Non-Mira Pulsating Red Giants and Supergiants

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Abstract We review the present understanding of (i) non-Mira pulsating red giants, that is, those with visual amplitudes less than 2.5 magnitudes, and (ii) pulsating red supergiants. We also identify some unsolved problems with these stars. We highlight the contributions by skilled amateur astronomers in the AAVSO and other organizations, using visual, photoelectric, and CCD photometry.

1. Definition

This paper reviews the development of our present understanding of pulsating red giants (PRGs) with V amplitudes less than 2.5. For convenience, we shall call them smaller-amplitude pulsating red giants or SAPRGs. Those with larger amplitudes are classified in the *General Catalogue of Variable Stars* (GCVS; Kholopov *et al.* 1985) as Mira stars, and are reviewed by Willson (2012) elsewhere in this volume. The choice of Δmag = 2.5 as a cutoff is somewhat arbitrary. First of all, the amplitude is highly wavelength dependent; a Mira star can have a visual amplitude of almost ten magnitudes, and a bolometric amplitude of less than two magnitudes. This phenomenon is due to the behavior of molecular bands in the spectrum, such as TiO; it is therefore dependent on the chemical composition of the atmosphere. Furthermore: there are stars with amplitudes equal to 2.5, and stars whose amplitude varies from above to below 2.5.

Red stars of luminosity class II and I (bright giants, and supergiants) show variability properties similar to those of red giants. We shall discuss pulsating red supergiants in section 9.

Henry *et al.* (2000) carried out a photometric survey of 187 G and K giants, and concluded that giants cooler than K5 are all variable, due to radial pulsation.

Some warmer giants are also pulsating variables, but the pulsation is more similar to that of the sun than to the K5-M-type pulsators. Here we exclude the discussion of G-K giants, for which asteroseismology with the Kepler space telescope has completely revolutionarized the field (see, for example, Bedding *et al.* 2010, 2011).

There are a dozen excellent essays on Mira and semiregular/SAPRG variables in the "Variable Star of the Season" archives on the AAVSO website. There are also many relevant papers in the proceedings of the *Biggest, Baddest, Coolest Stars* workshop (Luttermoser *et al.* 2009).

2. Discovery and observation

Variable star observing was initially done visually. Variables with amplitudes of 2.5 are easy to detect and study visually, those with smaller amplitudes less so. Many bright red giants (and other stars) were initially suspected of variability—incorrectly.

Photographic monitoring programs, such as that at the Harvard College Observatory, led to the discovery and study of large numbers of Miras and semiregulars, leading to the determination of periods of hundreds and thousands of days. Many of these stars have been in the AAVSO visual observing program for a century. Only with such systematic, long-term monitoring is it possible to study the variability of these stars on all relevant time scales.

By 1930, photoelectric photometry of PRGs was well underway; Stebbins and Huffer (1930) published a photoelectric study of the variability of such stars, carried out at Washburn Observatory. During the 1970s, Olin Eggen (1977 and references therein) published several photoelectric studies of SAPRGs of various kinds, with a view to determining their kinematical, physical, and pulsational properties.

In the 1980s, long-term photoelectric photometry of SAPRGs was carried out both by the AAVSO PEP Program (Percy *et al.* 1996) and by robotic telescopes (for example, Percy *et al.* 2001). By the 1990s, massive CCD surveys of SAPRGs in galactic fields and in the Magellanic Clouds were being carried out; some of these are described in section 10. See Figure 1 for examples of PEP V light curves of a selection of SAPRGs.

3. Incidence

All M-type giants (and supergiants) are variable, as are mid- to late-K giants—but with very small amplitude. Pulsating red giants are the most numerous variables among the bright stars. Of the 9,096 stars in the *Bright Star Catalogue* (Hoffleit and Jaschek 1982), 545 are M type or equivalent, and all these are giants or supergiants. There are an additional 2,233 K stars, almost all giants or supergiants. About ten percent of the stars in the catalogue are K5-M9 giants, almost all of them SAPRGs, so they are the most numerous variables among the bright stars (followed closely by pulsating B/Be stars).

In the *General Catalogue of Variable Stars* (on-line version, Samus *et al.* 2012), there are 7,587 Mira or Mira: stars, 6,063 SR stars, and 3,746 Lb or Lc or L: stars.

4. Classification

Pulsating red giants, other than Mira (M) stars, are classified in the GCVS (Kholopov *et al.* 1985) as semiregular (SR) or irregular (L); SR are subdivided into SRa and SRb (giants), where SRb have less obvious periodicity than SRa, and SRc (supergiants). There are also SRs variables which are SR variables with "short" periods (generally 30 days or less); about 100 stars are placed in this (arbitrary) class. L are divided into Lb (cool giants) and Lc (cool supergiants).

These types are defined thus: SR: "...giants or supergiants of intermediate and late spectral types showing noticeable periodicity in their light changes, accompanied or sometimes interrupted by various irregularities...." L: "Slow irregular variables. The light variations of these stars show no evidence of periodicity, or any periodicity present is very poorly defined, and appears only occasionally...." Clearly these definitions are qualitative at best, but they were reasonable in the early days of variable star astronomy, especially if they were based on dense, long-term visual or photographic light curves.

Eggen (1977 and references therein) obtained extensive photoelectric photometry of pulsating red giants, and classified them as large-amplitude (LARV), medium-amplitude (MARV), small-amplitude (SARV), and σ Lib stars with very small amplitude. Again: there is actually a continuous spectrum of amplitudes from 2.5 mags to very small; the subclasses are arbitrary.

It is also useful to classify red giants according to their atmospheric composition: M (normal oxygen-rich), C (carbon rich), or S (intermediate).

An important classification is by pulsation mode. This can be done if the star is pulsating in two or more modes, or if its luminosity and temperature are both known, as described below.

5. Physical properties

SAPRGs are solar-type stars which, towards the ends of their lives, are exhausting the hydrogen fuel in their cores, and expanding and cooling to become red giants. They occupy the red giant branch in the Hertzsprung-Russell Diagram. Subsequently, they ignite helium fusion in their cores; as they exhaust the helium, they again expand and cool to become "asymptotic red giants" because they occupy the asymptotic giant branch in the HRD. In the sun, energy is transported by convection in a "convection zone" in the outer layers. In a red giant, the convection zone extends deep in the star. Convection is a poorly-understood process in astrophysics, so theoretical models of PRGs are uncertain.

One consequence of the convection is that, in some red giants, material which has been processed by nuclear reactions is transported to the surface, and the spectrum of the star shows strong lines of carbon. The star is a carbon star, as compared with normal red giants whose composition is similar to that of the sun. Indeed, the spectra of red giants can be very complex because, at their low temperatures, molecules such as TiO are very abundant in their atmospheres.

The best-understood SAPRGs are those near enough to have accurate *Hipparcos* parallaxes. They also have negligible reddening, especially at near-infrared wavelengths. The excellent study by Tabur *et al.* (2010) shows the power of studying nearby SAPRGs.

6. Pulsation properties

The stars that we are reviewing have periods between a few days and a few hundred days. For stars with known physical properties (especially distance), these periods can be shown to be low-order radial pulsation periods (Percy and Parkes 1998; Percy and Bakos 2003). This can also be shown by stars with two or more pulsation modes (Kiss *et al.* 1999: larger-amplitude SAPRGs, Percy *et al.* 2003: smaller-amplitude SAPRGs), since period ratios can be determined observationally, and compared with theoretical pulsation models of the stars. The radial pulsation can be confirmed by spectroscopic radial velocity measurements (Cummings 1999).

Massive surveys of stars in the Magellanic Clouds, or of nearby stars with known physical properties (discussed below) show that the stars obey sequences of period-luminosity relations, corresponding to different low-order radial modes.

The amplitudes of these stars range downward from 2.5 magnitudes (by definition) to the limits of detectability; the majority of red giants have pulsation amplitudes of only a few hundredths of a magnitude.

Kiss *et al.* (1999) have carried out a comprehensive time-series analysis of AAVSO visual observations of a large sample of SR variables; most have one period; some have two periods; and a few have three periods. Their sample included five L-type variables: AA Cas, DM Cep, TZ Cyg, V930 Cyg, and CT Del. They found a period of 367 days for DM Cep (possibly an artifact), 247 days for V930 Cyg, and 138 and 79 days for TZ Cyg, and apparently no periods for the other two stars. Some of the stars in this study showed significant changes in amplitude (Kiss *et al.* 2000). Percy *et al.* (2003) also found significant changes in amplitude in their multi-mode pulsators, on time scales of 2,000–3,500 days.

Percy and his students are currently analyzing several dozen SRa/SRb stars not analyzed by Kiss *et al.* (1999), using visual observations in the AAVSO

International Database (AID). These stars exhibit a very wide range of behavior, from highly periodic, to irregular, to non-variable.

As for the irregular (L-type) variables, Percy and Terziev (2011) analyzed visual observations of 125 such stars in the AID. They found 20 to be periodic, 18 to be possibly periodic, but with small amplitude, 55 to be truly irregular, some with amplitudes less than 0.1, and 32 to be probably non-variable.

7. Long secondary periods

Astronomers have known for decades that large numbers of PRGs have long secondary periods (LSPs), an order of magnitude longer than the primary pulsation periods (Payne-Gaposchkin 1954; Houk 1963). When period-luminosity relations can be formed, it is clear that the LSPs are correlated with the primary periods, or both are correlated with some property of the star such as its radius. The nature and cause of the LSPs is not known. Peter Wood and his collaborators have investigated a multitude of possible causes; most recently, Nicholls *et al.* (2009) have examined both physical and geometrical mechanisms for producing such periods, and conclude "We are unable to find a suitable model for the LSPs...."

8. Importance of SAPRGs

Mira variability plays an important role in mass loss and evolution of stars with masses of approximately 1 to 8 solar masses, and therefore in the general recycling of matter in galaxies. SAPRGs do not undergo significant mass loss. However, because of their shorter periods and smaller amplitudes, SAPRGs are easier to analyze in detail, and their physical properties are easier to determine—especially for nearby stars. It may therefore be possible to use them to refine evolution and pulsation models of these stars. Since they obey period-luminosity relations, it may also be possible to use them for distance determination.

9. Pulsating red supergiants

All red supergiants are pulsating variables; Antares, Betelgeuse, and μ Cephei are well-known examples. These are of special interest to the public because of their brightness and color, and their "imminent" demise as supernovae. They are also of astrophysical interest because of their crucial role in stellar evolution and mass loss, and therefore in galactic ecology. Also: because these stars are very luminous, there have been many studies of possible period-luminosity relations in these stars (Stothers 1969; Pierce *et al.* 2000).

The most comprehensive study of light variations in pulsating red supergiants was published by Kiss *et al.* (2006), who analyzed AAVSO data for forty-eight supergiants, collected over the last century. They were able to measure two significant and distinctly different periods for more than a third of the studied stars (Figure 2). Theoretical models imply low-order radial pulsations for the shorter periods, while periods greater than 1,000 days form a period-luminosity relation that is similar to that of the long secondary periods of the asymptotic giant branch stars. Despite the well-defined periodicities, red supergiant variability is far from being predictable: there is strong evidence that oscillations are constantly affected by stochastic processes, adding a certain level of irregularity that is very similar to the pulsation characteristics seen in the sun.

Systematic, sustained spectroscopic observations have also provided useful insight into both the regular and the chaotic motions in red supergiants such as Betelgeuse (Gray 2008).

10. Massive surveys of pulsating red giants in selected starfields

Time-domain surveys have become one of the hottest topics in observational astronomy with the advent of the largely autonomous or fully remote-controlled telescopes with digital detectors. The flagship surveys included the MACHO, OGLE, and EROS projects, each observing millions of stars towards the Magellanic Clouds and the Galactic Bulge, hunting for unpredictable brightenings and fadings of background stars caused by the gravitational microlensing effect of a massive object passing in front of the stars. Of these, the OGLE (Optical Gravitational Lensing Experiment) project, so far with three distinct phases of operations and the fourth in progress, has been the most successful in making a full census of pulsating red giants in the Magellanic Clouds. The importance of these objects lies in the fact that all stars are located at a known distance and the luminosities are thus well known. Recently, Soszyński *et al.* (2009) and Soszyński *et al.* (2011) presented the most extensive catalogues for the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC), with almost 92,000 long period variables in the LMC and 20,000 in the SMC, drawing an exquisite picture of red giant variability in whole galaxies. These samples are dominated by short-period (less than 100 days) and small-amplitude (less than 0.5 magnitude in the *I* band) semiregular variables, identified by Kiss and Bedding (2003) as stars still evolving on the first red giant branch, when their energy production is located in hydrogen-burning shells around the yet-to-be-ignited helium cores.

The most fruitful approach so far has been the study of period-luminosity (PL) relations in the Magellanic Clouds. The rich structure in the period-absolute magnitude plane has been studied by many authors, see Soszyński *et al.* (2007) and references therein. OGLE data analyzed by Soszyński *et al.* (2007) revealed fourteen different period-luminosity sequences, some of them consisting of three closely spaced ridges. The multitude of the PL relations comes partly from the presence of many different modes of pulsations, partly from the full sample being a mixture of red giants with different chemical composition and evolutionary state.

The latest and still ongoing survey producing M giant light curves never seen before is that of the Kepler space telescope, which has been observing several thousand red giants since mid-2009 in its fixed field of view in the constellations Cygnus and Lyra. The unprecedented light curves—in most cases well into the sub-millimagnitude range in precision—are becoming more and more useful for the semiregular variables as their time-span becomes longer by each day of operations. Kepler targets include such well-known bright variable stars as the semiregular variable AF Cyg and the symbiotic semiregular star CH Cyg, with promising results to come soon.

11. Surveys of nearby pulsating red giants with known physical properties

Tabur *et al.* (2010) presented the results of a unique five and a half-year photometric campaign that monitored 247 southern bright semiregular variables with useful Hipparcos parallaxes. Using the periods from the light curves and geometric distances, they constructed the period-luminosity sequences of the sample, revealing a negligible difference between the red giant PL-relations in the two Magellanic Clouds and in the Milky Way. A comparison of other pulsation properties, including period-amplitude and luminosity-amplitude relations, has shown that pulsation properties of stars on the first red giant branch are consistent and universal, indicating that their PL-sequences are suitable as high-precision distance indicators. Also, M-type giants with the shortest periods (less than 10 days) bridge the gap between G and K giant solar-like oscillations and M-giant pulsation, revealing a smooth continuity as we ascend the giant branch.

12. Current problems and directions in SAPRG research

- Studies of multiperiodicity, mode switching, amplitude and period variations in these stars. Can these be linked with evolution?
- What is the source of the semiregularity or irregularity?
- Specifically: what is the relative role of kappa-mechanism pulsation, and convection, and how does this vary with the physical properties of the star?
- What determines which mode(s) will be excited in a given star?
- What is the nature and cause of the long secondary periods?
- How can we use pulsating red giants as distance indicators and tracers of Galactic structure?

All the surveys mentioned above have nicely demonstrated that studying ensemble properties is a powerful new way of scientific research, one that has only become available in the recent years of enormous technical development. We can expect that answers to most of these questions will be found by further studies of large samples or extremely sophisticated analyses of individual stars.

13. The roles of amateur observations

The time-scale of M giant variability is so long that meaningful analyses require many years, often decades of observations. The longest, homogeneous surveys with modern instrumentation are barely longer than ten years in time-span. Consequently, the role the amateurs play will remain very important in the studies of long period variables. Even though the visual observations have very limited accuracy, their real strength comes from being homogeneous for many cycles of the pulsations. For example, for a semiregular star with a dominant pulsation period of 200 days (think of Z UMa and alikes), detecting the effects of convection on the oscillations requires several decades of data, something that is only possible with the coordinated work of amateur astronomers. On the other hand, an increasing number of amateurs are getting involved in photometric measurements, either with CCDs or DSLR cameras. These enable the observers to improve accuracy by one or two orders of magnitude compared to the visual data, hence detecting variability at much lower amplitudes (and usually with much shorter periods) than ever seemed to be possible for non-professionals.

In conclusion, pulsating red giants have always been prime targets for amateurs and they will remain so. While large surveys have been extremely successful in finding tens of thousands of (faint) pulsating red giants, the bright end is still problematic, with stars that saturate in almost every survey data. We think this field will keep being an important meeting point of amateurs and professionals, where the shared interest in these beautiful stars will bring us together in the forthcoming years.

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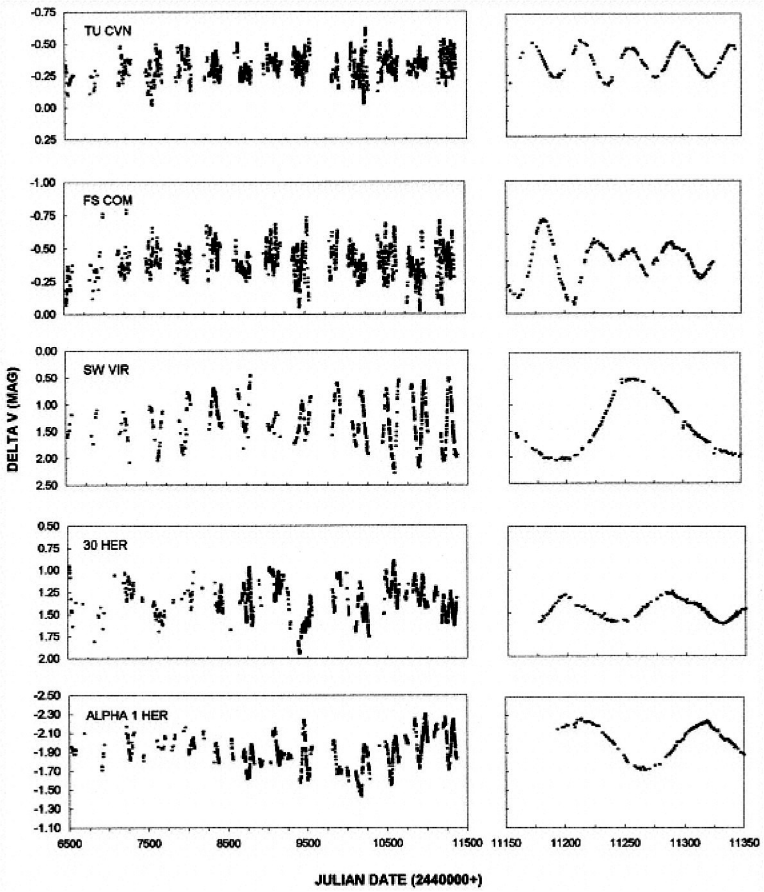

Figure 1. A selection of PEP V light curves of SAPRGs; left: 5,000 days, right: 200 days. TU CVn has a single short period; FS Com is multiperiodic; SW Vir has a longer period and larger amplitude; all of the stars show variability on both shorter and longer periods. From Percy *et al.* (2001).

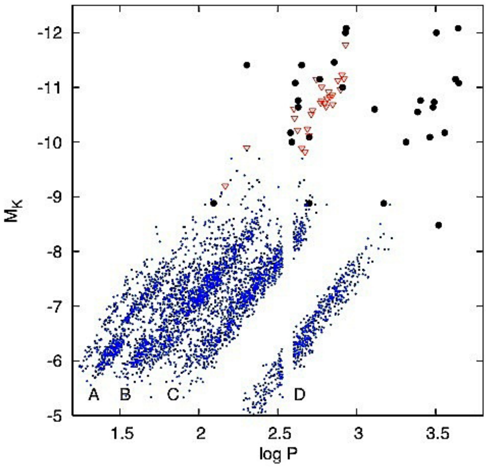

Figure 2. Period-luminosity (absolute K magnitude) relations for red supergiants in our galaxy (black circles) and the Large Magellanic Cloud (red triangles) and for red giants in the LMC (blue dots), the latter taken from the MACHO database. See Kiss *et al.* (2006) for further details. Note the separate PRG period-luminosity relations, corresponding to different pulsation modes; the supergiant sequences are extensions of these. Sequence D corresponds to long secondary periods.