Why Galaxies Care About AGB Stars:
A Continuing Challenge through Cosmic Time
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Characterisation of long-period variables in the Magellanic Clouds

Michele Trabucchi[1], Peter R. Wood[2], Josefina Montalbán[1], Paola Marigo[1], Giada Pastorelli[1] and Léo Girardi[1,3]

[1]Dipartimento di Fisica e Astronomia Galileo Galilei, Universitá di Padova, Vicolo dell'Osservatorio 3, I-35122 Padova, Italy
email: michele.trabucchi@unipd.it

[2]Research School of Astronomy and Astrophysics, Australian National University, Canberra, ACT2611, Australia

[3]Astronomical Observatory of Padova–INAF, Vicolo dell'Osservatorio 3, I-35122 Padova, Italy

Abstract. Variability due to stellar pulsation on the Asymptotic Giant Branch (AGB) has a great potential for applications such as distance measurements, the study the evolution of stars and galaxies, and the estimate of global stellar parameters, as well as to constrain stellar evolutionary models. Given the importance of long-period variables (LPVs) in this sense, and given the lack of recent, updated sets of pulsation models, we computed an extended grid of pulsation models widely covering the space of AGB stellar parameters, including up-to-date opacities and accounting for the chemical evolution associated with third dredge-up events. We present the relevant properties of this grid and discuss the main results it allowed to obtain in terms of the interpretation of the observed properties of LPVs in the Large Magellanic Cloud (LMC).

Keywords. stars: AGB and post-AGB, stars: variables: other, Magellanic Clouds

1. Introduction

Long-Period Variables (LPVs) are evolved red giant stars exhibiting intrinsic variability due to stellar pulsations. They have periods of a few days to $\gtrsim 1000$ days and amplitudes from a milli-magnitude level to several magnitudes. They are often multi-periodic, although it is common practice to examine their properties in terms of a single pulsation mode, called "primary" period, *i.e.*, the one associated with the largest amplitude of variability in their light curve. It was first shown by Wood *et al.* (1999) using MACHO observations of the LMC (see also Wood (2000)) that LPVs follow several distinct period-luminosity (PL) relations, or "sequences", as displayed in the left panel of Fig. 1. LPVs are usually classified into the following three types, according to their variability properties: Miras (large-amplitude, fundamental mode pulsators with their primary periods on sequence C), semi-regular variables (SRVs, with lower amplitudes than Miras, and pulsating primarily in the first overtone (1O) and fundamental modes, with periods on sequences C′ and C, respectively), and OGLE Small Amplitude Red Giants (OSARGs, with several distinct radial and non radial modes and primary periods on sequences from A′ to C′). All of these sequences are the result of pulsation due to acoustic waves propagating in the stellar envelope. In addition to these modes, LPVs show another type of variability, the so-called long secondary periods (LSPs), the origin of which is still unknown. Despite of their name, they are often detected with amplitudes larger than regular modes, and thus classified as primary periods. This results in the formation of sequence D in the PL diagram.

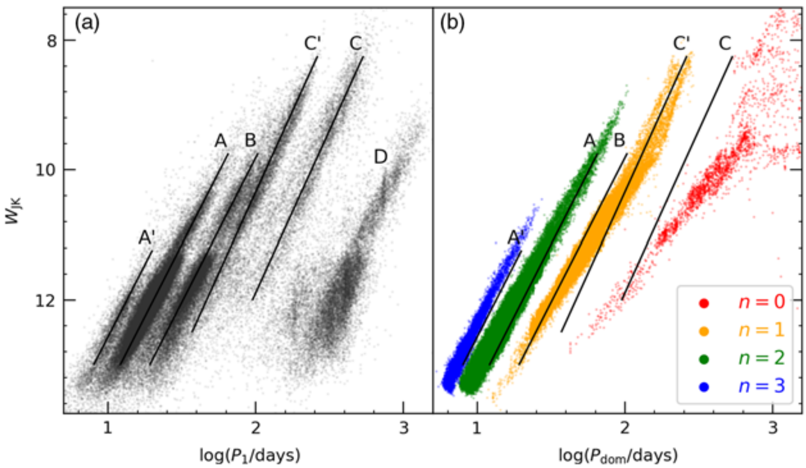

Figure 1. Left: primary periods of the LPVs in the LMC from OGLE-III data (Soszyński *et al.* (2009)). Right: periods of the dominant modes in a simulation of the population of LPVs in the LMC (Trabucchi *et al.* (2017)), labelled according to the radial order: $n = 0$ for the fundamental mode, and $n = 1, 2, 3$ for the first overtone (1O), second overtone (2O) and third overtone (3O) modes. The 4O mode is always stable in the models, and not required to reproduce observations. The Wesenheit index $W_{\rm JK} = K_{\rm s} - 0.686\,(J - K_{\rm s})$ is an approximately reddening-free measure of luminosity.

LPVs are experiencing a growing interest from the scientific community for several reasons, the primary one being their great potential as distance indicators. This is especially true for Miras (*e.g.*, Whitelock *et al.* (2013), Menzies *et al.* (2015), Huang *et al.* (2018), see also Whitelock, these proceedings), owing to their high luminosity and large-amplitude pulsations, that allow for their detection and identification even in relatively distant extra-galactic systems. The potential of SRVs and OSARGs as standard candles is also being probed (Rau *et al.* (2018)).

Additionally, LPVs are of significant importance to study the evolution of stars and galaxies. Pulsation in AGB stars plays a key role in their mass loss by creating the conditions for the condensation of dust grains, that are accelerated by radiation pressure, resulting in strong stellar winds that contribute substantially to pollute the interstellar medium (*e.g.*, Höfner & Olofsson (2018)). Therefore, understanding LPVs is crucial both to improve our knowledge of complex processes related to advanced stellar evolution and to study the chemical evolution of galaxies.

Finally, observed periods and amplitudes of LPVs depend upon global stellar parameters, allowing for mass and radius estimates, as well as the calibration of the temperature scale, and in general provide an effective mean to constrain stellar models.

Such applications require a robust theoretical background, able to account for the interpretation of observations and for a consistent identification of the modes responsible for the PL sequences.

2. Pulsation Models

Extended grids of pulsation models of luminous red giants have long been missing from the scientific literature, since the works of, *e.g.*, Fox & Wood (1982); Ostlie & Cox (1986); Wood (1990). Important advancements were recently achieved using 3D models (Freytag *et al.* (2017) and references therein) and improving the treatment of convection (Xiong *et al.* (2018), and references therein). The time-consuming nature of such models, however, makes them unsuitable for the calculation of large grids. The main shortcomings of existing sets of models are (1) their limited sampling of the space of stellar parameters, especially in terms of chemical composition, and (2) the use of opacity data for scaled-solar mixtures only, not appropriate for the chemistry of TP-AGB stars (often drastically altered by the third dredge-up), in particular for C-stars.

Aiming to fill this gap, we computed a new grid of pulsation models, soon to become public (Trabucchi et al., in prep.), widely covering the variety of stellar parameters experienced during the TP-AGB, in accordance with recent results based on the `COLIBRI` evolutionary code (Marigo *et al.* (2017)). The grid provides full coverage of the mass-luminosity range of AGB evolution, as well as multiple values of core mass (to describe both quiescent evolution and thermal pulses) and of effective temperature. It also spans several values of metallicity, hydrogen mass fraction, and C/O ratio. All models are computed with opacity data (from the Opacity Project [Seaton (2005)], and the `ÆSOPUS` code [Marigo & Aringer (2009)]) consistent with the specific metal mixture assumed for the stellar envelope. We computed pulsation models with a linear, non-adiabatic code (Wood & Olivier (2014), and references therein), and provide periods and growth rates for five radial modes (from the fundamental to the 4O mode) for each model.

3. Discussion

We combined the grid of pulsation models with results from the population synthesis code `TRILEGAL` (Girardi *et al.* (2005))) to simulate the population of LPVs in the LMC (Trabucchi *et al.* 2017). We found the models to reproduce reasonably well the observed period-luminosity diagram (Fig. 1, right panel), with sequences A′ and A corresponding to dominant pulsation in the 3O and 2O modes, respectively, and the 1O mode being responsible for both sequences B and C′. The latter result is explained by a selection effect: stars developing a primary period on sequence D often have another period in the region between sequences B and C′. Since only primary periods are usually displayed in PL diagrams, the inclusion of LSPs on sequence D in the observed sample causes the exclusion of 1O periods between sequences B and C′, resulting in the appearance of a gap between those sequences. Models cannot describe sequence D variability, thus a consistent comparison requires LSPs to be removed from the sample. When this is done, primary periods are found to form a continuous distribution in place of the two sequences B and C′. These findings allow to bring into alignment the two main interpretations, incompatible with each other, previously suggested for the observed PL sequences (see, e.g. Wood (2015)).

Models are currently unable to reproduce correctly the observed sequence C, due to fundamental mode pulsation and associated with Mira variables. This is not only due to fundamental mode periods being overestimated at large luminosities, but also to the fact that theoretical growth rates, used to predict the edges of the PL sequences, depend on the treatment of convection and of its coupling with pulsation, and are thus uncertain. Preliminary tests suggest that a better agreement with observations can be obtained by assuming the mixing length parameter to decrease as a function of luminosity in evolutionary tracks, which effect is that of increasing the effective temperature, and thus of shortening the period, in the high-luminosity range. This is, however, insufficient to account for the discrepancy between theory and observations. We compared our results with periods obtained from a number of analytic prescriptions present in the literature (Fox & Wood (1982); Ostlie & Cox (1986); Wood (1990); Xiong & Deng (2007)), applied to the same synthetic stellar population model. The comparison shows that in all cases the fundamental mode periods are overestimated to some extent, and the models are unable to simultaneously reproduce the 1O and fundamental mode periods, as observed in SRVs on sequences C′ and C. This calls for an improvement of the models used to describe fundamental mode pulsation, especially desired for the interpretation of the observations from upcoming multi-epoch large sky surveys, such as LSST.

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Discussion

Uttenthaler: In your 1.5 $M_\odot$ model, the fundamental mode only dominant for a relatively short time, during which the period is strongly changing. Do you think this is realistic? In that case most fundamental mode pulsators (Miras) should have strongly changing periods, while we know from observations that this is not the case.

Trabucchi: Current linear pulsation models tend to underpredict fundamental mode growth rates, resulting in a short duration of the phase in which the fundamental mode is dominant (the Mira phase). Fundamental mode periods are overestimated at large luminosities, likely causing the rather large changes in period during the last thermal pulses of the tracks. Non-linear models, more appropriate for large-amplitude pulsation, could help in this respect.