AGB stars in intermediate age Clusters

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Why AGB Stars?

- Are among the most important polluters of the interstellar medium.
- Provide an important contribution to the IR light of galaxies.
- AGB stars as laboratory of physics beyond the standard model.

Why in Stellar Clusters?

- We can directly observe an "evolutionary track". The AGB lifetime is rather short, indeed, so the variation of the mass along the isochrone is negligible.
- The mass of AGB stars can be easily estimated, once the cluster age is known.

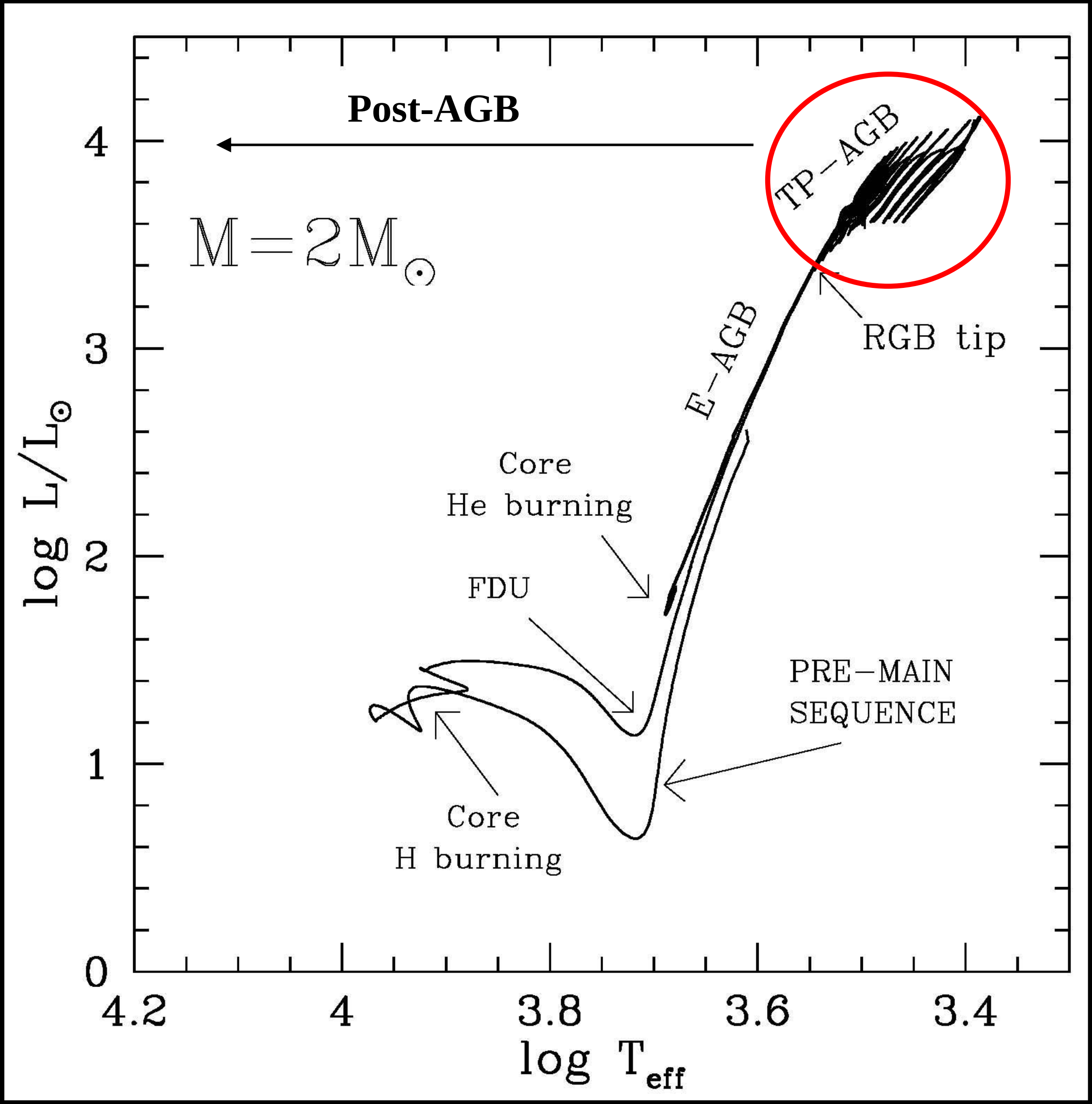
Cluster observations allow us to constrain the physics and the nucleosynthesis of AGB stars.

The variation of the chemical composition along the evolutionary sequence is the result of a complex interaction between nuclear processes occurring in the deep interior and macroscopic mixing episodes.

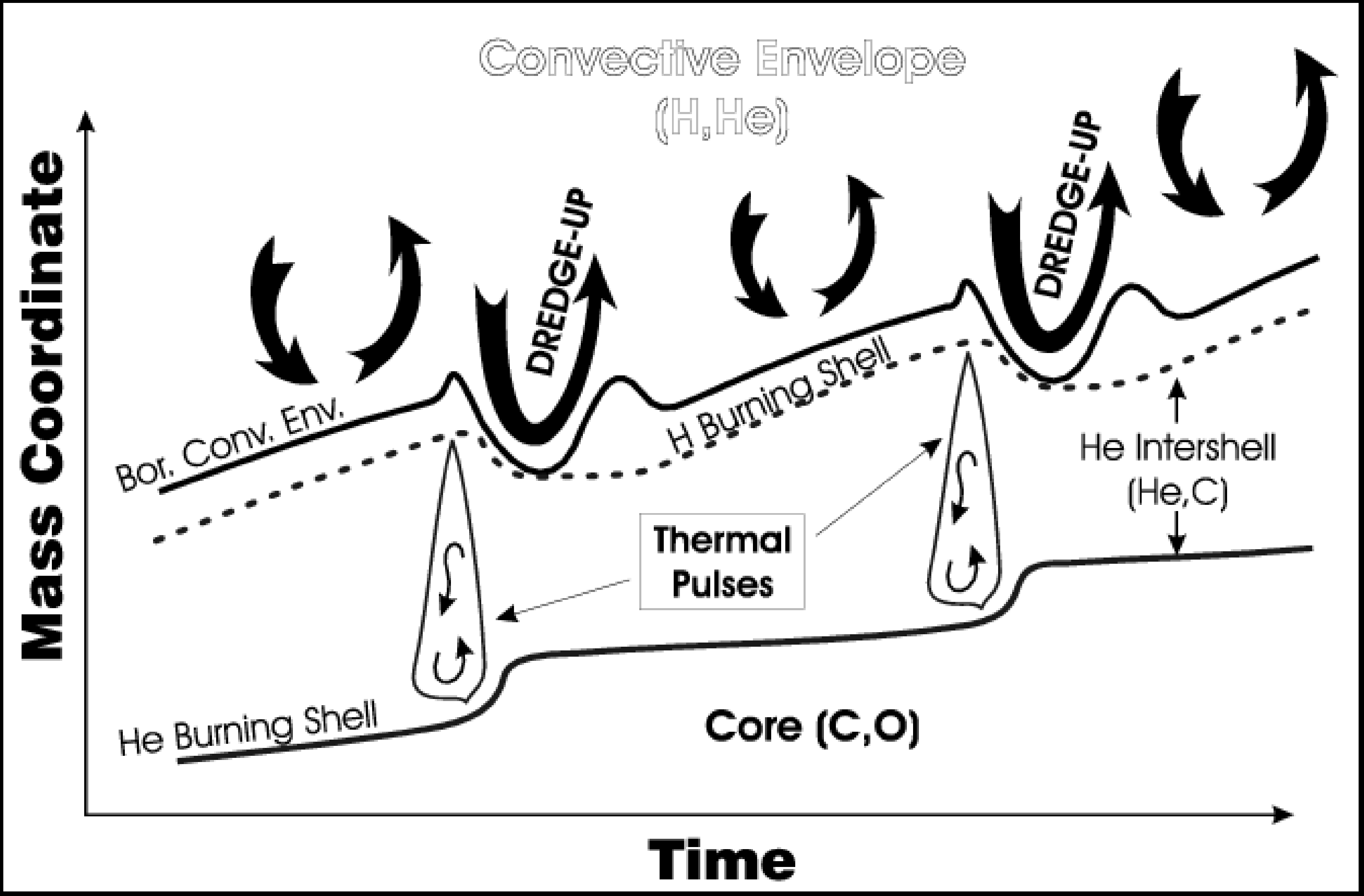
Why intermediate age clusters?

- Intermediate age clusters are ideal targets to study the AGB contributors to GCE, i.e. evolved stars with mass ranging between 1.5 and 6 $M_{\odot}$
- GCs with age ranging between 0.1 to 2 Gyr,, can be found in the Magellanic Clouds or in Dwarf Spheroidal galaxies
- Galactic GCs are very old (13-14 Gyr). The mass of the present-day AGB stars is 0.6-0.7 $M_{\odot}$ (0.8-0.9 initial). Too small for AGB dredge up
- Galactic Open Clusters are younger, but contain a limited number of stars. Very few AGBs can be found, if any.

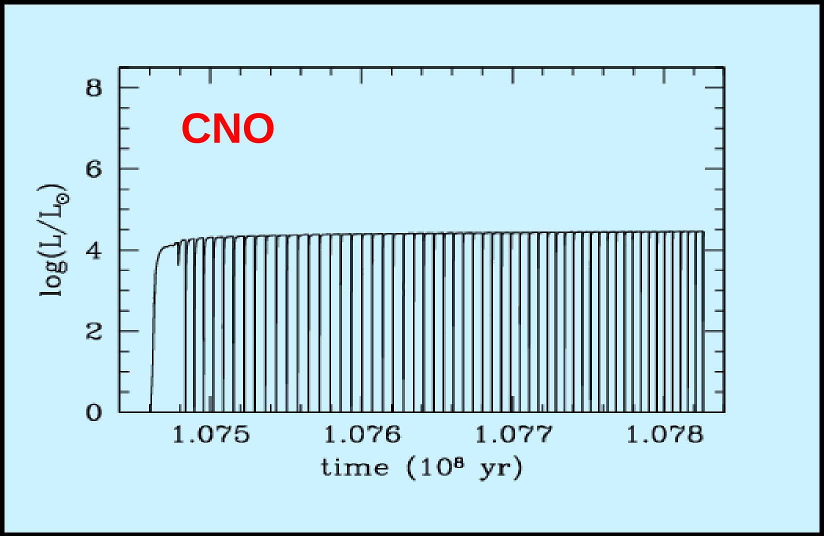
The H-R diagram

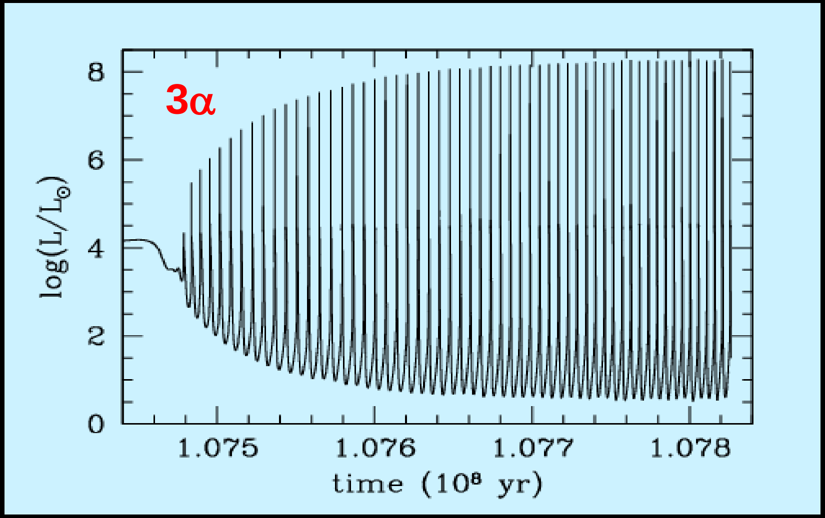


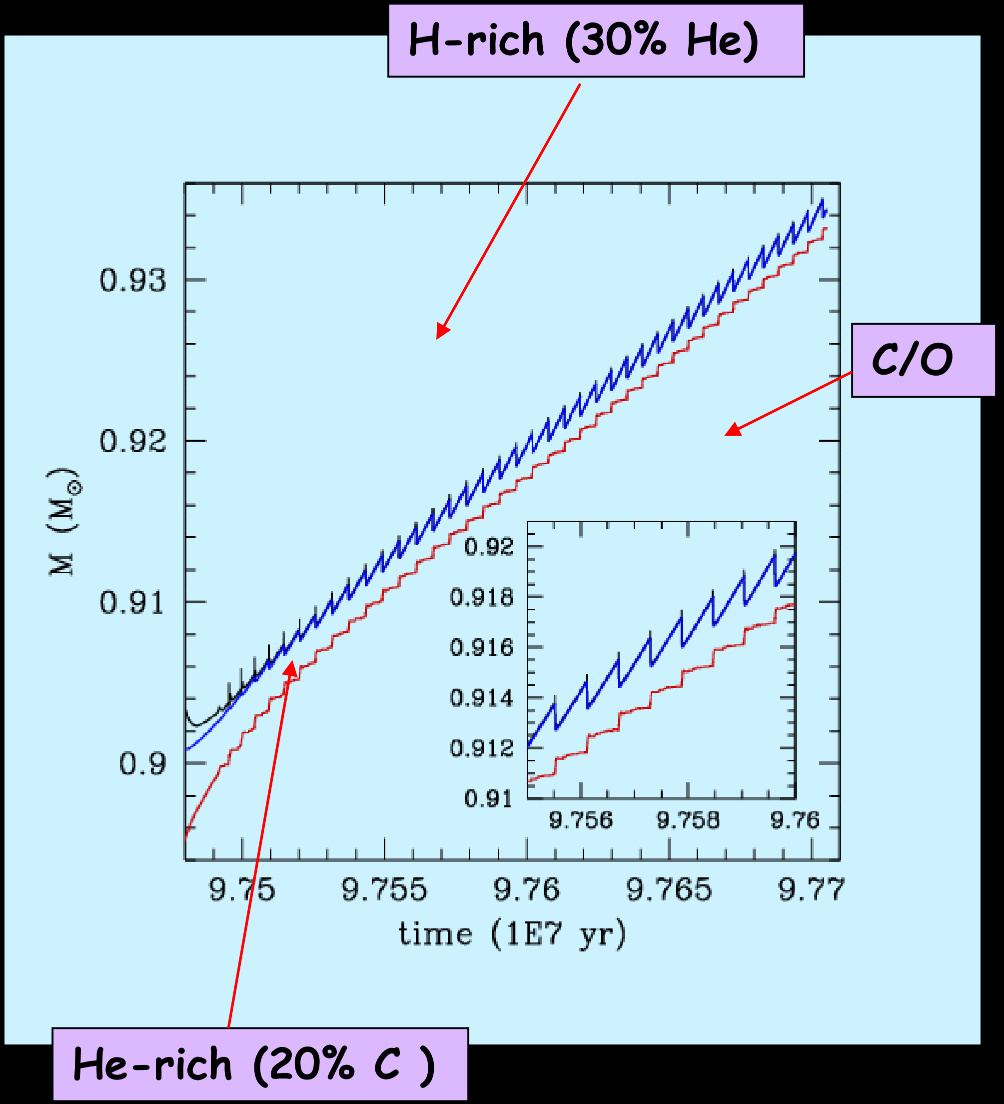
Pulse-interpulse-pulse sequence



Thermally Pulsing AGB stars







A (theoretical) classification

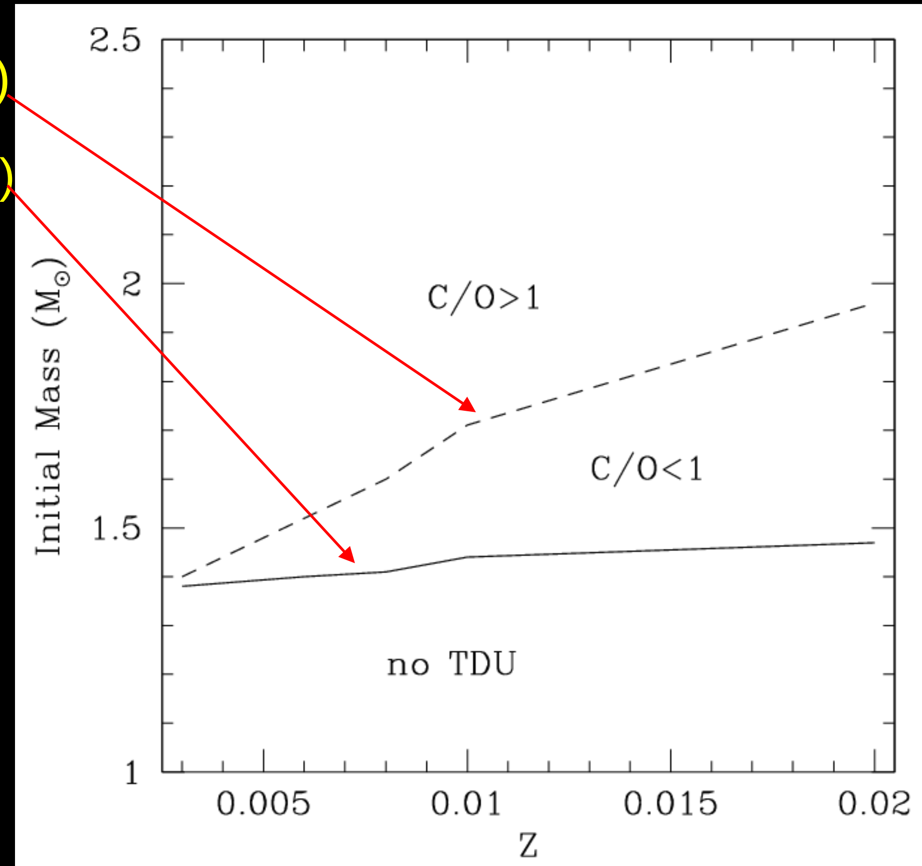
	Type I	Type II	Type III	Type IV	Type V	Type VI super-AGB
Mass range: $Z=Z_\odot$ Z=0.0001	<1.3 <1.1	1.3-1.8	1.8-3.5 1.1-2.5	3.5-6 3-5.5	6-8 5.5-7	8-10 7-9
TDU	NO	YES	YES	YES	No	No
HBB	NO	NO	NO	marginal	strong	strong
s-process: $^{22}Ne(\alpha,n)^{25}Mg$ $^{13}C(\alpha,n)^{16}O$	No	Yes marginal dominant	Yes marginal dominant	Yes dominant marginal	No	No
Final core mass	0.5-0.6	~ 0.6	~ 0.7	0.7-1.0	1-1.1	1.1-1.3
C/O	0.35 0.1	0.5-0.9	0.5-2 0.5-1000	0.5 to >1 0.5 to >1	<1 <1	<1 <1
spectral type	M	M, MS, S	M,MS,S.C	M,MS,S.C	M	M

minimum C-star mass (dashed)

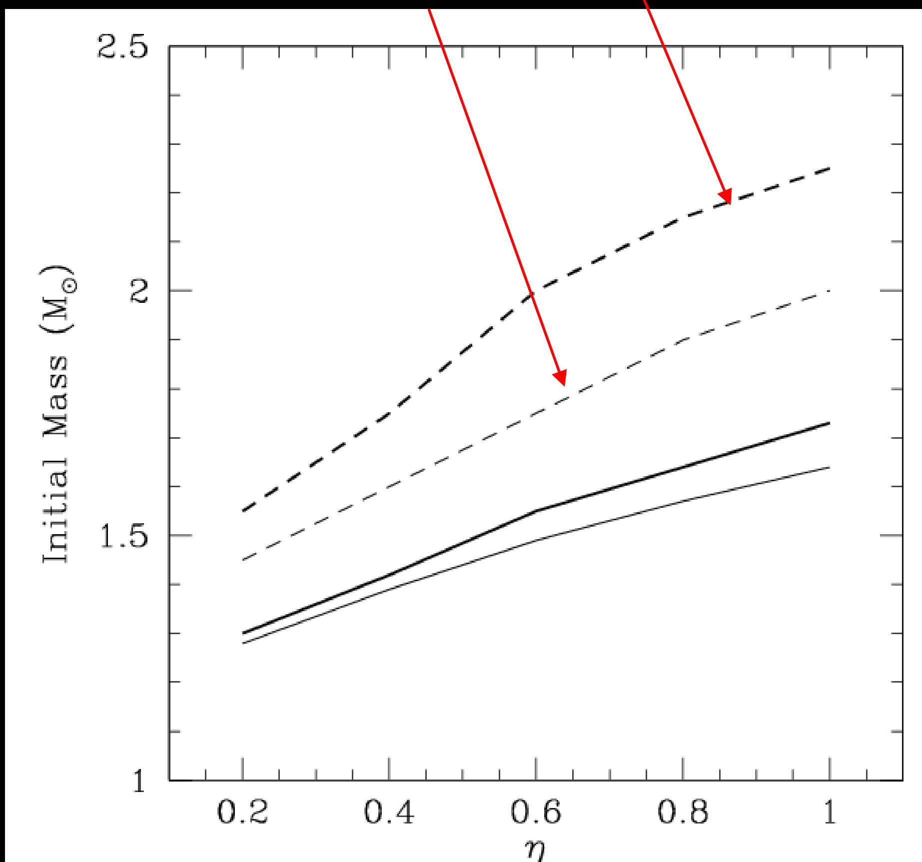
minimum dredge-up mass (solid)

minimal dredge up (thick)

Best s-process fit (thin)



versus metallicity



versus mass loss

Straniero et al. 2003, PASA

The puzzling case of NGC 1846 & 1978

- Both are intermediate age GCs of LMC. about 1.5 (±0.3) Gyr (isochrones fitting) .

- Mass of the present-day M type AGB stars: M=1.8 (±0.2) $M_{\odot}$. (isochrones & pulsation)

- Similar metallicity and O enhancement: [Fe/H]=-0.5, [O/Fe]=+0.2

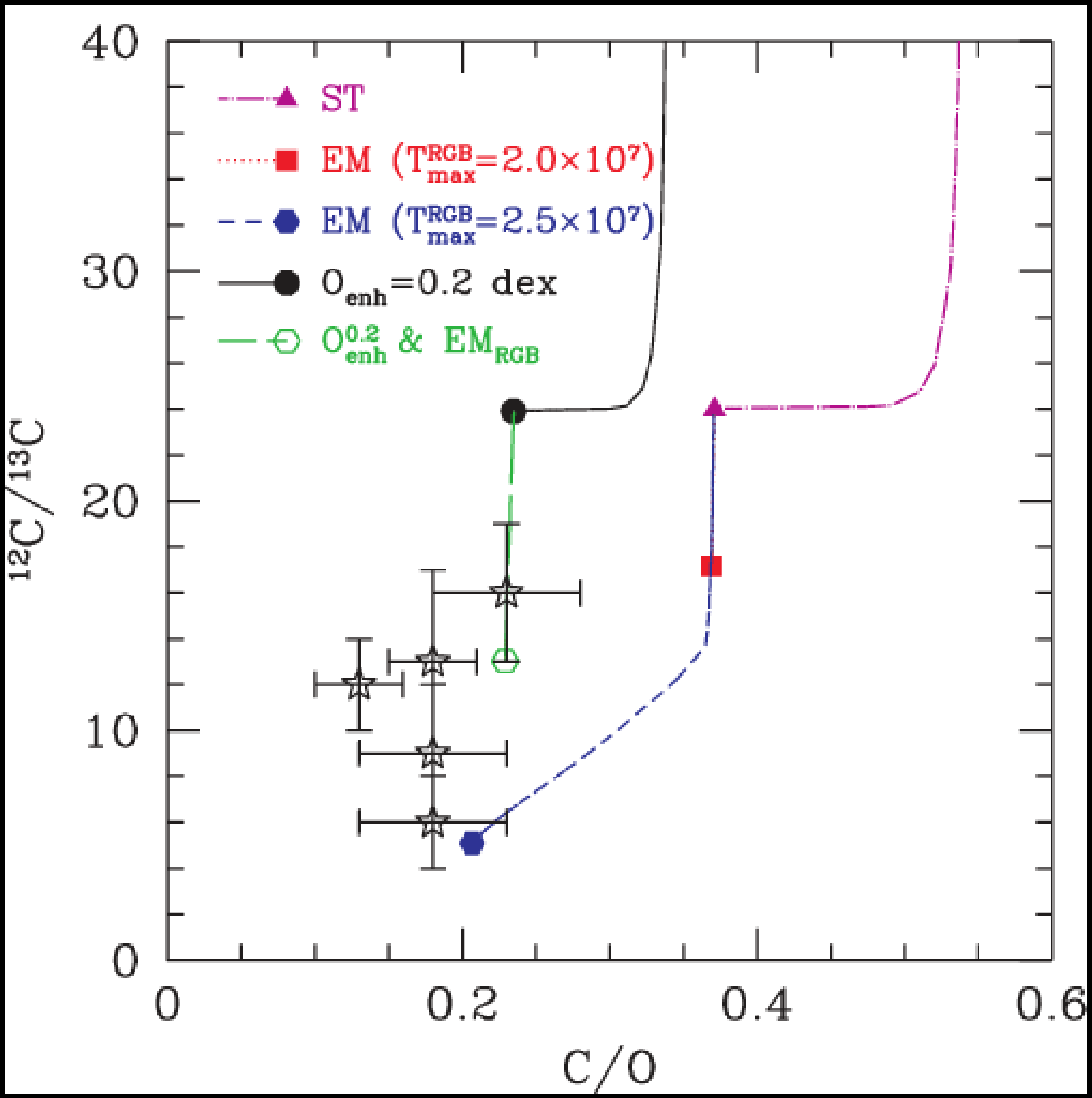
How to read the pre AGB variations of C and O

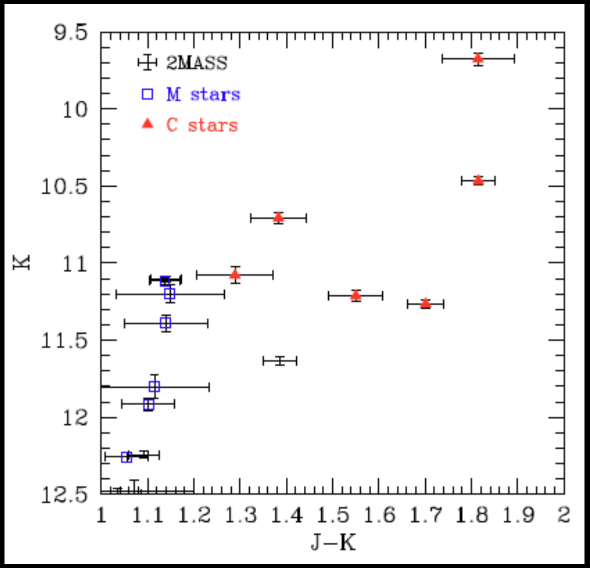
- Initial abundances for scaled scaled solar composition (Lodders 2003): **$^{12}C/^{13}C$=89, C/O=0.5**.
  C/O lower if O enhanced.

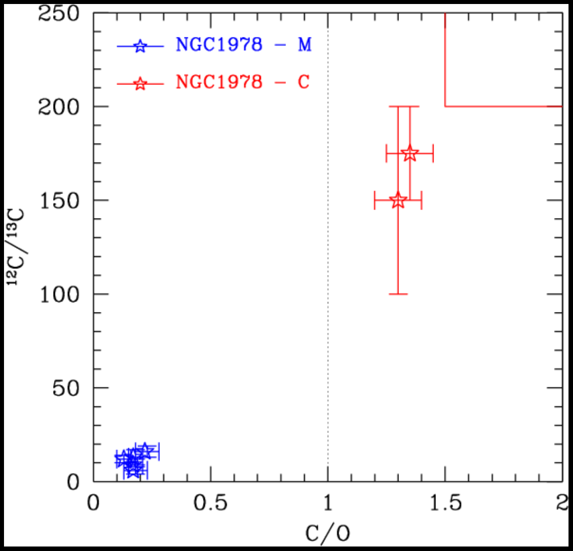
- After the first dredge up ^{12}C decreases, ^{13}C increases, whle O almost unchenged: **$^{12}C/^{13}C$=20-25 C/O=0.35**

- In case of moderate RGB deep mixing (T_{MAX}<20 MK), ^{13}C decreases ($^{12}C/^{13}C$ down to 16) C/O unchanged.
  Deeper mixing: further reduction of $^{12}C/^{13}C$ (down to 5) and C/O reduced (down to 0.2)

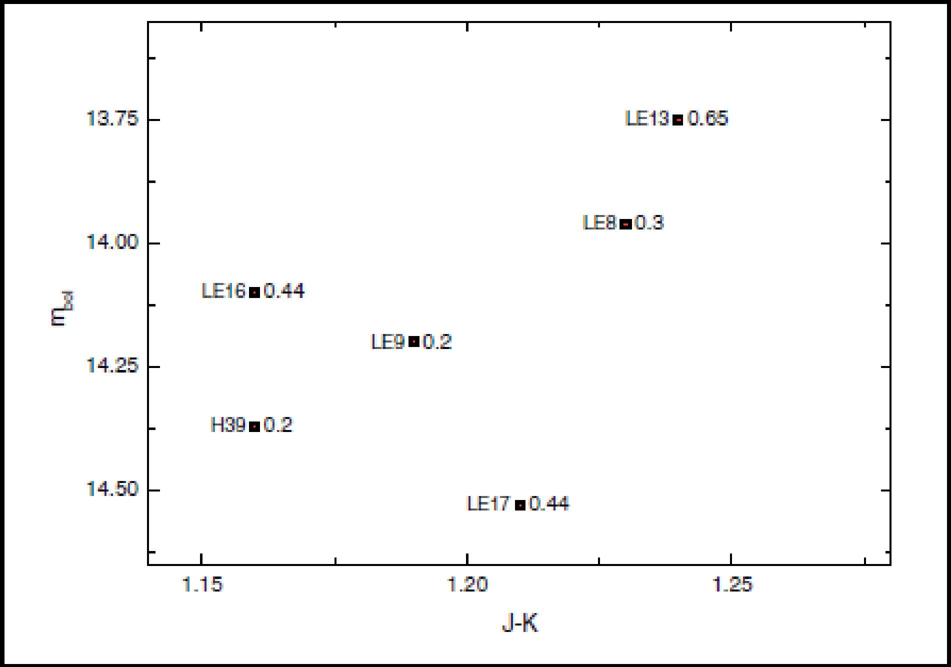
M stars in NGC 1978 (Lederer 2009): Operation of deep mixing in RGB

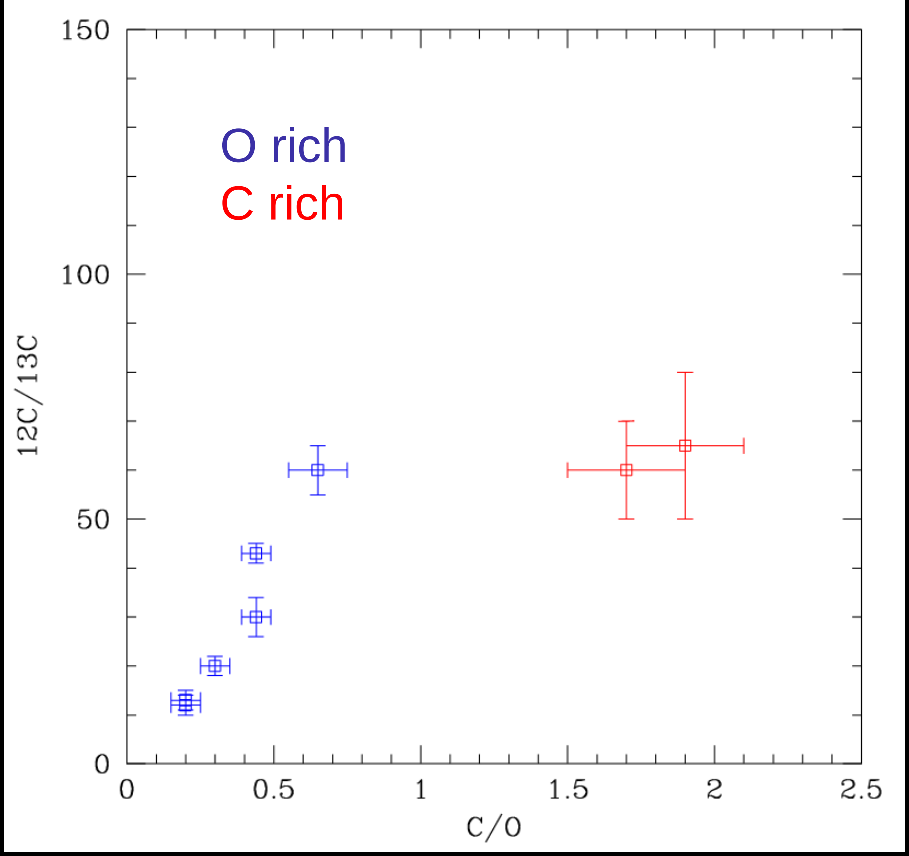






NGC 1846 (Lebzelter et al. 2008) : O-rich AGB stars. First evidence of AGB chemical evolution





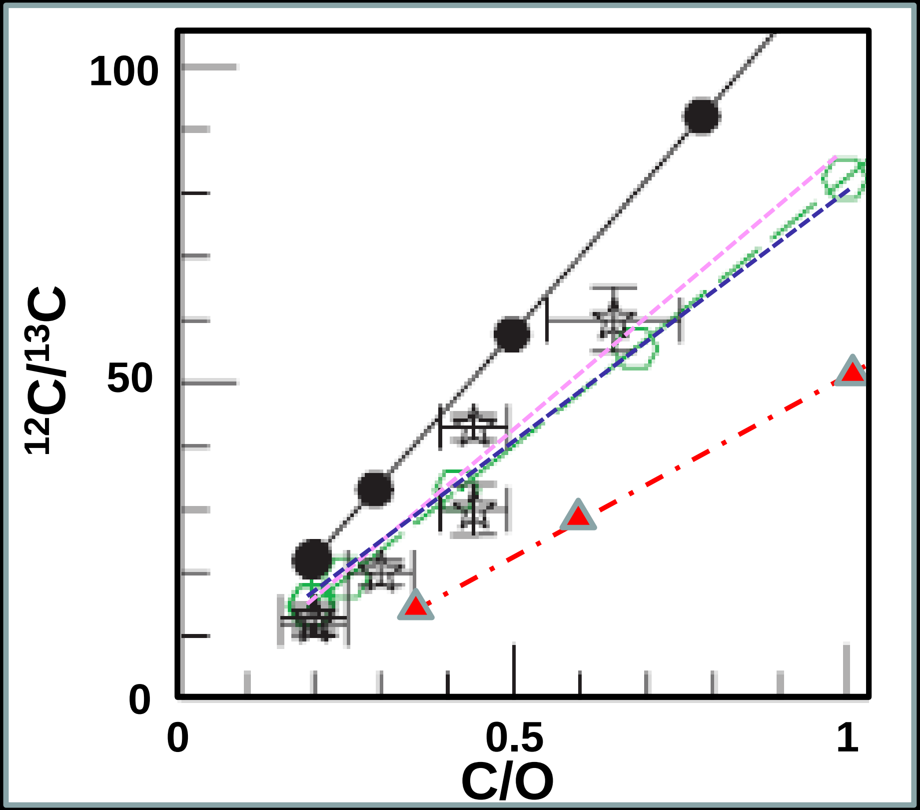
How to read the C-O var. along the AGB

- ^{12}C is the main product of the shell-He burning. **Its abundance increases after each TDU** (third dredge up).

- ^{16}O is depleted by the shell-H burning and marginally produced by the He burning occurring within the convective zone generated by a TP. **Its abundance is marginally affected by the TDU**. However, if a sizable overshoot takes place at the base of the convective TP, the O abundance may increase.

- ^{13}C is produced by the H burning in the zone of incomplete CNO, while it is destroyed in deeper layers. **Its abundance does not significantly change due to the TDU**. However it is extremely sensitive to the occurrence of deep mixing during interpulse periods.

M-MS-S stars in NGC 1846.



Mass from turn-off age and LPV analysis (Lebzelter & Wood 2007).

$M=1.9\ M_\odot$ (1.8 on the AGB)

Z=0.006

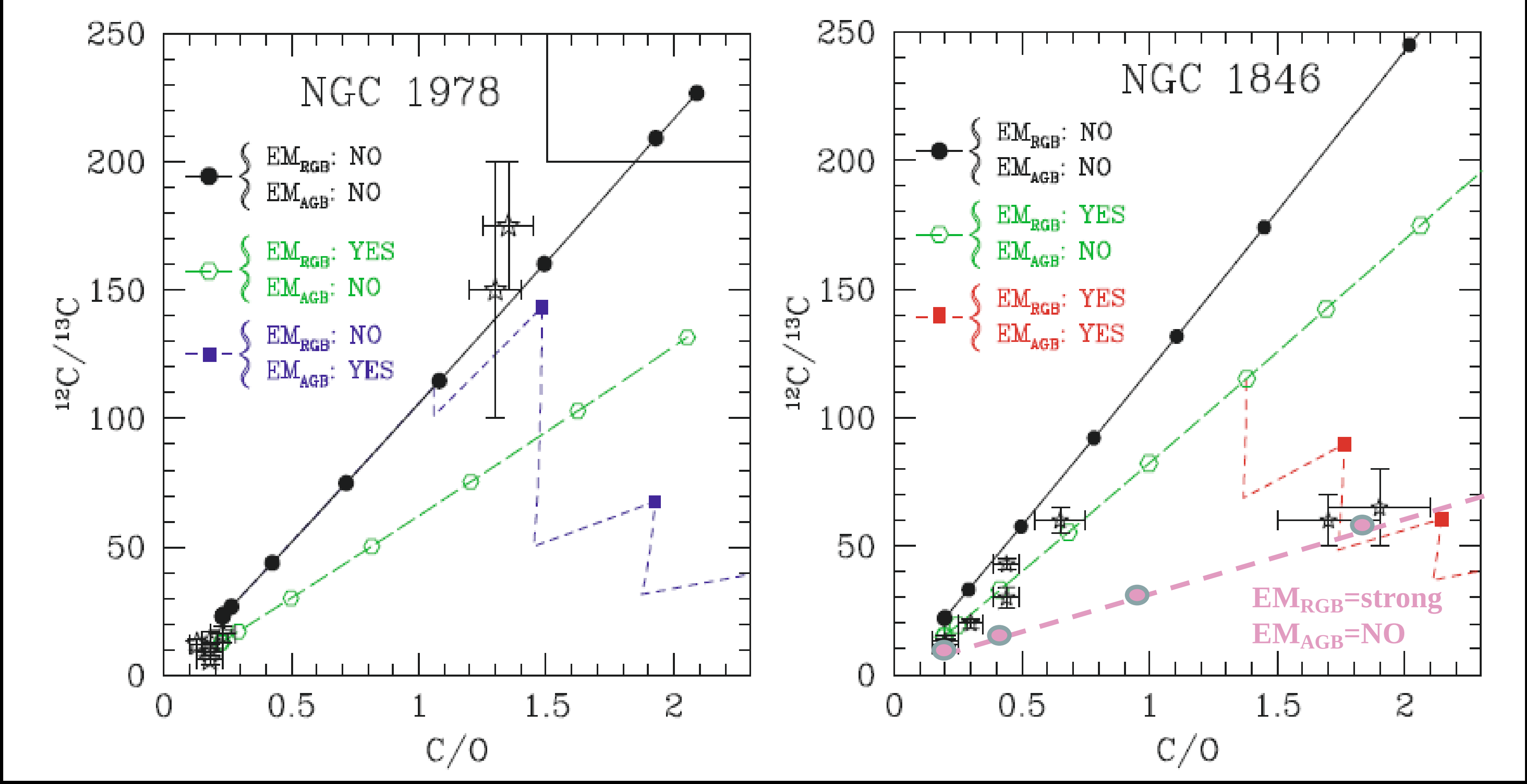
Y=0.27

$[\alpha/Fe]=0.2$

Possible variations of the model parameters:

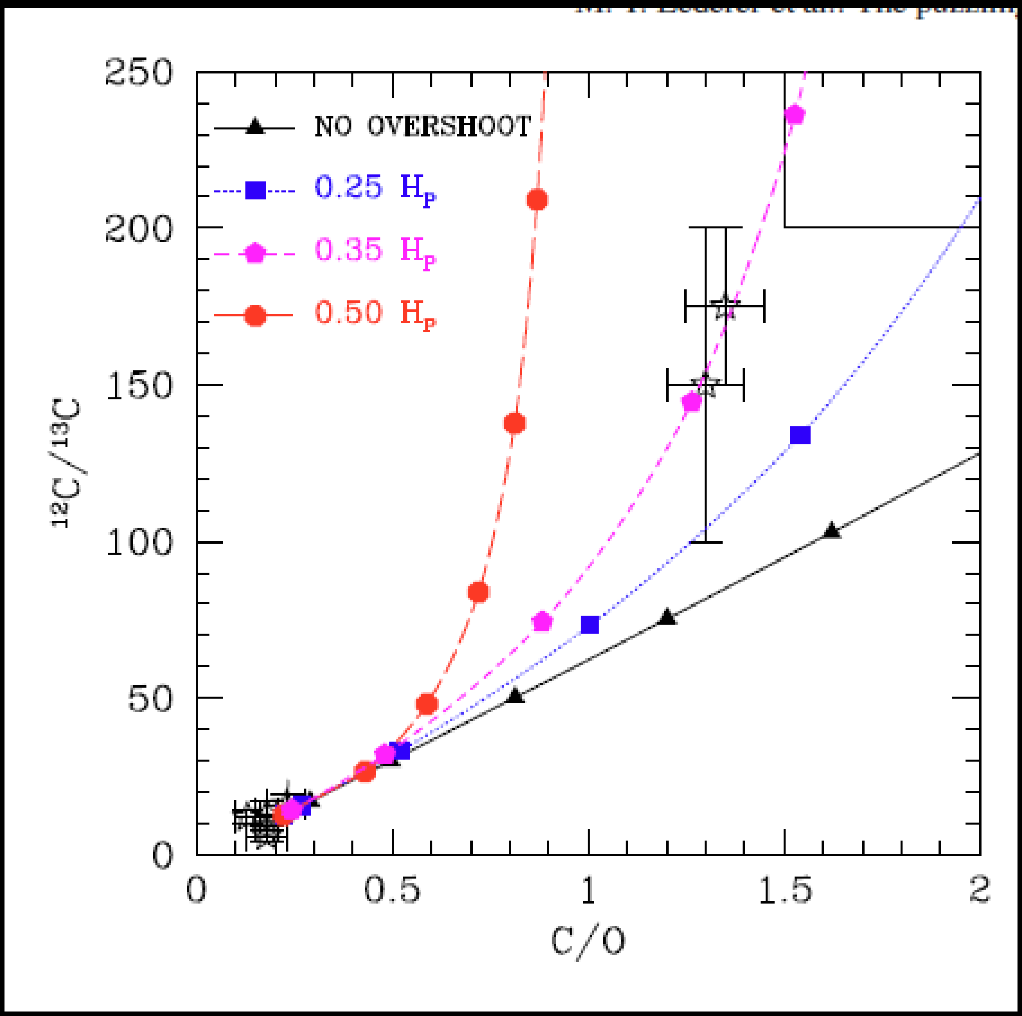
- $^{12}C/^{13}C=15$ --> RGB deep mix $T_{max}=20$ MK (dashed line green).
- $M=1.5\ M_\odot$ (dotted line blue).
- metallicity Z=0.003 (dotted line magenta).
- scaled solar composition (dot-dashed line red). Implies C/O=0.35 (instead of 0.2) in early-AGB.
- No RGB deep mix (solid line). Implies $^{12}C/^{13}C=24$ (instead of 15).

C-isotopic ratio versus C/O as a test for dredge up and deep mixing



Lederer et al. 2009

C stars in NGC 1978:
Overshoot at the base of the convective zone generated by Thermal Pulses?



There are good physical arguments to discard such an hypothesis: the steep entropy barrier produced by the He burning. As a matter of fact, hydro-dynamical simulations show that in these conditions the overshoot is negligible.

The puzzling case of NGC 1846 & 1978

- M stars show evidences of moderate RGB deep-mixing
- MS and S stars compatible with standard theoretical models, no AGB deep mixing and no overshoot from TP convective zone.

- C stars in NGC 1846: low $^{12}C/^{13}C=60$ (C/O=1.5)

a) delayed deep-mixing in AGB; would allow a simultaneous fit of O-rich and C stars

b) strong RGB deep-mixing ($^{12}C/^{13}C=8$ for M stars) or scaled solar composition (C/O=0.35 for M stars)

- C stars in NGC 1978: high $^{12}C/^{13}C>150$ (C/O=1.5)

a) No RGB deep-mixing ($^{12}C/^{13}C=24$ for M stars)

b) overshoot TP convective zone

Multiple populations or prolonged star formation: further pieces of the puzzle

(see Milone et al. 2009 and references therein).

- For example, C/O>1 is more easily attained if the initial O is lower. C stars may preferentially belong to a different SP

- MP may explain the lack of MS and S stars in NGC 1978. The mass of the oldest stars (first generation) is smaller, too small for the TDU.