Vul has clearly changed over the course of recorded observations, as have the amplitude (also clearly seen in the light curve in Figure 1) and the mean magnitude. To determine the rate of period change dP/dt, we fit a line through the time-period measurements between JD 2435000 and 2454000, and obtained a rate of period change of -2.5×10^{-3} d/d (= –0.91 d/y) from the slope of the line. For comparison with the Mira stars given in Templeton *et al.* (2005), this rate of period change yields a fractional rate of period change $d\ln P/dt = -7.11 \times 10^{-3}\ y^{-1}$. This is the second-largest fractional period change among all of the AGB stars with known period changes, with only that of T UMi being larger, at $-8.4 \times 10^{-3}\ y^{-1}$. For most Mira variables it is below $10^{-5}\ y^{-1}$. This rate of change is consistent with those predicted by stellar evolution calculations (Wood and Zarro 1981; Vassiliadis and Wood 1993).

The changes in amplitude and mean magnitude are apparent both in the light curve itself and in the time-frequency analysis. The amplitude declines throughout the light curve, but is marked by an abrupt drop around JD 2439000 (late 1965); likewise the mean magnitude shows a weak brightening trend, marked by an abrupt increase of 0.6 magnitude (nearly seventy-five percent in luminosity) at the same time. The changes in amplitude and mean light seem to occur because the minima suddenly become brighter (by over one magnitude). The brightness of the maxima have changed very little over the recorded history of RU Vul, but the very sudden brightening of the minima is remarkable. Curiously, these changes occur not at the start of the period decline (circa JD 2435000) but several thousand days later.

Finally, we note the detection of a secondary pulsation mode in the spectrum of RU Vul. There is a long-term oscillation in mean light apparent in the light curve, and when we analyze the light curve with a *clean*-based Fourier transform (Roberts *et al.* 1987), we find a second strong period at approximately 2,450 days. The period is too long to measure reliably whether it, too, is changing, but it does produce peaks at integer multiples of the main period in an autocorrelation diagram, and is also apparent as a modulation in the maxima and minima throughout the light curve. It is not as apparent to the eye in the light curve over the past 5,000 days.

3. Discussion

RU Vulpeculae is clearly an object in transition. The period change is dramatic; it has declined by thirty percent over the past fifty-five years, and only the Mira stars T UMi, LX Cyg, and BH Cru have rates of period change of similar magnitude. Like T UMi, RU Vul appears to have begun its dramatic changes as we have watched.

Both the GCVS and the earliest AAVSO observations indicate that the period remained constant between 1935 and the 1950s, when it began to steadily decline. If we can extrapolate the evolution calculations of thermally pulsing Mira-like stars to the semiregulars, the pre-decline constancy of period and the subsequent rate of period decline are like what is predicted for the onset of a thermal pulse. RU Vul may therefore be the second example of an AGB star initiating a thermal pulse during the history of recorded observations, after T UMi.

The similarity of RU Vul's period history to the pulsation periods predicted from thermally pulsing models is striking, but it is by no means proven that thermal pulses are responsible for the large period declines observed in this star or any other AGB pulsator. The fact that the mean magnitude has undergone a slight *increase* throughout the observational record—contrary to the model prediction of decreasing luminosity—may be important evidence against a thermal pulse. Both the evolutionary tracks of Vassiliadis and Wood (1993) and the period-luminosity relations for Miras and semiregulars in the solar neighborhood (Bedding and Zijlstra 1998) predict decreases of nearly half a magnitude when the period changes by the amount observed, for both fundamental and first overtone pulsation modes. The increase observed (nearly a magnitude) is too large to be due to an increase in effective temperature, since it would require an unphysically large change in (B–V) (see Stanton 1981 for the transformation equation from V to visual). The picture is further complicated by RU Vul being a semiregular variable, which are by definition unstable, and for which the cause of instability is unknown. Although the light curve is modulated by the long secondary period of 2,450 days, it would not account for the long-term trend in mean magnitude. Such a trend would require a period far longer than the time span of the light curve itself. Proposed non-evolutionary mechanisms for global changes in AGB stars include feedback between the pulsations and the stellar structure (e.g., Ya'ari and Tuchman 1996; Lebzelter and Wood 2005) and secular changes in the opacity (e.g., Zijlstra *et al.* 2004) resulting in global changes to the equilibrium structure. Several pulsating AGB stars have also been observed to undergo substantial changes in pulsation amplitude with only slight changes in period, such as Y Per (Kiss *et al.* 2000), W Tau, and RT Hya (Mattei *et al.* 1990). Templeton *et al.* (2005) showed in a purely statistical sense that the number of AGB pulsators with measurable period changes (about one to two percent) is consistent with the relative times that Mira variables spend in the thermally pulsing and interpulse stages of the AGB, but unfortunately we can say nothing about whether an *individual* star is itself undergoing a thermal pulse. However, we are much less likely to observe a star during the *onset* of a thermal pulse during the course of a century's observations. The probability of any given AGB star undergoing this process is about 0.1 percent, or one in 1,000; again it is simply the duration of the rapid period change (about a century) relative to the total interpulse lifetime (of order 10^5 y). If we assume that both T UMi and RU Vul were caught at this stage, and if we assume that there are about 500 well-observed AGB stars among the variables in the AAVSO archives, then more objects than are expected are undergoing this behavior. We are limited by the small sample size at hand, but it does suggest that there may be another explanation for this behavior besides thermal pulses. As a further caveat, we note the existence of yet another evolved star, V725 Sgr, which has also undergone a large period change (Percy *et al.* 2006), and has transformed from Cepheid to semiregular over the past century. The cause of this transformation is also unknown, although Percy *et al.* (2006) speculate that V725 Sgr is in the middle of a blue loop through the Cepheid instability strip, and has moved back to the giant branch.

The theoretical picture of pulsations in AGB stars is far more complicated than what is seen in other pulsators, due in part to the critical importance of convection, complex chemistry and dust formation, the extremely high amplitudes, and the role of mass loss. Theoretical modeling involving many of these considerations is ongoing, and will reveal much about the physical behavior and evolution of these stars. A crucial question to answer will be how exactly do pulsations modify the physical properties of the star? One suggestion by Ya'ari and Tuchman (1996) and Lebzelter and Wood (2005) is that the star must undergo some relaxation process while it is pulsating, but it is not clear why such a process would start spontaneously when a star is already pulsating at a reasonable limiting amplitude, as both RU Vul and T UMi were doing prior to the onset of period changes.

Future long-term monitoring of both RU Vul and T UMi will also be key to understanding these stars. If both stars are moving through the AGB instability strip, then we may see them change pulsation mode or cease pulsating altogether in the future. It will be particularly interesting to monitor the behavior of these objects in coming decades, as T UMi is approaching the canonical lower amplitude limit for classification as a Mira star, and the variations of RU Vul appear to be vanishing altogether. Both objects are fascinating examples of stars evolving before our eyes, and warrant our attention in the future. We encourage observers—visual and instrumental—to begin and continue monitoring these fascinating objects in the coming decades.

4. Acknowledgements

Once again, we are indebted to the many thousands of observers worldwide who have contributed observations of RU Vul and many other stars to the AAVSO International Database, and we look forward to tracking the evolution of RU Vul in the coming decades through the devoted work of the amateur community. We thank the referee, John Percy, for several helpful suggestions that improved the content of the paper.

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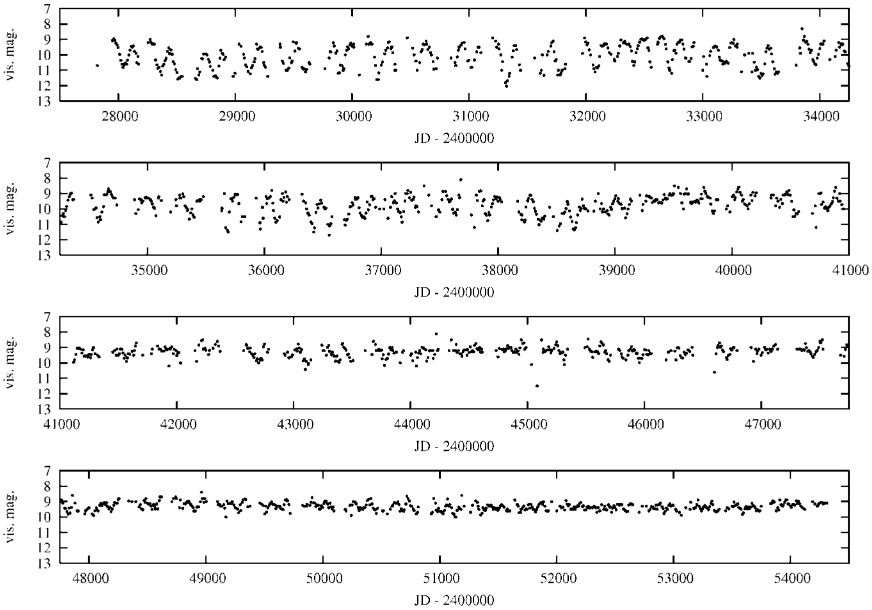

Figure 1. The visual light curve of RU Vul from the AAVSO International Database (January 1935–July 2007). Data points are 10-day means of visual magnitude estimates.

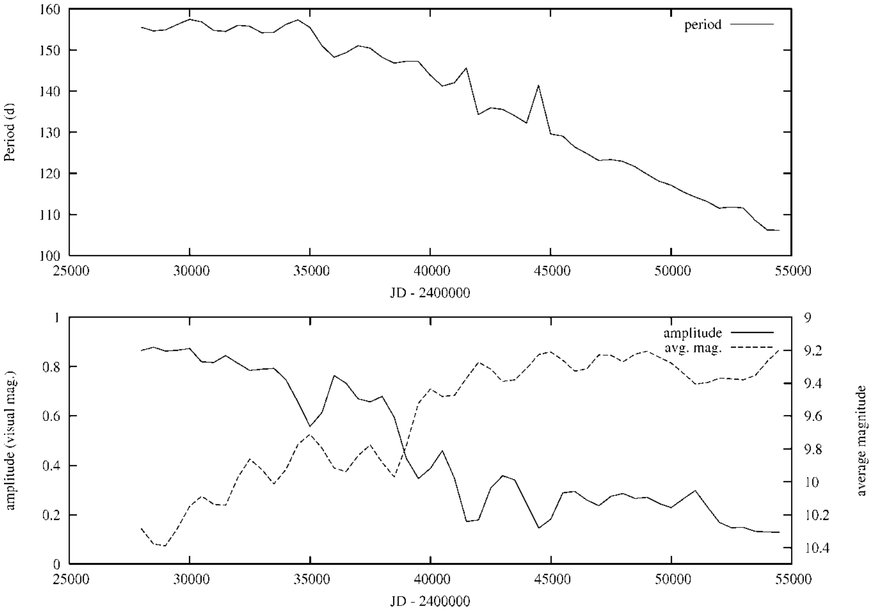

Figure 2. The period (top panel), amplitude (bottom panel, solid line), and mean magnitude (bottom, dashed) for RU Vul as calculated using the wwz (Foster 1996) time-frequency algorithm. The period has dropped dramatically since JD 2435000, declining continuously from about 155 days earlier this century to the current value of less than 110 days.