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Photometric Variability of Red Giants

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Abstract. We review the work of our group, and others, on the photometric variability of red giants, and describe some new results from merged AAVSO and robotic telescope photometry of 13 stars, and from *VRI* photometry of 34 stars. Topics include: periods and amplitudes; pulsation modes; multiperiodic pulsation; long-term and very-long-term variability; wavelength dependence of amplitude; amplitude variability; period variability; and red supergiant variability. This work has benefitted from the contributions of skilled amateur astronomers, and of undergraduate and high school research students.

1. Introduction

Red giants make up about 10 percent of the bright stars. They are photometrically variable, in varied and complex ways that reflect their astrophysical complexity. Some aspects of their variability are poorly understood – pulsation in the presence of convection, for instance. Other aspects, such as their long secondary periods (LSPs), are not understood at all. See Wood (2007) for an excellent recent mini-review.

An additional attraction is the fact that both amateur astronomers and undergraduate students can usefully observe and analyze red giant variability. I (JRP) have a long and happy history of working with both these groups.

The primary subject of this paper is small-amplitude pulsating red giants (SAPRGs). These are much more common than their more famous relatives, the Mira stars. They have periods that are more manageable – a few tens of days. Unfortunately, they are often dismissed as "semi-regular", as if they have nothing to offer. I hope to show that they may have *more* to offer than purely periodic variables. For instance, some have multiple periods, which can potentially provide multiple quantities for comparison with models.

The stars in our samples are bright stars, typically $V = 7$ or brighter. This means that they are accessable to other techniques such as spectroscopy or interferometry. The results of our work also provide a model for the analysis of the fainter but much more numerous SAPRGs discovered in surveys such as MACHO and OGLE.

SAPRG pulsation is driven by the standard ionization zone ("kappa") mechanism. We will *not* discuss the variability of warmer (G to early K) giants whose

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oscillations are excited by convection, like those of the sun. The *Microvariability and Oscillations of STars (MOST)* satellite, Canada's "Humble Space Telescope", has begun to carry out asteroseismological studies of warmer red giants such as ϵ Oph (G9III, Barban et al. 2007), and *MOST* and *COROT* will undoubtedly continue to do so. Brown (2007) has carried out a comprehensive study of the complex radial velocity variations of Arcturus (K1.5III).

2. Previous Studies

Our research builds upon the early work of Stebbins and Huffer (1930) and Olin Eggen who, in the 1970s, published a series of papers on SAPRGs. In the early 1980s, a combination of circumstances led to a "golden age" of photoelectric photometry by amateur astronomers. One of us (JRP) and J.A. Mattei established the AAVSO Photoelectric Photometry (PEP) Program. Unlike some other PEP programs in which amateurs participated, it took a decade for the AAVSO program to bear fruit, but the eventual harvest was a rich one: Percy et al. (1996) published a 10-year study of two dozen SAPRGs in the AAVSO PEP program. Subsequently, one of us (GWH) made available, to JRP and his students, 5000 days of *VRI* photometry of 34 SAPRGs. This photometry was obtained with an automatic (robotic) photometric telescope (APT), and is publicly available on GWH's website. The results of the analysis of the APT *V* data were published by Percy et al. (2001).

These studies, and related ones (see Percy 2002, 2003a for summaries), established or confirmed the basic properties of SAPRGs: they make up about 10 percent of the bright stars; variability sets in at about K2-5III; the typical amplitude increases with decreasing temperature; the basic period is a few tens of days, and is consistent with low-order radial pulsation; about a third of the stars show long secondary periods, an order of magnitude longer than the pulsation periods; many of the stars are multiperiodic; the mode amplitudes vary on a time scale of years; indeed, a few stars switch modes on this time scale.

3. Pulsation Modes, Multiperiodic SAPRGs

We first (Percy & Polano 1998, Percy & Parkes 1998, Percy & Bakos 2003) estimated the pulsation modes by determining observational Q-values from the periods, radii (from the temperatures, and luminosities from *Hipparcos* parallaxes), *assuming their masses to be solar*. The Q-values corresponded to pulsation in the fundamental, first, second, or third overtone modes of radial pulsation.

A dozen of the stars proved to be multiperiodic (Percy et al. 2003b, Percy et al. 2004), and the pulsation modes could be determined from the observed period ratios. Using theoretical Q-values for these modes, and radii determined as above, it was possible to determine "pulsation masses" for the stars. They ranged from 0.7 to 1.9 times solar, as would be expected.

At the same time, Wood (2000) and others were identifying multiple period-luminosity (P-L) relations for SAPRGs discovered in MACHO, OGLE, and other large-scale surveys. These sequences correspond to different pulsation modes – again, low-order radial modes. Wood (2000) also identified a P-L sequence corresponding to the long secondary periods, and another corresponding to binary systems.

Multiple periods, and long secondary periods were also studied in a large sample of medium-amplitude semi-regular red variables by Kiss et al. (1999); the long secondary periods in these stars have been known for over half a century.

4. Merged AAVSO and APT Data

The AAVSO has recently re-reduced all of its PEP data, using improved comparison star magnitudes and reduction procedures, and has made the data publicly available on its website. Since there are 13 stars in common between the AAVSO sample and the APT sample, we have analyzed merged V data on these stars. The merged datasets are typically 1.8 times longer than the individual datasets, and contain up to 1.5 times as many points. This provides more precise values for the periods, and more information about long-term and very-long-term variability. The AAVSO PEP program is continuing: the stars on this program are too bright for convenient CCD photometry.

As usual (Percy et al. 1996, Percy et al. 2001), we use both Fourier and self-correlation (Percy & Mohammed 2004 and references therein) analysis, in addition to inspection of the light curves. Self-correlation analysis describes the cycle-to-cycle behavior of the variability, averaged over the dataset.

The detailed results will be published elsewhere. They are summarized in Table 1. Four of the 13 stars have well-determined LSPs, and almost all of the stars have *very* long term variations in mean magnitude and/or amplitude.

The cause of the LSPs is not known (Wood et al. 2004), but they have listed several possibilities: radial pulsation, non-radial pulsation, episodic dust formation, starspots, binarity, rotation of a prolate spheroid, or a convection-induced oscillatory thermal mode. None of these explains the bulk of the LSPs, though we note that, in EG And, the LSP is exactly half of the known binary period. One or more of the above-mentioned processes may explain the very long term variability of SAPRGs.

Two of the "simpler" stars in Table 1 are EU Del and η Gem. For these, we plotted phase diagrams with the known periods – 62.45 and 233.2 days, respectively. For EU Del, the scatter around the phase diagram was uniform or random but, for η Gem, the phase curve was smooth with the exception of occasional fadings of about 0.3 mag. We note that η Gem is a binary with a period of 2983 days (McLaughlin & Van Dijke 1944), though the fadings do not appear to occur with this period. Our results suggest that some of the long-term variability in η Gem takes the form of occasional fadings.

5. Wavelength Dependence of Amplitude

Percy et al. (2001) analyzed APT V data, but not the RI data. The relative VRI amplitudes can potentially provide information on the processes that cause the variability, especially the LSPs. We have therefore determined VRI amplitudes using Fourier and self-correlation analysis, for those stars with well-determined pulsation periods and/or LSPs. Typical results are shown in Figures 1 and 2.

Table 1. Variability and periods (days) of Small-Amplitude Pulsating Red Giants.

Star	Period (d)	Long period (d)	Very Slow Variations?
TV Psc	55	550	no
EG And	29	244	no
RZ Ari	37.7, 56.5	370:	yes
η Gem	234	none	no
V614 Mon	90, 67:	none	yes
RS Cnc	225, 137:	none	yes
VY UMa	125, 188:	none	yes
FS Com	38.2, 55.4	680	yes
SW Vir	154	none	yes
R Lyr	64.3, 46	none	yes
EU Del	61.6	none	yes
V1070 Cyg	64, 100:, 42:	none	yes
W Cyg	131, 250:	none	yes

For both the pulsation periods and the LSPs, the amplitude decreases with increasing wavelength, as it does for Mira stars. There is no apparent difference in the amplitude-wavelength behavior for the two cases, with the possible exception of EG And, in which the *VRI* amplitudes are more comparable. This is a star in which the LSP appears to be associated with binarity.

6. Why Are SAPRGs Not Strictly Periodic?

One reason is because, based on our sample, at least a third of SAPRGs are multiperiodic, having two or possibly three periods. More of the stars may be multiperiodic, or have three or more periods, but the signal-to-noise ratio may be too small to detect them.

The amplitudes of the pulsation modes may change with time. Many Mira stars (including Mira itself) have variable amplitudes, though they are not usually considered “semi-regular”. Kiss et al. (2000) studied the amplitude variability of several long-period, larger-amplitude semi-regular variables. These included stars with amplitude modulation, with or without changes in mean magnitude, stars which slowly changed modes, and one case (Y Per) in which the amplitude varied significantly within a cycle or two. Percy et al. (2003b) found that, in five multiperiodic SAPRGs, the amplitudes of the modes varied on a time scale of years.

Preliminary analysis of our merged APT+AAVSO data suggests that the amplitudes may also vary from cycle to cycle. Figure 3 shows the time variation of the amplitudes in three stars, including the two different periods in RZ Ari. Although there seem to be trends on time scales of years, there are also significant variations on a time scale of half a season, or a cycle or two in the pulsation.

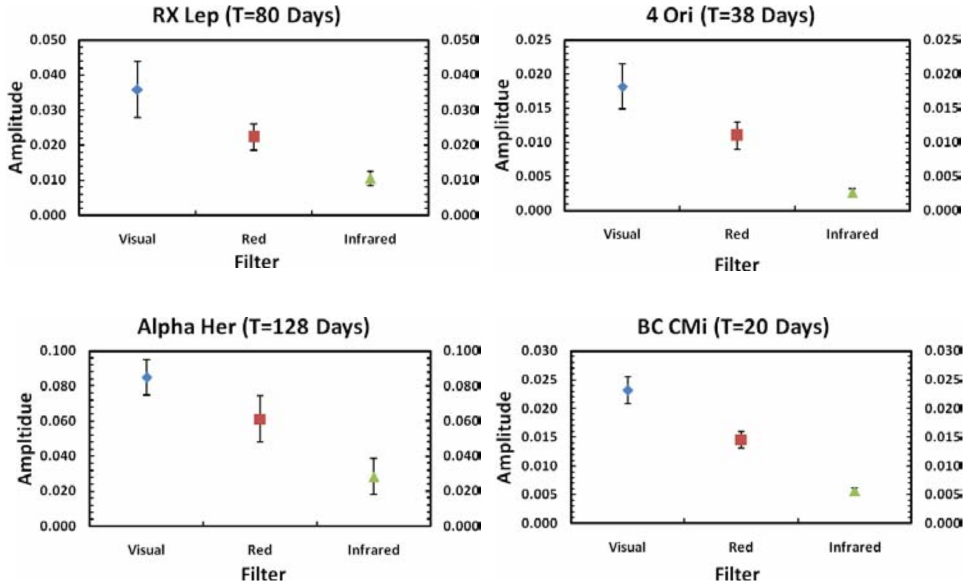

Figure 1. The amplitude of the pulsational variations of the red giants RX Lep, 4 Ori, α Her, and BC CMi as a function of wavelength (filter): V – yellow; R – red; I – near-infrared.

For W Cyg, there is definitely amplitude variation on a time scale of a decade or two, as was also found by Kiss et al. (2000).

7. Period Changes in PRGs

One potential use of any class of pulsating variable star is to measure period changes as a possible test of evolutionary models. This has been done successfully for Cepheids (Turner et al. 2006a, for instance), using the (O-C) method (Sterken, 2005). Unfortunately the (O-C) diagrams of Mira stars are dominated by random cycle-to-cycle period fluctuations (Eddington & Plakidis 1929, Percy & Colivas 1999 and references therein), though Percy & Au (1999) were able to use period changes to detect the slow, normal evolution of Mira stars at the 1.5σ level.

Percy et al. (1993) presented an (O-C) diagram for EU Del, based on limited data, and it would be worth repeating this analysis with a longer dataset. The evolution of this star should be too slow to detect, though it may be possible to detect random cycle-to-cycle period fluctuations in this star, if they occur.

Stars on the upper AGB undergo “blue loops” on the H-R diagram, due to instabilities in the nuclear-burning shells on time scales of hundreds to thousands of years. Templeton et al. (2005) have analyzed visual data on 547 Mira stars, and have identified up to 57 that may show significant period changes due to this rapid evolution. Some of the results may be artifacts of the random fluctuations, but it is clear that many of the stars are undergoing real evolutionary period changes.

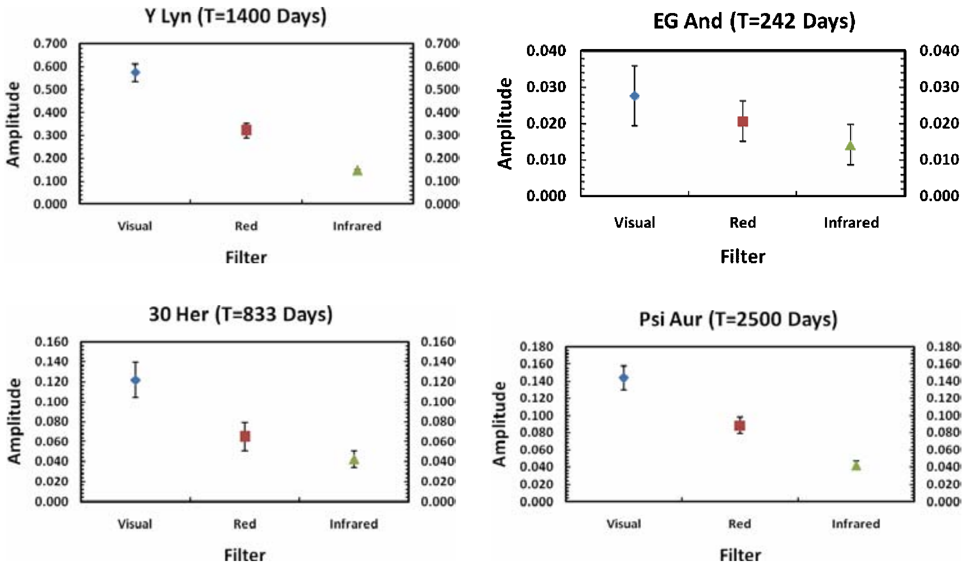

Figure 2. The amplitude of the long secondary period variations of the red giants Y Lyn, EG And, 30 Her, and ψ Aur as a function of wavelength (filter): V – yellow; R – red; I – near-infrared.

The most dramatic case of an apparently-evolutionary period change in a SAPRG is that of V725 Sgr (Percy et al. 2006) which changed from a 12-day Population II Cepheid to a garden-variety 90-day SAPRG in the course of a century!

8. Pulsating Red Supergiants

Our interest in these variables was piqued by a long-term study, by Turner et al. (2006b), of BC Cyg, based on AAVSO visual data, and photographic data from the Harvard Observatory plate collection. This study suggested that the period of BC Cyg might be changing, and that this star might be in a relatively rapid evolutionary phase. About the same time, Kiss et al. (2006) presented the results of a comprehensive study of 48 semi-regular or irregular red supergiants, using up to a century of AAVSO visual data. They found at least one pulsation period in most of the stars, and LSPs in many. They noted that the peaks in the Fourier spectrum could be represented as Lorentzian envelopes that they ascribed to convective noise.

We have begun an anaysis of some of the same stars, using the same data, in which we determine times of maximum in order to search for random cycle-to-cycle period fluctuations and – if possible – use (O-C) diagrams to set upper limits to the rate of evolution.

For the largest-amplitude variable, VX Sgr (period 754 days), we find an average cycle-to-cycle fluctuation of 0.092 period or 9.2 percent. This is more than twice the average value for Mira stars. These random cycle-to-cycle period fluctuations may well be caused by what Kiss et al. (2006) call convective noise.

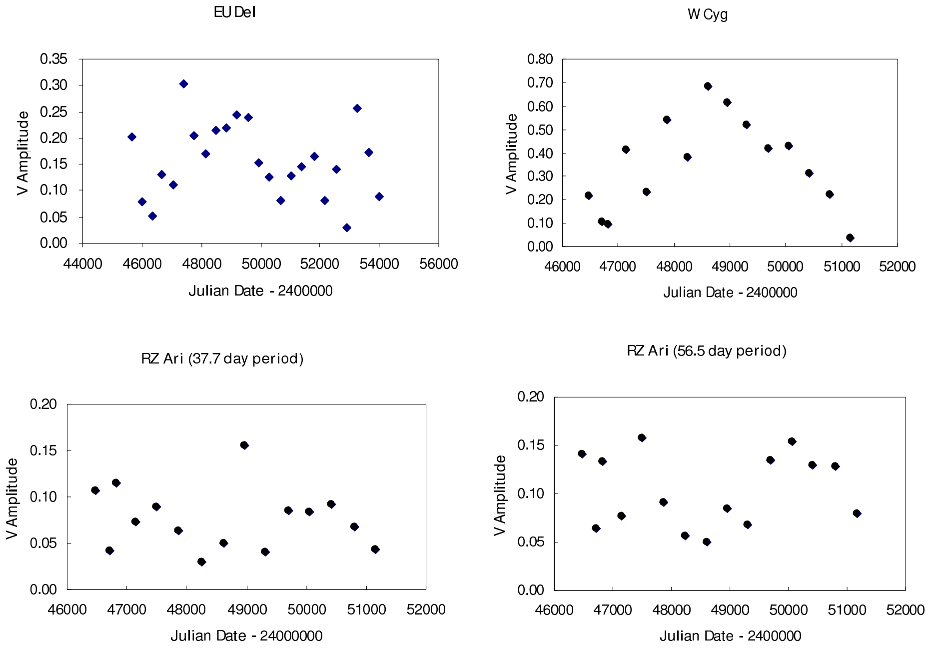

Figure 3. The pulsational V amplitude variability, with time, of the red giants EU Del, W Cyg, and RZ Ari (37.7 and 56.3 day modes).

9. Educational Perspectives

The University of Toronto students who have contributed to this and our previous papers on the photometric variability of PRGs have done so through five different programs: (i) the senior thesis course AST425H; (ii) the Ontario Work-Study Program; (iii) summer research assistantships, especially those funded through the Natural Sciences and Engineering Research Council of Canada; (iv) the Research Opportunities Program (ROP), through which second-year students can participate in a research project for full-course credit; and (v) the University of Toronto Mentorship Program (UTMP), through which outstanding senior high school students can participate in research projects at the university. Several of the projects described in this paper have been presented at the annual Research Fair of the ROP or the UTMP.

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