The Magellanic System: Stars, Gas, and Galaxies
Proceedings IAU Symposium No. 256, 2008
Jacco Th. van Loon & Joana M. Oliveira, eds.

doi:10.1017/S1743921308028743

Thermally-pulsing asymptotic giant branch stars in the Magellanic Clouds

Paola Marigo[1], Léo Girardi[2], Alessandro Bressan[1], Martin A. T. Groenewegen[3], Bernhard Aringer[4], Laura Silva[5] and Gian Luigi Granato[5]

[1]Dipartimento di Astronomia, Università di Padova, Vicolo dell'Osservatorio 2, I-35122 Padova, Italy — email: `paola.marigo@unipd.it`

[2]Osservatorio Astronomico di Padova – INAF, Vicolo dell'Osservatorio 5, I-35122 Padova, Italy

[3]Royal Observatory of Belgium, Ringlaan 3, B-1180 Brussels, Belgium

[4]Department of Astronomy, University of Vienna, Tuerkenschanzstr. 17, A1180 Wien, Austria

[5]Osservatorio Astronomico di Trieste – INAF, Via Tiepolo 11, I-34131 Trieste, Italy

Abstract. We present the latest results of a theoretical project aimed at investigating the properties of thermally-pulsing asymptotic giant branch (TP-AGB) stars in different host systems. For this purpose, we have recently calculated calibrated synthetic TP-AGB tracks — covering a wide range of metallicities ($0.0001 \leqslant Z \leqslant 0.03$) up to the complete ejection of the envelope by stellar winds (Marigo & Girardi 2007) — and used them to generate new sets of stellar isochrones (Marigo *et al.* 2008). The latter are converted to about 25 different photometric systems, including the mid-infrared filters of *Spitzer* and *AKARI* as the effect of circumstellar dust from AGB stars is taken into account. First comparisons with AGB data in the MC field and stellar clusters are discussed.

Keywords. stars: AGB and post-AGB, stars: carbon, stars: evolution, globular clusters: individual (47 Tuc), Magellanic Clouds, infrared: stars

1. Introduction

Owing to their intrinsic brightness and distinctive spectral features, TP-AGB stars play an important role in many properties of their host systems. For instance, the TP-AGB contribution to the total luminosity of single-burst stellar populations reaches a maximum of about 40% at ages from 1 to 3 Gyr (Frogel *et al.* 1990), and account for most of the bright-infrared objects in resolved galaxies, as clearly demonstrated by DENIS, 2MASS, SAGE, S^{3}MC, and *AKARI* IRC data (Cioni *et al.* 1999; Nikolaev & Weinberg 2000; Blum *et al.* 2006; Bolatto *et al.* 2007; Ita *et al.* 2008) for the Magellanic Clouds (MC). Despite its large relevance, the description of the TP-AGB phase in evolutionary models of galaxies has always been far from detailed and physically accurate.

Our goal is to provide complete sets of TP-AGB models useful for the evolutionary population synthesis of galaxies — both resolved and unresolved into stars — taking into consideration all the processes and physical inputs which are known to be critical in determining the evolution along this phase, and reproducing its basic observables. The Magellanic Clouds play a key role in our project, as we can rely on rich and complete samples of well-observed TP-AGB stars, to be used in the calibration of the basic model parameters.

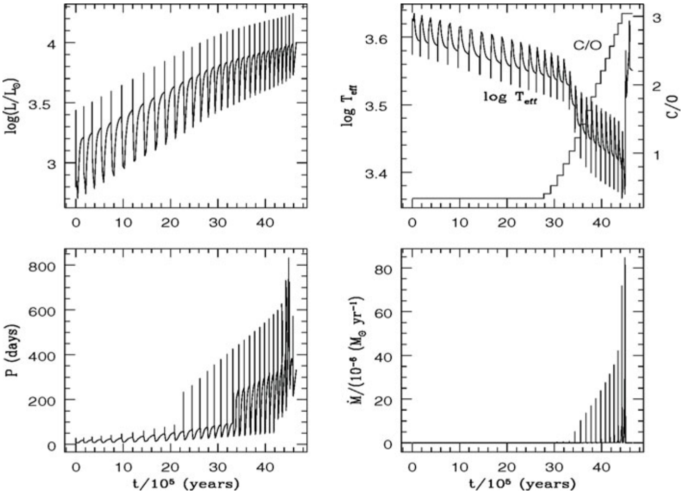

Figure 1. Predicted evolution of luminosity, effective temperature, surface C/O ratio, pulsation period, and mass-loss rate during the TP-AGB evolution of a 1.8 M$_\odot$, $Z = 0.008$ star from Marigo & Girardi (2007). Notice the sudden cooling of the track as the star becomes of C-type (C/O > 1), which is due to the abrupt change in the main sources of molecular opacity.

2. Synthetic TP-AGB tracks and their calibration

The TP-AGB evolutionary tracks used here have been described in Marigo & Girardi (2007) and Marigo *et al.* (2008). They include a series of crucial aspects such as: the complex luminosity evolution over the pulse-cycle, the third-dredge-up efficiency as a function of stellar mass and metallicity, the derivation of the effective temperatures from the integration of stellar envelope models, hot-bottom burning at the base of convective envelopes, the dramatic changes in low-temperature opacities when the stellar envelopes become C-rich (Marigo 2002), different mass loss descriptions for M- and C-type stars, the dependence of mass loss on pulsation period, the transition from the first overtone pulsation mode to the fundamental one, etc.

The evolutionary tracks contain a few free parameters (mainly related to the third dredge-up) which were calibrated so as to reproduce two basic observables of the LMC and SMC: the carbon star luminosity functions (Groenewegen 2002), and the C- and M-type lifetimes as a function of turn-off mass as derived from MC star clusters (Girardi & Marigo 2007a). One example of our TP-AGB evolutionary tracks is presented in Fig. 1.

3. From stellar tracks to synthetic samples of AGB stars

The TP-AGB evolutionary tracks were attached to the Girardi et al. (2000) tracks for the previous evolutionary phases, and used to build the Marigo *et al.* (2008) isochrones. They consider the reprocessing of radiation by dust in the circumstellar envelopes of mass-losing stars. The web interface in http://stev.oapd.inaf.it/cmd provides these isochrones — and their derivatives, such as luminosity functions and integrated magnitudes — for more than 25 optical-to-far-infrared photometric systems, including those more useful to the study of MC AGB stars (e.g., OGLE, DENIS, 2MASS, *Spitzer* IRAC+MIPS, and *AKARI*).

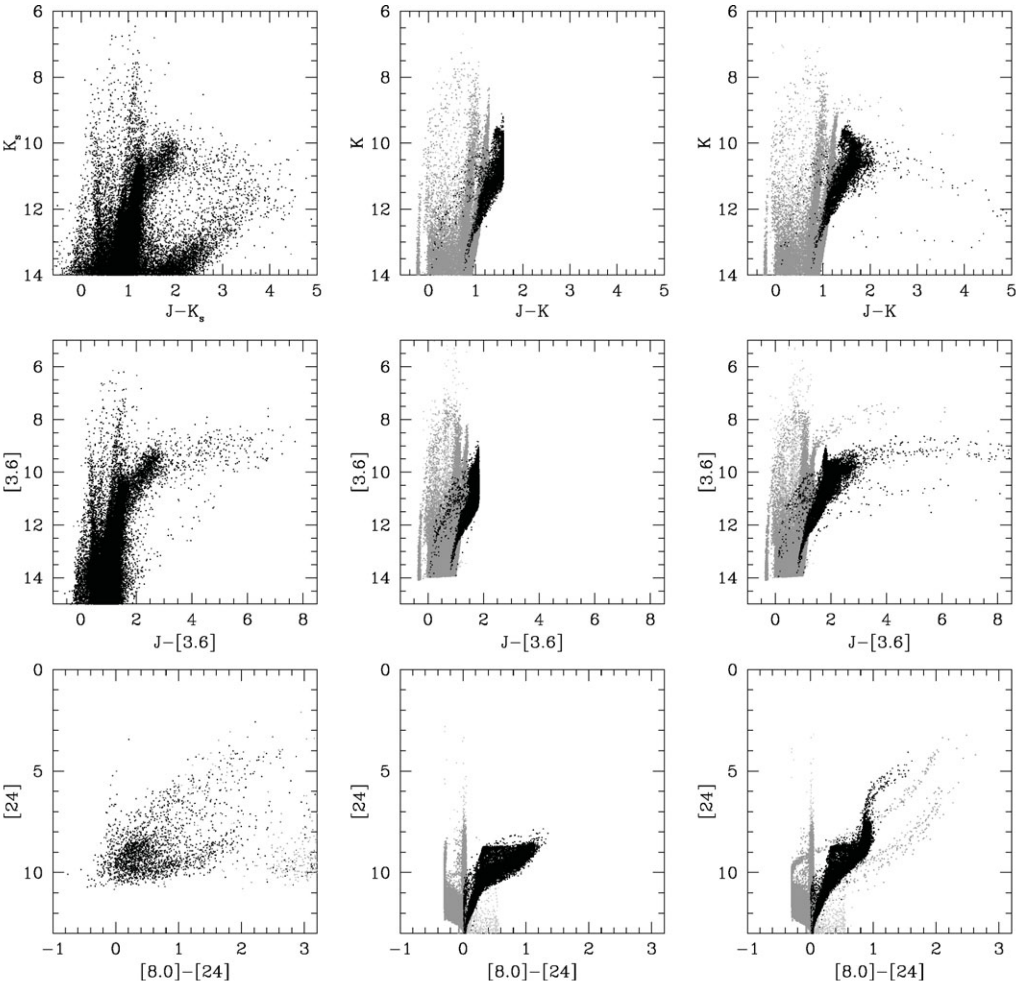

Figure 2. Comparison between 2MASS and *Spitzer* near- and mid-infrared data for the LMC (left panels), and the simulated photometry without (middle panels) and with (right panels) the effect of AGB circumstellar dust. Predicted carbon stars are marked with black points.

In the process of building the isochrones, we have used the sequences of synthetic C star spectra from Loidl *et al.* (2001). These cover well the $T_{\rm eff}$ range of C stars in the Magellanic Clouds and in the Milky Way galaxy, but not the wide intervals of surface gravities and C/O ratios expected for such stars. Moreover, they have been computed for C stars of initial solar metallicity. We are now extending the database of C star spectra, using the COMARCS code (Lebzelter *et al.* 2008), so as to cover the complete parameter space expected from the evolutionary tracks (Aringer *et al.*, in preparation).

This set of theoretical models have been included in the TRILEGAL code (Girardi *et al.* 2005) for simulating the photometry of resolved stellar populations. The code has been adapted (Girardi & Marigo 2007b) so as to deal with the luminosity and temperature variations driven by thermal pulse cycles, and to consider additional variables such as the pulsation period of LPVs, the mass loss rate, the optical depth of circumstellar dust, etc. This allows us to simulate complete samples of AGB stars together with their main optical-to-infrared properties, for any history of star formation and chemical enrichment.

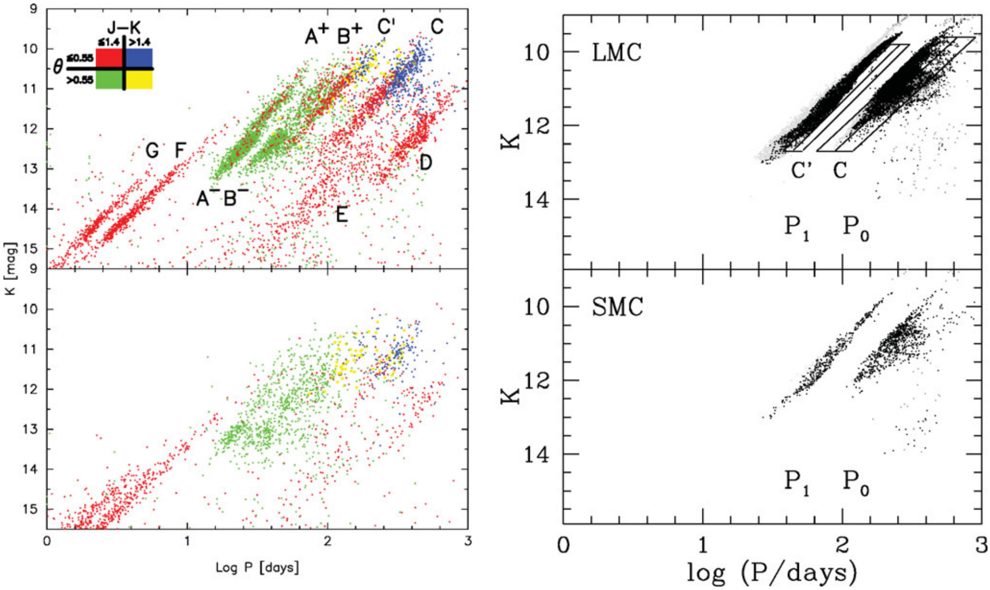

Figure 3. Comparison between predicted period-luminosity relations (in the K-band) for LPVs in the MCs (right panels) and the observed data (left panels; Ita *et al.* 2004). The models contain the fundamental and first overtone modes only. The faint plume at longer periods leaking from the P_0 sequence consists of models with $\dot{M} > 10^{-6}$ $M_\odot$ yr^{-1}, i.e. corresponding to dust-enshrouded stars.

4. Comparison with basic observables in Magellanic Cloud fields

We are presently dealing with simulations of the fields in the LMC and SMC, using published SFHs and age–metallicity relations (e.g., Harris & Zaritsky 2004; Javiel *et al.* 2005; Pagel & Tautvaišienė 1998). Figs. 2 and 3 presents the typical results regarding the photometry and LPV periods of the sample. The models do a reasonable job in reproducing the number counts, magnitudes and colors of AGB stars in the Magellanic Clouds, which is no surprise since the evolutionary models have been originally calibrated using MC data. Looking at the quantitative details, however, we are accumulating several hints on the aspects of the models which *need* to be improved. One of the most obvious deficiencies is in the description of the pulsation periods for C stars (Fig. 3), which requires more reliable pulsation models (e.g., computed with the right molecular opacities, as in Lebzelter & Wood 2007) than we have used so far. Moreover, although our models describe well the sequences of mass-losing stars in mid-infrared CMDs (Fig. 2), they fail to describe the detailed color distributions. This likely means that we have to adjust the mass loss prescriptions, which, in turn, would imply the recalculation and recalibration of the TP-AGB tracks. We are implementing such iterative process, which is however not simple and quite demanding in terms of CPU time. No doubt the final target is well worth of the effort.

5. Comparison with basic observables in 47 Tuc

The old globular cluster 47 Tuc is of particular interest to us, thanks to the detailed information available for its AGB stars, and to its metallicity which is comparable to those found in young and intermediate-age populations of the MCs. Figure 4 presents the period-luminosity diagram of 47 Tuc LPVs (Lebzelter & Wood 2005). They

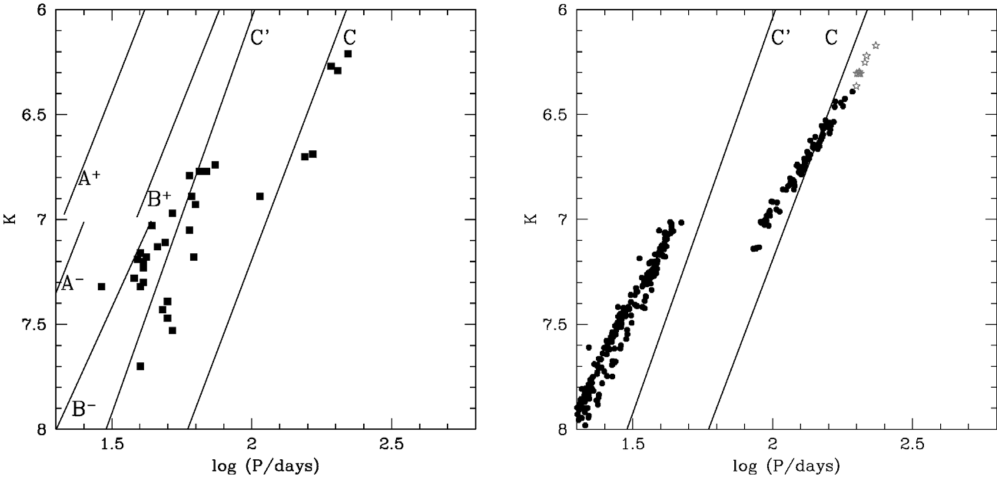

Figure 4. Comparison between predicted period–luminosity relations (right panel) for LPVs in 47 Tuc (actually simulated for a much more massive cluster), and the Lebzelter & Wood (2005) data (left panel). Starred symbols correspond to TP-AGB models with $\dot{M} > 10^{-7}$ M$_\odot$ yr^{-1}.

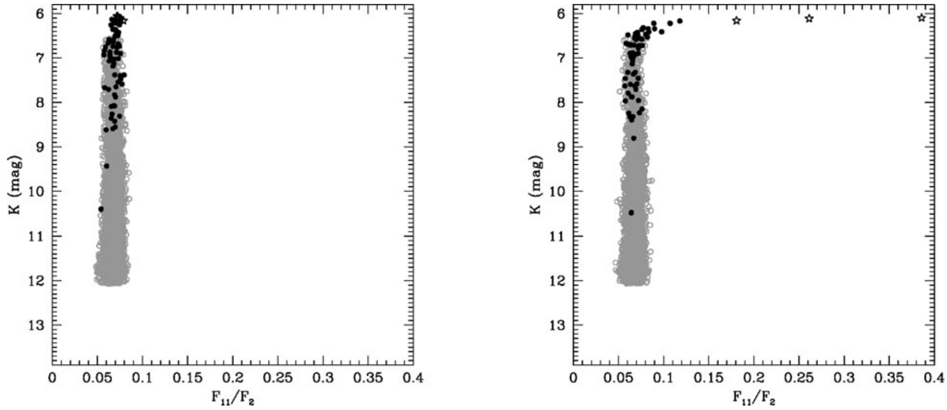

Figure 5. Theoretical CMDs for 47 Tuc simulated in the *AKARI* filters, without (left panel) and with (right panel) the effect of AGB circumstellar dust. TP-AGB stars are plotted with black dots, and those with $\dot{M} > 5\ 10^{-7}$ M$_\odot$ yr^{-1} are marked with starred symbols.

clearly distribute on two sequences, with the switch from the first overtone to the fundamental mode occurring at $K \sim 6.7$ mag. Our models show the same transition, but at $K \sim 7$ mag.

Moreover, our simulations (Fig. 5) reproduce the behavior of the mid-IR colors that has been recently measured by *AKARI* (Ita *et al.* 2007): the only stars that present a prominent mid-IR excess are those at the very tip of the AGB (see also van Loon *et al.* 2006; Lebzelter *et al.* 2006). This reinforces the idea that the bulk of dust formation occurs at the end of the AGB, with the role of RGB stars being quite marginal, if not negligible (see also Boyer *et al.* 2008, for ω Cen).

6. Other perspectives

In addition to the detailed work allowed by the MCs and by 47 Tuc, we are involved in different projects aiming at the calibration of the TP-AGB tracks at lower and higher metallicities. In particular, it has become clear that dwarf galaxies provide a useful testbed for the models at small metallicities, using either near-infrared observations of nearby dwarfs (such as Leo II and Leo I; Gullieuszik *et al.* 2008, and work in preparation) or *HST* photometry of more distant dwarfs (Dalcanton *et al.* 2008, and work in preparation). Moreover, the Spitzer mid-infrared spectrum of Virgo ellipticals clearly shows the signatures of mass-losing AGB stars (Bressan *et al.* 2006; Clemens *et al.* 2009). The detailed modelling of all these galaxies will eventually help us to constrain the AGB evolution over a wide range of metallicities.

Acknowledgements

This study was partially supported by the University of Padova (CPDA052212) and by INAF/PRIN07 (CRA 1.06.10.03). B.A. acknowledges funding by Austrian FWF project P19503.

References

Blum, R. D., Mould, J. R., Olsen, K. A., *et al.* 2006, *AJ*, 132, 2034
Bolatto, A. D., Simon, J. D., Stanimirović, S., *et al.* 2007, *ApJ*, 655, 212
Boyer, M. L., McDonald, I., van Loon, J. Th., *et al.* 2008, *AJ*, 135, 1395
Bressan, A., Panuzzo, P., Buson, L., *et al.* 2006, *ApJ*, 639, L55
Cioni, M. R., Habing, H. J., Loup, C., *et al.* 1999, in P. Whitelock, & R. Cannon (eds.), *The Stellar Content of Local Group Galaxies*, IAUS 192 (San Francisco: ASP), p. 65
Clemens, M. S., Bressan, A., Panuzzo, P., Rampazzo, R., Silva, L., Buson, L., & Granato, G. L. 2009, *MNRAS*, 392, 982
Dalcanton, J. J., *et al.* 2008, *ApJS*, submitted
Frogel, J. A., Mould, J., & Blanco, V. M. 1990, *ApJ*, 352, 96
Girardi, L., Bressan, A., Bertelli, G., *et al.* 2000, *A&AS*, 141, 371
Girardi, L., Groenewegen, M. A. T., Hatziminaoglou, E., & da Costa L. 2005, *A&A*, 436, 895
Girardi, L. & Marigo, P. 2007a, *A&A*, 462, 237
Girardi, L. & Marigo, P. 2007b, in F. Kerschbaum, C. Charbonnel, & R. F. Wing (eds.), *Why Galaxies Care About AGB Stars: Their Importance as Actors and Probes*, ASP Conference Series 378 (San Francisco: ASP), p. 20
Groenewegen, M. A. T. 2002, arXiv:astro-ph/0208449
Gullieuszik, M., Held, E. V., Rizzi, L., *et al.* 2008, *MNRAS*, 388, 1185
Harris, J. & Zaritsky, D. 2004, *AJ*, 127, 1531
Ita, Y., Tanabé, T., Matsunaga, N., *et al.* 2004, *MNRAS*, 347, 720
Ita, Y., Tanabé, T., Matsunaga, N., *et al.* 2007, *PASJ*, 59, 437
Ita, Y., Onaka, T., Kato, D., *et al.* 2008, *PASJ*, 60, S435
Javiel, S. C., Santiago, B. X., & Kerber, L. O. 2005, *A&A*, 431, 73
Lebzelter, T. & Wood, P. R. 2005, *A&A*, 441, 1117
Lebzelter, T., Posch, T., Hinkle, K., *et al.* 2006, *ApJ*, 653, L145
Lebzelter, T. & Wood, P. R. 2007, *A&A*, 474, 643
Lebzelter, T., Lederer, M. T. , Cristallo, S. *et al.* 2008, *A&A*, 486, 511
Loidl, R., Lançon, A., & Jørgensen, U. G. 2001, *A&A*, 371, 1065
Marigo, P. 2002, *A&A*, 387, 507
Marigo, P. & Girardi, L. 2007, *A&A*, 469, 239
Marigo, P., Girardi, L., Bressan, A., *et al.* 2008, *A&A*, 482, 883
Nikolaev, S. & Weinberg, M. D. 2000, *ApJ*, 542, 804
Pagel, B. E. J. & Tautvaišienė, G. 1998, *MNRAS*, 299, 535
van Loon, J. Th., McDonald, I., Oliveira, J. M., *et al.* 2006, *A&A*, 450, 339