The final stages of low- and intermediate-mass stars

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Origin of the hot gas and silicate emission in ETGs: AGB stellar winds and PN ejection?

2D hydrodynamical simulations of the interaction between the ambient ISM and the AGB wind + PN ejection


Spitzer spectra of early-type galaxies in Virgo

Silicate emission at 10\(\mu\)m due to O-rich mass-losing dusty AGB stars?

Input stellar parameters:
- AGB mass loss rates
- duration of the super-wind phase
- PN masses
- expansion velocities
Origin of LINERS: ionizing photons from Post-AGB stars?

Debate on ionizing sources:
- Low accretion-rate AGNs
Ionizing photon rates of simple stellar populations

Post-AGB stars:
- harder ionization field than massive OB stars
- Drop of ~ 5 orders of magnitude in $q_H$ at ages $\sim 10^8$ yr, then flat evolution.

Agreement between different SSPs models only qualitative.
Variations in $q_H$ by up to 1 dex for ages $> 10^8$ yr.
Differences in ionizing flux for ages $\geq 10^8$ yr should be attributed to:

- Different treatments of the TP-AGB phase (initial-final mass relation)
- Different treatments of the post-AGB phase (evolutionary time-scales)
- Metallicity
- IMF
Basic Stellar Evolution of C-O WD Progenitors

- From ~0.9 to 8 M\textsubscript{\odot}
  - Thermally Pulsing AGB
  - Unique nucleosynthesis
  - 3d dredge-up
  - 2d dredge-up
  - Strong mass loss

AGB star structure

- ZAMS
- H \rightarrow He
- He \rightarrow C_{1,0}
- To PN and WD...

Deep convective envelope

- Thin radiative zone
- H burning shell
- Helium-rich intershell
- Helium burning shell
- CO core

Adapted from Lattanzio
AGB and Post-AGB evolution

Hot Advanced Evolution of Low- and Intermediate-Mass Stars

- Post-AGB: H-burners
- Post-AGB: He-burners
- Post-early AGB
- Hot HB and AGB-manquè stars
UV evolutionary paths for low-mass and intermediate-mass single stars

**Post-AGB (P-AGB) stars:**
- the end result of the AGB phase
- expected in a wide range of stellar populations
Initial masses 0.8 - 8 $M_\odot$
MS lifetimes: $10^8$ - $10^{10}$ yr

**PE-AGB and AGB-manqué stars:**
- the result of insufficient envelope masses to allow a full AGB phase.
- are expected to be particularly prominent at high helium or $\alpha$ abundances when the mass loss on the RGB is high.
Initial masses < 2 $M_\odot$
MS lifetimes $\gtrsim 0.6 \times 10^9$ yr

**Graphical Representation:***
- $P - AGB$: $10^3$-$10^4$ yr
- $PE - AGB$: $10^5$-$10^6$ yr
- $AGB - Manquè$: $10^6$-$10^7$ yr
- $ZAHB$:

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PAGB: Vassiliadis & Wood ’94
All others: Bressan, Marigo, Girardi et al. 2012
Ionisation rates during the Post-AGB evolution of the central star

More massive CS:
- hotter and brighter
- faster evolution

MAIN PARAMETERS:
- Luminosity $\propto$ CS mass $\Rightarrow$ AGB evolution
- Effective temperature $\Rightarrow$ post-AGB evolution

Marigo et al. 2001
Post-AGB evolution: I. the central star mass

62 white dwarfs, most in open clusters
Extension to the low-mass end:
CPMPs Catalan et al. 2008
old open clusters Kalirai et al. 2008
change of slope at \( M_i \approx 4 M_\odot \)

\( M_{WD} \) and \( t_{cooling} \): spectral fitting
(Teff and g) +
grid of WD models and theoretical M-R relation

\( M_i \): \( \tau(M_i) = \tau(\text{cluster}) - t_{cooling}(WD) \)

Uncertainties due to stellar evolution
Age and metallicity of clusters
overshooting
Thickness of the WD H/He layers
Composition of the WD core
(He, C-O, O-Ne)
The core mass growth on the TP-AGB depends on (1) the efficiency of stellar winds (uncertain). The longer the AGB lifetime, the larger the final mass.

Pulsation-assisted dust-driven wind

Superwind $\Rightarrow$ PN ejection

$\text{exp}$


Ramstedt et al. 2009
The core mass growth on the TP-AGB depends on (2) the efficiency of the third dredge-up (uncertain).

The efficiency

$$\lambda = \frac{\Delta m_{\text{du}}}{\Delta m_{\text{H}}}$$

is poorly known.
Calibration of the AGB phase needed!

Ongoing ERC project:

The ACS Nearby Galaxy Survey Treasury

- 62 dwarf galaxies
  - $d < 4$ Mpc
  - All metallicities down to very low

AGB LFs $\Rightarrow$ lifetimes


- Initial-final mass relation of intermediate-age WD progenitors $\Rightarrow$ core mass growth

Post-AGB evolution: II. evolutionary speed

- \( t_{tr} \): transition time from AGBtip to onset of H-ionization (few \(10^2\) – few \(10^4\) yr)
- Onset of the radiation-driven fast wind
- \( t_{cr} \): Crossing time from ionization to hottest point

Depends on erosion rate of the envelope =
At the top: stellar wind (uncertain) +
At the bottom: displacement of the H-shell
Post-AGB evolution: III. H vs He burners

Luminosity and evolutionary speed affected by TPC phase $\phi$ at which the star leaves the AGB:

- Larger $\phi \Rightarrow$ H-burners ($L \sim L_H$)
- Lower $\phi (< 0.25) \Rightarrow$ He-burners ($L \sim L_{He}$)

**He-burners (15-25%)**
- More prone to experience a LTP
- Slower evolution
- Less luminous
He-burners have longer timescales than H-burners.

An example: a post-AGB star with $M \sim 0.6 \, M_\odot$

The He burner emits more ionizing photons than the H-burner does (factor of a few).
Ionizing rates of SSPs: $M_i-M_f$ relations

- **Mi-Mf relation:** Weidemann 2000
- **Mi-Mf relation:** Williams 2007
- **Mi-Mf relation:** Kalirai et al. 2008
Stellar Mass-Loss rates from detailed AGB evolutionary models

Sample output of a TP-AGB model (Mi=5 M⊙, Zi=0.008) computed up to the ejection of the envelope

Specific rate of mass loss from SSPs

Mass injection rates in ETGs: stellar winds and SNIa

\[ \dot{M}_* (12 \text{ Gyr}) = 3.6 \times 10^{-12} \, L_B \left( \frac{L_B}{L_B,\odot} \right) \, M_\odot \, \text{yr}^{-1} \quad \text{(ongoing calibration)} \]

\[ \dot{M}_* (12 \text{ Gyr}) = 4.1 \times 10^{-11} \, L_B \left( \frac{L_B}{L_B,\odot} \right) \, M_\odot \, \text{yr}^{-1} \]

\[ \dot{M}_{\text{SNIa}} (12 \text{ Gyr}) = 2.2 \times 10^{-13} \, L_B \left( \frac{L_B}{L_B,\odot} \right) \, M_\odot \, \text{yr}^{-1} \]
FINAL REMARKS

- Details of AGB and Post-AGB evolution critical to investigate the feedback of these stars on galaxy properties.

- Many uncertainties ⇒ AGB calibration needed, new post-AGB models needed

- Post-AGB ionizing rates: Mi-Mf relation, H/He burners, crossing times

- AGB mass injection: theoretical predictions with detailed AGB evolution models covering wide ranges of ages and metallicities are now feasible.

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UV evolutionary paths in UVIS and Galex filters

Evolutionary tracks

HST/WFC3-UVIS

Galex

PHAT data of M31

Globular Clusters

Helium-enhanced HB models: stronger far-UV flux compared to the normal helium models


HR diagrams and SEDs of a simple stellar population
[Fe/H] = −0.9
age=11 Gyr

Helium-rich stars evolve faster ⇒ they have lower masses at given age.

<Teff> of HB stars with Y = 0.33 is
~ 11,500 K higher than for Y = 0.23

Y=0.23
normal helium

Y=0.33
enhanced helium