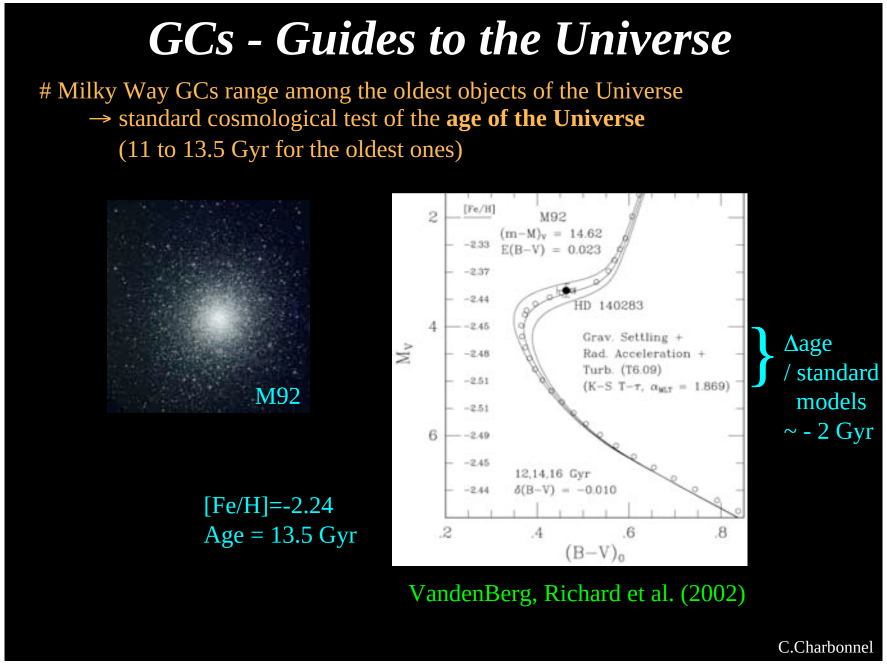
Cycle stellaire et nucléosynthèse dans les amas globulaires galactiques

Corinne Charbonnel
CNRS & Geneva Observatory

In collaboration with
T.Decressin, S.Eckström, G. Meynet (Geneva)
& N.Prantzos (IAP)



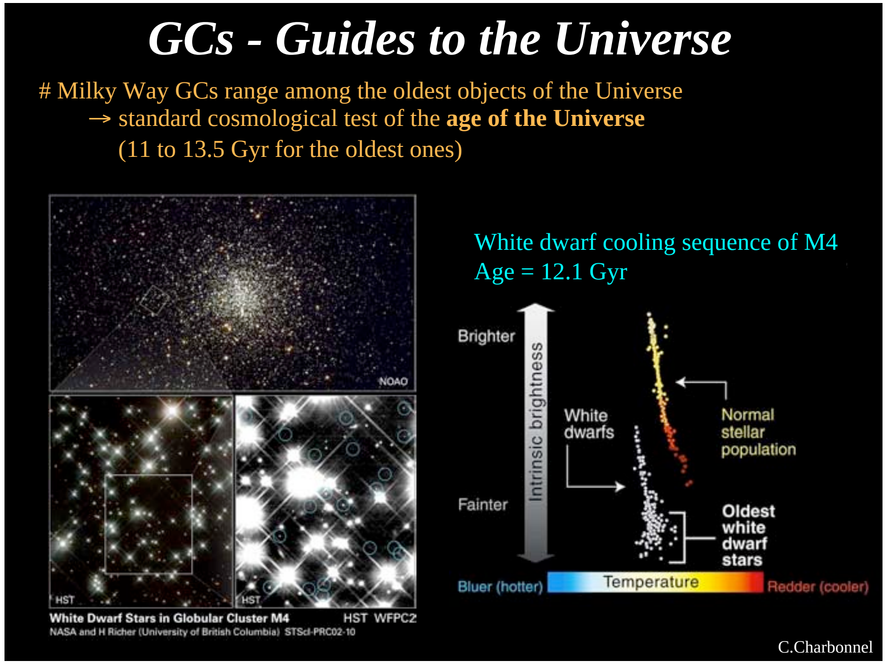
GCs - Guides to the Universe

Milky Way GCs range among the oldest objects of the Universe
→ standard cosmological test of the **age of the Universe**
(11 to 13.5 Gyr for the oldest ones)

[Fe/H]=-2.24
Age = 13.5 Gyr

} Δage / standard models ~ - 2 Gyr

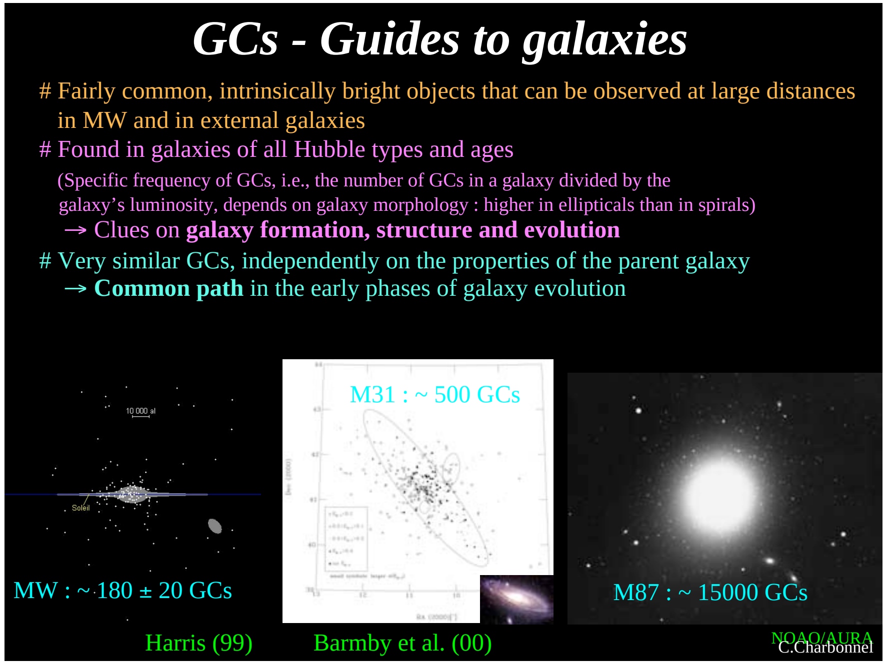
VandenBerg, Richard et al. (2002)



GCs - Guides to the Universe

Milky Way GCs range among the oldest objects of the Universe
→ standard cosmological test of the **age of the Universe**
(11 to 13.5 Gyr for the oldest ones)

White dwarf cooling sequence of M4
Age = 12.1 Gyr



GCs - Guides to galaxies

Fairly common, intrinsically bright objects that can be observed at large distances in MW and in external galaxies

Found in galaxies of all Hubble types and ages
(Specific frequency of GCs, i.e., the number of GCs in a galaxy divided by the galaxy's luminosity, depends on galaxy morphology : higher in ellipticals than in spirals)
→ Clues on **galaxy formation, structure and evolution**

Very similar GCs, independently on the properties of the parent galaxy
→ **Common path** in the early phases of galaxy evolution

MW : ~ 180 ± 20 GCs
M31 : ~ 500 GCs
M87 : ~ 15000 GCs

Harris (99) Barmby et al. (00)

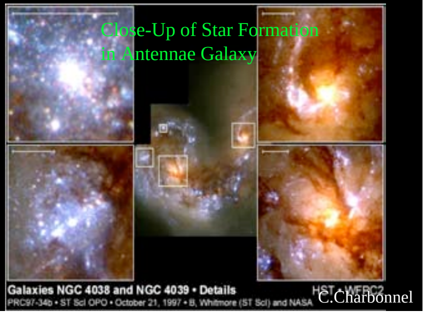
GCs - Guides to galaxies

\# GCs are not all uniformly old
LMC, SMC, M31 and M33 contain intermediate-age and young GCs
“Populous young clusters” in LMC : 10 Myr - 2 Gyr
R136 in 30 Doradus : 3 - 4 Myr

\# There is much evidence for continued GC formation in Local Group galaxies
\# Some GCs are currently forming in ongoing mergers and starburst galaxies
from large molecular-gas complexes

→ Clues on **stellar formation** in various environments


Nascent GC R136 in 30 Doradus (LMC)
WFPC2 Image HST
Credit NASA John Trauger & James Westphall


Close-Up of Star Formation in Antennae Galaxy
Galaxies NGC 4038 and NGC 4039 • Details
PRC97-34b • ST ScI OPO • October 21, 1997 • B. Whitmore (ST ScI) and NASA

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GCs - Guides to stellar dynamics

\# Evolve dynamically
\# Fundamental dynamical processes (relaxation, mass segregation, core collapse)
take place in GCs on timescales shorter than the Hubble time
\# Interactions with the environment


Globular Cluster NGC 6093

PRC99-26 • Space Telescope Science Institute • Hubble Heritage Team (AURA/STScI/NASA)

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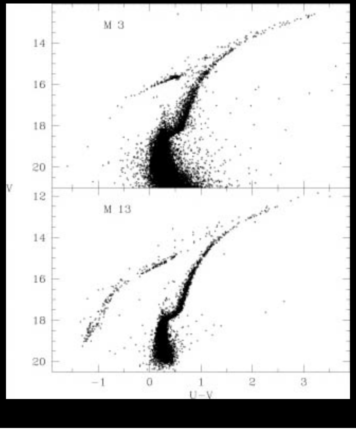
GCs - Guides to stars

\# Contain ~ 10^5-10^6 stars packed into a volume ~ $(10pc-30pc)^3$, possibly of same age
and with the same Fe abundance (except Ω Cen),
although Z varies considerably from cluster to cluster
→ natural laboratories to study **stellar formation and evolution**

\# Host a wide variety of interesting and unusual objects (milisecond pulsars, blue stragglers, low-mass X-ray binaries, …)




M3, Globular cluster

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GCs in modern astrophysics & cosmology

GC studies bring insight on
cosmology,
galaxy formation and evolution,
stellar dynamics,
stellar evolution and nucleosynthesis

However, exact formation mechanism and evolution still unknown

\# Until recently, the common paradidm for GC formation was that they constitute
a “simple stellar population” of stars
that formed from a chemically homogeneous cluster medium
within a relatively short interval of time

\# However, GGCs probably did evolve chemically
and certainly consist of multiple stellar generations
The subject of the present talk …

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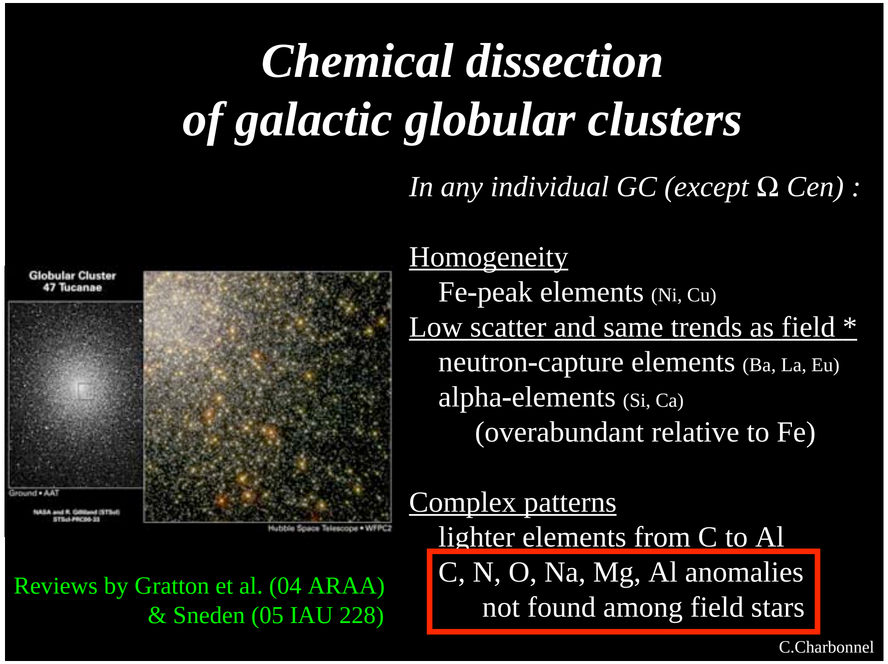

Chemical dissection of galactic globular clusters

In any individual GC (except Ω Cen) :

Homogeneity

Fe-peak elements (Ni, Cu)

Low scatter and same trends as field *

neutron-capture elements (Ba, La, Eu)

alpha-elements (Si, Ca)

(overabundant relative to Fe)

Complex patterns

lighter elements from C to Al

C, N, O, Na, Mg, Al anomalies
not found among field stars

Reviews by Gratton et al. (04 ARAA)
& Sneden (05 IAU 228)

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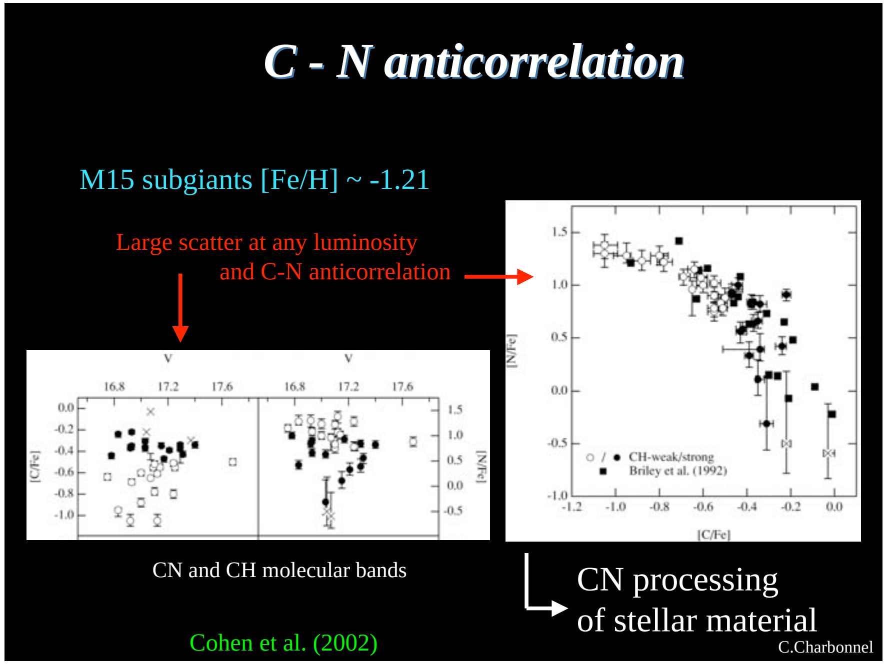

C - N anticorrelation

M15 subgiants [Fe/H] ~ -1.21

Large scatter at any luminosity
and C-N anticorrelation

CN and CH molecular bands

CN processing
of stellar material

Cohen et al. (2002)

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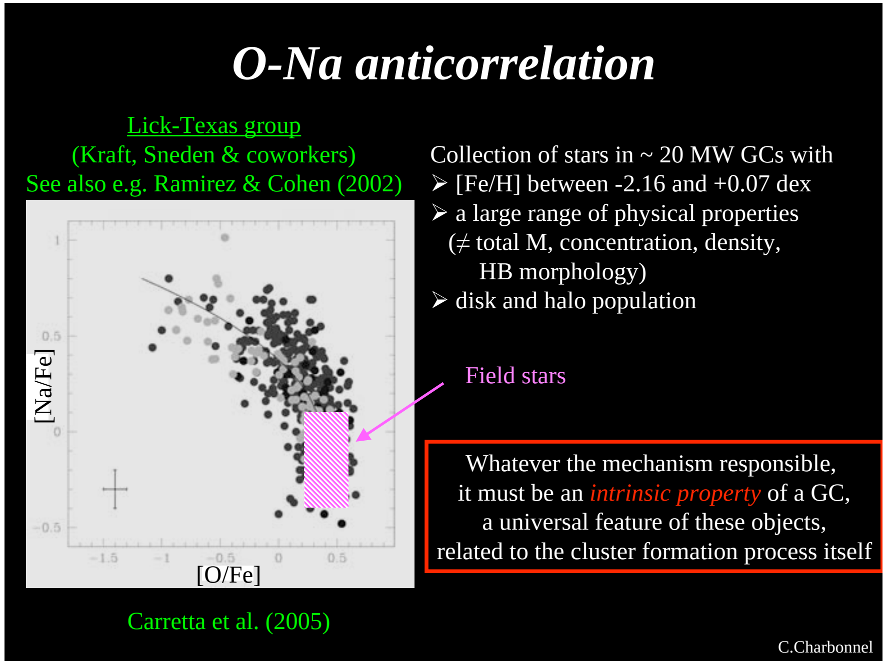

O-Na anticorrelation

Lick-Texas group
(Kraft, Sneden & coworkers)
See also e.g. Ramirez & Cohen (2002)

Collection of stars in ~ 20 MW GCs with
- [Fe/H] between -2.16 and +0.07 dex
- a large range of physical properties (≠ total M, concentration, density, HB morphology)
- disk and halo population

Field stars

Whatever the mechanism responsible,
it must be an *intrinsic property* of a GC,
a universal feature of these objects,
related to the cluster formation process itself

Carretta et al. (2005)

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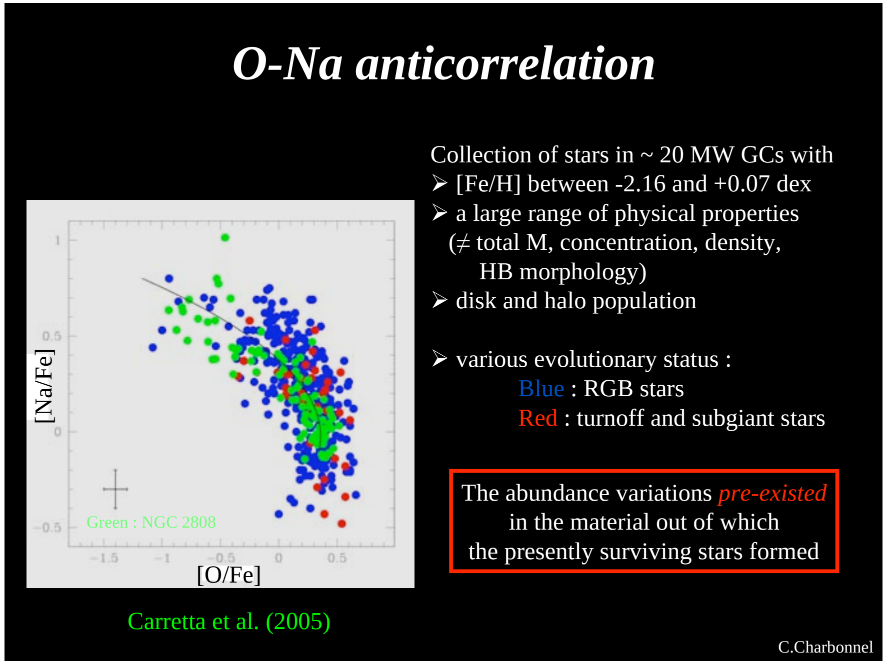

O-Na anticorrelation

Collection of stars in ~ 20 MW GCs with
- [Fe/H] between -2.16 and +0.07 dex
- a large range of physical properties (≠ total M, concentration, density, HB morphology)
- disk and halo population

- various evolutionary status :
  Blue : RGB stars
  Red : turnoff and subgiant stars

The abundance variations *pre-existed*
in the material out of which
the presently surviving stars formed

Carretta et al. (2005)

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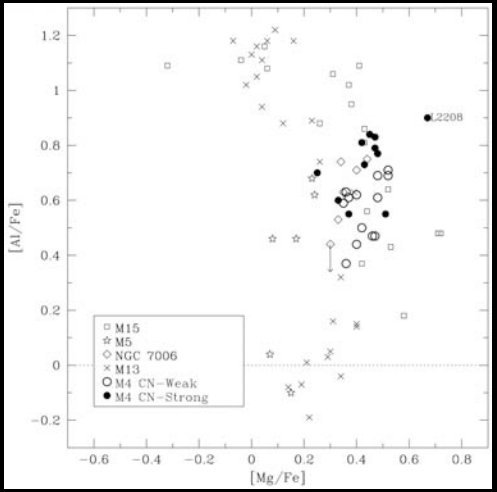
Mg-Al anticorrelation



Ivans et al. (1999)

Observed both in bright giants and faint turnoff members
Ramirez & Cohen (2002), Gratton et al. (01), Grundhal et al. (03)

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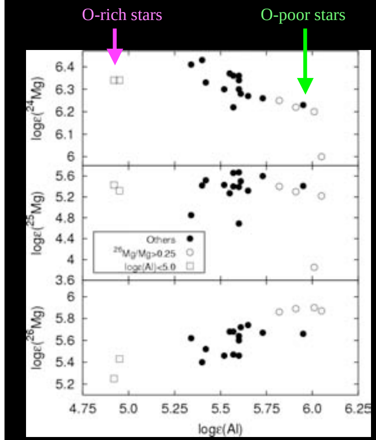
Mg isotopes



NGC 6752
[Fe/H] = -1.42

Yong et al. (2003)

^{24}Mg declines slightly
with increasing Al abundance
(discovered by Shetrone 1996)

^{25} Mg ~ constant
over the 1.1 dex range in Al abundance

^{26}Mg is well correlated with Al abundance,
with a total spread of a factor of ~ 4

Same in M3 and M71 (Yong et al. 2005)

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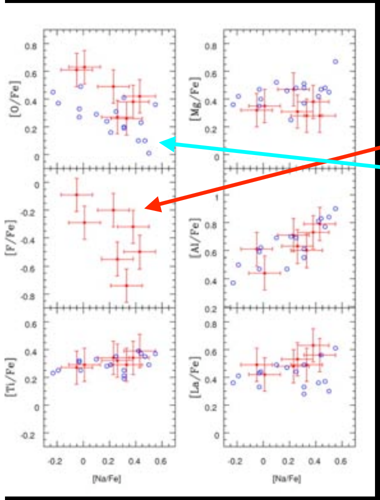
Fluorine abundance variations

M4 (NGC 6121) Smith et al. (2005)



Abundance of ^{19}F
varies by more than a factor of 6
anticorrelated with Na and Al variations
correlated with O variations

Open blue : M4 stars from Ivans et al (99)
Filled red : M4 stars with F determinations

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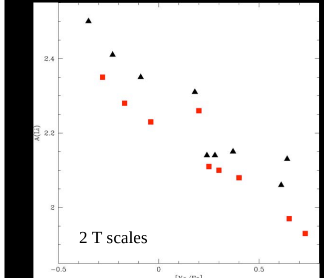
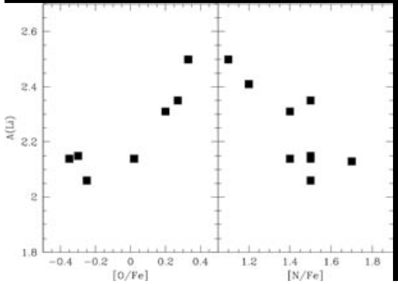
Lithium abundance variations



NGC 6752 Pasquini et al. (2005)
Turnoff stars

Li-Na anticorrelation



Li-O correlation, Li-N anticorrelation

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What type of nucleosynthesis?

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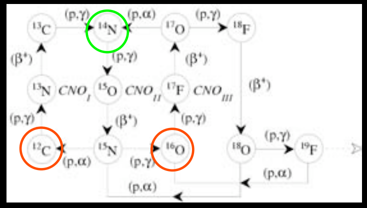
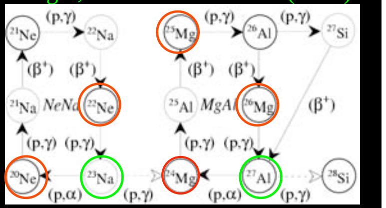
H-burning through CNO, NeNa, MgAl

Denissenkov & Denissenkova (1990)
Langer, Hoffman & Sneden (1993)





$T \geq 15 \times 10^6$ K : CN

$T \geq 25 \times 10^6$ K : CNO, ^{22}Ne → ^{23}Na

$T \geq 40 \times 10^6$ K : CNO, ^{20}Ne → ^{23}Na

^{25,26}Mg → ^{26}Al, ^{27}Al

$T \geq 70 \times 10^6$ K : ^{24}Mg (and ^{25,26}Mg) → ^{26}Al, ^{27}Al

Arnould et al. (1999)

Observed Mg isotopic ratios

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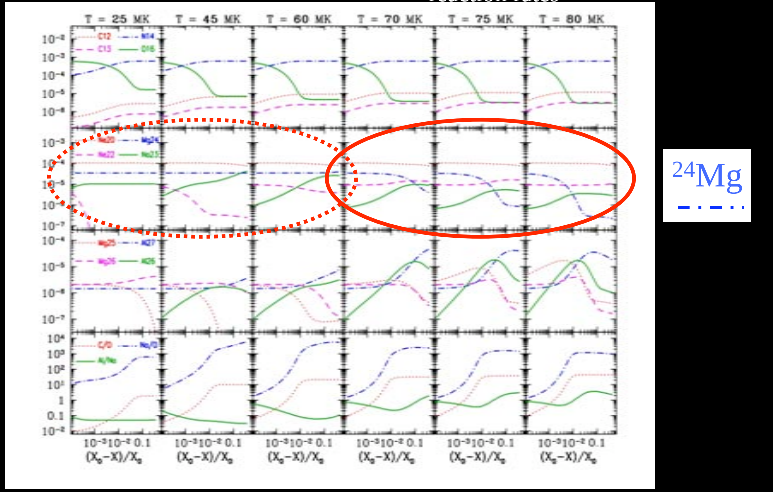
Proton-capture nucleosynthesis at constant *T*

Prantzos & Charbonnel (2006b)
With NACRE and Illiadis' update reaction rates



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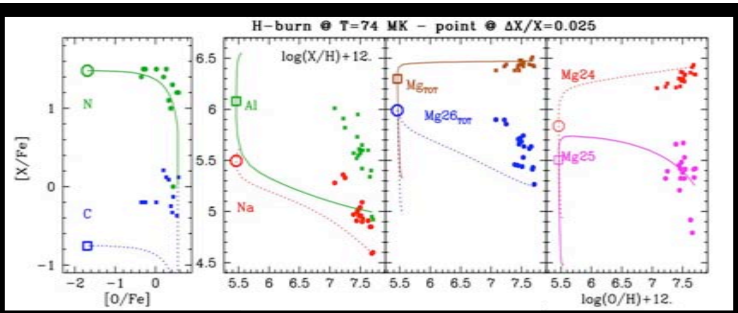

Curves:
abundance evolution at
T = constant = 74 MK

Filled symbols:
NGC 6752 observations

We never see *directly* abundances of the H-burning zone
(O would be ~ 200 times below its initial value)
but always some ***<u>mixture with pristine material</u>***

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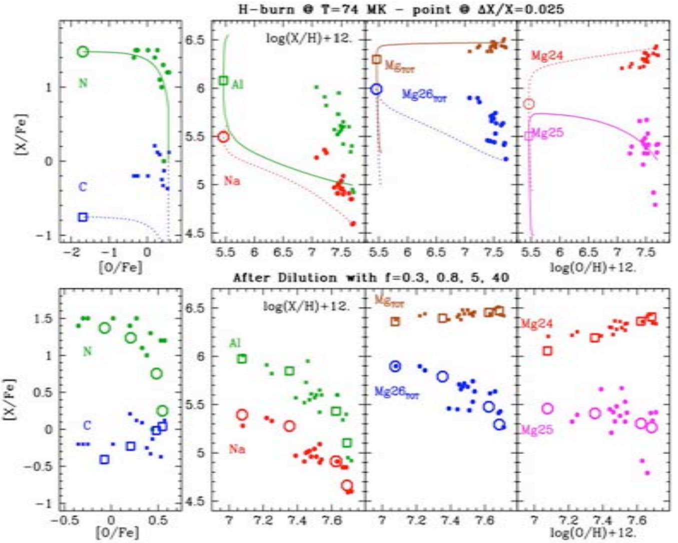
Prantzos & Charbonnel (2006b)

Open symbols
(extreme left =
O in equilibrium):
abundances
correponding to a
consumed H fraction of
$\Delta X/X_0 = 0.025$

⇓

Open symbols:
Results of mixing
abundances X_{BURN}
in H-burning zone
(points at extreme left)
with initial one X_{INIT}
with various
mixing (<u>dilution</u>) factors
i.e. with a <u>fraction f of</u>
<u>primordial matter</u>
f = 0.3, 0.8, 5, 40



$$X = \frac{X_{BURN} + f\ X_{INIT}}{1 + f}$$

Filled symbols:
NGC 6752 observations

Prantzos & Charbonnel (2006b)

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Open symbols
(extreme left =
O in equilibrium):
abundances
correponding to a
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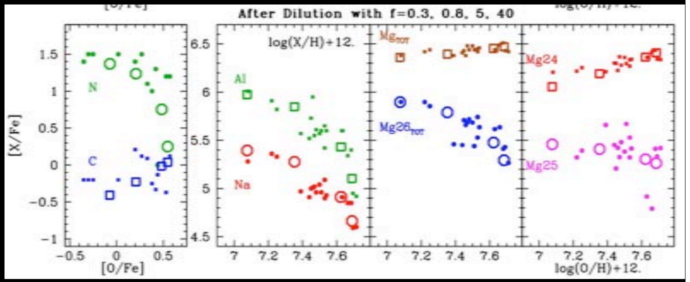
i.e. with a <u>fraction f of</u>
<u>primordial matter</u>
f = 0.3, 0.8, 5, 40

Dilution factors
0.3 to 40
« Extreme » O-poor, Na-rich stars :
30% of non-processed material
70% of processed-material



$$X = \frac{X_{BURN} + f\ X_{INIT}}{1 + f}$$

Filled symbols:
NGC 6752 observations

Prantzos & Charbonnel (2006b)

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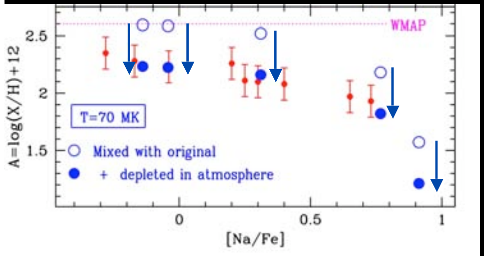
Li in NGC 6752 (Pasquini et al. 2005)



Depletion factor
in Pop II (field) stars
(i.e., Spite plateau vs WMAP)

↓

Low-mass stars in GCs
did undergo the same Li depletion
as their halo counterparts
on the Spite plateau

Prantzos & Charbonnel (2006b)

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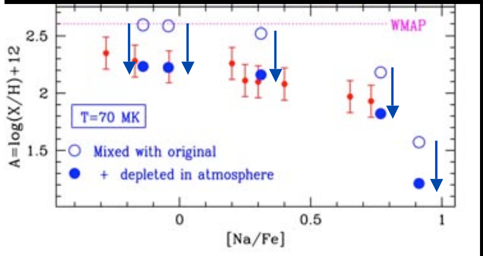
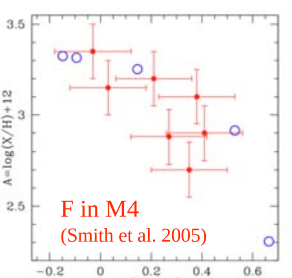
Li in NGC 6752 (Pasquini et al. 2005)





Mixture of H-burning products
with pristine material
explains easily the presence of
<u>Lithium and Fluorine</u>
(that are both destroyed in
H-burning zone)
In Na-rich stars

No need for the polluters
to produce Li nor F

Otherwise difficult to explain
a Li abundance so close from the
primordial (BBN) value

Prantzos & Charbonnel (2006b)

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The abundance variations are observed in both *turnoff and evolved stars*

↓

The observed patterns *pre-existed*
in the material out of which
the presently surviving stars formed

↓

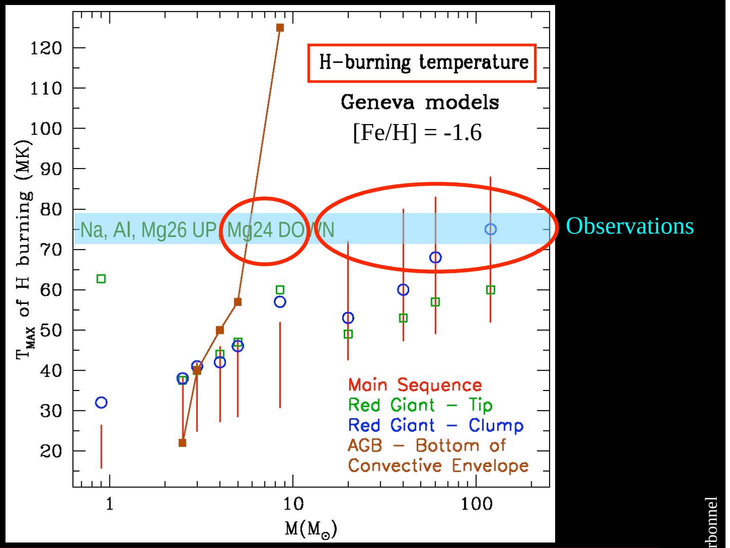
Implies *pollution of the intra-cluster gas*
by a first generation of *more massive*
rapidly evolving *stars*
in which H burns at ~ 72-78MK!

⇔ *Self-enrichment scenario*

Hunting for the polluters

In which stars does H burn at T~70-80 MK ?

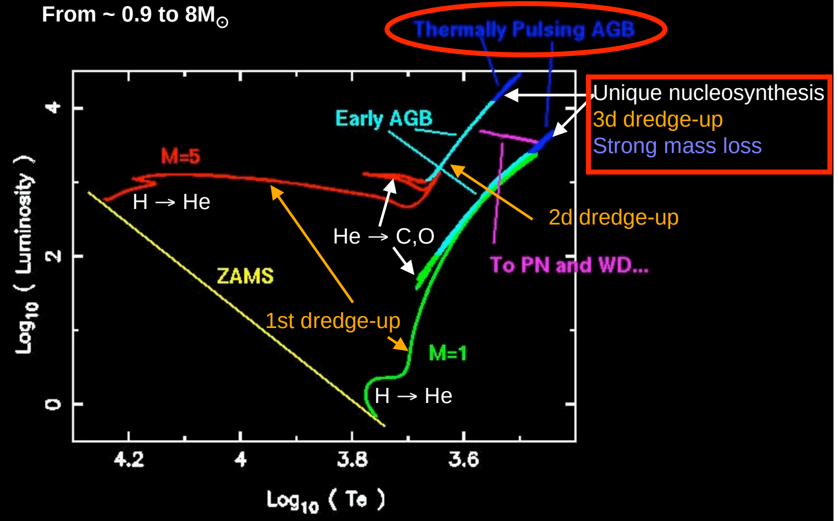
Prantzos & Charbonnel (2006b)



Potential « polluters » : winds of **massive AGBs** and of **massive stars**

Massive AGB stars?

From ~ 0.9 to 8$M_\odot$



Adapted from Lattanzio

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The « classical » candidate polluters : Low-Z, massive AGB stars

Hot bottom burning (HBB)
→ CNO, NeNa and MgAl processing
→ No synthesis of α or Fe-peak elements
→ Few thermal pulses before superwind phase and relatively massive stars
→ s-elements not necessarily enhanced
→ Strong mass loss (up to 80% of the total M_*)
→ Low-speed winds may be retained in the cluster with a trend to be concentrated toward the center (radial trend in CN distr. in a few GC as 47Tuc)
→ UV energy produced during the PN phase too low to expel the gas away
→ Timescale low-enough (50-100Myr) to be compatible with the GC formation

Cottrell & Da Costa (81) : The AGB ejecta may have been mixed into the intracluster medium from which a 2d generation of stars may have formed within the GC ($\neq$ accretion scenario)

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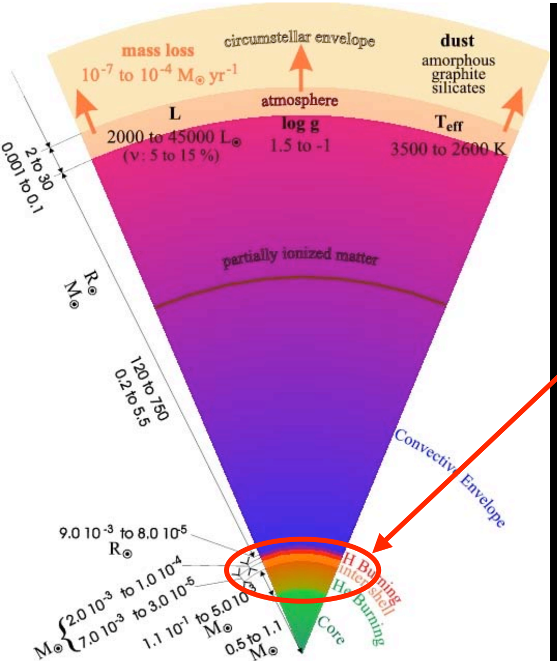

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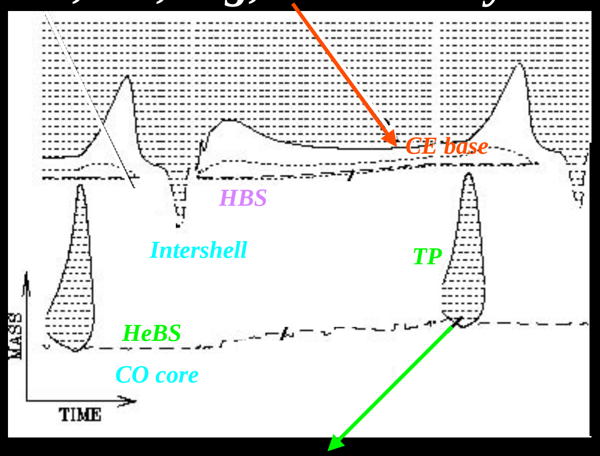
Figure by M.Forestini

TP-AGB : Kippenhahn diagram and O, Na, Mg, Al nucleosynthesis



Zones convectives ▨
Zones radiatives □

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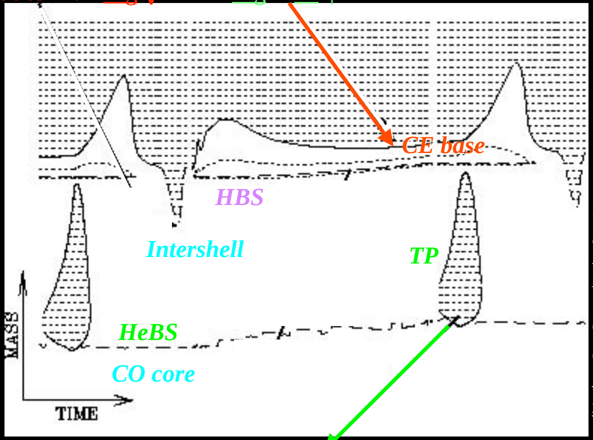
HBB ($M > 4M_{\odot}$) CNO, NeNa, MgAl

A + haute T, $^{23}Na(p,\gamma)^{24}Mg$

^{26}Al produit aux dépends de ^{25}Mg

Très haute T : ^{24}Mg ↓ → ^{25,26}Mg ^{27}Al ↑



Strong mass loss

3d dredge-up ashes of the thermal pulse brought to the convective envelope ^{16}O, ^{22}Ne, ^{25}Mg, ^{26}Mg

Zones convectives ▩
Zones radiatives ☐

He burning 3α → ^{12}C → $^{12}C(\alpha,\gamma)^{16}O$
^{14}N (CNO) → $^{14}N(\alpha,\gamma)^{18}F(\beta+)^{18}O(\alpha,\gamma)^{22}Ne$
$^{22}Ne(\alpha,n)^{25}$**Mg**, $^{22}Ne(\alpha,\gamma)^{26}$**Mg**

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Subtle competition between

- ✓ Third dredge-up ($M \geq 1.5M_{\odot}$ at $Z_{\odot}$)
  - products of He-burning in the TP
  - ^{4}He, ^{12}C, ^{16}O, ^{22}Ne, $^{25,26}Mg$, s-process elements increase
- ✓ Hot-bottom burning ($M \geq 4 - 4.5M_{\odot}$)
  - CN-cycle : $^{12}C \rightarrow {}^{14}N$ ON-cycle : $^{16}O \rightarrow {}^{14}N$
  - NeNa : → Na ↑ and ↓ at higher T
  - MgAl : Al increases at the expense of $^{25,26}Mg$ and eventually of ^{24}Mg

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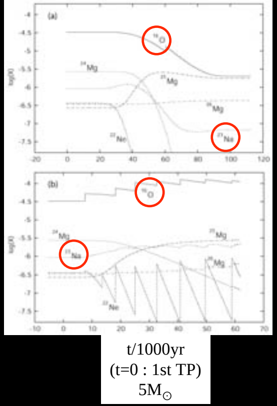
O, Na evolution at the surface of a low-Z massive TP-AGB star

Delicate interplay of 3d dredge-up and hot bottom burning



(a) No 3DUP, only HBB
→ Large ^{16}O depletion
→ ^{23}Na depletion
(due to the lack of ^{22}Ne dredged-up)

(b) Strong 3DUP, HBB, no mass loss
→ 3DUP of the ^{16}O-rich layers below the TP
→ ^{23}Na increase (from dredged-up ^{22}Ne)
→ Mg isotopes as in (a) (only affected by HBB)

Denissenkov & Herwig (03)

Full evolution models

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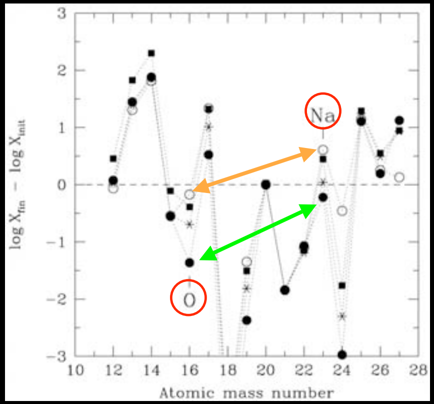
O, Na evolution at the surface of a low-Z massive TP-AGB star

Parametric models with varying efficiency of the 3DUP and HBB

Denissenkov & Herwig (03)
Denissenkov & Weiss (04)



Simultaneous depletion of ^{16}O and enhancement of ^{23}Na requires fine-tuning of the 3DUP and HBB

Final envelope abund. vs initial ones
after 8 TPs with a parametric
AGB model of a $5M_{\odot}$, Z=0.0001 star ([Fe/H] ~-2.3)

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O, Na evolution at the surface of a low-Z massive TP-AGB star

Parametric models with varying efficiency of the 3DUP and HBB

Denissenkov & Herwig (03)
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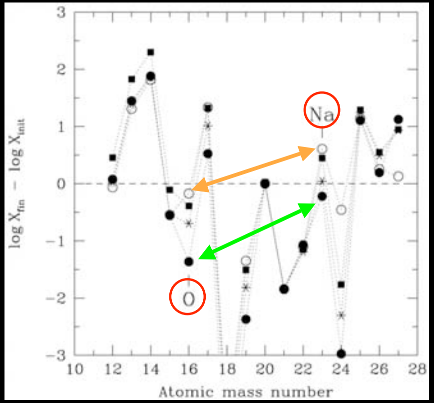

<u>Final envelope abund. vs initial ones</u>
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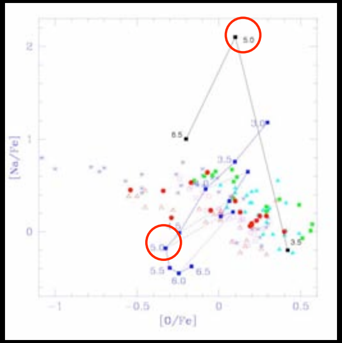
AGB model of a 5M$_\odot$, Z=0.0001 star ([Fe/H] ~-2.3)

Simultaneous depletion of ^{16}O and enhancement of ^{23}Na requires fine-tuning of the 3DUP and HBB

→ Robustness of this process at the origin of the O-Na anticorrelation in GCs?

Impact of convection

Ventura & D'Antona (05 II)
See also Renzini & Voli (81),
Sackmann & Boothroyd (91),
Blöcker & Schönberner (91),
D'Antona & Mazzitelli (96)



<u>Ventura & D'Antona (05II)</u>
Full Spectrum of Turbulence (Canuto & Mazzitelli 91)
→ **<u>much more efficient HBB</u>** than with MLT
(on the AGB : higher L, stronger mass loss)

Stronger O depletion, but
underproduction of ^{23}Na due to smaller number of 3DUP episodes and larger T

<u>Fenner et al.(04)</u>
MLT
Overproduction of (primary) ^{23}Na
due to the burning of dredged-up ^{20}Ne

Both sets are unable to reproduce the data

« The predictive power of AGB models
is still undermined by many uncertainties » (VD'A05)

Chemical evolution of globular clusters including AGB yields

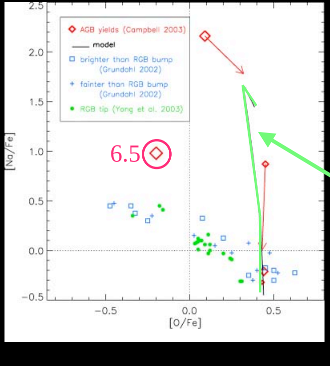
-

A summary of the difficulties

GCCE model including AGB predictions

Self-consistent, 2stage-formation model of the chemical evolution of <u>NGC 6752</u>
1stage) - Pop II burst → [Fe/H] = -1.4, α-enriched gaz
2stage) - the products of SNII are completely expelled from the GC
- the material ejected from * with M < 7M$_\odot$ is retained
- Kroupa et al. (93) IMF

Fenner et al. (04)

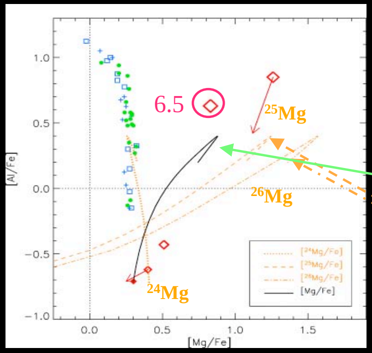


Diamonds :
1.25, 2.5, 3.5, 5.0, <u>6.5</u> **stellar models**
Arrows : Changes in the mass loss
(Vassiliadis & Wood 93 vs Reimers 75)

GCCE model :
Overproduction of Na (primary)
Very low O-depletion
Independant of the IMF

GCCE model including AGB predictions

Diamonds :
1.25, 2.5, 3.5, 5.0, 6.5 **stellar models**
Arrows : Changes in the mass loss
(Vassiliadis & Wood 93 vs Reimers 75)



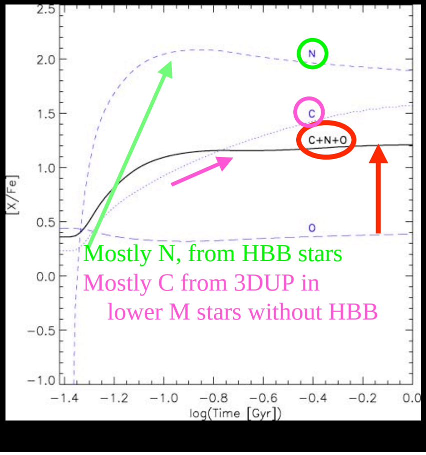
GCCE model :
Spread in [Al/Fe], but too low by ~ 0.6 dex
Total Mg abundance increases with Al
Dramatic increase of ^{25,26}Mg

Fenner et al.(04)

Yong et al. (03)
NGC 6752
^{24}Mg:^{25}Mg:^{26}Mg =
80:10:10 in the least polluted *
60:10:30 in the most polluted *

Further difficulties for the AGBs being the polluters

Fenner et al. (04)



Mostly N, from HBB stars
Mostly C from 3DUP in
lower M stars without HBB

Almost 1 order of magnitude rise
of [C+N+O / Fe]
within 1Gyr of formation
(due to the DUP of the products
of He-burning)

C+N+O is found to be ~ constant
in many GCs
(Pilachowski et al. 88,
Dickens et al. 91,
Smith et al. 96, Ivans et al. 99)

Difficulty for the AGB scenario :
Competition between
hot bottom burning
and 3d dredge-up :

↗ He-burning products

Have we really identified the culprit polluter ?

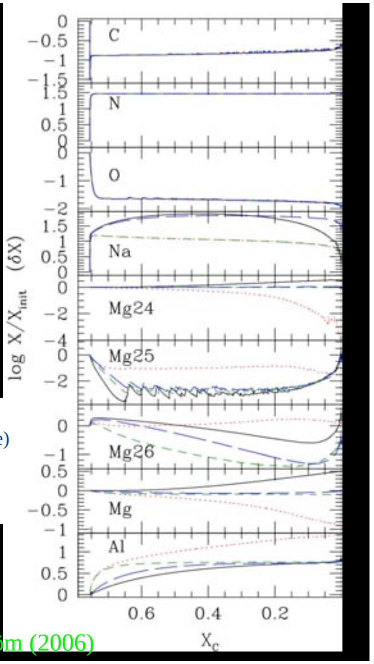
Massive stars ?

60 $M_\odot$

[Fe/H] = -1.5

Tc ∈ [48 ; 75] x 10^6 K on the MS

Evolution of the **central abundances** :



NACRE (full black)

Illiadis et al. (01), Hale et al. (02, 04) nominal (long dashed blue)

Id experimental limits (short dashed green)

Id & 24Mg(p,γ) (Illiadis et al. 01)

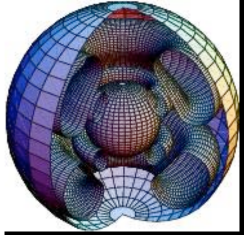
x 10^3 @ ~ 50MK and x $10^{1.5}$ @ ~ 60MK (dotted red)

Decressin, Charbonnel, Meynet, Prantzos, Ekström (2006)

✓Abundance patterns due to nuclear reactions in the H-burning core of massive main sequence stars do mimic the chemical trends observed in GC low-mass stars

✓ How does the star expel these products into the interstellar medium?

⇒ The crucial role of rotation on stellar winds (at any Z)



Courtesy of G.Meynet

Transport of angular momentum and chemicals by meridional circulation and shear turbulence

Zahn (1992), Maeder & Zahn (1998), Meynet & Maeder (2000)

C.Charbonnel

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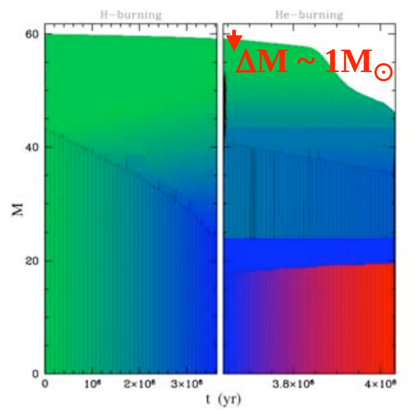
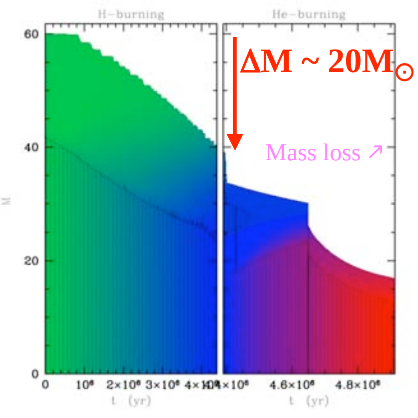
60 $M_\odot$, Z = 5 x 10^{-4}

No rotation



Rotation Vini = 800 km.sec^{-1}

Ω/Ωc = 0.95



Green : % of H

Blue : % of He

Red : % of C + O

Decressin, Meynet, Charbonnel, Prantzos, Ekström (2006)

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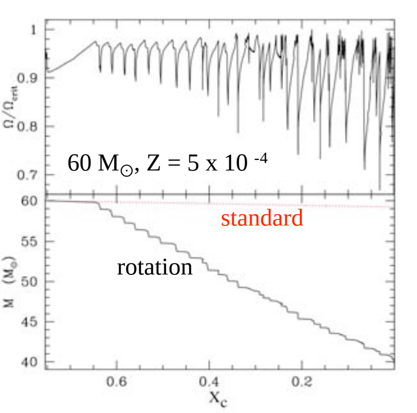
Rotation Vini = 800 km.sec^{-1} ⇔ Ω/Ωc = 0.95

Critical velocity ⇔Equatorial surface velocity is such that centrifugal acceleration exactly balances gravity

(In practice, we remove the supercritical layers)

At break-up matter is removed from the surface together with AM.

BUT meridional circulation transports AM from the fast core to the envelope



Decressin, Meynet, Charbonnel, Prantzos, Ekström (2006)

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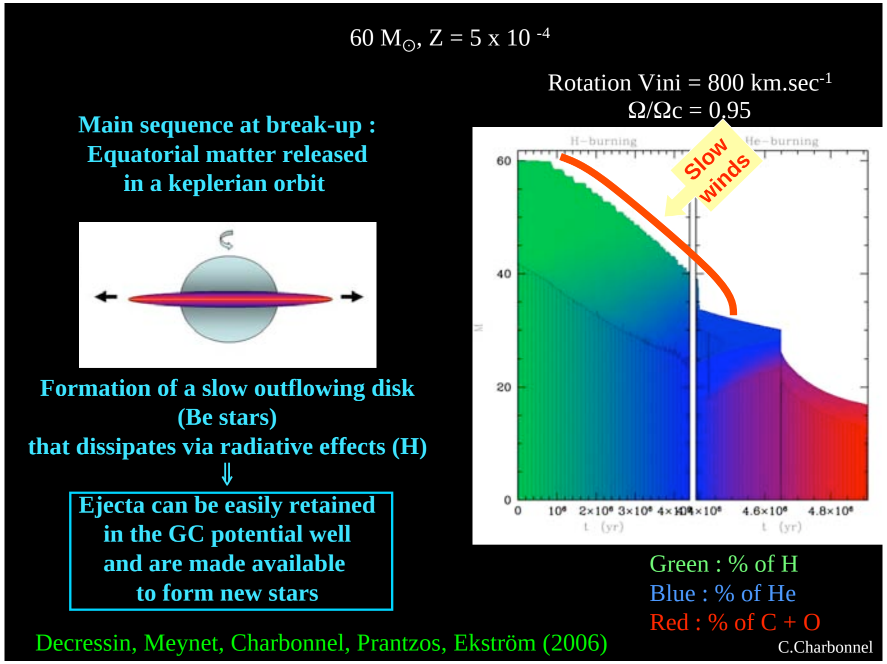

60 M$_\odot$, Z = 5 x 10^{-4}

Rotation Vini = 800 km.sec^{-1}
Ω/Ωc = 0.95

Main sequence at break-up :
Equatorial matter released
in a keplerian orbit

Formation of a slow outflowing disk
(Be stars)
that dissipates via radiative effects (H)
⇓

Ejecta can be easily retained
in the GC potential well
and are made available
to form new stars

Green : % of H
Blue : % of He
Red : % of C + O

Decressin, Meynet, Charbonnel, Prantzos, Ekström (2006)

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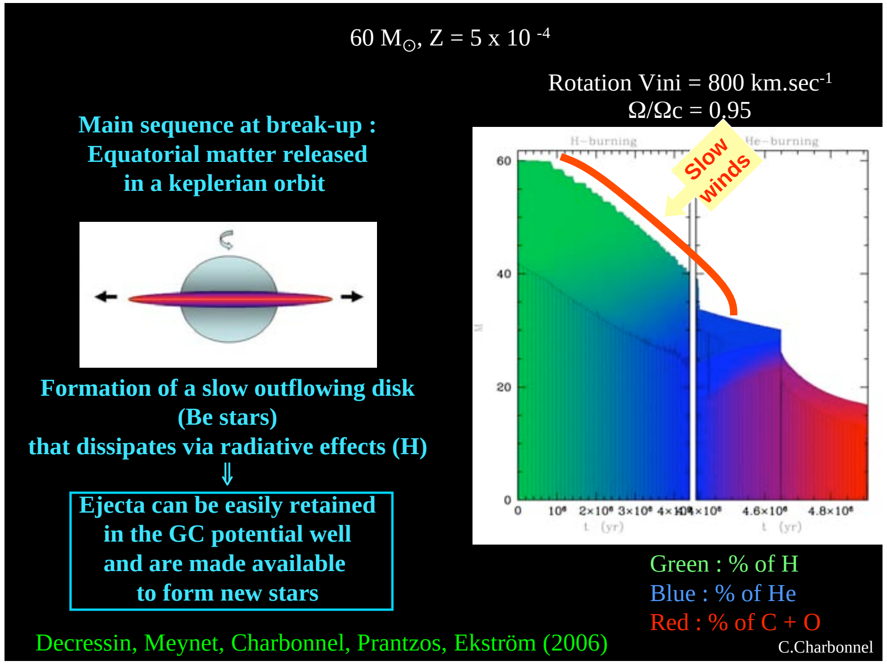

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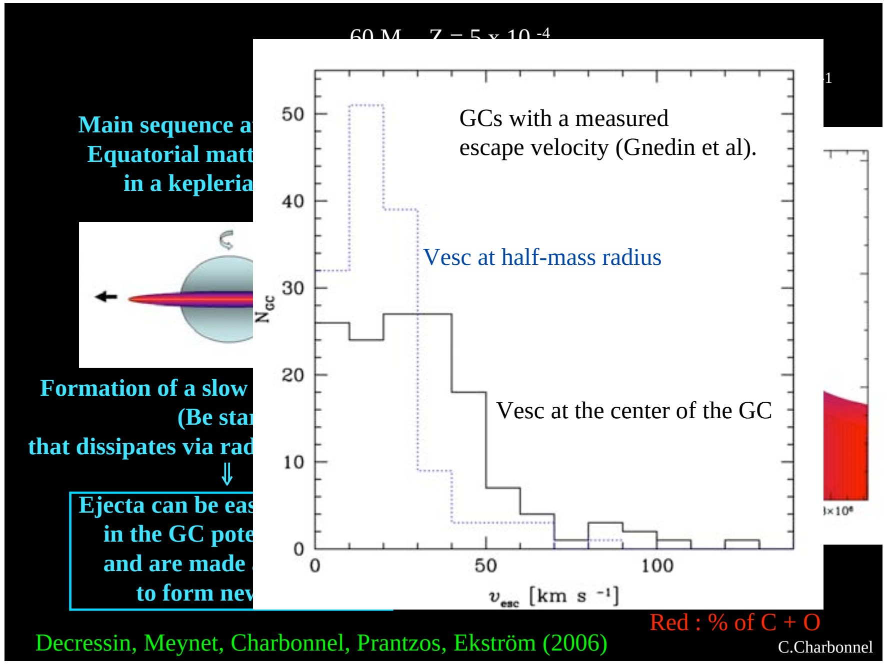
C.Charbonnel



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Equatorial matt
in a kepleria

Formation of a slow
(Be sta
that dissipates via rad
⇓

Ejecta can be eas
in the GC pote
and are made
to form nev

GCs with a measured
escape velocity (Gnedin et al).

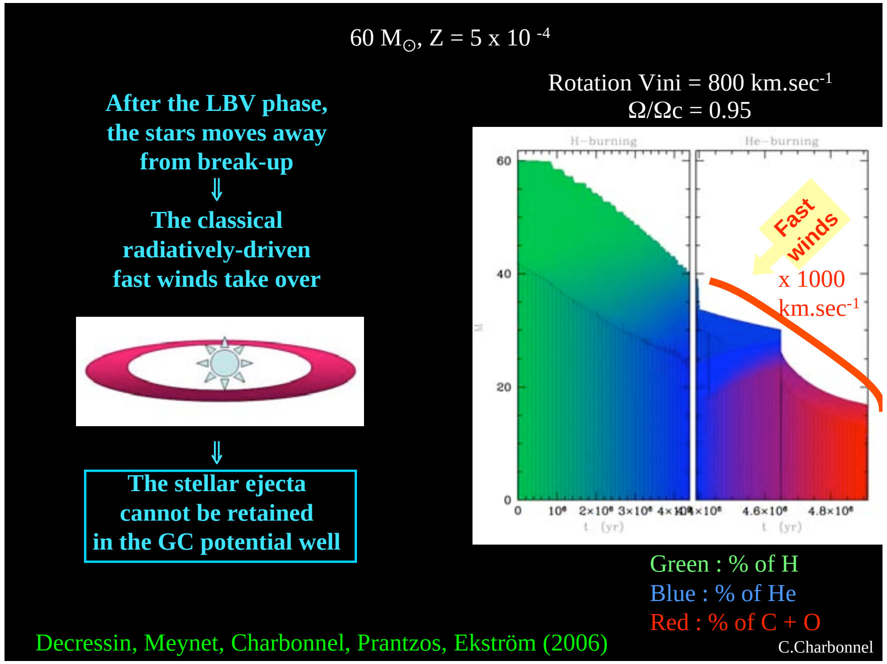
Vesc at half-mass radius

Vesc at the center of the GC

Red : % of C + O

Decressin, Meynet, Charbonnel, Prantzos, Ekström (2006)

C.Charbonnel



60 M$_\odot$, Z = 5 x 10^{-4}

Rotation Vini = 800 km.sec^{-1}
Ω/Ωc = 0.95

After the LBV phase,
the stars moves away
from break-up
⇓
The classical
radiatively-driven
fast winds take over

⇓

The stellar ejecta
cannot be retained
in the GC potential well

Green : % of H
Blue : % of He
Red : % of C + O

Decressin, Meynet, Charbonnel, Prantzos, Ekström (2006)

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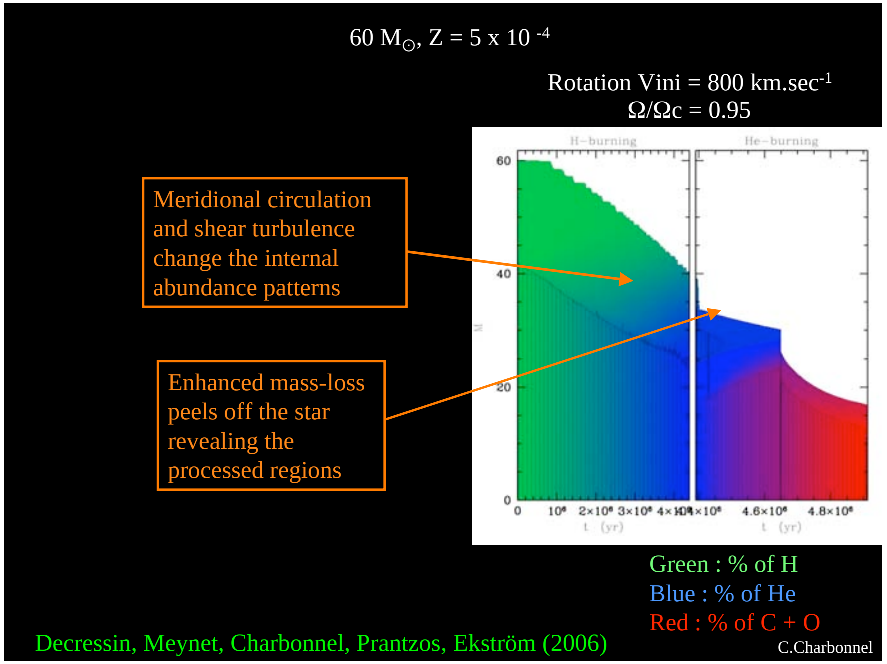

60 $M_\odot$, Z = 5 x 10^{-4}

Rotation Vini = 800 km.sec^{-1}
Ω/Ω_c = 0.95

Meridional circulation and shear turbulence change the internal abundance patterns

Enhanced mass-loss peels off the star revealing the processed regions

Green : % of H
Blue : % of He
Red : % of C + O

Decressin, Meynet, Charbonnel, Prantzos, Ekström (2006)

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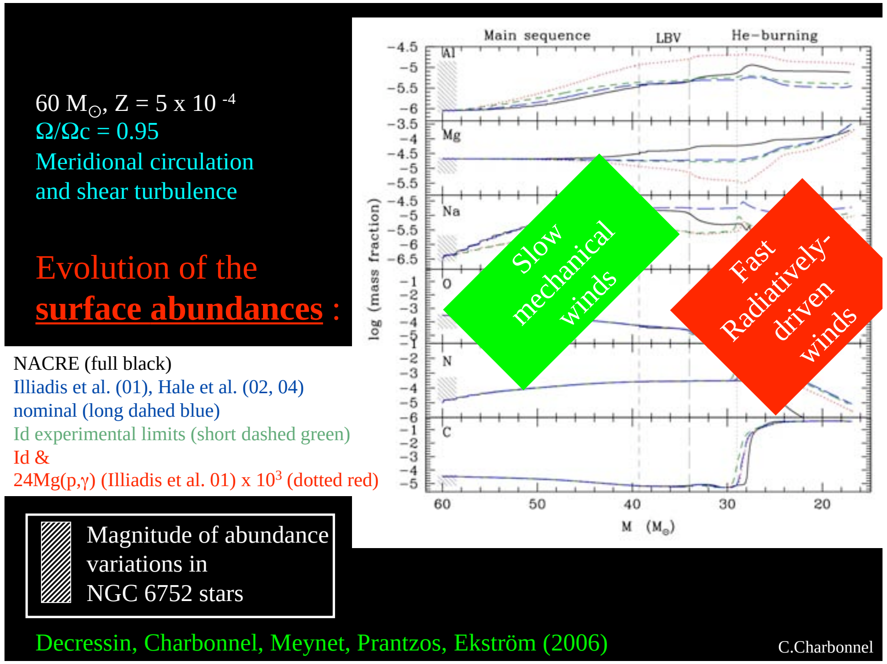

60 $M_\odot$, Z = 5 x 10^{-4}
Ω/Ω_c = 0.95
Meridional circulation and shear turbulence

Evolution of the **surface abundances** :

NACRE (full black)
Illiadis et al. (01), Hale et al. (02, 04)
nominal (long dahed blue)
Id experimental limits (short dashed green)
Id &
24Mg(p,γ) (Illiadis et al. 01) x 10^3 (dotted red)

▨ Magnitude of abundance variations in NGC 6752 stars

Decressin, Charbonnel, Meynet, Prantzos, Ekström (2006)

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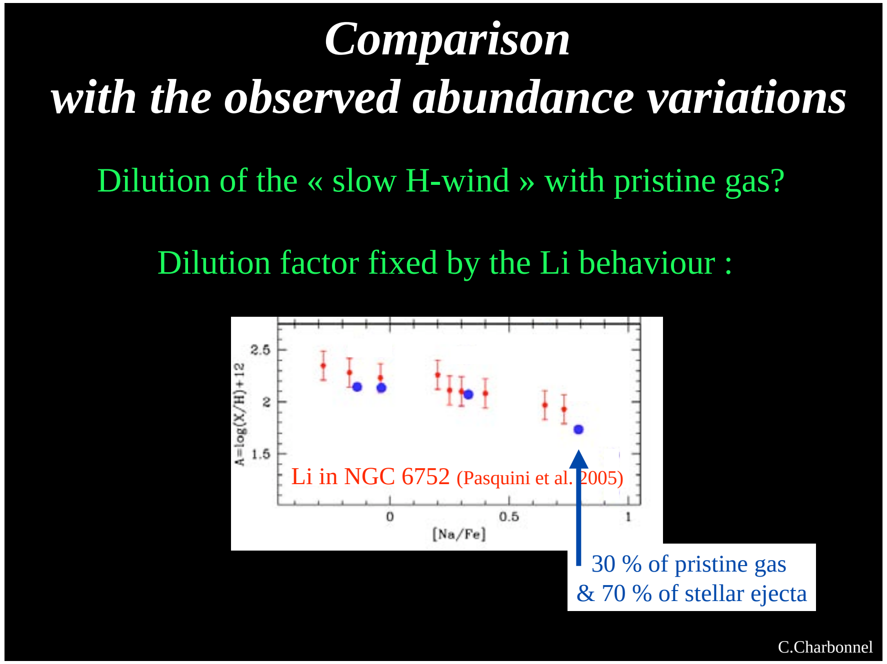

Comparison with the observed abundance variations

Dilution of the « slow H-wind » with pristine gas?

Dilution factor fixed by the Li behaviour :

Li in NGC 6752 (Pasquini et al. 2005)

30 % of pristine gas
& 70 % of stellar ejecta

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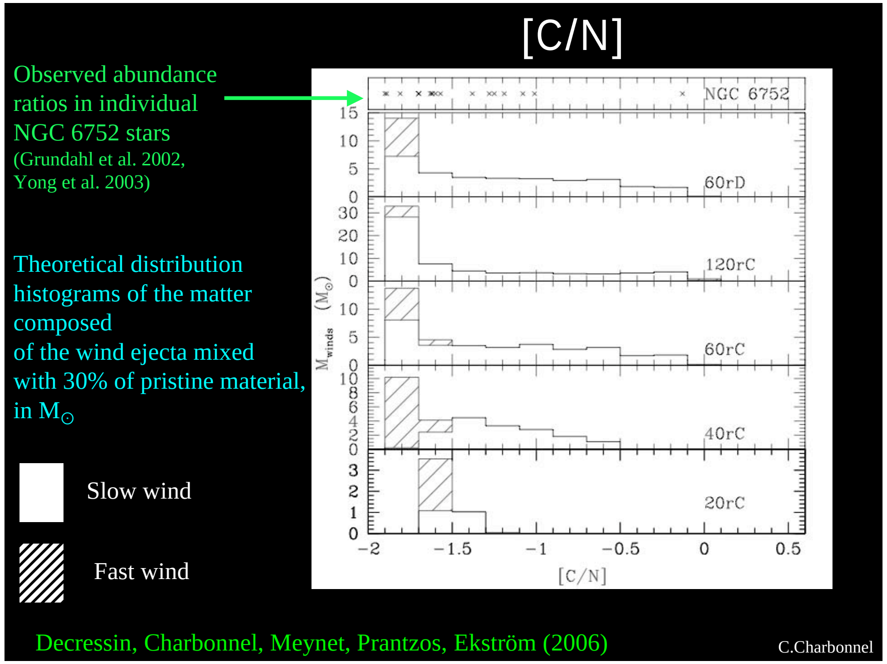

[C/N]

Observed abundance ratios in individual NGC 6752 stars (Grundahl et al. 2002, Yong et al. 2003)

Theoretical distribution histograms of the matter composed of the wind ejecta mixed with 30% of pristine material, in $M_\odot$

☐ Slow wind

▨ Fast wind

Decressin, Charbonnel, Meynet, Prantzos, Ekström (2006)

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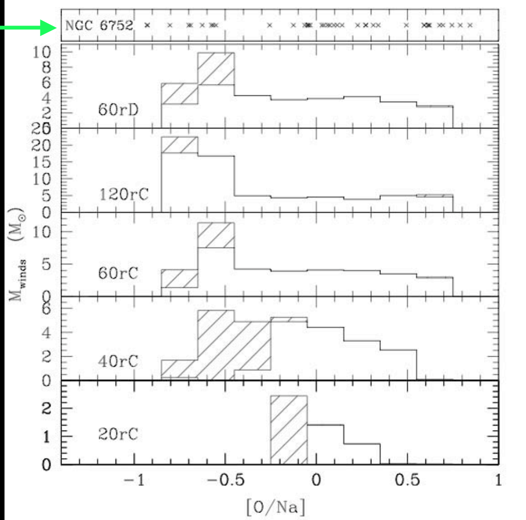
[O/Na]

Observed abundance ratios in individual NGC 6752 stars
(Carretta et al. 2005)



Theoretical distribution histograms of the matter composed
of the wind ejecta mixed with 30% of pristine material, in $M_\odot$

☐ Slow wind

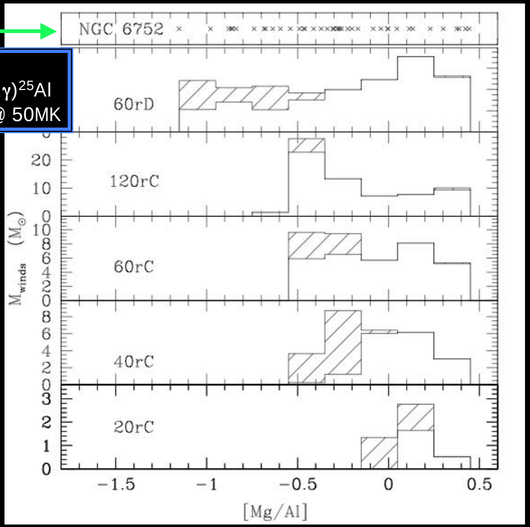
▨ Fast wind

Decressin, Charbonnel, Meynet, Prantzos, Ekström (2006)

[Mg/Al]

Observed abundance ratios in individual NGC 6752 stars
(Grundahl et al. 2002, Yong et al. 2003)

If
$^{24}Mg(p,\gamma)^{25}Al$
X 10^3 @ 50MK



Theoretical distribution histograms of the matter composed
of the wind ejecta mixed with 30% of pristine material, in $M_\odot$

☐ Slow wind

▨ Fast wind

Decressin, Charbonnel, Meynet, Prantzos, Ekström (2006)

A
schematic view
of the
self-enrichment
in GCs

A few 10^6 yr → WMS

A few 10^7 yr → SN

~10^8 yr → AGB (4-9 MO)

The slow winds of fast-rotating massive stars, loaded in H-burning products, are realeased within the ISM, opening up cavities

Also, they *mix* with the ISM, enriching it with their H-burning products

The fast winds and hot SN ejecta *escape* preferentially along the cavities and/or the rotational axis and no heavy elements (>He-burning) are retained in the system

The ionisation front and/or the subsequent SN shock waves trigger collapse of the enriched ISM and *formation* of 2nd generation stars

AGB ejecta are released and form a rarefied medium, but in the absence of a trigger no new stars are formed from those ejecta.

At longer times (>10^8 yr) tidal effects remove those AGB ejecta from the cluster

Prantzos & Charbonnel (2006a)

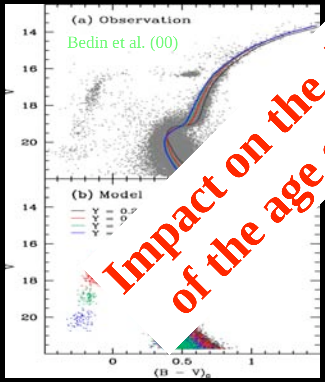
He enrichment : Hints from the CMD

- He is the main product of H-burning
  - ⇒ Polluted stars have higher He
    - ⇒ Their turnoff mass is smaller
    - ⇒ If mass loss on the RGB is unaffected, they will occupy a bluer HB loci

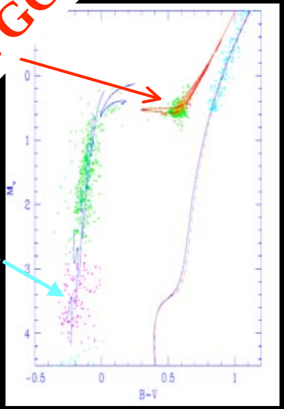
C 2808

Caloi (04)

Impact on the determination of the age of galactic GCs?



(Lee et al. 05)



Observations by Bedin et al. (00)

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Summary

! C-N, O-Na and Mg-Al anticorrelations seen in GCs only require early polution of the intra-cluster gas by a first generation of massive and fast evolving stars

! *Intrinsic property* of a GC related to the cluster formation process itself

! p-capture nucleosynthesis at relatively high T (~ 75 MK)
Explains all the patterns (C, N, O, Mg, Al, Mg isotopes and even Li and F) : dilution with pristine gas

! 2 potential polluters :
Massive AGB stars
Massive rotating stars

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Summary

! Difficulties of the AGB scenario

⇔ Dredge-up of He-products

& No process to trigger latter star formation

? Reliability of the AGB model predictions ?

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The Wind of Fast Rotating Massive Stars scenario

! Gently blowing winds of rapidly rotating massive stars
⇒ ejection of slow material loaded in H-burning products only
⇒ May trigger star formation in their vicinity
One cause for two processes
A very interesting candidate polluter of GCs
Decressin, Meynet, Charbonnel, Prantzos & Ekström (2006)

! Fast rotation may help to resolve other questions
He-rich stars in GCs (Maeder & Meynet 2006)
C-rich stars (Meynet et al. 2006)
Primary N production (Chiappini et al. 2006)

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The Wind of Fast Rotating Massive Stars scenario

! Gently blowing winds of rapidly rotating massive stars
⇒ ejection of slow material loaded in H-burning products only
⇒ May trigger star formation in their vicinity
One cause for two processes
A very interesting candidate polluter of GCs
Decressin, Meynet, Charbonnel, Prantzos & Ekström (2006)

! May somewhat relieve constraints on the polluter IMF (Salpeter 1.35)
→ Constraints from [O/Na] in NGC 2808 satisfied for slopes
$X_2 < 0.75$ in the case of massive stars (30 - 100 $M_\odot$)
$X_2 < 0.45$ in the case of massive AGBs (4 - 9 $M_\odot$)
Prantzos & Charbonnel (2006)

! Detailed observations of abundance distributions, combined with realistic predictions for the stellar yields, will allow us to constrain convicingly the polluter IMF

The future

! Future : Link the macroscopic (dynamical evolution of a GC) and microscopic (evolution of single and multiple stars) phenomena

→ How does the general dynamical evolution of the cluster influence the fate of member stars?
Rotation ?
Binarity ?
Stellar encounters ?
Mass loss ?
Blue stragglers ? Horizontal branch morphologie ?
Multiple generations ?

← How does stellar evolution influence the dynamical evolution of the cluster as a whole?
Survival vs disruption