

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 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 (\sim 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 (SSP), 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, hereafter 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: while Bruzual & Charlot (2003, hereafter BC03) use sets of stellar evolutionary tracks, in the M05 models the TP-AGB contribution is described by the integrated nuclear fuel (emitted light), bypassing the details of stellar evolution.

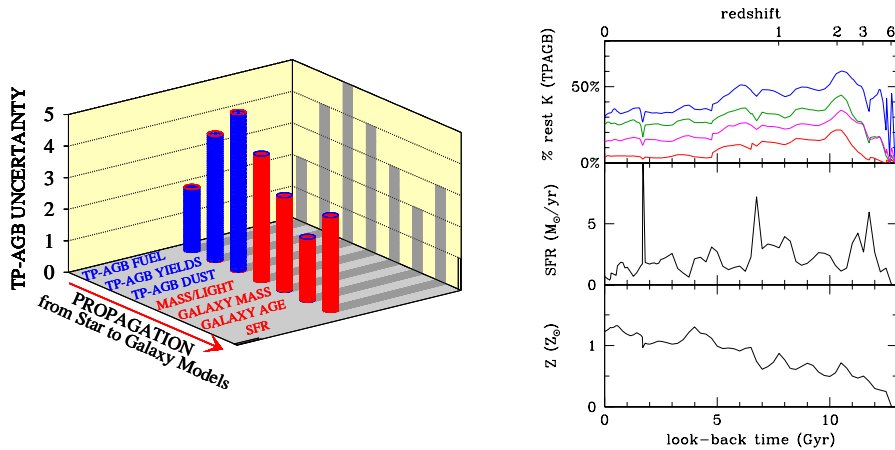


Figure 1. Current uncertainties in the TP-AGB evolutionary phase and their propagation into galaxy models in terms of integrated fluxes, mass-to-light ratios, stellar masses, galaxy mean ages, and star-formation rates (SFR). *Left*: Moving along the direction of the arrow the first three bars show the relative uncertainty range in basic predictions of TP-AGB models: the integrated TP-AGB fuel (emitted light), chemical yields, and dust yields. The next four bars illustrate how these stellar uncertainties undermine basic predictions of SPS models of galaxies. These estimates are derived from comparing various sources of models in the literature, and are partly discussed in Conroy (2013) and Marigo et al. (2013). *Right*: From top to bottom it presents the predicted contribution by TP-AGB to the (rest-frame) K-band flux, the cosmic star formation rate, and the chemical enrichment as a function of the look-back time, derived from 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 Stéphane Charlot.

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 in 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 (see Fig. 1).

The inescapable bottom line is that a decisive step forward in the calibration of the TP-AGB phase is urgently needed!

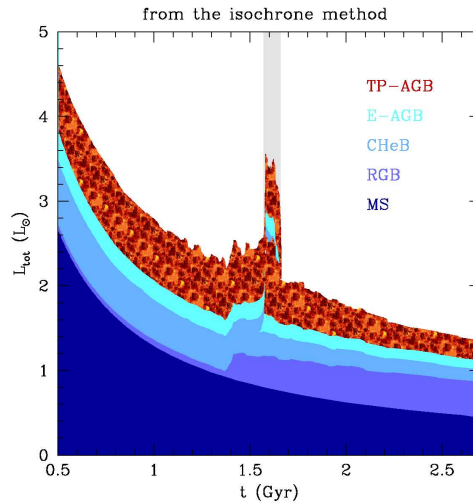


Figure 2. Evolution of the integrated bolometric luminosity of a simple stellar population as derived from detailed stellar tracks and isochrones, as a function of age (Bressan et al. 2012; Marigo et al. 2013; Girardi et al. 2013). From bottom to top the sequence of different evolutionary phases, marked in blue/grey tones, correspond to 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. Note the presence of the AGB-boosting period at ages 1.6 Gyr, marked by the shaded vertical bar.

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 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 result to 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-star burst 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 observed 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 develops, 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 ≈ 2 (see Fig. 2). The boost takes place for turn-off masses of $\approx 1.75M_{\odot}$, just in vicinity of the predicted peak in the TP-AGB lifetimes (for MC metallicities; see Fig. 4), and for ages of ≈ 1.6 Gyr. Coincidentally, 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 EPS models, are found. As a consequence, the expected boosting of TP-AGB stars in intermediate-age MC clusters may account for the excess of TP-AGB in current models (Maraston 2005; Marigo et al. 2008).

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 (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 detailed sets of stellar evolutionary tracks and isochrones.

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 $^{12}\text{C}/^{13}\text{C}$ isotopic ratio, and other elements affected by the TP-AGB nucleosynthesis (e.g. F, Li) (Lebzelter et al. 2014; Kamath et al. 2012; Lebzelter & Wood 2011; Kamath et al. 2010; Lebzelter et al. 2008; Lebzelter & Wood 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 calculations 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.

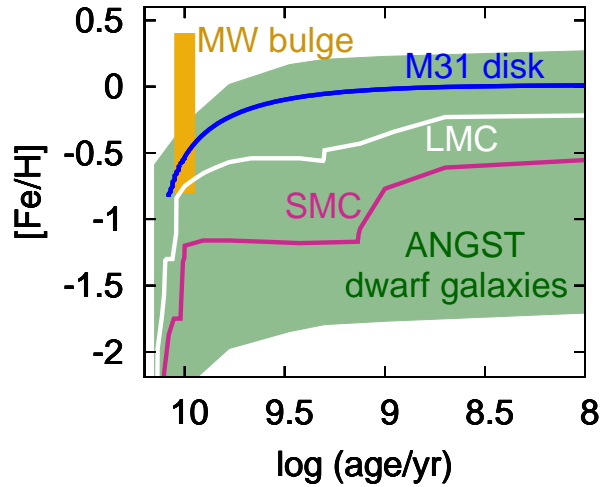


Figure 3. The relevant area in the age–metallicity diagram that needs to be covered for a reliable TP-AGB calibration. Notice that the inclusion of M31 (PHAT data), of ANGST dwarf galaxies, and of the bulge (WISE) largely increases the sampling of this plane, compared to previous calibrations (Maraston 2005; Marigo et al. 2008) which were based only on the Magellanic Clouds.

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. 3). Moreover, most star clusters have uncertain ages, and previous analyses do not include the fact that these clusters have multiple age sub-populations and they cannot be assumed to be single stellar populations. *referimenti?*

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 spaced-resolved SFHs for fields and clusters, and (ii) to extend largely the metallicity range of the calibration, as shown in Fig. 3.

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 PHAT survey, which also includes more than 500 star clusters (*ref?* see Girardi’s contribution, this conference), metal-poor dwarf galaxies up to 4 Mpc from ANGST survey and other LG dwarf galaxies (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), as well as for MCs fields with spa-

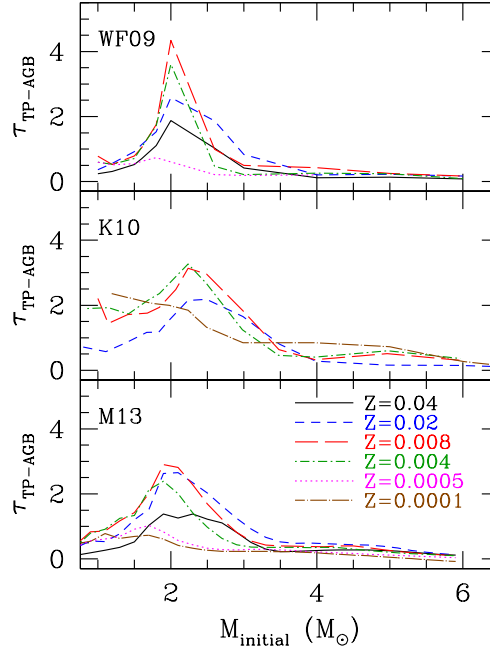


Figure 4. TP-AGB lifetimes as a function of the stellar initial mass and metallicity. Predictions of three recent studies are shown, from top to bottom: Weiss & Ferguson (2009, WF09), Karakas (2010, K10), Marigo et al. (2013, M13).

tially resolved SFH derived from the VMC survey, 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 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), together with detailed information about pulsation properties of AGB stars provided by the OGLE data (Soszyński et al. 2009).

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, $\tau_{\text{TP-AGB}}$, 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, $E_{\text{TP-AGB}} \propto \int_0^{\tau_{\text{TP-AGB}}} L(t) dt$, 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 the ejecta expelled into to the interstellar medium.

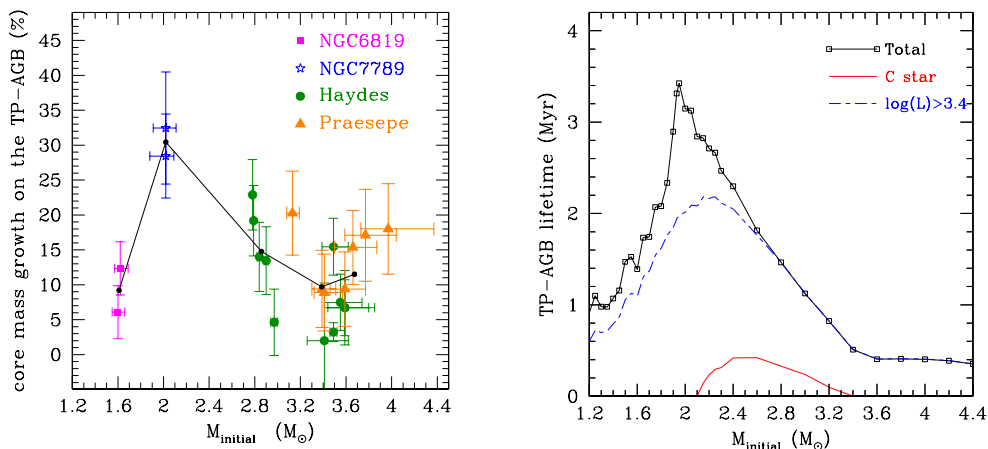


Figure 5. *Left:* Core-mass growth on the TP-AGB (right panel) relative to new homogeneous, high signal-to-noise WD mass data in intermediate-age open clusters (Kalirai et al. 2014). *Right:* The TP-AGB lifetimes from Marigo et al. (2013) models with initial metallicity $Z_{\text{initial}} = 0.02$. The predicted TP-AGB core-mass growth in these models fits the new (Kalirai et al. 2014) measurements very nicely.

While in older TP-AGB models large differences in $\tau_{\text{TP-AGB}}$ existed among different studies, a closer agreement is found in more recent works (Fig. 4). All predicted relations between $\tau_{\text{TP-AGB}}$ and the initial stellar mass display a prominent peak at of $M_{\text{initial}} \approx 2 M_{\odot}$, 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 $\tau_{\text{TP-AGB}}$ 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 $\tau_{\text{TP-AGB}}$ are provided by the nearby dwarf galaxies observed with ANGST (Dalcanton et al. 2009).

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 near-IR star counts and luminosity functions of low-mass low-metallicity TP-AGB, it is necessary that significant mass loss rates ($\dot{M} \approx 10^{-7} - 10^{-6} M_{\odot} \text{ yr}^{-1}$) 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.

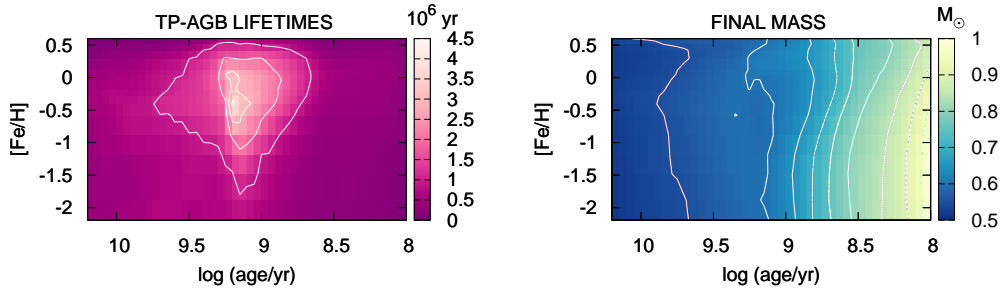


Figure 6. Maps of TP-AGB lifetimes (left panel) and final core masses (right panel) over the relevant age-metallicity plane occupied by TP-AGB stars. Results correspond to the TP-AGB calculations of Marigo et al. (2013) with the new prescriptions for pre-dust mass loss as in Rosenfield et al. (2014), and the indications from the new IFMR data of Kalirai et al. (2014).

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 TP-AGB the fuel is expelled in the form of chemical yields (Marigo & Girardi 2001). A direct constraint comes from the semi-empirical $M_{\text{initial}} - M_{\text{final}}$ 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: 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 $M_{\text{initial}} - M_{\text{final}}$ relation at $Z \approx 0.02$ 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, $1.6 M_{\odot} \lesssim M_{\text{initial}} \lesssim 3.8 M_{\odot}$, 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), we derive that at $Z \approx 0.02$ i) the carbon star formation should be little efficient at $Z \approx 0.02$, taking place only in stars with $2.1 M_{\odot} \lesssim M_{\text{initial}} \lesssim 3.4 M_{\odot}$ (see Fig. 5), which is in line with independent findings for metal-rich fields of M31 (Boyer et al. 2013); ii) the peak of TP-AGB lifetimes reaches ≈ 2 Myr at $M_{\text{initial}} \approx 2.0 M_{\odot}$ for luminosities brighter than the RGB tip; iii) the

integrated emitted light peaks at $M_{\text{initial}} \simeq 2.4M_{\odot}$ with $E_{\text{TP-AGB}} \sim 12 \cdot 10^{10} L_{\odot} \text{ yr}$. We note that the corresponding TP-AGB nuclear fuel ($\simeq 0.13M_{\odot}$) 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 over the age-metallicity plane, in terms of lifetimes and final core masses (Fig. 6). 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. Such a TP-AGB island encompasses the metallicities going from solar-like values to those typical of the MCs, while the favourite ages (\sim Gyr) correspond to initial stellar masses in the range $1.5 - 2.5 M_{\odot}$. 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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