Why Galaxies Care About AGB Stars:
A Continuing Challenge through Cosmic Time
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Mid-IR colors and surface brightness fluctuations as tracers of stellar mass-loss in the TP-AGB

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Abstract. I present integrated colors and surface brightness fluctuation magnitudes in the mid-IR, derived from stellar population synthesis models that include the effects of the dusty envelopes around TP-AGB stars. The models are based on the Bruzual & Charlot CB* isochrones; they are single-burst, range in age from a few Myr to 14 Gyr, and comprise metallicities between Z = 0.0001 and Z = 0.04. I compare these models to mid-IR data of AGB stars and star clusters in the Magellanic Clouds, and study the effects of varying self-consistently the mass-loss rate, the stellar parameters, and the output spectra of the stars plus their dusty envelopes.

Keywords. stars: AGB and post-AGB, stars: mass loss, stars: carbon, stars: evolution, Magellanic Clouds, infrared: stars, galaxies: stellar content, galaxies: star clusters

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Asymptotic Giant Branch (AGB) stars are central to the chemical evolution of galaxies, and understanding the contribution of these evolved stars to the spectral energy distribution (SED) of galaxies is essential for the interpretation of galactic emission in the near and mid-infrared (IR). Thermally pulsing AGB (TP-AGB) evolution is very complex, however, on account of a large number of physical processes at work, and the difficulties to constrain them (see, for a brief recent summary, Marigo *et al.* 2013). While several processes and parameters —dredge-up efficiency, mixing-length, hot-bottom burning, pulsations— are degenerate on their effects on both TP-AGB lifetimes and luminosity functions, there is no doubt that mass-loss is the most important parameter determining the duration of the phase (e.g., Rosenfield *et al.* 2014; Rosenfield *et al.* 2016). On the other hand evolutionary synthesis models for the study of stellar populations have particular challenges: they are required to account for the mass-loss rate ($\dot{M}$) and the emission of the stellar dusty envelopes for all TP-AGB evolutionary stages and all metallicities. For this, they need an analytic approach, since there are no empirical spectra for all phases and metallicities. Furthermore, a good calibration of all the parameters involved in individual TP-AGB stars does not exist for supersolar Z.

I adopt the view (e.g., Willson 2000) that empirical relations between mass-loss and stellar parameters are the result of very strong selection effects, since stars with a low rate will not be detected as mass-losing, whereas stars with a high rate will be obscured by dust and/or extremely short-lived. In other words, regardless of the actual rate, mass-loss will appear to follow a Reimers' type relation† (Reimers 1975; Reimers 1977), and such relations give the properties of stars undergoing mass-loss, but do not describe how any

† $\dot{M} = \eta LR/M$, where M and L are, respectively, the stellar mass and luminosity, $R(L, M, Z)$ is the stellar radius, and η is a fitting parameter.

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one star loses mass over time. Consequently, rather than, for example, varying η while leaving the stellar parameters unchanged, I vary together $\dot{M}$ and the stellar parameters, in a consistent fashion. The whole procedure has been described in detail in Appendix A1 of González-Lópezlira *et al.* (2010), and is quite iterative: a variation in $\dot{M}$ will imply changes in L, R, temperature, pulsation period, carbon to oxygen ratio, and wind expansion velocity $v_{\rm exp}$. For the calculation of the SEDs, the dust opacity τ is a function of $\dot{M}$, specific extinction coefficient κ_λ, gas-to-dust ratio Ψ, $v_{\rm exp}$, and L, but at the same time $\dot{M}$ is a function of L and τ, κ_λ is a function of τ, Ψ is a function of $\dot{M}$ and τ, and $v_{\rm exp}$ depends on L and $\dot{M}$. Lifetimes t and hence star numbers in a particular phase also change with $\dot{M}$, according to the fuel consumption theorem Renzini & Buzzoni (1986), i.e., assuming that the product Lt is constant (and equal to the value for fiducial $\dot{M}$).

I have compared the models to the integrated mid-infrared colors of individual AGB candidates (Srinivasan *et al.* 2009), and to integrated colors and surface brightness fluctuations (SBF) of eight artificial "superclusters, i.e., coadded data of Magellanic star clusters in bins with similar ages and metallicities, according to classes I - VII in the Searle *et al.* (1980) SWB categorization scheme, plus an ultra-young (pre-SWB) supercluster. The SWB types constitute a smooth, one-dimensional sequence of increasing age and decreasing Z; coaddition reduces the stochastic uncertainty produced by the inadequate sampling, in sparse clusters, of stars evolving through short evolutionary phases, of which the AGB is a prime example. If the numbers of stars in different evolutionary stages have a Poissonian distribution, then the theoretical relative errors scale as $M_{\rm tot}^{1/2}$, with $M_{\rm tot}$ the total mass of the cluster.

My conclusions are as follows (González-Lópezlira 2018): models with different mass-loss rates and metallicities differ significantly in their predicted mid-IR colors and SBF magnitudes; models with a higher than fiducial $\dot{M}$ are needed to fit the mid-IR colors of "extreme" single AGB stars in the LMC; the range of mid-IR colors of individual MC clusters is consistent with models with $\mathrm{Z} = 0.008$, $\dot{M}$ between fiducial and 5 $\times$ fiducial, and the stochastic errors expected for a cluster population between 5 $\times 10^3$ and $5 \times 10^4\,\mathrm{M}_\odot$; in the case of artificial "superclusters", although models are compatible with the observations, integrated colors cannot strongly constrain $\dot{M}$, given the present data and theoretical uncertainties (the colors of the 3 Gyr old SWB VI cluster, however, suggest a higher than fiducial mass-loss rate); model SBF magnitudes are quite sensitive to metallicity for 4.5 μm and longer wavelengths, basically at all stellar population ages; fluctuation magnitudes are powerful diagnostics of mass-loss rate in the TP-AGB; the SBF measurements of the MC superclusters suggest a mass-loss rate close to fiducial.

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