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Calibrating the role of TP-AGB stars in the cosmic matter cycle

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Abstract. In the last ten years three main facts about the thermally pulsing asymptotic giant branch (TP-AGB) have become evident: 1) the modelling of the TP-AGB phase is critical for the derivation of basic galaxy properties (e.g. mass and age) up to high redshift, with consequent cosmological implications; 2) current TP-AGB calibrations based on Magellanic Cloud (MC) clusters come out not to work properly for other external galaxies, yielding a likely TP-AGB overestimation; 3) the significance of the TP-AGB contribution in galaxies, hence their derived properties, are strongly debated, with conflicting claims in favour of either a *heavy* or a *light* TP-AGB. The only way out of this condition of persisting uncertainty is to perform a reliable calibration of the TP-AGB phase as a function of the star's initial mass (hence age) over a wide range of metallicity, from very low to super-solar values. In this context, I will review recent advancements and ongoing efforts towards a physically-sound TP-AGB calibration that, moving beyond the classical use of the MC clusters, combines increasingly refined TP-AGB stellar models with exceptionally high-quality data for resolved TP-AGB stars in nearby galaxies. Preliminary results indicate that a sort of "*TP-AGB island*" emerges in the age-metallicity plane, where the contribution of these stars is especially developed, embracing preferentially solar- and MC-like metallicities, and intermediate ages (∼ few Gyr).

1. Broad context: the TP-AGB issue in galaxy models

It has been known for long time that, owing to their high intrinsic brightness, TP-AGB stars contribute significantly to the total luminosity of single-burst stellar populations, reaching a maximum of about 40% at ages from 1 to 3 Gyr (Frogel et al. 1990), and accounting for most of the infrared-bright objects in resolved galaxies, as clearly demonstrated in the Magellanic Clouds (MC; e.g., Bolatto et al. 2007; Blum et al. 2006; Nikolaev & Weinberg 2000).

However, the high influence of TP-AGB stars in stellar population synthesis (SPS) models of galaxies was recognized only after Maraston (2005, herefater M05) pointed out that they can dramatically alter the mass-to-light ratio for 0.5 – 2 Gyr old stellar populations, hence affecting the determination of stellar masses and ages of high-redshift galaxies by factors of 2 or more.

While the importance of the TP-AGB phase is now universally acknowledged, since M05 a number of *conflicting results* have been produced about the *overall impact of TP-AGB stars*. In this context, many recent papers have focused on comparing the performances of two popular SPS models that differ radically in the technique adopted to include the TP-AGB phase. Bruzual & Charlot (2003, hereafter BC03) use sets of stellar evolutionary tracks, while in the M05 models the TP-AGB contribution

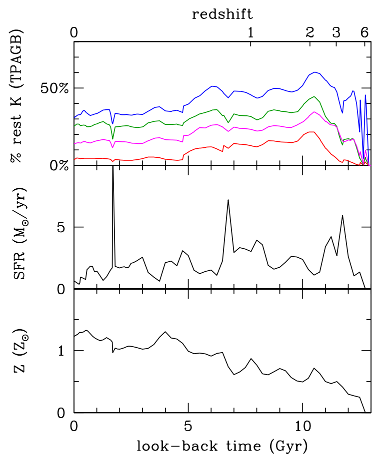

Figure 1. Predicted contribution by the TP-AGB to the (rest-frame) K-band flux, the cosmic star formation rate (SFR), and the metal enrichment (Z) as a function of the look-back time, derived from SPS models applied to the Millennium Cosmological Simulation (Springel et al. 2005). The different curves correspond to different prescriptions of the TP-AGB phase, mainly related to various efficiencies of mass loss and third dredge-up. It also shows how the TP-AGB contribution is boosted after each major episode of star formation (i.e. in the post-starburst phase). Courtesy of S. Charlot and G. Bruzual.

is described by the integrated nuclear fuel (emitted light), bypassing the details of stellar evolution. The appropriateness of M05 (favouring a heavy TP-AGB) and BC03 (characterized by a light TP-AGB) models is a matter of lively debate, yielding discordant claims. For instance, while M05 appears to overpredict the near-infrared part of the spectral energy distributions of post-starburst galaxies at moderate-to-high redshifts (Kriek et al. 2010; Zibetti et al. 2013) and BC03 models are better performing, the observed HCN spectral features in the nuclear regions of AGNs are in closer agreement with M05 models (Riffel et al. 2007, see also Riffel's contribution, this conference).

What strikingly emerges is that the uncertainties intrinsic to population synthesis models – and especially those related to the TP-AGB contribution – often dominate over the observational errors when drawing galaxy properties across cosmic times, impinging dramatically on the derivation of the stellar mass-to-light-ratios, masses and ages from the integrated light of galaxies (Conroy 2013; Taylor et al. 2011; Zibetti et al. 2009; Eminian et al. 2008; Bruzual 2007; Maraston et al. 2006, see also Figs. 1-2).

The inescapable bottom line is that a decisive step forward in the calibration of the TP-AGB phase is urgently needed! As we will show, this challenging goal may be only achieved with TP-AGB stellar evolution models, able to predict individual physical properties to be compared with observations of resolved stars. The potential contribution of other approaches, e.g. those based on the integrated TP-AGB fuel, is much weaker as they cannot, by construction, be tested against the wealth of information about resolved TP-AGB stars available nowadays (Sect. 3).

2. Magellanic Cloud clusters as TP-AGB calibrators

2.1. The classical approaches and insidious problems

Historically, the calibration of the TP-AGB as a function of the age is based on the globular star clusters in the Magellanic Clouds (MCs), relying on the star counts, integrated fluxes and spectral classification. The pioneer work in this field was carried out by Frogel et al. (1990), who derived the fractional luminosity contributed by TP-AGB stars as well as the luminosity functions of M and C stars as a function of SWB type, which is a proxy for the age (Searle et al. 1980). Since that work, following studies

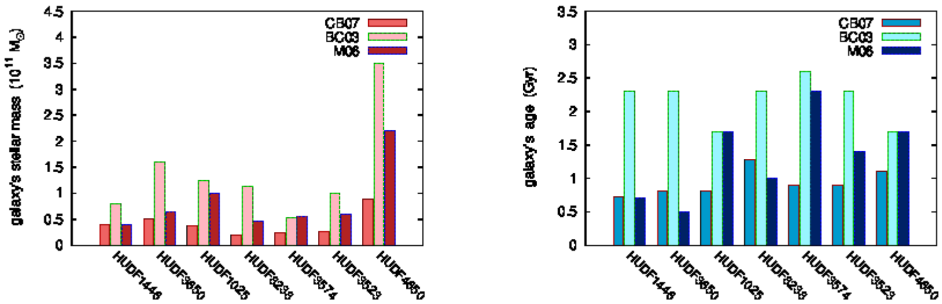

Figure 2. An example of the current uncertainties in the mean ages and stellar masses of galaxies (up to a factor of ~ 2-3), due to the propagation of the uncertainties in the underlying TP-AGB models. The bars show the estimates for a sample of seven intermediate-redshift galaxies in the Hubble Ultra-Deep Field (HUDF) derived with three different SPS models that mostly differ in the treatment of the TP-AGB: Bruzual & Charlot (2003, BC03), Maraston et al. (2006, M06), Bruzual (2007, CB07) based on the TP-AGB tracks of Marigo & Girardi (2007).

employed the MC cluster data of AGB stars for calibration purposes, either using the measured integrated luminosities or broad-band visual and near-IR colors to estimate the nuclear fuel burnt during the TP-AGB phase (Maraston 2005; Noël et al. 2013), or dealing with the direct star counts to derive the TP-AGB lifetimes with the aid of stellar tracks and isochrones (Charlot & Bruzual 1991; Girardi & Marigo 2007).

Despite these calibration efforts based on different techniques, when present-day TP-AGB models are applied to other external galaxies they overestimate, to various extents, the TP-AGB contributions in integrated spectra of galaxies or star counts. For instance, M05 models show an excess of IR flux that is not observed in post-starburst galaxies (Kriek et al. 2010; Zibetti et al. 2013). On the other hand, Marigo & Girardi (2007) tracks predict, on average, 40% more TP-AGB stars than counted in a sample of nearby galaxies observed with ANGST, which translates in a factor of ~ 2 in the integrated near-IR flux (Melbourne et al. 2012).

The question that arises is, therefore: Why TP-AGB models calibrated on MC clusters are not equally adequate for other galaxies, even with metallicities comparable to the MCs?

Recently, Girardi et al. (2013) have pointed out a specific aspect, related to the physics of stellar interiors, that is likely the main cause of this conundrum. As soon as stellar populations attains the ages at which red giant branch stars first arise, an abrupt increase in the lifetime of the core He-burning phase causes a transitory boost in the production rate of the later evolutionary phases, including the TP-AGB. For a time interval of about 0.1 Gyr, triple TP-AGB branches grow at somewhat different initial masses, making their frequency and contribution to the integrated luminosity of the stellar population to raise by a factor of $\simeq 2$ (see Fig. 3). The boost takes place for turn-off masses of $\simeq 1.75 M_\odot$, just in vicinity of the predicted peak in the TP-AGB lifetimes for MC metallicities, and for ages of $\simeq 1.6$ Gyr (see Fig. 5). Coincidently, this relatively narrow age interval contains the few very massive MC clusters where most of the TP-AGB stars, used to constrain stellar evolution and SPS models, are found. As a

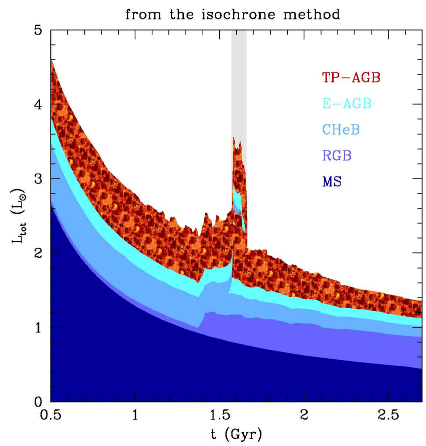

Figure 3. Evolution of the integrated bolometric luminosity of a simple stellar population as derived from detailed stellar tracks and isochrones, as a function of age (Bressan et al. 2012; Marigo et al. 2013; Girardi et al. 2013). From bottom to top the sequence of different evolutionary phases is shown: main sequence (MS), red giant branch (RGB), core helium-burning (CHeB), and Early-AGB (E-AGB). The brightest region, filled with wavy pattern, refers to the TP-AGB contribution. The AGB-boosting period at ages ~1.6 Gyr is marked by the shaded vertical bar.

consequence, the expected boosting of TP-AGB stars in intermediate-age MC clusters may account for the excess of TP-AGB in current models.

Two main implications can be drawn: i) all classical estimates on the relative role of TP-AGB stars to the integrated light of intermediate-age stellar populations are likely biased towards too high values (including Maraston 2005; Marigo et al. 2008), and ii) TP-AGB star populations in intermediate-age MC clusters await to be carefully revised, promisingly with the aid of sets of stellar evolutionary tracks and isochrones calculated with the level of detail necessary to reveal the TP-AGB boosting.

2.2. Enhancing the classical TP-AGB calibration based on MC clusters

Recently, the classical use of MC clusters, commonly based on photometry and star counts, has been expanded to include other key properties of TP-AGB stars, namely: pulsation and nucleosynthesis. We have now information about the pulsation periods and pulsational masses of TP-AGB stars and their location on different period-luminosity sequences (that are likely related to different pulsation modes), as well as on surface chemical abundances, in particular the C/O ratio, the $^{12}C/^{13}C$ isotopic ratio, and other elements affected by the TP-AGB nucleosynthesis (e.g., F, Li) (Kamath et al. 2012, 2010; Lederer et al. 2009; Lebzelter et al. 2014, 2008; Lebzelter & Wood 2011, 2007; Maceroni et al. 2002).

The challenge that AGB models have to face is to reproduce various observables at the same time, i.e the giant branch temperatures, the oxygen to carbon transition luminosity (when C/O overcomes unity due to the third dredge-up), the AGB-tip luminosity, the period-luminosity relations, and the observed elemental abundances.

Despite severe difficulties still unsolved, these studies have clearly shown that, with the aid of targeted observations coupled to detailed TP-AGB nucleosynthesis cal-

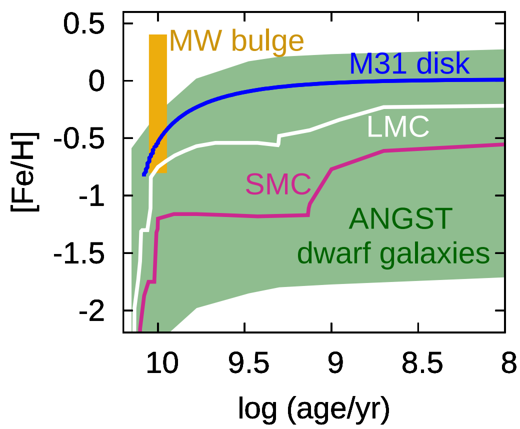

Figure 4. The relevant area in the age–metallicity diagram that needs to be covered for a reliable TP-AGB calibration. Notice that the inclusion of M31 (PHAT data), of ANGST dwarf galaxies, and of the Galactic bulge (OGLE, WISE) largely increases the sampling of this plane, compared to previous calibrations (Maraston 2005; Marigo et al. 2008) which were based only on the Magellanic Clouds.

culations and a parametrized description of the convective boundaries, it is possible to derive important constraints on crucial but poorly known quantities, such as the extent of the envelope overshoot, the depth of the partially-mixed zone, the intershell composition, the minimum core mass and the efficiency of the third dredge-up.

These all-round approaches are promising and deserve to be developed further, hopefully also in combination with population synthesis studies.

3. The need to move beyond the MC clusters: wide age-metallicity sampling and characterization

Though the MC clusters represent a key benchmark to test and calibrate the TP-AGB models, at the same time they are affected by two severe limitations, namely: the low-number statistics of TP-AGB stars with associated large Poisson fluctuations, and the narrow sampling of the age-metallicity plane (see Fig. 4). Moreover, most star clusters have uncertain ages, and previous analyses do not include the fact that many of these clusters have multiple age sub-populations and they cannot be assumed to be single stellar populations (Goudfrooij et al. 2014, and references therein).

With the new generation of large imaging and spectroscopic surveys of nearby galaxies, the quantity and quality of the data potentially useful for calibrating TP-AGB models are dramatically increasing. This data set will make it possible (i) to improve substantially the exploitation of the MC data thanks to the detailed and spatially-resolved star formation histories (SFH) for fields and clusters, and (ii) to extend largely the metallicity range of the calibration, as shown in Fig. 4.

We now have excellent quality data for resolved AGB stars in regions with well-characterized SFH, spanning a wide range in metallicity, such as the metal-rich fields of M31 from the Panchromatic Hubble Andromeda Treasury (PHAT) survey, which also includes more than 500 star clusters (Dalcanton et al. 2012; Johnson et al. 2012, see Girardi's contribution, this conference), metal-poor dwarf galaxies up to a distance of 4 Mpc from the ACS Nearby Galaxy Survey Treasury (ANGST) survey and other dwarf galaxies of the Local Group (see Rosenfield's, Boyer's, and Menzie's contributions, this conference), a complete census of AGB stars in the Magellanic Clouds at near and intermediate IR wavelengths from 2MASS and Spitzer surveys (Nikolaev & Weinberg 2000; Blum et al. 2006; Bolatto et al. 2007, see also Sloan's contribution, this conference), as well as for MCs fields with spatially resolved SFH derived from the VMC survey (Rubele et al. 2012), AGB data for the Milky Way (MW) bulge from 2MASS, OGLE and WISE (Nikutta et al. 2014). Additional observational constraints are provided by the distributions of mass-loss rates of AGB stars in the MCs derived from radiative transfer models and spectral fitting of Spitzer data (Gullieuszik et al. 2012; Riebel et al. 2012, see also Srinivasan's contribution, this conference), wind expansion velocities, and circumstellar molecular and dust chemistry from sub-mm and radio observations with Herschel, ALMA, and other telescopes (Justtanont et al. 2012; Schöier et al. 2013; Nanni et al. 2014, 2013; Vlemmings et al. 2013; Ramstedt & Olofsson 2014, see also Olofsson's and Nanni's contributions, this conference), detailed information about the pulsation properties of AGB stars provided by the OGLE data (Soszyński et al. 2009, 2013), and stellar parameters from interferometry (Paladini et al. 2011; Klotz et al. 2013; van Belle et al. 2013).

4. A few steps along the calibration cycle

I will briefly address here two critical quantities the primarily need to be calibrated as a function of the stellar progenitor's mass and metallicity, namely: the TP-AGB lifetimes and the core-mass growth on the TP-AGB.

4.1. TP-AGB lifetimes

Assessing the duration of the TP-AGB, $\tau_{\rm TP-AGB}$, as a function of the initial stellar mass is of paramount importance for two main reasons. First, it controls the energy output of a TP-AGB star, $E_{\rm TP-AGB} \propto \int_0^{\tau_{\rm TP-AGB}} L(t)dt$, hence its contribution to the integrated light of the host system. Second, it regulates the number of thermal pulses suffered during the phase, hence the degree of surface chemical enrichment due to the mixing episodes, ultimately affecting the ejecta expelled into the interstellar medium.

While in older TP-AGB models large differences in $\tau_{\rm TP-AGB}$ existed among different studies, a closer agreement is found in more recent works (Fig. 5). All predicted relations between $\tau_{\rm TP-AGB}$ and the initial stellar mass display a prominent peak at of $M_{\rm initial} \approx 2M_{\odot}$, that takes place in the proximity of the critical stellar mass for the development of a degenerate He-core at the end of the main sequence, and corresponds to the minimum in the core mass at the onset of thermal pulses. We note that the dependence of $\tau_{\rm TP-AGB}$ on the initial metallicity is not monotonic, as it is the result of the interplay among many different factors (e.g., core mass at the first TP, evolution of the surface C/O, mass loss, etc.).

In general, the main parameter that directly governs TP-AGB lifetimes is the efficiency of mass loss, which may vary with the metallicity. In the low-metallicity regime, not covered by the MCs, valuable constraints on $\tau_{\rm TP-AGB}$ are provided by the nearby dwarf galaxies observed with ANGST (Dalcanton et al. 2009).

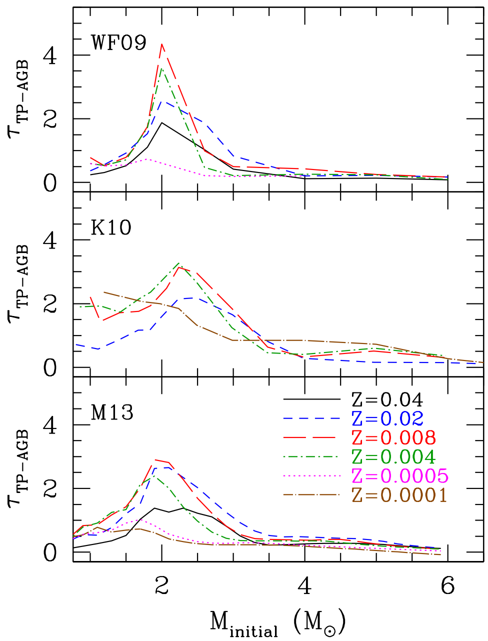

Figure 5. TP-AGB lifetimes as a function of the stellar initial mass and metallicity. Predictions of three recent studies are shown, from top to bottom: Weiss & Ferguson (2009, WF09), Karakas (2010, K10), Marigo et al. (2013, M13).

Following the analysis carried out by Girardi et al. (2010), and more recently by Rosenfield et al. (2014, see Rosenfield's contribution, this conference), it turns out that in order to reproduce the optical and nea-IR star counts and luminosity functions of low-mass low-metallicity TP-AGB, it is necessary that significant mass loss rates ($\dot{M} \approx 10^{-7} - 10^{-6}\, M_{\odot}\, \mathrm{yr}^{-1}$) are already attained at rather low luminosities, before the onset of large-amplitude pulsation, when dust is not expected to be the dominant driver of stellar winds. A suitable mode might be provided by the flux of Alfvén wave energy associated to cool chromospheres (Schröder & Cuntz 2005). In this framework novel theoretical efforts (Cranmer & Saar 2011) indicate that the mass-loss rate should have a steeper, rather than linear, dependence on the magnetic flux, which results into a higher mass-loss efficiency at lower metallicity.

4.2. The core-mass growth on the TP-AGB

Another parameter of high importance is the core mass growth on the TP-AGB, as it determines the amount of mass of the chemically enriched gas that is returned to the ISM, and fixes a lower limit to the nuclear fuel burnt ($\propto$ emitted light) during the TP-AGB phase. The remaining part of the TP-AGB fuel is expelled in the form of chemical yields (Marigo & Girardi 2001). A direct constraint comes from the semi-empirical $M_{\mathrm{initial}} - M_{\mathrm{final}}$ relation that links the initial mass of the progenitor to that of the white dwarf (WD). The Galactic data shows a clear positive correlation, but with a large scatter, which has so far prevented us from obtaining a stringent constraint on AGB models (see Marigo 2013, for a recent review), though some excellent work has been recently carried out on the low-mass end using WDs in old open clusters and in common-proper-motion pairs (Kalirai et al. 2008; Catalán et al. 2008).

Theory predicts that the final mass depends on the core mass growth during the TP-AGB, which is affected by two main processes: mass loss and third dredge-up. The final mass of a TP-AGB is expected to be lower at increasing efficiency of both processes:

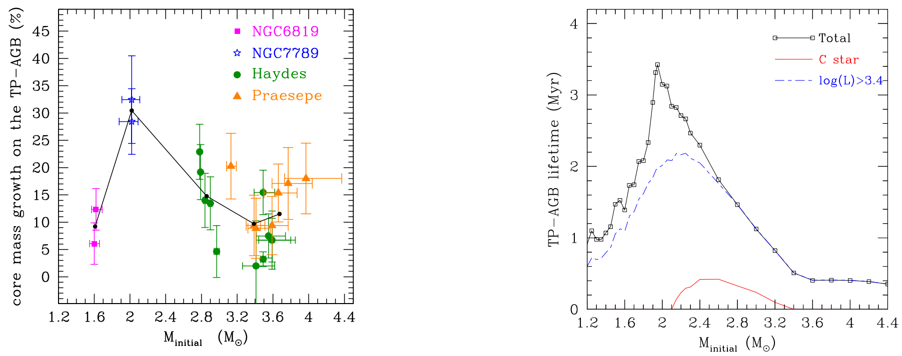

Figure 6. *Left*: Core-mass growth on the TP-AGB relative to new homogeneous, high signal-to-noise WD mass data in intermediate-age open clusters (Kalirai et al. 2014). *Right*: The TP-AGB lifetimes from Marigo et al. (2013) models with initial metallicity $Z = 0.02$. The predicted TP-AGB core-mass growth in these models fits the new (Kalirai et al. 2014) measurements very nicely.

while the strength of stellar winds directly controls the overall duration of the TP-AGB phase, the third dredge-up reduces the net increase of the core mass. Unfortunately, the efficiencies of both processes are quite uncertain on the theoretical grounds and need to be observationally constrained.

New constraints on the intermediate-mass range of the $M_{\rm initial} - M_{\rm final}$ relation at $Z \simeq 0.02$ have been recently established from newly discovered WDs in the nearby Hyades and Praesepe star clusters (Kalirai et al. 2014), and from an accurate re-analysis of the WD data in the older NGC 6819 and NGC 7789 star clusters, covering a range of progenitors' masses, $1.6\,M_{\odot} \lesssim M_{\rm initial} \lesssim 3.8\,M_{\odot}$, over which TP-AGB stellar models predict the maximum core growth.

Using the new WD data to calibrate the efficiencies of mass loss and third dredge-up in TP-AGB models (Marigo et al. 2013; Marigo & Aringer 2009), we derive that at $Z \simeq 0.02$ i) the carbon star formation should be little efficient, taking place only in stars with $2.1\,M_{\odot} \lesssim M_{\rm initial} \lesssim 3.4\,M_{\odot}$ (see Fig. 6), which is in line with recent findings for metal-rich fields of M31 (Boyer et al. 2013); ii) the peak of TP-AGB lifetimes reaches $\simeq$ 2 Myr at $M_{\rm initial} \simeq 2.0 M_{\odot}$ for luminosities brighter than the RGB tip; iii) the integrated emitted light peaks at $M_{\rm initial} \simeq 2.4 M_{\odot}$ with $E_{\rm TP-AGB} \sim 12 \times 10^{10}$ $L_{\odot}$ yr. We note that the corresponding TP-AGB nuclear fuel ($\simeq 0.13 M_{\odot}$) is lower by up a factor of 2 than previous estimates for $Z = 0.02$ (Maraston 2005; Marigo et al. 2008), supporting other independent claims towards a lighter TP-AGB (see Sect. 1).

5. The island of TP-AGB stars

Combining together the results of i) previous studies dealing with TP-AGB stars and WDs in the MCs and the Galaxy (Marigo & Girardi 2007; Weiss & Ferguson 2009; Bianchi et al. 2011; Kamath et al. 2012), ii) more recent works based on the ANGST galaxies in the low-metallicity regime (Girardi et al. 2010; Rosenfield et al. 2014), and iii) the new constraints on the initial-final mass relation at slightly super-solar metallicity (Kalirai et al. 2014), we can derive a preliminary map of the TP-AGB calibration

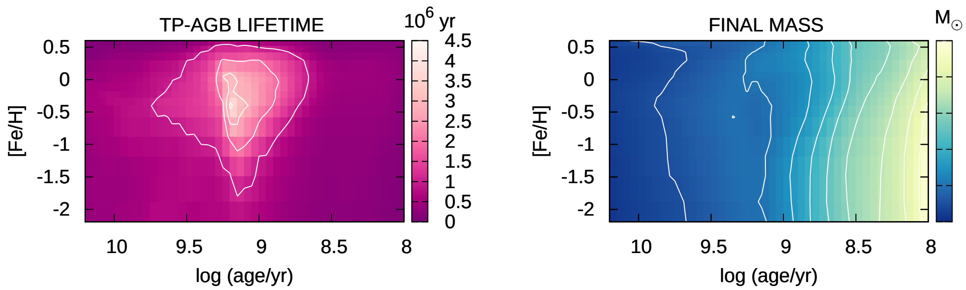

Figure 7. Maps of TP-AGB lifetimes (*left*) and final core masses (*right*) over the relevant age-metallicity plane occupied by TP-AGB stars. They derive from the TP-AGB calculations of Marigo et al. (2013) with the new prescriptions for pre-dust mass loss as in Rosenfield et al. (2014), and the indications from the new $M_{\rm initial} - M_{\rm final}$ relation of Kalirai et al. (2014).

over the age-metallicity plane, in terms of lifetimes and final core masses (Fig. 7). A striking result is that there seems to be a special region in the age-metallicity plane, a sort of island, which offers the best conditions for the development of TP-AGB phase. This fertile place encompasses the metallicities going from solar-like values to those typical of the MCs, while the favourite ages ($\sim$ few Gyr) correspond to initial stellar masses in the range $\sim 1.5 - 2.5\,M_\odot$. Of course, this finding needs to be tested and refined further, exploiting the plenty of observed data for resolved TP-AGB stars at our disposal today (Sect. 3). Work is in progress.

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