TP-AGB stars to date high-redshift galaxies
with the Spitzer Space Telescope

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Abstract. We present new stellar population models that include the contribution of the Thermally Pulsing Asymptotic Giant Branch (TP-AGB) phase also in the synthetic spectral energy distribution (SED). The TP-AGB phase is essential for a correct modeling of intermediate-age (0.2 ≤ t/Gyr ≤ 1 ÷ 2) stellar populations, because it provides ~ 40 % of the bolometric contribution, and up to ~ 80 % of that in the K-band. These models are obtained by coupling the energetic of the TP-AGB phase as calibrated with data of Magellanic Clouds star clusters ([9]), with empirical spectra of TP-AGB stars ([3]). Now that the Spitzer Space Telescope (SST) allows the sight of the rest-frame IR at high redshifts, these models provide the opportunity to use the TP-AGB phase as an age indicator also for high-redshift stellar populations. Here we focus on redshift ~ 3 and provide predictions of the colours of various galaxy models as will be measured by means of the IRAC imaging instrument on board the SST. We find a sizable magnitude difference between TP-AGB-dominated high-redshift stellar populations and those being older or younger. The first releases of GOODS data should allow a check of these predictions.

1 The dating of galaxies and the TP-AGB phase

The epoch(s) of galaxy formation is constrained by dating the stellar populations at zero as well as at high redshift, because the timescales of stellar evolution are independent of cosmological models. Such a constraint provides an important check of current models of hierarchical galaxy formation, in the framework of which the assembly of massive galaxies appears to occur over a rather extended redshift range, with a substantial amount of star formation at redshift lower than 1 (see reviews by S. White and R. Sommerville, this volume). Such prediction appears to be at odd with the old average age, and the small spread in ages, derived for local massive ellipticals (Es) using optical absorption features and chemical evolution arguments (Thomas, Maraston, Bender, this volume; see also G. Gavazzi, this volume; [5]). Also, the finding of galaxies already massive at high redshifts (see contributions by A. Cimatti; R. Genzel, this volume; [16]) is difficult to accommodate in such models. On the other hand, there are also galaxies whose average ages appear to be rather young and could indeed be consistent with small formation redshifts (z ≤ 1), like the so-called k+a galaxies ([13]), or lenticulars and some low-mass Es in the field (see Thomas, Maraston, Bender, this volume).

However, the dating of unresolved stellar populations by means of spectrophotometric indicators in the optical is limited by the well-known age/metallicity
degeneracy ([4], [17], [11]), i.e. the phenomenon that a low metallicity can mimic a low age, and vice versa. When a stellar population ages above $1 \div 2$ Gyr, the Red Giant Branch and the Main Sequence share almost equally the energy production (see e.g. Figure 3 in [9]), and their contributions evolve very smoothly with age. At the same time there are no other stellar phases of short duration and relevant energetics that become important and could be used as age indicators. Therefore, at old ages the age/metallicity degeneracy works at its best in confusing the age determination. To trace back the beginning of the formation of a stellar system it would be ideal to recognize it before it becomes a few Gyr old.

A clear signpost of intermediate age ($t \sim 1$ Gyr) stellar populations are Thermally-Pulsing Asymptotic Giant Branch stars (TP-AGB; [15], [9]). According to stellar evolution, the TP-AGB stellar phase, the brightest and the coolest on the HR diagram, becomes fully developed in stars with degenerate carbon-oxygen cores. The onset of such event in the life of a stellar population has been called the AGB-phase transition ([15]). The observational evidence of the onset of the TP-AGB is a sizable jump in the $V-K$ colour that increases from $\sim 1.4$ to $\sim 3.2$, as observed among the Magellanic Clouds globular clusters (see Section 2). The narrow interval in evolutionary mass ($1.5 - 3 M_\odot$) constrains the whole duration of the TP-AGB dominance to be $\sim 1$ Gyr ([9]). Therefore, picking up the TP-AGB is a powerful way of dating a stellar population, and this technique has been applied with success to local stellar populations ([12]).

How can we extend this approach of age dating to $z > 0$?

An early suggestion in this direction is due to [14], who indicated that the AGB phase transition potentially is an effective tool to date the high redshift formation of Es. Two factors has hampered the exploitation of this idea until now. First, the rest-frame IR at redshift $2 \div 3$ is sampled by the observed frame around $8 - 10 \mu$m. This window is only now available thanks to the advent of the S(plit)S(pace)T(elescope). Second, synthetic spectral energy distributions (SEDs) including the TP-AGB phase are clearly required, but usually evolutionary population synthesis models include only the early part of the AGB phase (so-called the Early-AGB), thereby missing the TP-AGB that is the one energetically important (see Section 2).

In this contribution we introduce model SEDs that include the TP-AGB phase (Section 3) and show the substantial effect on the integrated SEDs of intermediate-age stellar populations. In Section 4 we construct diagnostic colour-colour diagrams for the imaging instrument IRAC on board the SST for the illustrative redshift of 3. We further discuss the use of these models at every redshift.

2 TP-AGB in SSP models: state of the art

The TP-AGB is a critical stellar phase to be accounted for in a Stellar Population (SP) model, because its energetic and duration are affected by mass-loss and nuclear burning in the envelope, both phenomena requiring parametrizations to be calibrated with data ([21]). However, the TP-AGB phase is the dominant phase...
in intermediate-age stellar populations \((0.2 \text{ Gyr} \lesssim t \lesssim 1 \div 2 \text{ Gyr})\), contributing \(\sim 40\%\) to the bolometric light, as observed among the globular clusters (GCs) in the Magellanic Clouds ([6]). Maraston (1998, [9]) uses the fuel consumption theorem ([15]) to include the TP-AGB phase in SP models in a semi-empirical way, by calibrating the energetic of the TP-AGB phase with data of intermediate-age Magellanic Clouds GCs. The calibration of the bolometric contribution, and the

![Figure 1. From [9]. Left-hand panel. Calibration of the bolometric contribution of the TP-AGB phase of SP models as a function of age, with data of Magellanic Clouds GCs. Right-hand panel. Calibration of the synthetic \(V\) vs. \(U-B\) (higher solid line) with the same data. The intermediate-age objects are the filled circles. The lower solid line shows the same SPs but without the TP-AGB phase, to appreciate the deficit of IR flux in the latter case. The other line styles show SPs from other authors (see [9]).](image)

comparison of the synthetic broad-band colours with the same data of Magellanic Clouds GCs, is shown in Figure 1. The AGB phase transition among the intermediate-age GCs (filled circles) appears as an enhancement of the IR luminosity with respect to the optical one and with the \(V\) vs. \(K\) colour reaching values larger than 3. The figure shows that the inclusion of the TP-AGB phase (models as thick solid lines) is crucial to match the integrated near-IR colours of intermediate-age stellar populations, as emphasized by a model (solid thin line) in which the TP-AGB contribution has been subtracted on purpose and only the E-AGB considered. The SP models shown in Figure 1 were restricted at the broad-band colours due to the unavailability at the time of spectra, either theoretical or empirical, appropriate to TP-AGB stars. However, in order to use the TP-AGB-induced jump of the near-IR flux as an age indicator also at \(z > 0\), this phase has to be included in the synthetic spectral energy distribution. Such improvements of the models will be described in the next Section.
Recently, a library of observed spectra of carbon-rich and oxygen-rich type TP-AGB stars in the wavelength range $0.5 \div 2.5 \, \mu m$ has become available (3). We have used these empirical spectra and the calibrated TP-AGB fuel (9) to include the TP-AGB phase in the synthetic SEDs of SP models. The SEDs are constrained to match our previously published model broad-band colours, because these match the observed colours of the Magellanic Clouds GCs (Figure 1). Figure 2 shows as an example the 1 Gyr SED (thick solid line). The inclusion of

\begin{center}
\begin{tabular}{c}
\begin{tikzpicture}
\begin{axis}[
width=\textwidth,
height=0.5\textwidth,
legend style={at={(0.5,-0.15)},anchor=north},
]
\addplot[black, thick, mark=none] table[x=x, y=y, col sep=\,]{data1.dat};
\addplot[red, thick, mark=none] table[x=x, y=y, col sep=\,]{data2.dat};
\addplot[blue, dashed, mark=none] table[x=x, y=y, col sep=\,]{data3.dat};
\addplot[green, dotted, mark=none] table[x=x, y=y, col sep=\,]{data4.dat};
\legend{This work, no TP-AGB, This work, TP-AGB, BC03, Pegaso}
\end{axis}
\end{tikzpicture}
\end{tabular}
\end{center}

Fig. 2. The effect of the TP-AGB on the spectral energy distribution of a 1 Gyr old stellar population. The solid thick and thin lines show our models with and without TP-AGB. Dotted and dashed lines are models from the literature (1, 5).

the TP-AGB changes substantially the spectrum at wavelengths $\gtrsim 0.7 \mu m$, while leaving unchanged the optical side. Also shown are the SEDs of other models (1, 5). Since the latter do not include the TP-AGB phase in the synthesis, the detection of intermediate age SP in galaxies based on the near-IR predictions of these models should be taken with caution.

The models presented here are on course of publication, and we refer to the article for more details (11). In this proceeding we use them to compute the observed-frame colours of SP models at high-redshift in the imaging bands of IRAC-SST to illustrate the power of the TP-AGB-based diagnostic of SP ages.
4 How to find the TP-AGB at $z > 0$

At high redshifts when galaxies are dominated by $\sim 1$ Gyr old populations the TP-AGB signature in the rest-frame near-IR must show up, with e.g. the rest-frame $V-K$ colour mapping into the observed K$-10\,\mu$m at $z = 3$ ([14]). The conclusion of Chiosi et al. ([2]) that the jump in the mid-IR colours due to the AGB is “wiped out by cosmological effects” is due to their consideration of the observed $V-K$ at every redshift instead of the rest-frame one, as appropriate.

The fingerprint of the TP-AGB starts to be appreciable at rest-wavelength $\sim 0.7\mu$m (Figure 2). Already existing $K$-selected galaxy surveys like MUNICS and the K20 (see Drory; Cimatti, this volume) could be used to search for intermediate-age SP using these models in galaxies at moderate redshifts ($z \sim 1$), where the observed $K$ samples the rest $J$. This is the subject of a forthcoming paper.

Here we focus on redshift 3 to search for the TP-AGB signature in the progenitors of massive Es, for which the $\alpha$-enhancement of their stellar populations constrain the star formation history to be short (e.g. 1-2 Gyr, see D. Thomas, this volume). This maximizes the relative fraction of stars that spend the TP-AGB phase simultaneously. At $z = 3$ the rest-frame near-IR maps into the observed mid-IR ($3 \lesssim \lambda/\mu$m $\lesssim 10$) and therefore SST is required. Figure 3 shows colour-

Fig. 3. Diagnostic colour-colour diagrams for the IRAC-SST filters to detect intermediate-age SP at the illustrative redshift of 3. Various synthetic stellar populations with solar metallicity are shown for which the stars started to form 0.8 Gyr before $z = 3$: a single burst (SSP, filled circle) and models with exponentially declining star formation with e-folding times of 1, 2 and 10 Gyr (filled triangles). For comparison, an SSP in which the TP-AGB phase is not included is shown as an open circle. Also shown is a younger and metal-poor and an older and metal-rich SSP (pentagon and star, respectively)
advantage of being better sheltered than optical bands from other effects, such as dust attenuation or newly born hot stars. These effects will be explored in a forthcoming paper.

Various SP models are shown in Figure 3 in which the stars started to form 0.8 Gyr before redshift 3. The filled circle is a single burst, or Simple Stellar Population (SSP), that includes the TP-AGB. The empty circle shows the same model, but in which the TP-AGB phase has not been included.

Figure 3 displays the same effect as we saw in Figure 1 using the familiar Johnson bands: the presence of TP-AGB stars enhances the rest-frame mid-IR flux. The single burst maximizes the effect because of the single age of the stars. However, the TP-AGB signature is still visible when extended star formation histories are considered (filled triangles). As mentioned above, this is due to the fact that at this redshift the three reddest IRAC filters still sample the mid-IR region, where the impact of the very young stars is minimized. Also shown in Figure 3 is a young, pre TP-AGB model with lower metallicity (pentagon), and an old, post TP-AGB, but metal-enriched model (star). As it can be seen, the larger metallicity is not able to mimic the red colours due to TP-AGB. From Figure 3 we infer a sizable magnitude difference as the marker of the transition between young and intermediate-age SP that could be effectively used as age indicator for high-redshift galaxies. The data collected with SST will allow the TP-AGB-based dating of stellar populations at large look-back times.

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