Late stages of stellar evolution and their impact on spectrophotometric properties of galaxies

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Abstract.   The connection between AGB evolution of stellar populations and infrared vs. ultraviolet properties of the parent galaxies is reviewed relying on the updated lookout provided by population-synthesis theory. In particular, planetary-nebula events and hot horizontal-branch evolution are assessed in a unitary view to outline a plain general picture of galaxy spectrophotometric evolution. This will include a brief discussion of relevant phenomena such as the "UV upturn" in ellipticals and the stellar mass loss properties along the galaxy morphological sequence.

1.   Introduction

A detailed and physically self-consistent modelling of post Main Sequence (MS) stellar evolution has been a challenging effort of theoretical astrophysics since the decade of the sixties (see, e.g. Iben 1967, and references therein for a documental overview of the relevant pioneering works since then). One main issue in this regard is that post-MS lifetime of stars (at every mass range) is no longer governed by the nuclear timescale alone, but different mechanisms intervene to strongly affect stellar structure, acting from "inside out" (e.g. convection) and from "outside in" (e.g. mass loss by stellar wind).

This forcedly restrains any theoretical output to a preliminary empirical validation process by matching real observations of nearby resolved stellar systems in order to suitably tune up the wide range of free parameters potentially allowed by theory.[1] Any successful approach in this sense, however, suffers from evident limitations as far as distant (unresolved) galaxies are taken into account in our analysis. By surveying different cosmic epochs and environment conditions, in fact, one might need to leave apart the local interpretative framework, typically constrained by the observation of low-mass metal-poor stars.

To overcome this potentially shifty bias in the analysis of deep cosmological data, and considering that post-MS stars alone provide typically over 2/3 of galaxy total luminosity in bolometric (Buzzoni 1995, 2005), it is of paramount importance to assess on a more firm basis the leading phenomena that constrain stellar evolution along its latest stages, like the horizontal (HB) and the asymptotic (AGB) giant branches, among galaxies of different morphological type.

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[1]The study of Galactic globular cluster c-m diagrams is an illuminating example in this sense (e.g. Renzini & Fusi Pecci 1988; Chiosi et al. 1992).
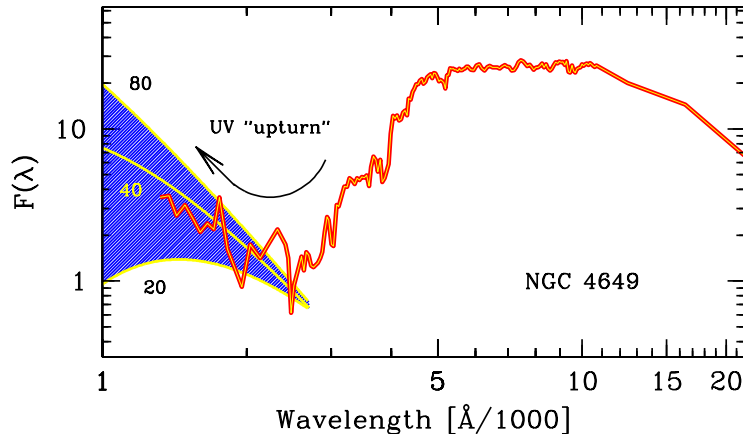
Figure 1.   The observed SED of the Virgo elliptical galaxy NGC 4649, one of the best example of the "UV upturn" phenomenon. The ultraviolet raising branch, shortward of 2000 Åis matched with three black-body curves, for 20, 40 and 80,000 K, as labelled on the plot. It is evident that stars around 40,000 K should be the main contributors to the observed UV galaxy emission, supplying in total about 2% of the galaxy bolometric luminosity.

2.   Horizontal branch morphology and the "UV-upturn" phenomenon in elliptical galaxies

The so-called "UV-upturn", that is the rising ultraviolet emission shortward of 2000 Å, sometimes featuring the spectral energy distribution (SED) of elliptical galaxies and the bulges of spirals (Code & Welch 1979) has been for long a puzzling problem for such old galaxy environments dominated by stars of mass comparable to the Sun.

In fact, the implied existence of an important contribution of (long-lived) O-B stars, hotter than 30 000 - 40 000 K and providing in the most striking cases about 2% of the galaxy bolometric luminosity (see Fig. 1), has been sometimes identified with binaries, blue stragglers, blue HB stars, AGB *manqué* stars, and post-AGB nuclei of planetary nebulae (PNe) (see Yi & Yoon 2004, for an updated review on this subject). Spectroscopy (Brown et al. 1997) and imaging (Brown et al. 2000) of resolved c-m diagrams for stellar populations in local galaxies, like M32, have definitely established that this UV excess mostly arises from the hot tail of a broad temperature distribution of HB stars further complemented, to a lesser extent, by a PN contribution.

As a blue HB morphology is more comfortably produced in old metal-poor globular clusters (e.g. Rood 1973) then, on this line, one should admit that UV stars in ellipticals represent the $Z \ll Z_\odot$ tail of an ostensibly broad metallicity distribution peaked at much higher values, around the solar abundance.[2]

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[2] A metal-rich chemical composition should be advocated for the star bulk in ellipticals given, for instance, a much stronger integrated Mg_2 Lick index for these galaxies, compared to Galactic globular clusters (see Fig. 2., and an extensive discussion in O'Connell 1999).
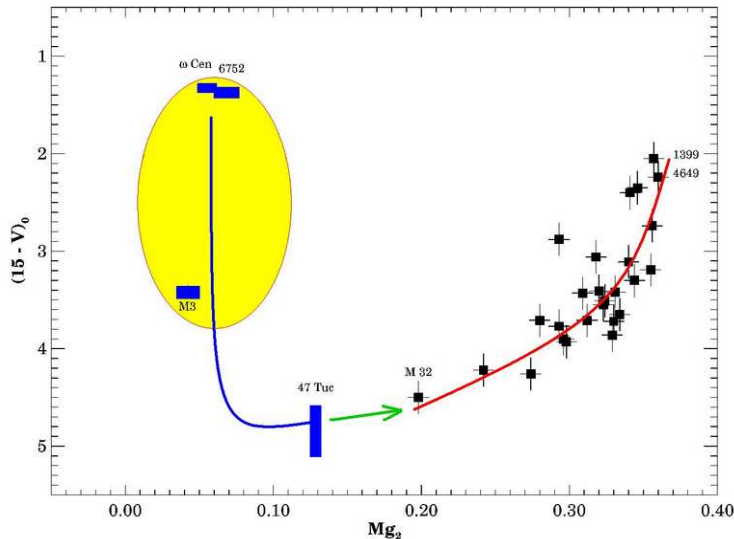
Figure 2. An illustrative sketch comparing UV-to-optical emission of Galactic globular clusters (vertical ellipse to the left) and elliptical galaxies (square-marker sequence to the right of the plot) after O'Connell (1999). The UV color is defined as $(15-V) = -2.5 \log[F(1500\text{Å})/F(V)]$. Some relevant objects are labelled for both groups. The Mg_2 Lick index is taken as standard metallicity indicator on the x-axis. It is evident that UV-enhanced integrated colors can be reached at the two extremes of the metallicity scale, in case of a blue HB morphology for metal-poorer globulars and due to EHB stellar contribution in case of the most metal-rich (giant) ellipticals. See text for discussion.

On the other hand, hot metal-rich HB stars might also be naturally predicted providing stars to approach the HB phase with a conveniently low external envelope, compared to their inner Helium core mass (Dorman et al. 1993; D'Cruz et al. 1996). Figure 3 is an illustrative example in this sense, displaying a full set of HB models of solar metallicity (i.e. red, intermediate and very blue stars) and their involved post-HB evolutionary paths, based on the Dorman et al. (1993) work. So-called "Extreme HB" stars (EHB), to be associated with hot SdO/SdB spectral types, have actually been observed, for example in ω Cen (D'Cruz et al. 2000) and in some old Galactic open clusters as well, like NGC 6791 (Kaluzny & Udalski 1992; Buson et al. 2006).

Though supplying a straightforward evolutionary framework for UV-enhanced elliptical galaxies, this hypothesis implies a quite delicate tuning of core mass size at the HB onset (as a result of RGB nuclear burning processes) and mass loss efficiency (to suitably "peel off", at the same time, stellar envelope). As a consequence, one has to expect the UV-to-optical color to be a quite fragile and quickly evolving feature in the SED of elliptical galaxies (Park & Lee 1997).

This is confirmed in Fig. 4, where we track back-in-time evolution of a 15 Gyr simple stellar population (SSP) of solar metallicity and intermediate HB morphology (such as to closely resemble the temperature distribution of stars
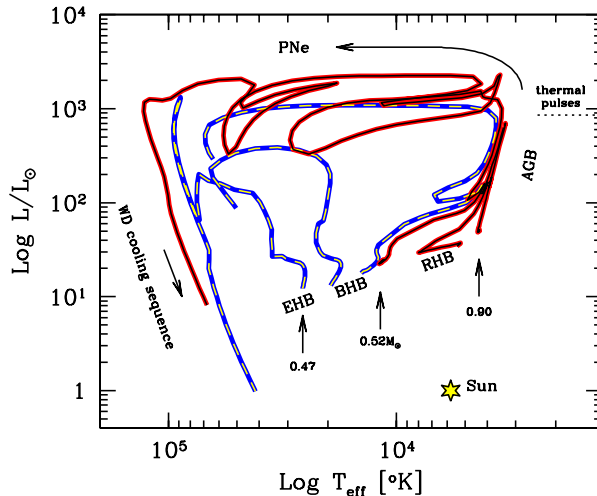
Figure 3. A selected set of HB evolutionary tracks with $Z = Z_\odot$ from Dorman et al. (1993). The starting track envelope roughly identify the HB locus with the value of three relevant stellar masses (namely 0.47, 0.52 and 0.90 M$_\odot$) labelled on the plot. Note the increasingly hotter HB temperature with decreasing stellar mass, with stars below ~ 0.50 M$_\odot$ occupying the EHB region of the diagram, pertinent to SdO/SdB spectral types, fully escaping the AGB phase (these are the so-called *"AGB-manqué"* stars) and directly fading along the white-dwarf (WD) cooling sequence. The reported value of ~ 0.52 M$_\odot$ is the threshold for post-HB stars to end up as PNe after completing AGB evolution and undergoing the thermal pulsing phase. The position of the Sun on the plot is located as a general reference for the reader.

in the M3 globular cluster), according to Buzzoni (1989) population synthesis code. Due to the presence of stars of increasingly higher mass at early epochs (giving rise to a red HB), one sees from the figure that the full UV burst event quickly recovers in about 3 Gyr, that is barely a ~ 20 % of galaxy's entire life. The UV-upturn can therefore fade by several magnitudes as the lookback time increases by a few Gyrs, making the effect in principle detectable at intermediate redshift ($z = 0.2 - 0.3$) (Brown et al. 2003, see also Ree et al, this conference).

3. Planetary Nebulae and the Initial-to-Final mass relation

Along the SSP evolution, a substantial fraction (up to 50%) of star mass can be lost during the AGB phase via stellar wind. If the mass-loss process is strong enough, low-mass stars entering the AGB phase can easily approach a critical C-O core mass threshold about $M_{core} \simeq 0.52$ M$_\odot$. This is the minimum mass for stars to fully complete AGB evolution and experience the so-called "thermal-pulsing" phase (Dorman et al. 1993; Blöcker 1995, see also Fig. 3 above). Along thermal pulses, stars venture in the region of Mira variables and end up through the so-called "superwind phase" by quickly ejecting their residual envelope and originate a PN (see Iben & Renzini 1983, for an exhaustive discussion of the process and its variants).
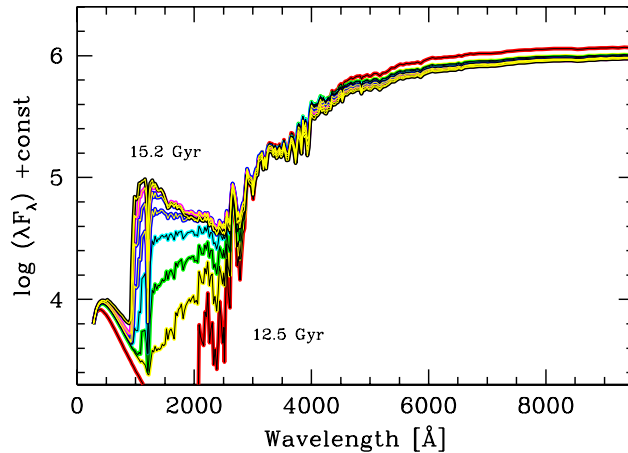
Figure 4. Integrated SED for a SSP of solar metallicity, Salpeter IMF and Reimers (1975) mass-loss parameter $\eta = 0.5$ after Buzzoni (1989). Spectral evolution is computed at steps of 200 Myr from $t = 15.2$ to 14 Gyr, plus a further model at 12.5 Gyr, as labelled on the plot. A broad temperature distribution of HB stars (matching the observed M3 HB morphology) is assumed at $t = 15.0$ Gyr. Note the quick evolution of the UV excess between 1000 and 2500 Å, that already disappeared in the 12.5 Gyr model in consequence of the corresponding reddening of the HB color distribution. A second and nearly steady minor UV bump can be recognized shortward of 1000 Å due to the contribution of PN nuclei.

Models indicate that the lack of a full AGB deployment (when $M_{\mathrm{core}} \lesssim 0.52\ M_\odot$) leads to a range of post-HB evolutionary paths (see, again, the sketch in Fig. 3),[3] as discussed in detail by Greggio & Renzini (1990). One relevant case in this regard is that of EHB objects, that evolve as *"AGB-manqué"* stars, thus fully escaping the PN ejection and fading directly along the high-temperature white-dwarf cooling sequence (Castellani et al. 1992, 1995; Dorman et al. 1993; D'Cruz et al. 1996; Yi et al. 1998).

Quite interestingly, therefore, the successful detection of PNe, even in distant unresolved galaxies, places a further interesting constraint to the final mass of the composing stellar population. More specifically, the PN number density per unit galaxy luminosity, a parameter often referred to in the literature as the "α ratio" (Jacoby 1980), can directly be linked to the characteristic lifetime of the nebulae, the latter closely tracing the mass distribution of their nuclei (see Buzzoni et al. 2006, for a full discussion). On the basis of these arguments, PNe can eventually help constraining the initial-to-final mass relation (IFMR) also in extragalactic systems.

For our galaxy, the IFMR can be derived empirically from the observation of the white dwarfs in nearby open clusters (like Hyades or Praesepe) of known age (as obtained, for instance by the isochrone fitting method of the cluster c-m

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[3]From the physical point of view, this would correspond to the He+H double-shell burning regime for low- and intermediate-mass stars.
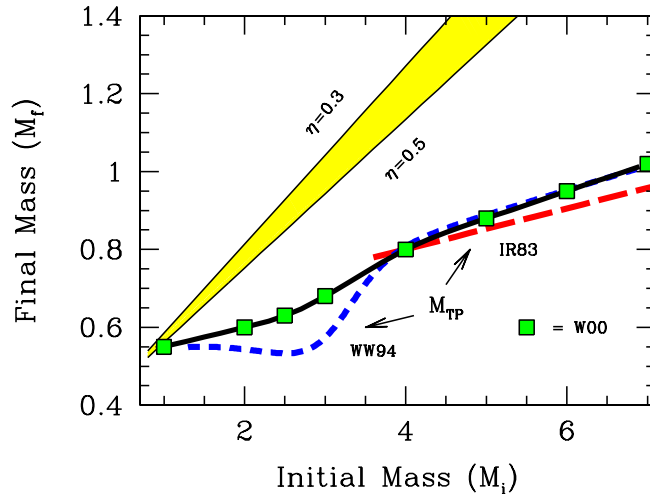
Figure 5. The initial-to-final mass relation according to different calibrations. The solid strip is the theoretical relation of Iben & Renzini (1983) for a standard mass loss parameter η in the range between 0.3 and 0.5, as labelled on the plot. Short- and long-dashed curves are the theoretical loci for stars to set on the AGB thermal pulsing phase ($M_{\rm TP}$), according to Iben & Renzini (1983) (IR83) and Wagenhuber & Weiss (1994) (WW94). Finally, big squares and solid curve report the Weidemann (2000) (W00) empirical relation based on the mass estimate of white dwarfs in Galactic open cluster.

diagram). In an exhaustive study of the available observed database, Weidemann (2000) found evidence that white-dwarf masses, for low- and intermediate-mass stars, closely match the theoretical core masses expected at the beginning of the thermal-pulsing AGB. This claim is accounted for in Fig. 5, where we compare the Weidemann (2000) IFMR with the Wagenhuber & Weiss (1994) updated set of AGB stellar tracks for Pop I stars, and with the original analytical relation for thermal-pulsing core mass for intermediate-mass stars by Iben & Renzini (1983). It is clear from Fig. 5 that, for a standard range of the Reimers (1975) mass-loss parameters pertinent to Galactic globular clusters (namely $\eta \simeq 0.4 \pm 0.1$, according to Fusi Pecci & Renzini 1976) the Iben & Renzini (1983) theoretical IFMR predicts unreliably high final masses for young ($t \lesssim 2$ Gyr) SSPs, requiring a value of $\eta \gg 1$ to match the Weidemann (2000) empirical relation.

As far as external galaxies are concerned, the Local Group represents a natural benchmark to assess the IFMR through the estimated α ratio from deep PN surveys. Quite surprisingly, in spite of the extreme variety of star formation histories among local galaxies, Buzzoni et al. (2006) have demonstrated that observations support a fairly constant value of α, with an average PN rate per unit galaxy luminosity between 1 and 6 PNe per 10^7 L$_\odot$ among systems representative of the whole late-type Hubble morphological sequence. Such a value is related to a quite narrow range of final stellar masses about 0.60-0.65 $M_\odot$.

Even in case of Local Group member galaxies, therefore, the mass-loss scenario supported by the PN observations better agrees with the Weidemann (2000) IFMR, which implies a substantially stronger mass loss for intermedi-
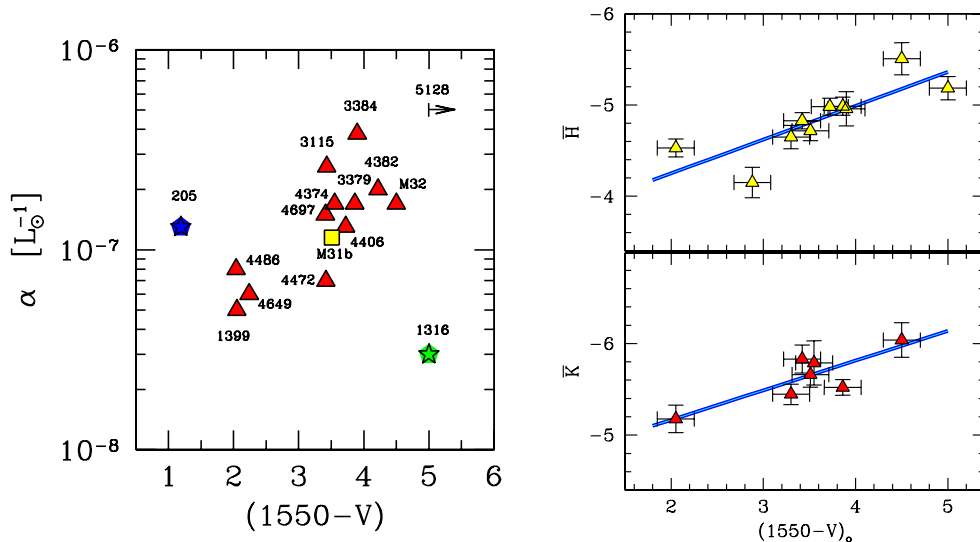
Figure 6. *Left panel:* the observed relationship between PN luminosity-specific rate α and integrated ultraviolet-to-optical emission (as defined in Fig. 2.) for a sample of elliptical galaxies in the Local Group and in the Virgo, Leo and Fornax clusters according to Buzzoni et al. (2006). The relevant case of outliers like NGC 205 (star-forming) and NGC 1316 (merger elliptical) are singled out in the plot. *Right panel:* the corresponding relationship in place among the Cantiello et al. (2003) sample of quiescent ellipticals vs. Tonry & Schneider (1988) effective magnitudes in the H and K infared bands. The most UV-enhanced galaxies display the faintest infrared effective magnitudes, sensitive of a less deployed AGB.

ate and high-mass stars compared to the standard scenario for Pop II stars as in Galactic globular clusters.

4. UV evolution and AGB connection in elliptical galaxies

One important consequence of the *"AGB-manqué"* evolution of EHB stars is that a tight and *inverse* relationship must be in place, especially involving elliptical galaxies, between the most PN-poor and UV-enhanced stellar systems. A prevailing fraction of hot (low-mass) HB stars in the galaxy stellar population, in fact, can be strongly favoured by a more efficient mass loss (at least along the RGB evolution), and this scenario, by itself, also plays against any full AGB deployment. Therefore, if this is the case, few stars (if any) can eventually reach the AGB feeding the PN production channel.

As shown in Fig. 6 (left panel) this correlation is actually displayed between PN luminosity-specific rate α and the $(1550 - V)$ color for elliptical galaxies in the Virgo and Fornax clusters, and in the Leo group, after Buzzoni et al. (2006). The sense is that more massive metal-rich systems (traced by a higher velocity dispersion σ_v and a stronger integrated Lick Mg_2 index) display at a time a stronger UV-upturn *and* a poorer PN population per unit galaxy luminosity.

The Buzzoni et al. (2006) relationship settles an old (and so far unexplained) empirical evidence for a trend of PN rate, seen to decrease among the reddest ellipticals (Hui et al. 1993).

As α can actually be considered as an indirect probe of galaxy AGB extension above the thermal-pulses threshold, this would naturally lead to expect some correlation between the PN luminosity-specific rate and galaxy infrared colors or, even better, with more sensitive and unbiased tracers of the cool galaxy stellar component. This is, for instance, the case of the infrared effective magnitudes, as derived from the surface-brightness fluctuation method of Tonry & Schneider (1988). Again, our guess is fully confirmed by a study of the Virgo and Leo elliptical sample (Buzzoni & González-Lópezlira, in preparation), as shown in the right panel of Fig. 6 based on Cantiello et al. (2003) compilation database.

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