Stars and their variability observed from space
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MODELLING LONG-PERIOD VARIABLES IN THE GAIA ERA

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Abstract. Luminous red giant stars exhibit variability due to stellar pulsation, that is interconnected with uncertain processes (convection, mass loss and dust formation) and results in observable features that are strongly related to stellar properties. These so-called long-period variables (LPVs) provide us with a powerful tool to infer global stellar parameters and constrain the physics of late evolutionary phases in intermediate- and old-age stellar populations. Moreover, their period-luminosity relations represent a highly promising distance indicator. Large-scale optical microlensing surveys carried out during the last few decades made ideal laboratories out of the Magellanic Clouds to investigate the ensemble properties of LPVs with low impact from distance and interstellar extinction. Building on those results, the second data release (DR2) from the *Gaia* mission is providing new insight on these objects and novel methods to exploit them in the study of the evolution of stars and stellar populations. These results, together with related developments, are summarized here.

Keywords: Stars: AGB and post-AGB, Stars: oscillations, Galaxies: Magellanic Clouds

1 Introduction

After the pioneering discovery of the multiple period-luminosity (PL) relations of LPVs, achieved by Wood et al. (1999) with data from the MACHO survey, the most important observational source of information for the study of bright, pulsating red giants has been the still-operating Optical Gravitational Microlensing Experiment (OGLE). With about eight years of observations, the extensive catalogs of LPVs from the OGLE-III data releases (Soszyński et al. 2009, 2011) allows us to study these objects to an unprecedented level of detail, mainly focusing on the Magellanic Clouds to effectively remove biases related to distance and interstellar reddening. Among the most important outcomes it is worth mentioning the discoveries of an additional PL relation at short periods (sequence A$'$ in Fig. 1, according to the nomenclature used by Wood (2015)) and of the fine structure of PL sequences, as well as the identification of a potential new variability sub-type labelled OSARG (OGLE Small Amplitude Red Giants Wray et al. 2004).

Two relevant features that made such an important source of the OGLE-III data sets are the high photometric sensitivity (to identify LPVs with amplitudes as small as a few milli-mags) and the inclusion of multi-periodicity information. In comparison, the *Gaia* DR2 catalog of LPV candidates (Mowlavi et al. 2018) provides a single period per star, limited to amplitudes larger than 0.2 mag in the *Gaia* G band. While improvement with respect to these aspects is expected from the upcoming data releases, *Gaia* is already enabling new science in the context of LPVs. This is clearly due to its full-sky coverage (Fig. 1, right panel), as well as its providing access to the variability of optically bright asymptotic giant branch (AGB) and red supergiant (RSG) stars that suffer from saturation in OGLE.

2 The Gaia-2MASS diagram

Using *Gaia* DR2 data together with 2MASS near-infrared (NIR) photometry for stars in the Large Magellanic Cloud (LMC), Lebzelter et al. (2018) constructed a diagram in which LPVs occupy different regions according to their initial mass and surface chemistry. This "*Gaia*-2MASS diagram" shows the $K_{\rm s}$ magnitude versus

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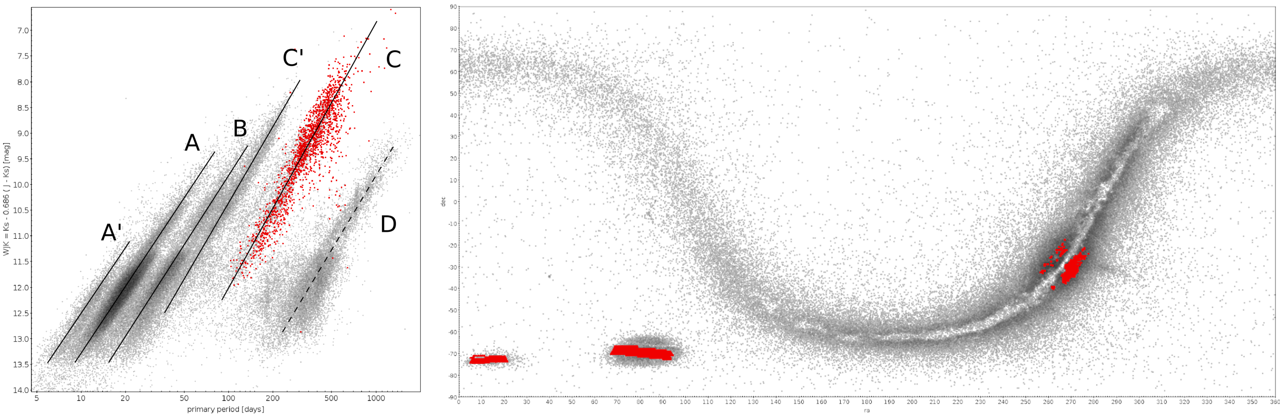

Fig. 1. Left: period-luminosity diagram of LPVs in the LMC as a function of the 2MASS K_s band. Red symbols are Mira variables identified by their variability amplitude larger than 0.8 mag in the I band. **Right:** sky coverage comparison between the OGLE-III catalogues of LPVs and the *Gaia* DR2 catalog of LPV candidates.

the difference between the Wesenheit indices obtained from 2MASS [$W_{\mathrm{J,K_s}} = K_\mathrm{s} - 0.686(J - K_\mathrm{s})$] and *Gaia* [$W_{\mathrm{BP,RP}} = G_{\mathrm{RP}} - 1.3(G_{\mathrm{BP}} - G_{\mathrm{RP}})$] photometry (Fig. 2, left panel).

Carbon-rich stars lie in the right side of the diagram, while the left side is populated by O-rich LPVs, a result confirmed by a classification based on low-resolution *Gaia* spectra*, as well as with the guide of state-of-the art stellar evolution models (Marigo et al. 2017). This dichotomy is due to the increased molecular abundance (and associated absorption) with decreasing surface temperature, combined with the different spectral ranges affected by oxygen-bearing molecules with respect to carbon-based ones. In contrast with ordinary colour-magnitude diagrams (CMDs), in which cool stars reside in the right (red) side of the diagram, LPVs move towards either side of the *Gaia*-2MASS diagram as they cool down, depending on their surface chemistry.

A convenient side effect of this splitting is the formation of a "gap" in the O-rich star distribution at $K_\mathrm{s} \sim 10$ mag, the brightness level corresponding to the initial mass range associated with the formation of C-stars (roughly 1.5 to 3.0 $\mathrm{M}_\odot$). In combination with the fact that the brightest, most massive O-rich stars are also relatively warm and unaffected by molecular formation, thus remaining in the central part of the diagram, this effect results in a splitting of O-rich stars into three branches, according their initial mass.

3 Application to the period-luminosity diagram

Building on the potential of the *Gaia*-2MASS diagram, Lebzelter et al. (2019) investigated the location of these different groups of LPVs in the PL diagrams (PLDs) obtained with different luminosity indicators, namely the K_s magnitude and the two Wesenheit indices $W_{\mathrm{J,K_s}}$ and $W_{\mathrm{BP,RP}}$ (Fig. 2, right panel), and extended the analysis to the Small Magellanic Cloud (SMC), finding consistent results. Thanks to the inclusion of a larger sample of bright O-rich LPVs with respect to the OGLE-III catalog, they were able to identify a systematic shift of these massive objects towards the left side of the corresponding K_s-log(P) PL relation, confirming the theoretical predictions of Wood (2015).

The same effect is found using $W_{\mathrm{J,K_s}}$, but no such displacement is observed with $W_{\mathrm{BP,RP}}$. This difference is due to the fact that the more massive stars are also warmer, and less affected by molecular absorption. As far as O-rich stars are concerned, the colour term involved in the $W_{\mathrm{J,K_s}}$ index is effectively insensitive to temperature. Hence the similarity between the K_s-log(P) and $W_{\mathrm{J,K_s}}$-log(P) diagrams. In contrast, both the magnitude and colour used in $W_{\mathrm{BP,RP}}$ are temperature-dependent, but the colour term is slightly more sensitive: at fixed mass, a cooler star is actually brighter in $W_{\mathrm{BP,RP}}$ than a hotter one.

Incidentally, this trend compensates almost exactly for the mass-related shift seen using NIR photometry. As a result, the $W_{\mathrm{BP,RP}}$-log(P) PL relation of LPVs, including the brightest objects up to $M_{K_\mathrm{s}} \sim -11.5$ mag, is considerably narrow and better defined than with IR photometry. These features represent a likely advantage in the promising application as distance indicator. However, due to this "compensation", the most massive LPVs (including RSGs), that lie on sequence C′ in the NIR PLDs, are actually found on sequence C in the $W_{\mathrm{BP,RP}}$-

* *Gaia* Image of the Week, 15/11/2018 (cosmos.esa.int/web/gaia/iow_20181115).

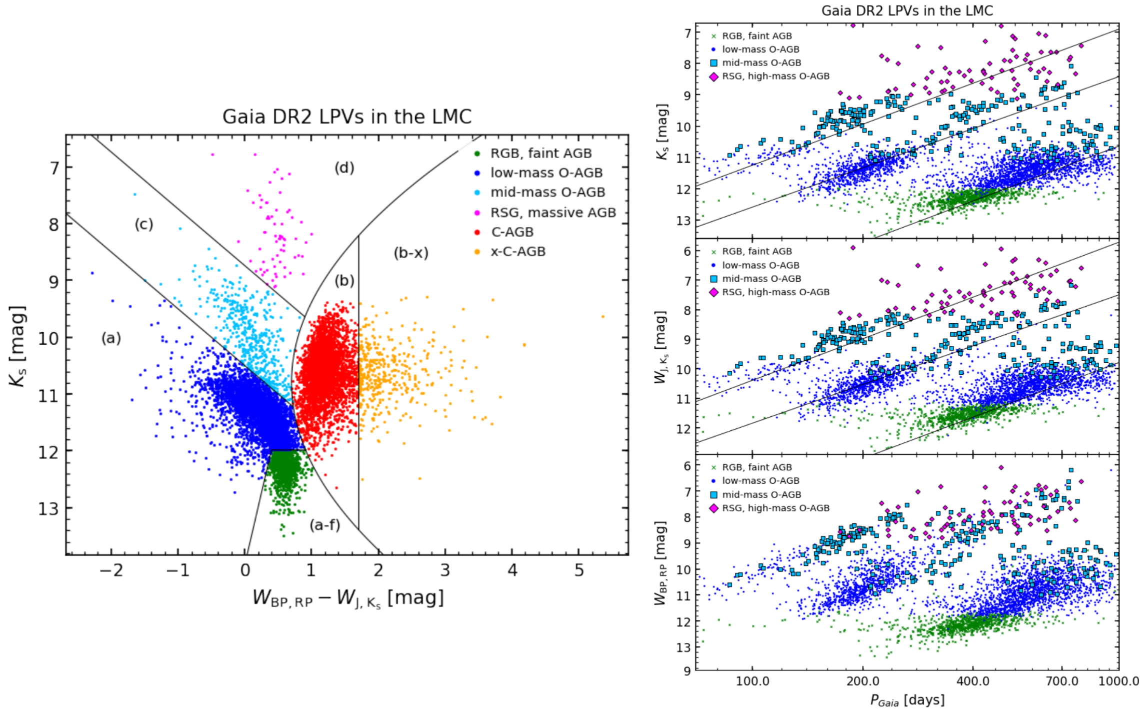

Fig. 2. Left: LMC stars from the *Gaia* DR2 catalog of LPV candidates in the *Gaia*-2MASS diagram, with the corresponding photometric classification of stars with different surface chemistry and initial mass range. **Right:** the same sample, limited to stars classified as O-rich, in the $K_{\rm s}$, $W_{\rm J,K_s}$, and $W_{\rm BP,RP}$ PLDs. (Adapted from Lebzelter et al. (2019).)

log(P) PLD. This clearly complicates the use of the PL relations to identify the pulsation modes responsible for the observed periods.

4 The role of pulsation

Given the important role played by pulsation in the mass-loss and dust-formation processes that terminate the AGB evolution, contributing significantly to the chemical enrichment of the interstellar medium, a better understanding of LPVs is definitely crucial. This is true not only for individual stars, but also for their collective properties. Recently, McDonald & Trabucchi (2019) have pointed out the connection between an increased mass-loss rate and the transition of a star between sequences B and C′ in the PLD, which Trabucchi et al. (2017) had previously linked with the unexplained long-secondary periods (LSPs) on sequence D (see Fig. 1).

The detailed analysis made possible by the *Gaia* DR2 suggests that future data releases, as well as planned ground- and space-based surveys (such as the Large Synoptic Survey Telescope and the James Webb Space Telescope) will revolutionize the way we investigate LPVs and their PL relations. A proper modelling framework will be necessary to exploit the full potential of such an upcoming wealth of data. Recently, Trabucchi et al. (2017) (see also Trabucchi et al. (2019)) have shown how the combination of pulsation models with stellar population synthesis tools is able to take up this challenge, but also pointed out some of the main shortcomings of current pulsation models of LPVs, that systematically overestimate the fundamental mode period of the brightest stars. This is exemplified in Fig. 3, showing an attempt to reproduce the PL relations of LPVs using theoretical period-mass-radius relations from several authors.

To address such issues is highly desirable in order for theory to keep up with observation, and a great opportunity to achieve a better understanding of stellar interiors.

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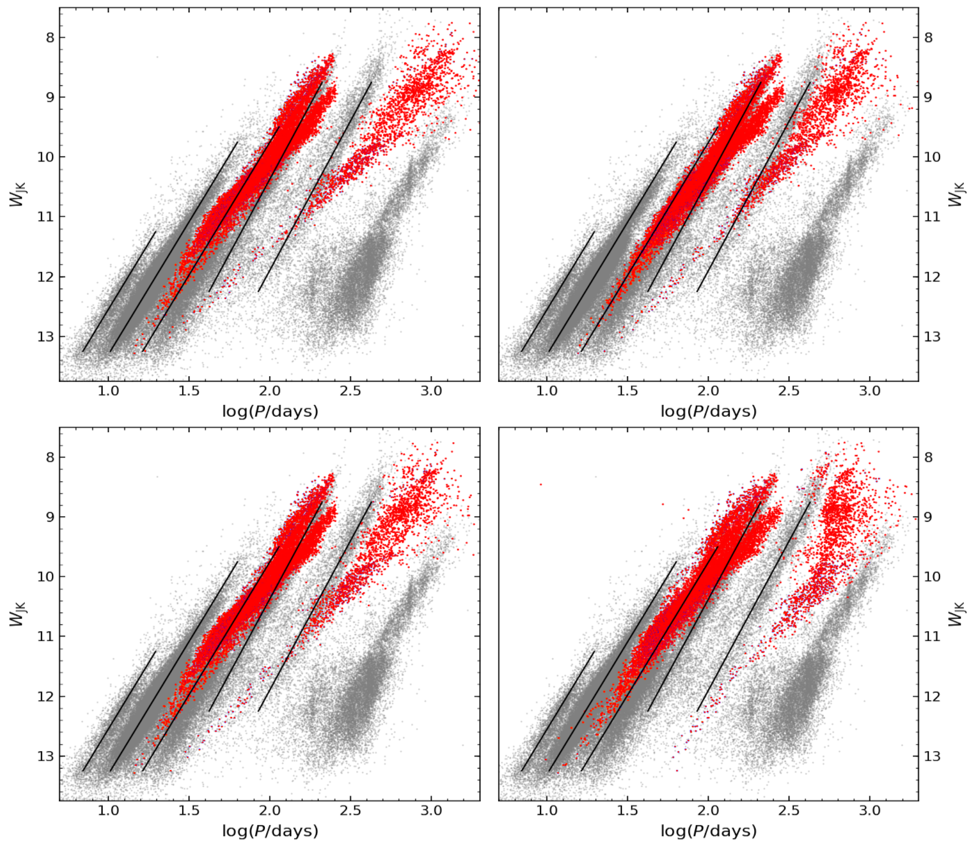

Fig. 3. Synthetic PLDs obtained by combining a LMC population model with prescriptions from the pulsation models by (clockwise from the upper left panel) Fox & Wood (1982), Ostlie & Cox (1986), Xiong & Deng (2007), and Wood (1990). Theoretical fundamental periods (right sequence of red points in each panel) are systematically longer than observed ones (grey points, from OGLE-III).

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