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Red giant variables: OGLE–II and MACHO

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Abstract. We review the recent impact of microlensing projects on our understanding of pulsating red giant stars. Discussed are red giant stars' pulsation properties (period–luminosity relations, period changes, mode switchings), Red Giant Branch pulsations, metallicity effects and the use of red giant variables to explore galactic structure.

Key words. Stars: AGB and post-AGB – Stars: late-type – Stars: oscillations – Stars: variables

1. Introduction

The major problem with observational studies of Mira and semiregular stars has been the long time scale of variability. Since the typical pulsation periods range from tens to hundreds of days, very few long-term monitoring surveys existed in the pre-microlensing era. The lack of extensive data and the lack of luminosity information for galactic stars prevented real breakthroughs in understanding the general properties of red giant oscillations. The current paradigm was born with the seminal works of Wood et al. (1999) and Wood (2000), in which MACHO (Alcock et al. 2000) observations of red giant variables in the Large Magellanic Cloud (LMC) were analysed in the period-luminosity (P–L) plane. The main results were summarized in Wood (2000): *(i)* there are five distinct period-luminosity relations for red giant variables, of which four contain AGB stars; *(ii)* Miras and some low-amplitude semiregulars are fundamental mode pulsators (sequence C); *(iii)* other semiregular stars can pulsate in the second and third overtone modes (sequences A and B); *(iv)* there are (first) red giant branch eclipsing binaries with their own P–L relation (sequence E); *(v)* a large fraction of stars shows long-secondary periods, whose origin is still ambiguous (sequence D; for updates see Wood, these proceedings).

Another major step in the field followed the publication of the OGLE-II (Udalski et al. 1997) database of variable stars in the Magellanic Clouds (Zebrun et al. 2001). This new interest in pulsating red giant stars has led to significant progress in several areas:

- pulsation properties
- the presence of distinct evolutionary states
- possible metallicity effects
- red giant variables as probes of galactic structure

In the following sections we summarize how this progress has affected our current view of Mira and semiregular variables.

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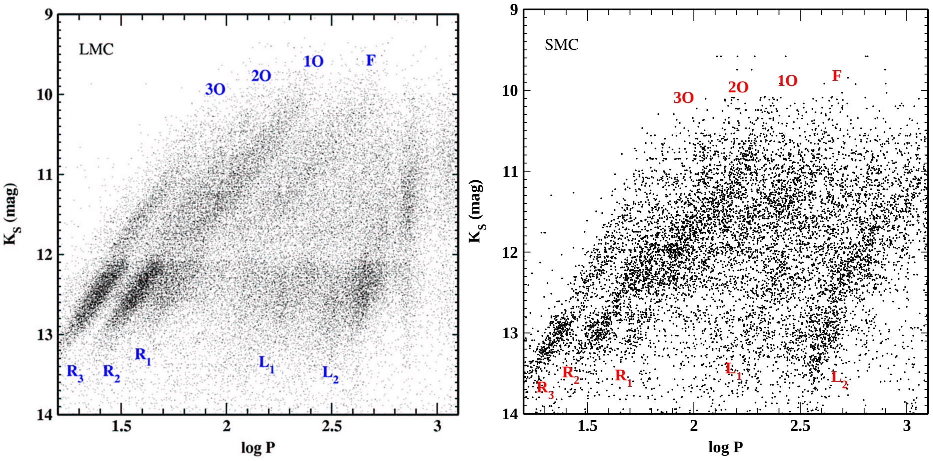

Fig. 1. Period-luminosity relations of variable red giants in the Magellanic Clouds, using the OGLE-II and 2MASS data (Kiss & Bedding 2003, 2004). Note the difference in the luminosity extents of ridges R_2 and R_3.

2. Pulsation properties

2.1. New features in the P–L plane

The new large samples of variable red giants have improved our understanding of their properties. Using OGLE data from both Magellanic Clouds, Kiss & Bedding (2003, 2004), Ita et al. (2004a&b) and Soszynski et al. (2004) revealed many new features in the period–luminosity plane. Groenewegen (2004) restricted his study to a sample of spectroscopically confirmed M-, S- and C- stars in the LMC and SMC OGLE data, while Fraser et al. (2005) analysed MACHO stars in the LMC only; SMC C-stars were studied by Raimondo et al. (2005). An extensive Bulge study was done by Wray et al. (2004). The number of stars studied ranged from about 1,000 (Raimondo et al. 2005) up to 20,000-24,000 (Kiss & Bedding 2003, Fraser et al. 2005). The original Wood (2000) half-square degree sample in the LMC contained only ~800 stars. The more than an order of magnitude increase in the number of variable red giants available for study has revealed new P–L sequences and sharp boundaries for the sequences. What originally seemed to be five sequences turned out to be an overlap of at least eight different P–L ridges, corresponding to both different modes of pulsations and distinct populations of stars.

Fig. 1 shows the P–L relations from multiperiodic light curve fits of variable red giants in the LMC and SMC (Kiss & Bedding 2003, 2004). The same parallel P–L sequences can be seen in both galaxies, which means that overall pulsation properties do not depend strongly on metallicity. The sharp discontinuity at $K_S \approx 12.05$ (LMC) and $K_S \approx 12.70$ (SMC) is exactly at the tip of the Red Giant Branch (TRGB). This suggests that low-amplitude and short-period stars below this edge belong to the shell hydrogen burning (first) Red Giant Branch. Further arguments for this interpretation are presented in the next Section. The classical view of Mira and semiregular stars have them located on the Asymptotic Giant Branch (AGB). These stars below the TBRG are a whole new family of previously unknown oscillating stars. They are short-period ($P < 50$ days) and low-amplitude ($A_I < 0.02$ mag) variables, which largely bridge the gap between the classical semiregular stars of early M spectral types and the very low-amplitude pulsating K-giants (Edmonds & Gilliland 1996). Variable stars of this new type have also been found in the Galactic Bulge (Wray et al. 2004). Their full potential for asteroseismology has yet to be

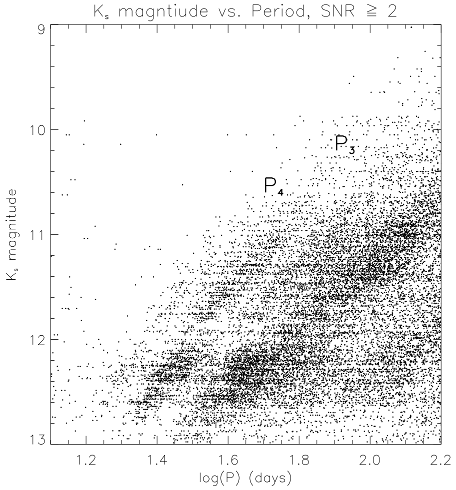

Fig. 2. The new shortest period P–L sequence of red giants in the LMC (marked P_4)

explored, including the identification of the excitation mechanisms in these stars ("Mira-like" vs. "solar-like" oscillations, Dziembowski et al. 2001).

The current sharpest view of the P–L sequences was presented by Ita et al. (2004a&b), who determined single periods for ~9,000 stars in the LMC and ~3,000 stars in the SMC. Apart from reducing the effects of spurious periods, they used SIRIUS *JHK* magnitudes that go much deeper than the 2MASS magnitudes. Multiperiodicity is a common feature of these variable stars and in most cases, secondary periods fall very close to the other P–L sequences. It is multimode pulsations that are largely responsible for the rich structure seen in Fig. 1.

Recently, Soszynski et al. (2004) combined OGLE-II data with OGLE-III observations to create a dataset that covers a time span comparable to the MACHO database. They found multiperiodicity for the vast majority of the 15,400 small amplitude variable red giants in the LMC (and 3,000 stars in the SMC) and also that about 30% of the sample exhibited two modes closely spaced in their power spectrum. This is likely to indicate non-radial oscillations that is otherwise hidden by the horizontal scatter of the P–L sequences. Soszynski et al. (2004) also noticed a previously overlooked high-order overtone sequence with periods of 8 to 50 days, sitting on the left-hand side of the ridges R_3 and 3O in Fig. 1 (A^+ and A^- in Ita et al. 2004a). This new sequence is also seen in the publicly available MACHO data (Fig. 2), if all frequencies with signal-to-noise ratios (SNR) greater than 2.0 are included in the successive prewhitening steps. This new P–L sequence pushes up the empirical limit for the acoustic cut-off frequency that traces the properties of the outermost atmospheric regions. This provides an important clue for the production of realistic stellar models.

2.2. Mode switching and period change

Mode switching in pulsating red giant stars was a rarely known phenomenon in the pre-microlensing era, because its detection requires very long observational records. Convincing evidence was found in a few cases from many decades of visual observations (e.g. Cadmus et al. 1991). These results suggested the complex dynamics of these oscillations but the low number of detected cases implies a low incidence rate of mode switching.

Groenewegen (2004) compiled a list of OGLE-II objects that were observed on photographic plates between 1977 and 1984 by various groups. With a total of 370 stars, he compared historic periods with the more recent OGLE-II values and found that about 10% of the sample exhibited more than 10% change in period over 17 years. In most cases, different periods clearly corresponded to different P–L relations (see fig. 8 in Groenewegen 2004). Furthermore, he also identified three stars that were classified oxygen-rich in the 1970's and carbon-rich in the 1990's, suggesting that they may have undergone a thermal pulse in the last 20 years and dredged-up enough carbon to switch spectral type.

Theoretically, helium-shell flashes that occur on the AGB can be detected in the form of very strong period changes in Mira variables (cf. Wood & Zarro 1981). The only problem is that Mira pulsations are intrinsically unstable in time and in many objects a 2–3% period jitter or quasi-regular period shifts is seen.

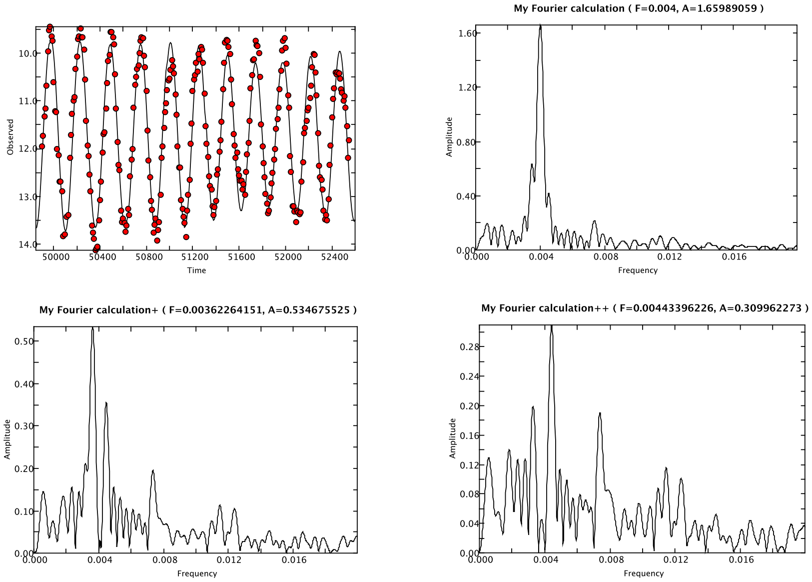

Fig. 3. Simulated T UMi-like light curve with the MACHO time span (*upper left panel*) and frequency spectra in three successive prewhitening steps (*upper right*: initial spectrum; *lower right*: residual spectrum after the first prewhitening; *lower left*: and after the second prewhitening)

Nevertheless, we know of a few galactic candidates for on-going thermal pulses. The best example is T Ursae Minoris (Templeton et al. 2005). We examined whether the microlensing data might be able to identify further candidates for thermal pulses. To do this we took two subsets of the visual light curve of T UMi, one with the OGLE-II time span and one with the MACHO time span. Both covered the strongest period change in that star (see more details on T UMi in Szatmáry et al. 2003). We then performed successive prewhitenings in the power spectrum and checked what frequencies resulted from this procedure.

The four years of OGLE-II would not have been enough to detect any measurable period change in a star like T UMi, because the period analysis resulted in only the mean period (250 days) and its harmonics. However, the eight years of the MACHO project would have allowed one to pick up the changing period of the star: the highest peaks after successive subtractions remained close to the initial one, being a good indicator of strong period change (see Fig. 3). We suggest that the existing MACHO data (or the combined OGLE-II+OGLE-III data) could be used for selecting candidates for on-going thermal pulses. Spectroscopic monitoring of these stars could help us better understand this intriguing phase of late stellar evolution.

3. RGB vs. AGB variables

The existence of pulsations at the tip of the first red giant branch was initially proposed by Ita et al. (2002). Kiss & Bedding (2003) and subsequently Ita et al. (2004a) suggested that short-period OGLE-II red giants below the TRGB are at least partly RGB stars. Besides the sharp edge in their luminosity function, they found a measurable period shift within the two most populated P–L sequences, which also occurred at the TRGB. This shift can be fully explained by the mean temperature difference of RGB and AGB stars at the same luminosity, which was the second argument for RGB pulsations. The third argument was presented by

Kiss & Bedding (2004), who compared multicolour luminosity functions of OGLE-II red giant variables in the LMC and SMC. The tip of the RGB, as determined from the *IJHK* luminosity functions, showed a colour and metallicity dependence that is in excellent agreement with the empirical results for globular clusters. Finally, Soszynski et al. (2004) have shown quantitatively that the short-period P–L sequences below the TRGB are in fact a mixture of RGB and AGB variables, except the newly identified sequence (cf. Fig. 2) that contains second ascent AGB red giants.

These low-amplitude pulsations in RGB stars have a number of interesting applications. They may explain the long-standing problem of "velocity jitter" in field and globular cluster red giants (Gunn & Griffin 1979, Carney et al. 2003). This phenomenon manifests as a higher than expected dispersion in radial velocity measurements, with the greatest velocity variations seen within 0.5 mag (in V) of the TRGB. Although Carney et al. (2003) argued against radial pulsations, we propose that these newly identified RGB oscillations, that have their largest photometric amplitudes around the TRGB, can cause this "velocity jitter". The multiperiodic nature of these pulsations coupled with seemingly irregular behaviour (mode switching, sudden amplitude changes) is the likely reason why existing radial velocity observations showed only a random scatter. The low-amplitude RGB pulsations may also be connected to the Ca II K emission line asymmetries seen in red giants (Smith & Shetrone 2004).

4. Metallicity effects

Using the large microlensing datasets it is possible to do a comparison of the Magellanic Clouds and the Galactic Bulge looking for metallicity effects on red giant pulsations and P–L relations. A zero-point differences of the order of 0.1 mag were found by Glass & Schultheis (2003) and Ita et al. (2004a), while slight changes in the slopes for each relation were also detected by Ita et al. (2004a) and Lah et al. (2005). Furthermore, Schultheis et al. (2004) made a comprehensive comparison of the Magellanic Clouds and the Bulge and found that the proportion of stars that vary decreases at lower metallicities and the minimum period associated with a given amplitude increases. At any given period, the most metal-rich stars in the Bulge have the highest photometric amplitude and the most metal-poor stars in the SMC have the lowest. This agrees with expectations as the optical amplitudes will in general be smaller at lower metallicity as they have weaker bands of highly sensitive molecules like TiO. This would favour small amplitude variability in metal-poor environments and explains the smaller fraction of large amplitude variables in the SMC compared to the LMC and the Galactic Bulge. Plotting over 60,000 periods and amplitudes for ~23,000 stars in the LMC and 10,000 period-amplitude pairs for ~3,200 stars in the SMC reveals this general trend (Fig. 4): at any given period, the maximum I-band amplitude of variation is roughly twice as large in the LMC as in the SMC.

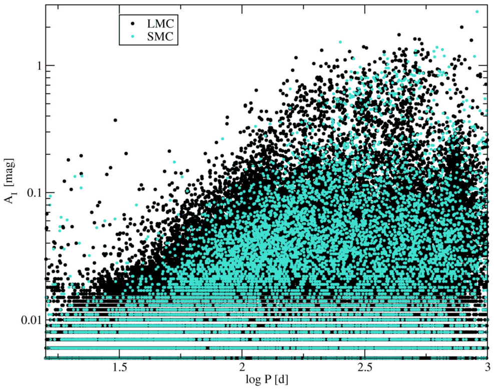

Fig. 4. OGLE-II I-band period–amplitude relations for the LMC (black dots) and the SMC (light gray dots).

Other differences between the red giant pulsations in the three galaxies include different luminosity ranges for each P–L sequences (Wray et al. 2004, Schultheis et al. 2004; also visible in Fig. 1) and the different fraction of multiperiodic stars with certain period ratios (Soszynski et al. 2004). The emerging view of metallicity effects is very complex which offers strong empirical constraints for theory.

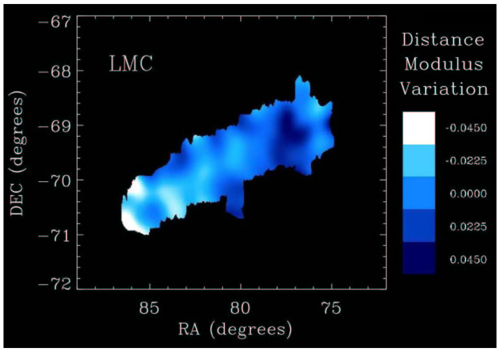

Fig. 5. A 3-D representation of the LMC. The lighter regions are closer to us and the darker regions are further away.

5. Galactic structure from pulsating red giants

The width of the P–L relations is affected by many different factors, one of which is the line-of-sight distance variations of the galaxy in question. Lah et al. (2005) presented the first attempt to use red giant P–L relations to constrain the three-dimensional structure of the Magellanic Clouds. For this work it is was assumed that for a star, at a given period, the vertical difference between its observed K magnitude and the mean linear P–L relation can be taken as the star's distance modulus relative to the average distance to the host galaxy. A distance modulus from one star will have great uncertainty, but from thousands of stars a clear trend produced by the inclination of the galactic disk can be seen. In Fig. 5 we show the structure traced by 4,276 RGB pulsators in the LMC bar, which is in excellent agreement with the view based on other distance indicators (Cepheids, red clump stars, etc.): the east side of the LMC is closer than the west, while the inclination angle of the LMC bar is ~30° and the distance variation across the face of the LMC is measured at ~2.4 kpc.

Recent Bulge studies include Wray et al. (2004) and Groenewegen & Blommaert (2005). Both papers discussed the geometry of the Galactic Bar from pulsating red giants, making use of the excellent statistical properties of the OGLE-II sample. Although red giant P–L relations are not as tight as that of the Cepheids, it is evident that the large number of Mira and semiregular stars makes them valuable distance indicators.

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