Abundance Anomalies in Globular Clusters: The Role of AGB Stars

John Lattanzio, Amanda Karakas, Simon Campbell

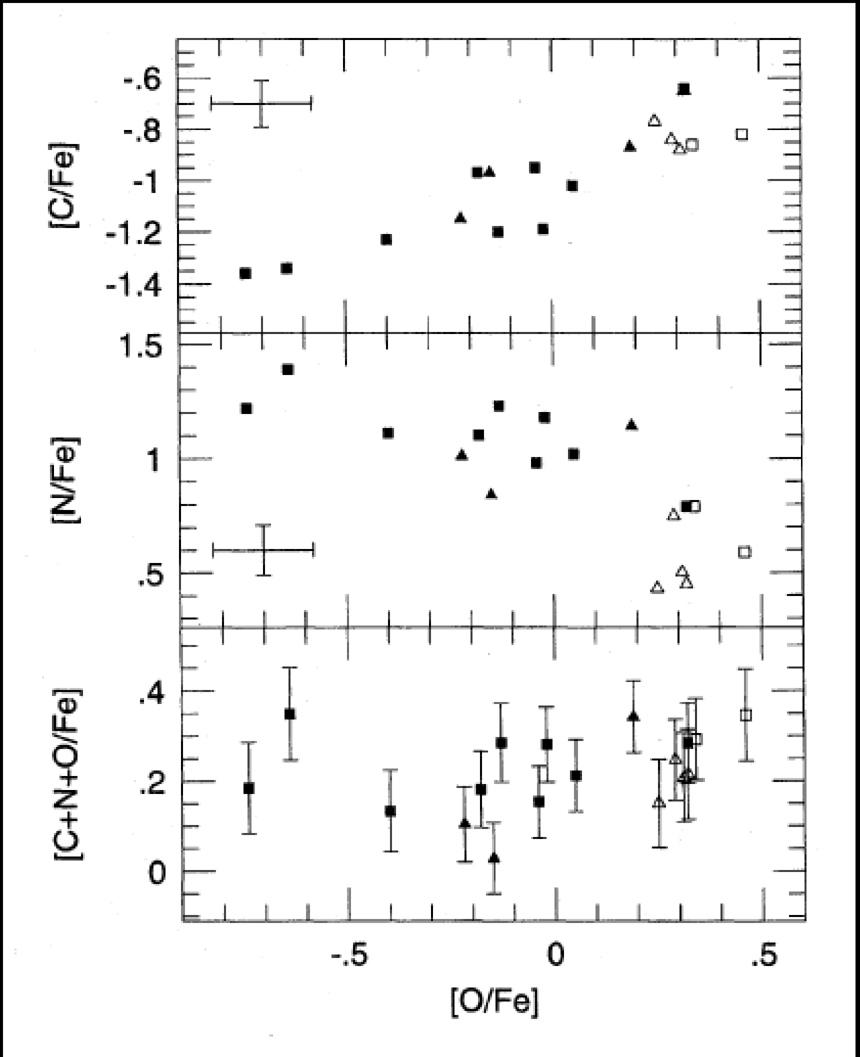
Centre for Stellar and Planetary Astrophysics, Monash University,Australia

Yeshe Fenner, Brad Gibson

Centre for Astrophysics and Supecomputing, Swinburne University, Australia

1970s: Norris, Da Costa and Cottrell

- CN varies from star to star in some clusters
- Some stars have C down and N up
- C+N+O = constant
- Indicates CNO cycling



Interior composition: CN cycling

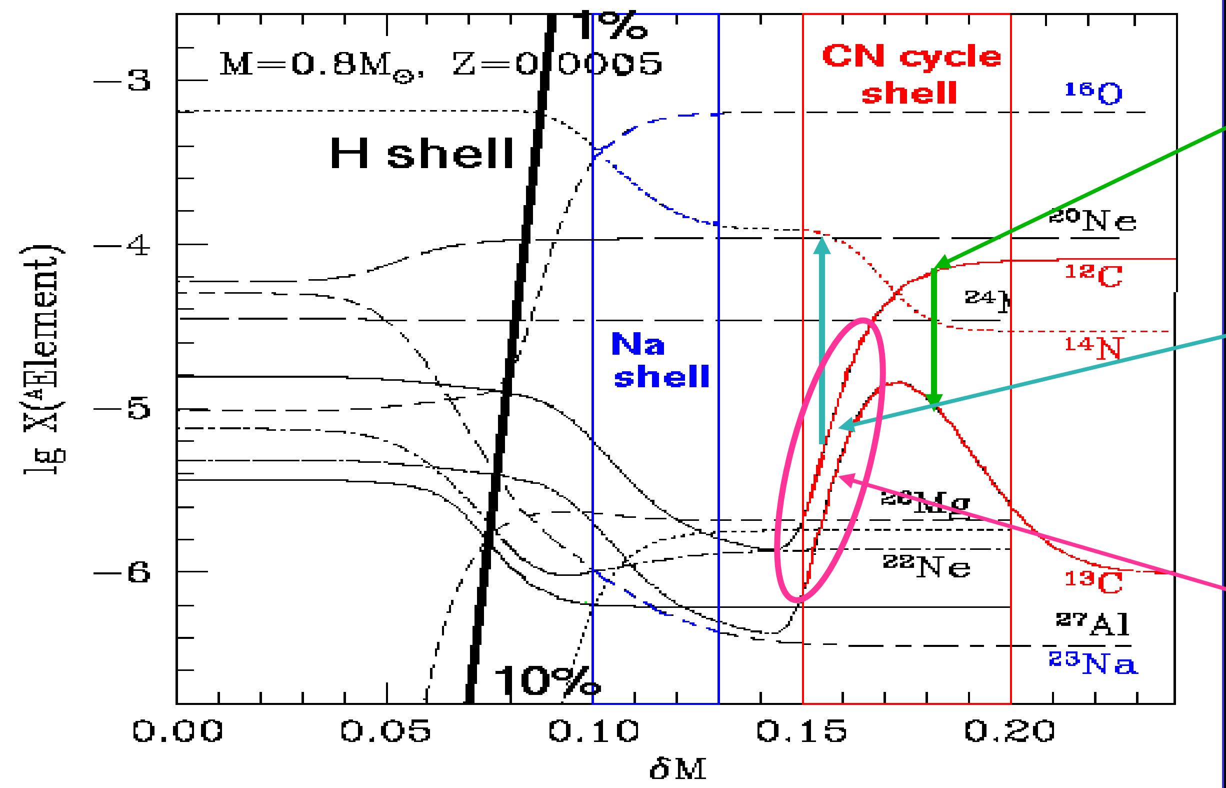


Fig. 1. Abundance profiles for a number of nuclides participating in the CNO-, NeNa- and MgAl-cycles in radiative layers adjacent to the HBS in a $M = 0.8\,M_\odot$ model star having $\lg(L/L_\odot) = 3.0$ and $Z = 5\,10^{-4}$ approximately matching metallicities of the globular clusters M 13 and ω Cen. The mass coordinate δM is measured from the HBS in units of the mass separating the HBS and BCE. The vertical segments on the abscissa show locations of layers where (from right to left) 1, 5 and 10 percent of H were consumed

$^{12}C \rightarrow {}^{13}C$

^{12}C and ^{13}C

$\downarrow$

^{14}N

$^{12}C/{}^{13}C \approx 3.5$

C burns to N

C+N = const

Interior composition: ON cycling

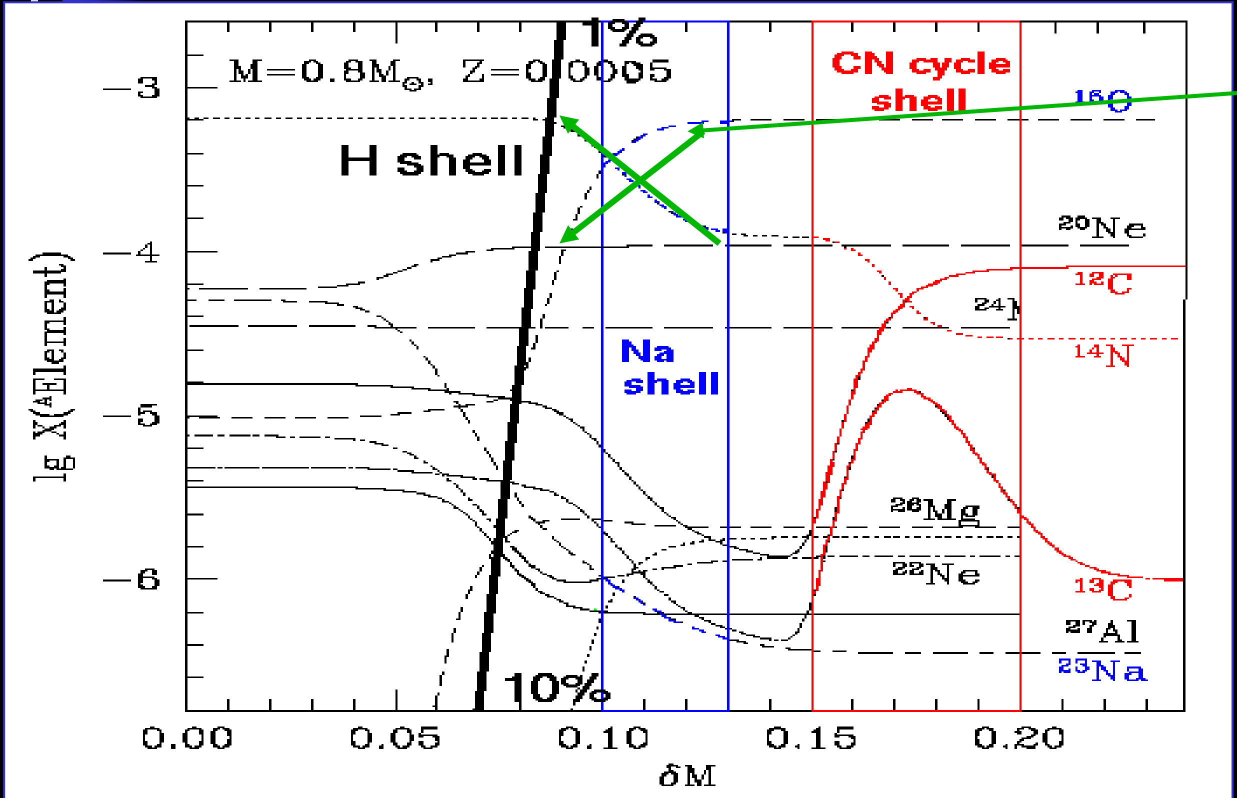


Fig. 1. Abundance profiles for a number of nuclides participating in the CNO-, NeNa- and MgAl-cycles in radiative layers adjacent to the HBS in a $M = 0.8\ M_\odot$ model star having $\lg(L/L_\odot) = 3.0$ and $Z = 5\ 10^{-4}$ approximately matching metallicities of the globular clusters M 13 and ω Cen. The mass coordinate δM is measured from the HBS in units of the mass separating the HBS and BCE. The vertical segments on the abscissa show locations of layers where (from right to left) 1, 5 and 10 percent of H were consumed

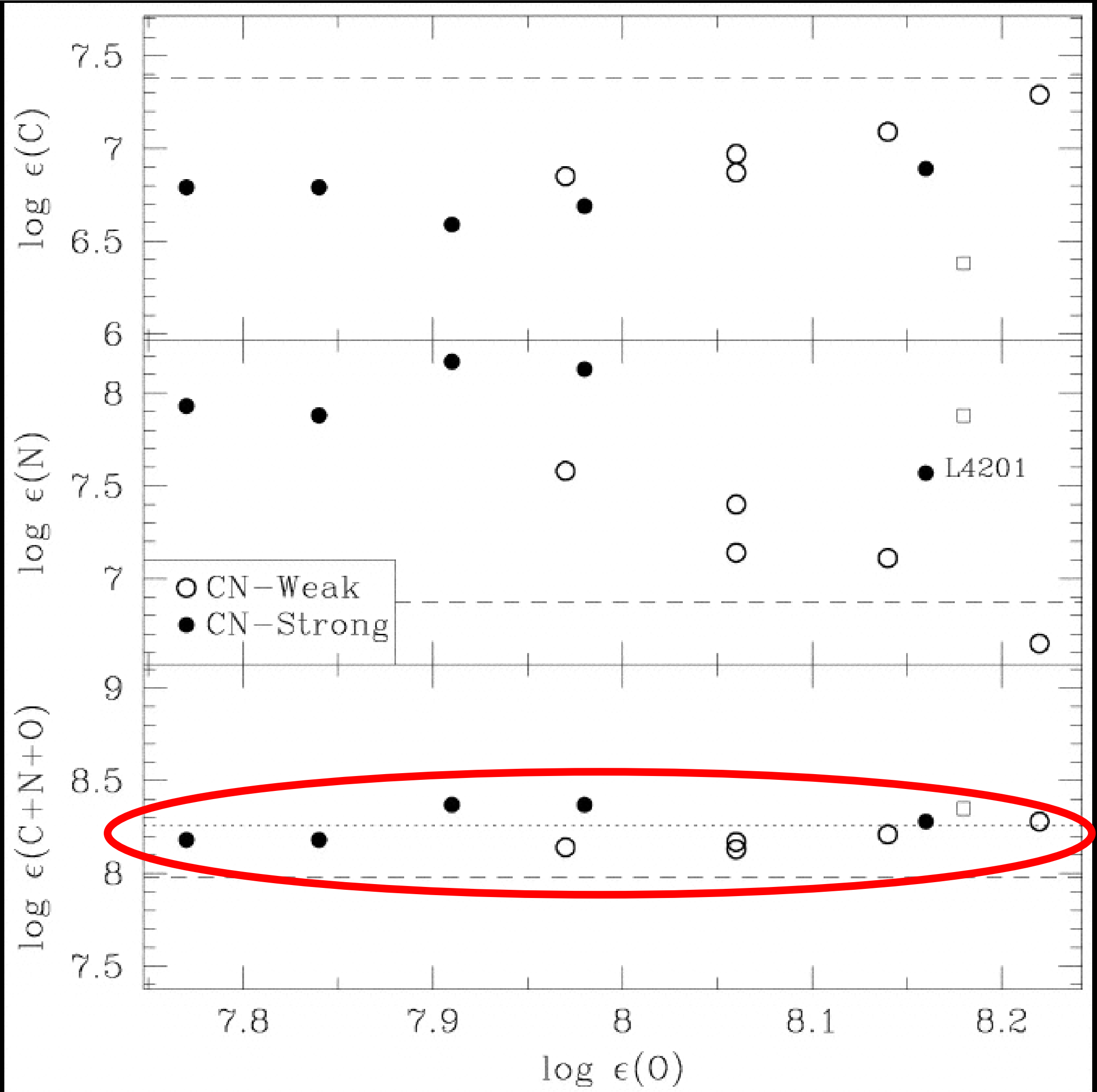
$^{16}O \longrightarrow {}^{14}N$

O burns to N

C+N+O = const

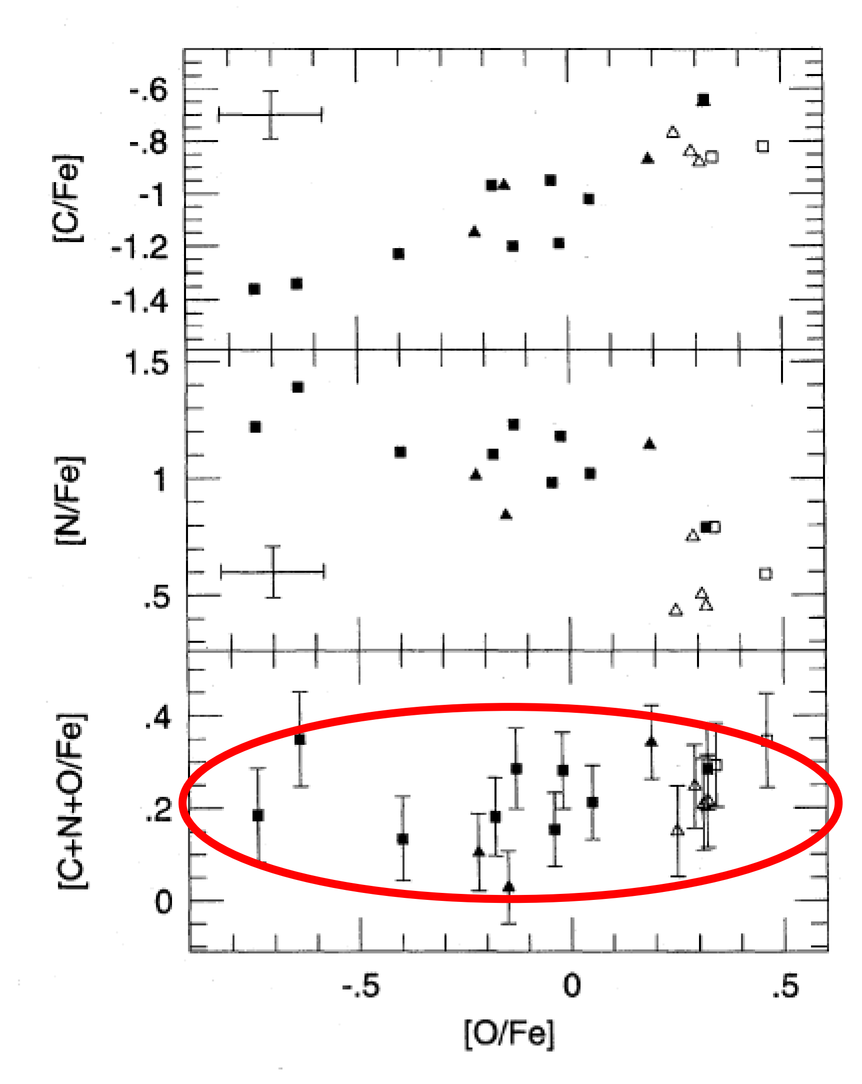
C+N+O in M4

- Ivans et al 1999



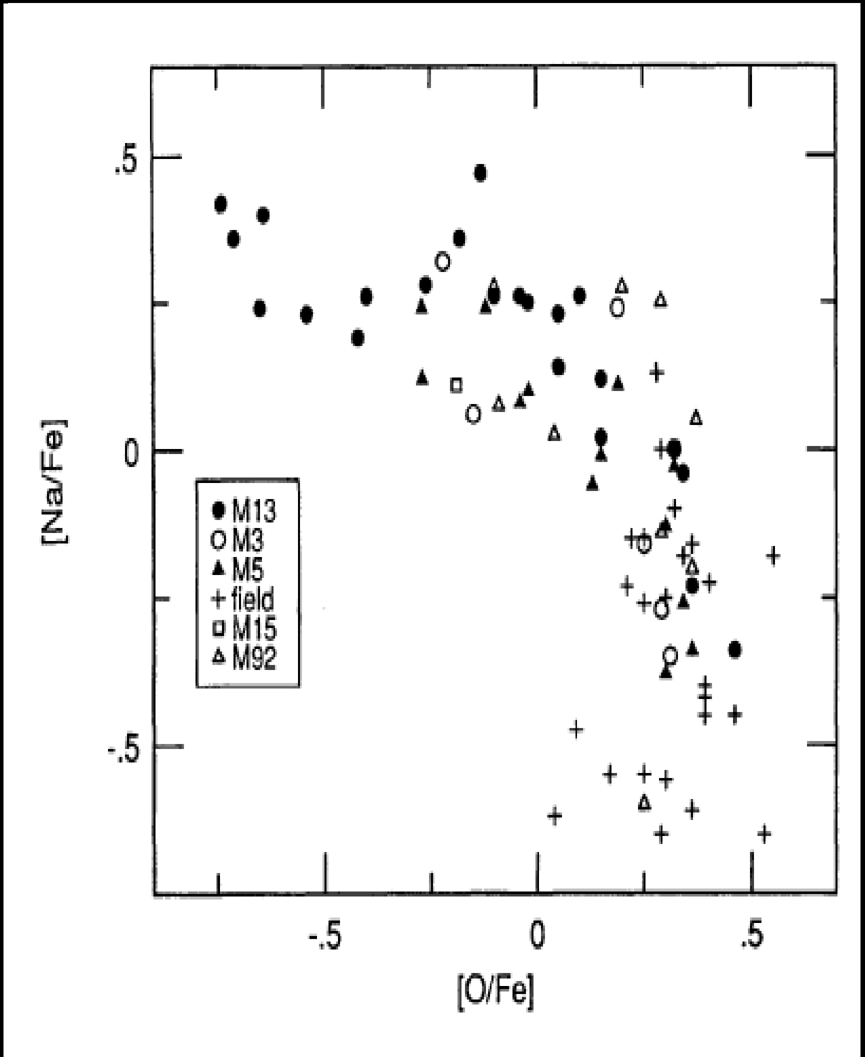
C+N+O in M13

- Smith et al 1996

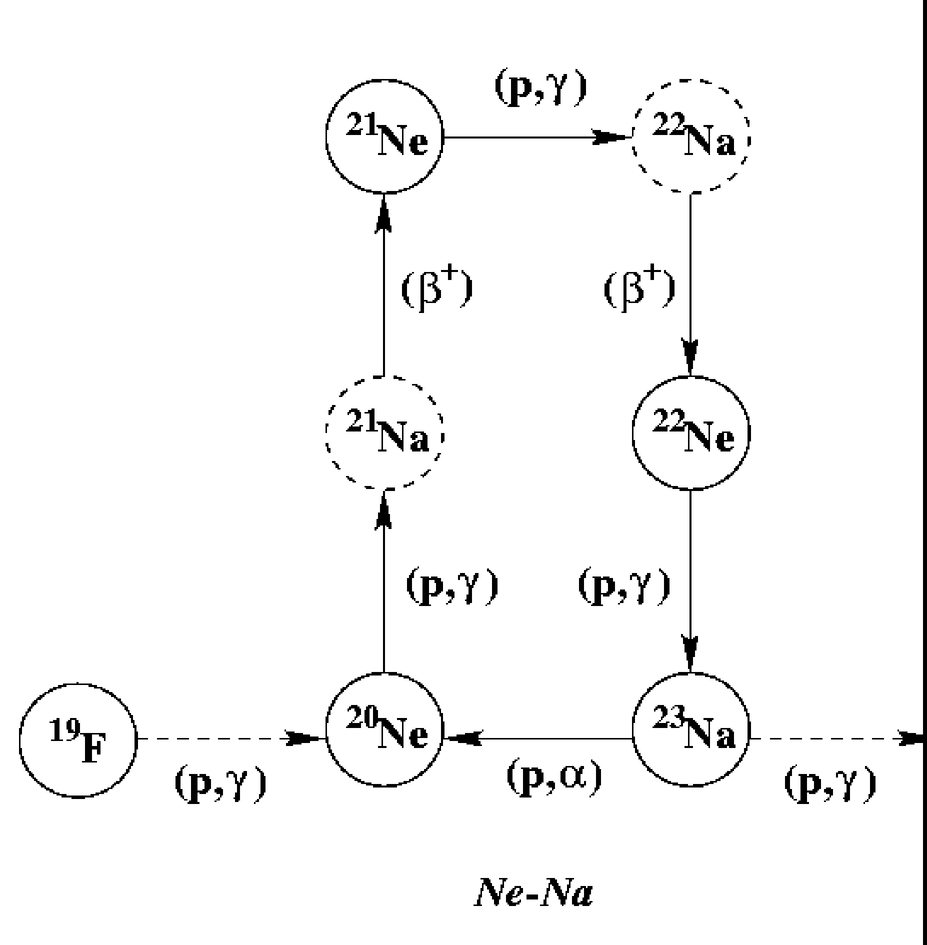


1970s: Norris, Da Costa and Cottrell

- CN varies from star to star in some clusters
- Some stars have C down and N up
- C+N+O = constant
- Indicates CNO cycling
- Soon added Na
- O down, Na up



Ne-Na cycle/chain



$T_6 < 50$: it is a cycle;
$T_6 > 50$: it is a chain, with leakage into Mg-Al.

Interior composition: NeNa “cycling”

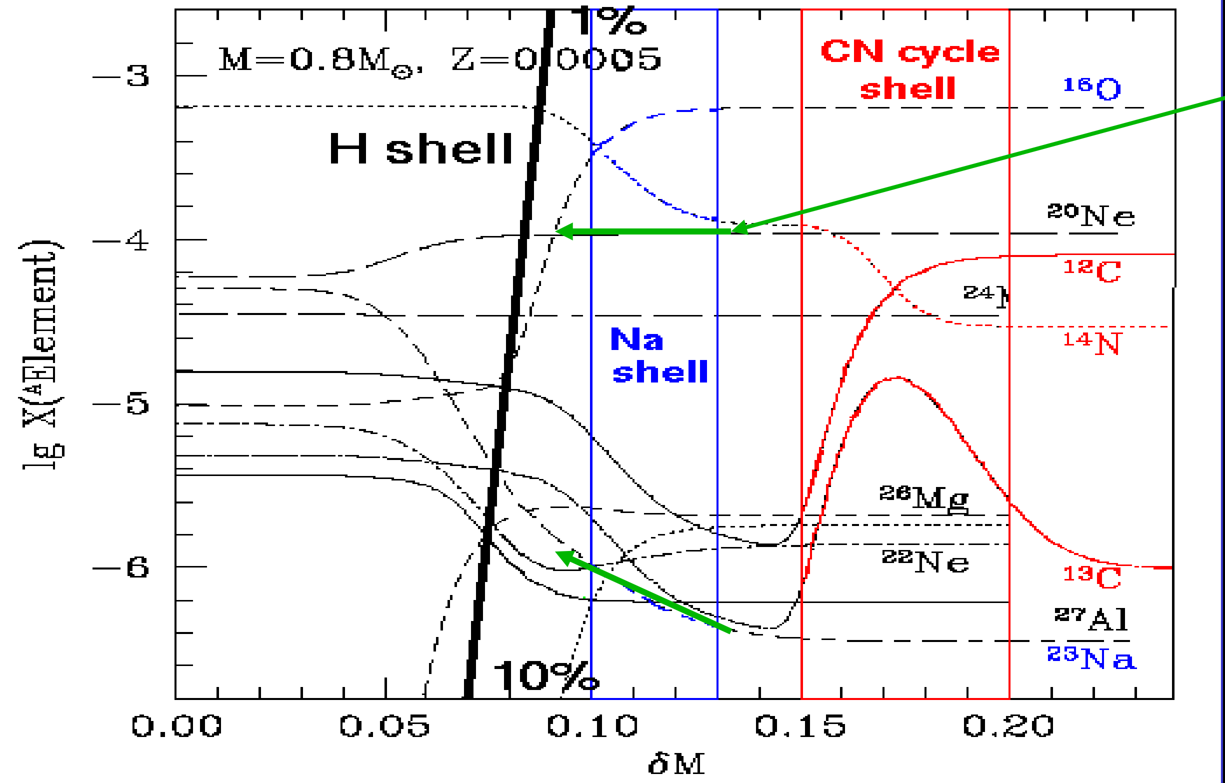


Fig. 1. Abundance profiles for a number of nuclides participating in the CNO-, NeNa- and MgAl-cycles in radiative layers adjacent to the HBS in a $M = 0.8\,M_\odot$ model star having $\lg(L/L_\odot) = 3.0$ and $Z = 5\,10^{-4}$ approximately matching metallicities of the globular clusters M 13 and ω Cen. The mass coordinate δM is measured from the HBS in units of the mass separating the HBS and BCE. The vertical segments on the abscissa show locations of layers where (from right to left) 1, 5 and 10 percent of H were consumed

^{20}Ne → ^{23}Na

Ne burns to Na

MONASH UNIVERSITY

Implicates H burning

- CN variations: CN cycling
- O-Na variations: ON and Ne-Na cycling

- All indicate H burning...

More recent problems: Mg and Al

- Near tip of GB we see:
  1) O down and Na up

- But sometimes we also see:
  1) Mg down and Al up

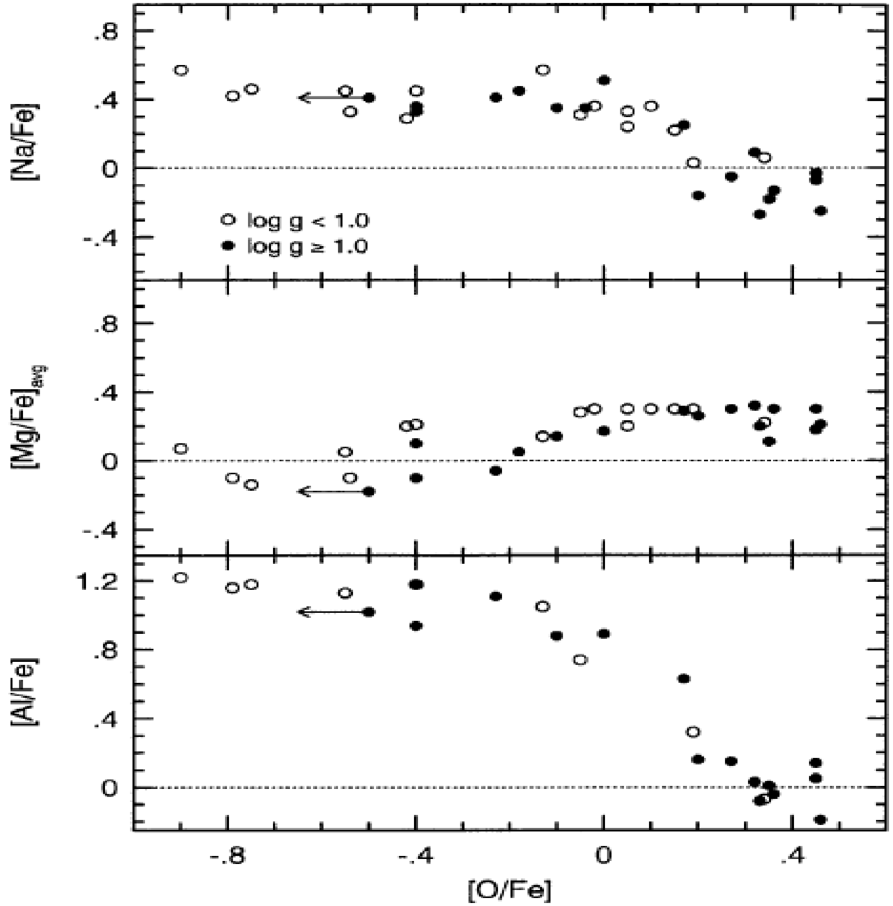
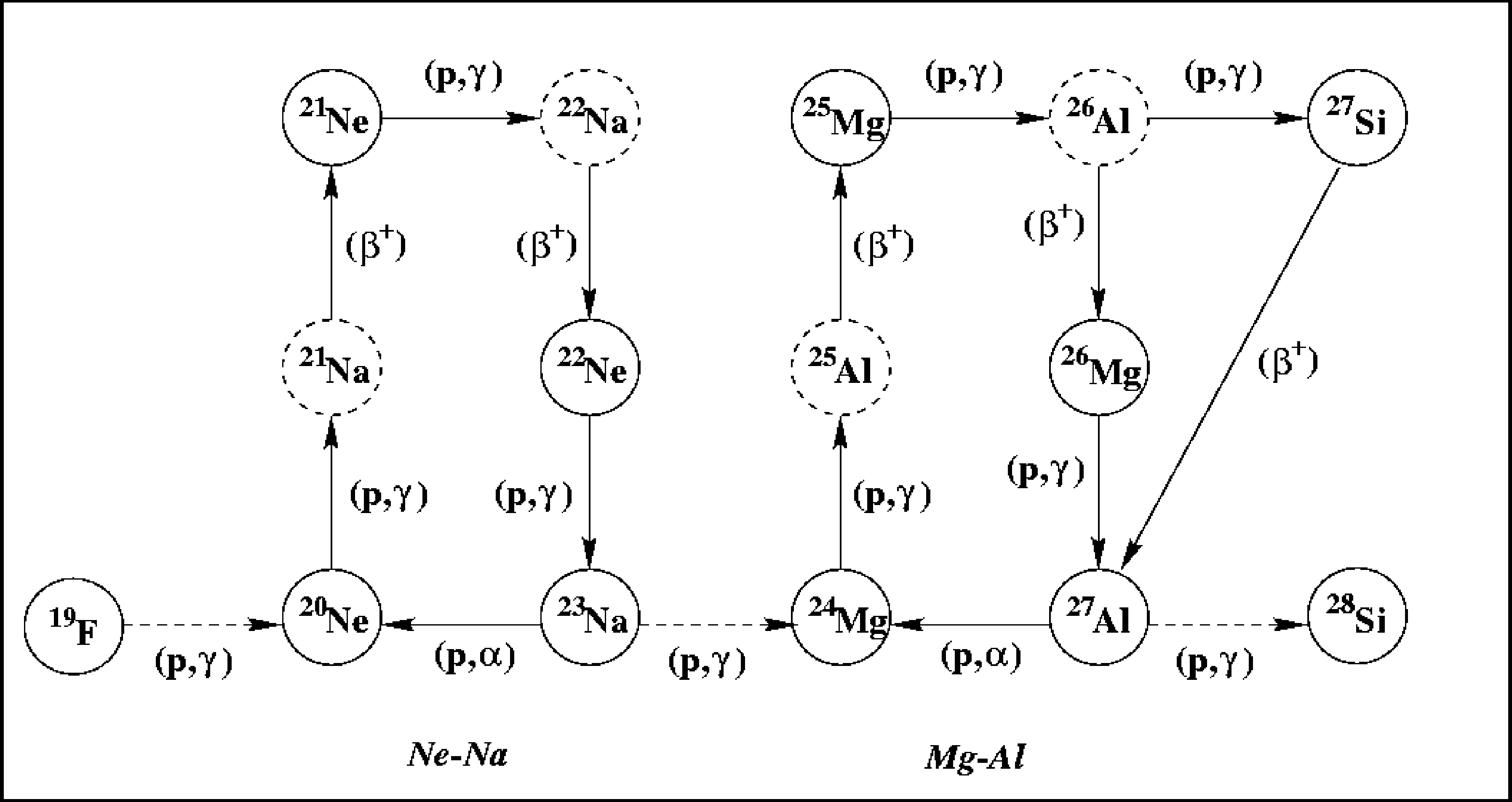
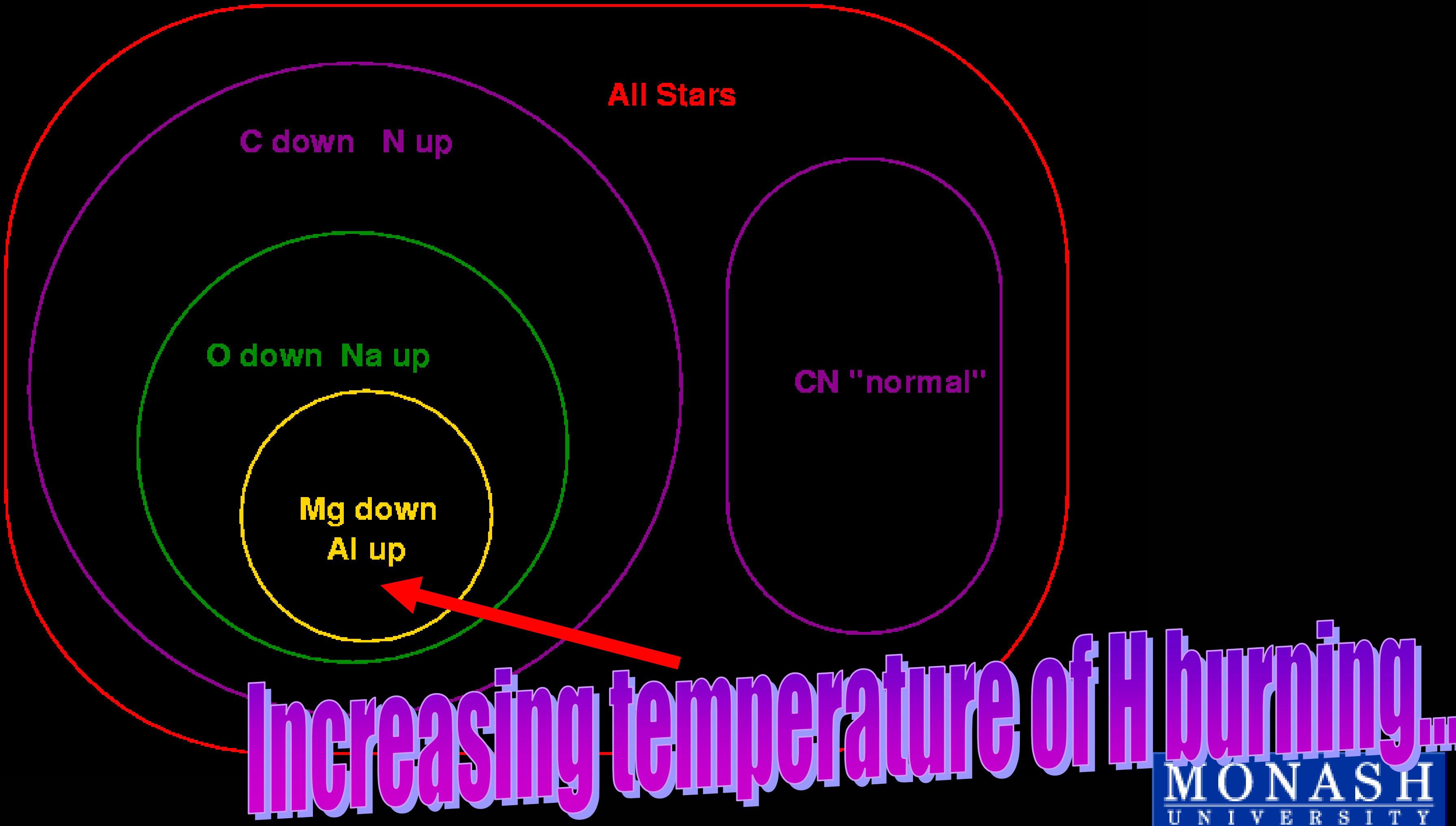


FIG. 9. Relative abundances of proton-capture elements sodium, magnesium, and aluminum as functions of relative oxygen abundances. Different symbols denote RGB tip and lower luminosity M13 giants. The horizontal dotted lines represent the solar abundances of these three elements.

Implicates H burning again (MgAl Chain – not cycle!)



Summary of the situation:



Two obvious explanations

- Evolutionary Origin
  1) some *internal* process within the star
  2) results mixed to surface
  3) observations are for giants (the bright stars): deep convective envelopes and hot shells
  4) not predicted by standard theory
  5) some “deep mixing”?

- Primordial Origin
  1) some process *external* to the star
  2) an inhomogeneous proto-cluster cloud?
  3) not due to a collision between two proto-cluster clouds, because [Fe/H] is very constant!
  4) not due to supernovae because [Fe/H] is constant

Important Point!

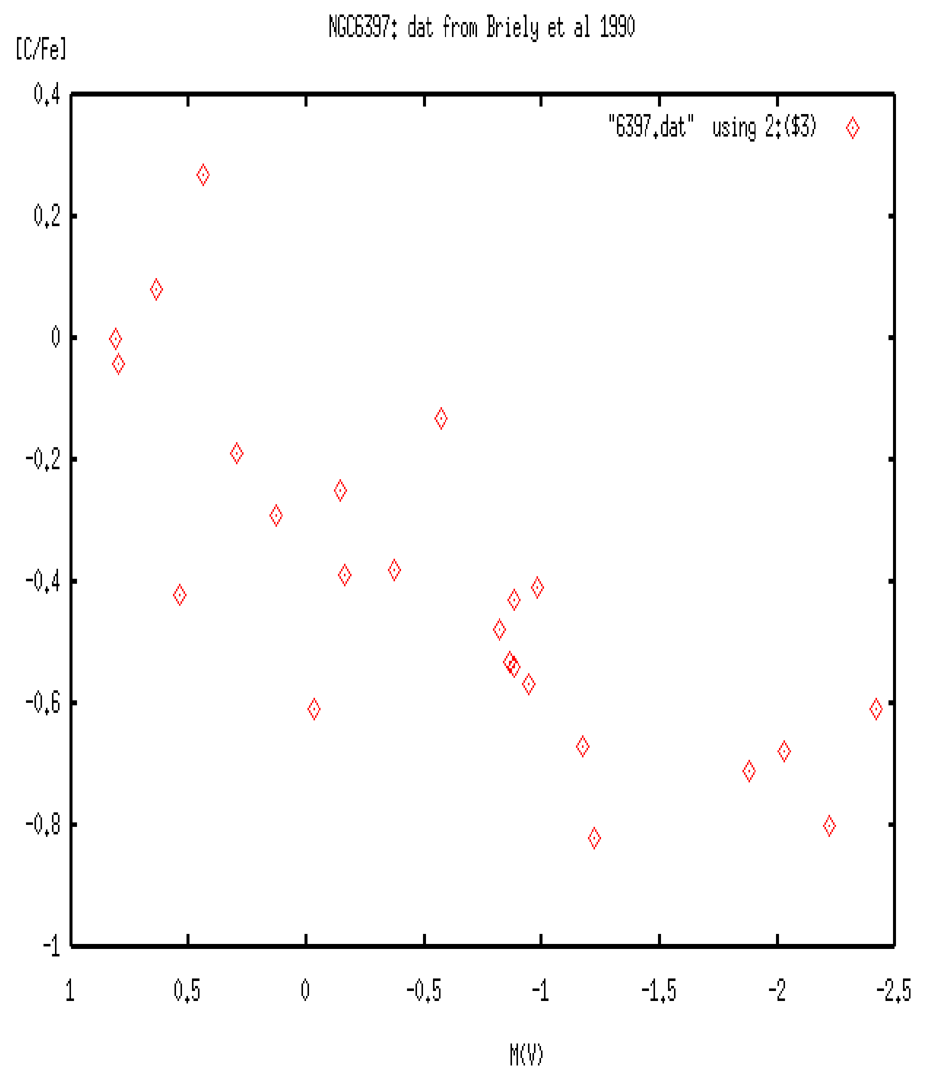
- These abundance anomalies are NOT seen in field stars!
- Stars somehow know they are in a globular cluster...

Is this really true?

Yes and No...

There is variation with evolution!

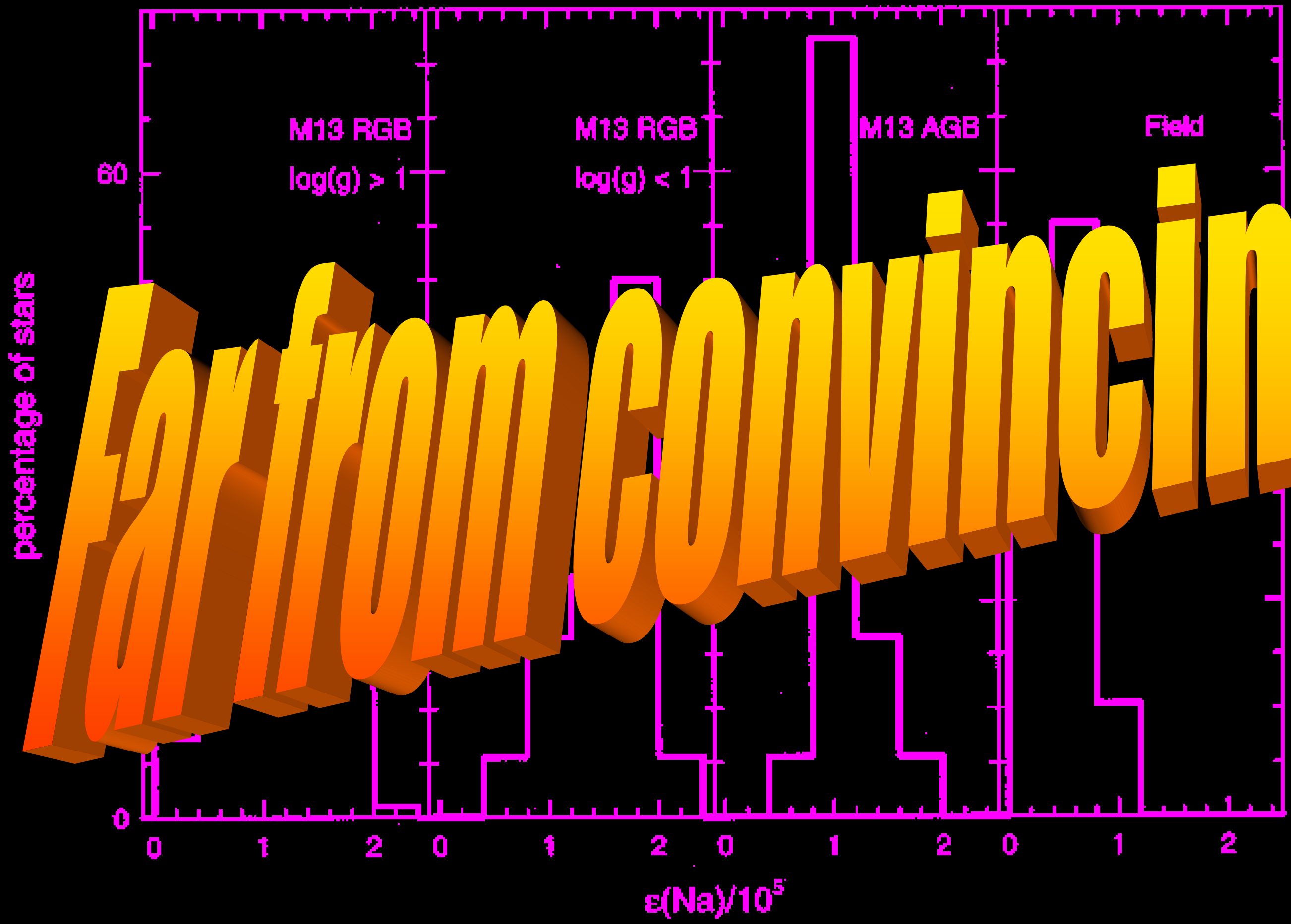
- In metal poor clusters there is a decrease of C with stellar luminosity (ie evolution)
- C down as L up
- Hard to understand if origin is external to star!



Strong evidence for internal process

- Assuming some process not seen in standard models can mix the material to the surface...eg meridional circulation...
- But this is for C (and N). What about other elements?

Na in M13: Pilachowski et al 96



Far from convincing!

See also Charbonnel et al 2004...

GC stars are like Field Stars after all!

- The only species shown to vary with L is C (and hence N)
- Same as field stars
- Same as pre-solar grains
- Some internal mixing involved in CN cycle species
- GC stars and Field stars are not *behaving* differently after all
- The other abundance differences *must be environmental*

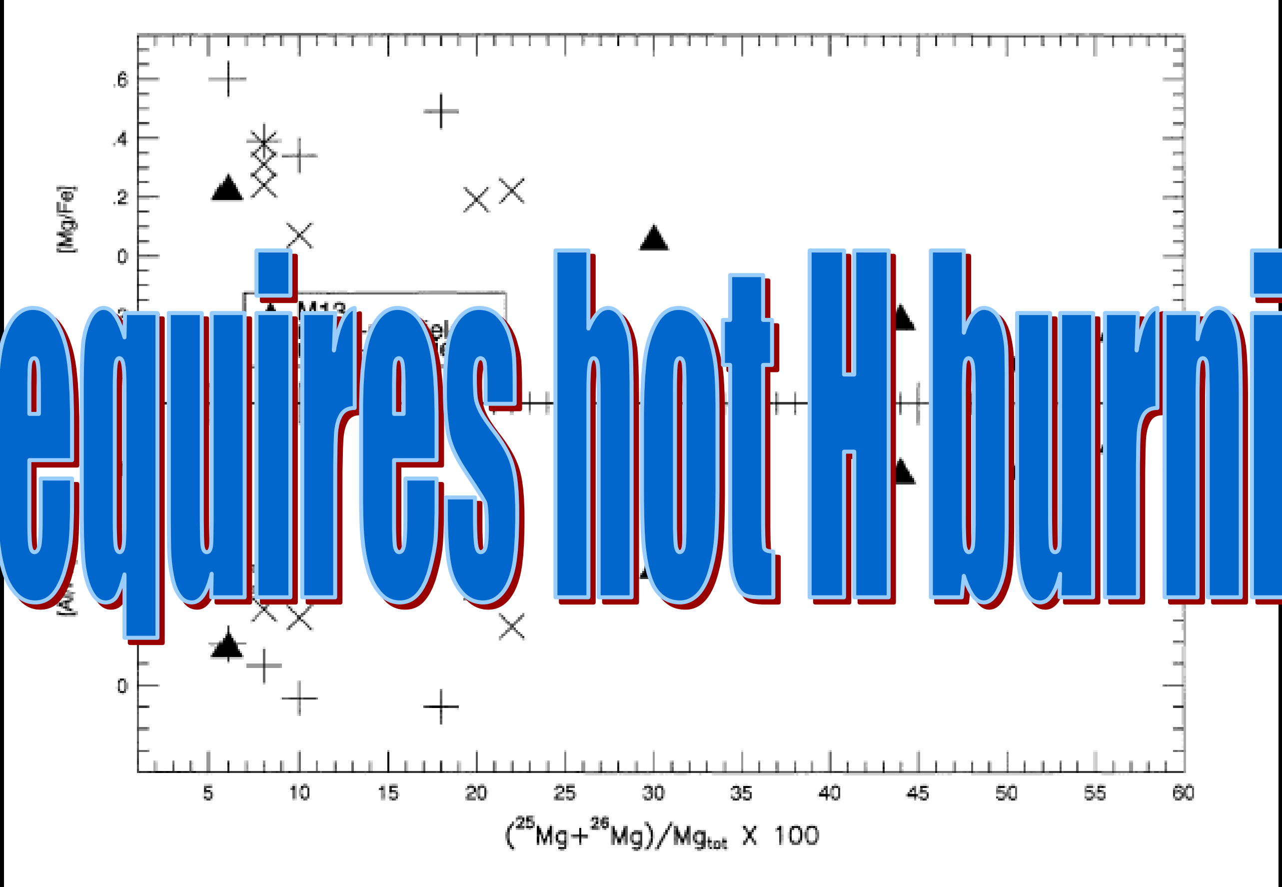
MONASH
UNIVERSITY

Mg and Al: any hints?

- Mg has 3 stable isotopes:
  1) ^{24}Mg: mostly made in supernovae
  2) ^{25}Mg and ^{26}Mg: mostly made in AGB stars
- Can we learn which isotopes are involved in GC stars?

Mg isotopes in M13: Matt Shetrone

Red giants near tip of GB in M13



Requires hot H burning

Mg^{24} down as Al up!

Mg isotopes in NGC6752: Yong et al

- Were able to separate ^{25}Mg and ^{26}Mg
- Found very similar results to M13
    1) ^{25}Mg varied very little
    2) ^{24}Mg decreased as Al increased
    3) Heavy isotopes of Mg much more abundant that solar composition

- More on this data later...

What about below the Giant Branch?

- All observations discussed so far are for bright giants
- Giants have hot shells and mixing, so can be internal processes, in principle
- If same abundance variations are seen on MS then its hard to explain by mixing!
- For heavy elements it may be impossible to explain by mixing!

C and N in Sub-giants and MS stars

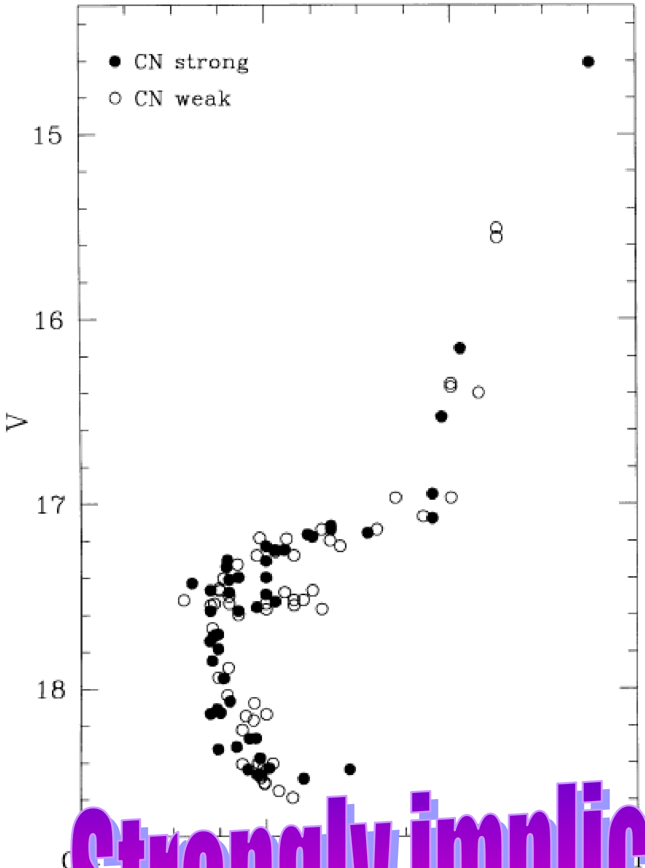


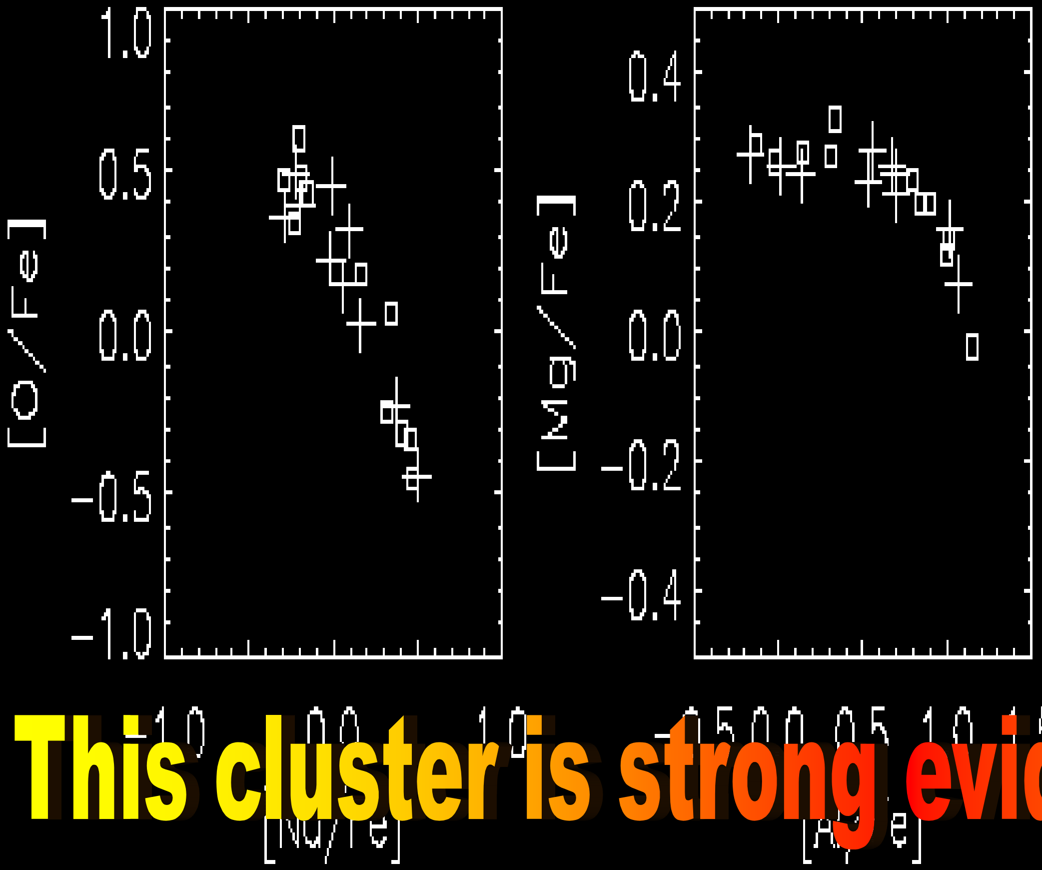
Figure 6. Th[illegible] agram, using the same data as Fig. 2 but with the symbols of Fig. 4 to distinguish between the CN-strong and CN-weak stars.

- 47 Tuc: Cannon et al
- CN variations exist on the main sequence!
- Same situation seen in M71 by Cohen et al

Strongly implicates primordial source!

MONASH UNIVERSITY

Below the bump...in NGC6752



- Gratton et al looked at NGC6752
- Na-O anti-correlation seen in MS stars
- Briley et al looked at Mg-Al below the giant branch bump: and found variations!

This cluster is strong evidence for pollution!

Summary of Requirements

- Internal mixing to alter CN
- O down and Na up
  1) Requires ON and NeNa cycles
- Mg24 down and Al up
  1) Requires MgAl cycle at high T
- H burning involved...at fairly high T
- Fe constant so no SN involved

AGB Stars Favoured as Polluters?

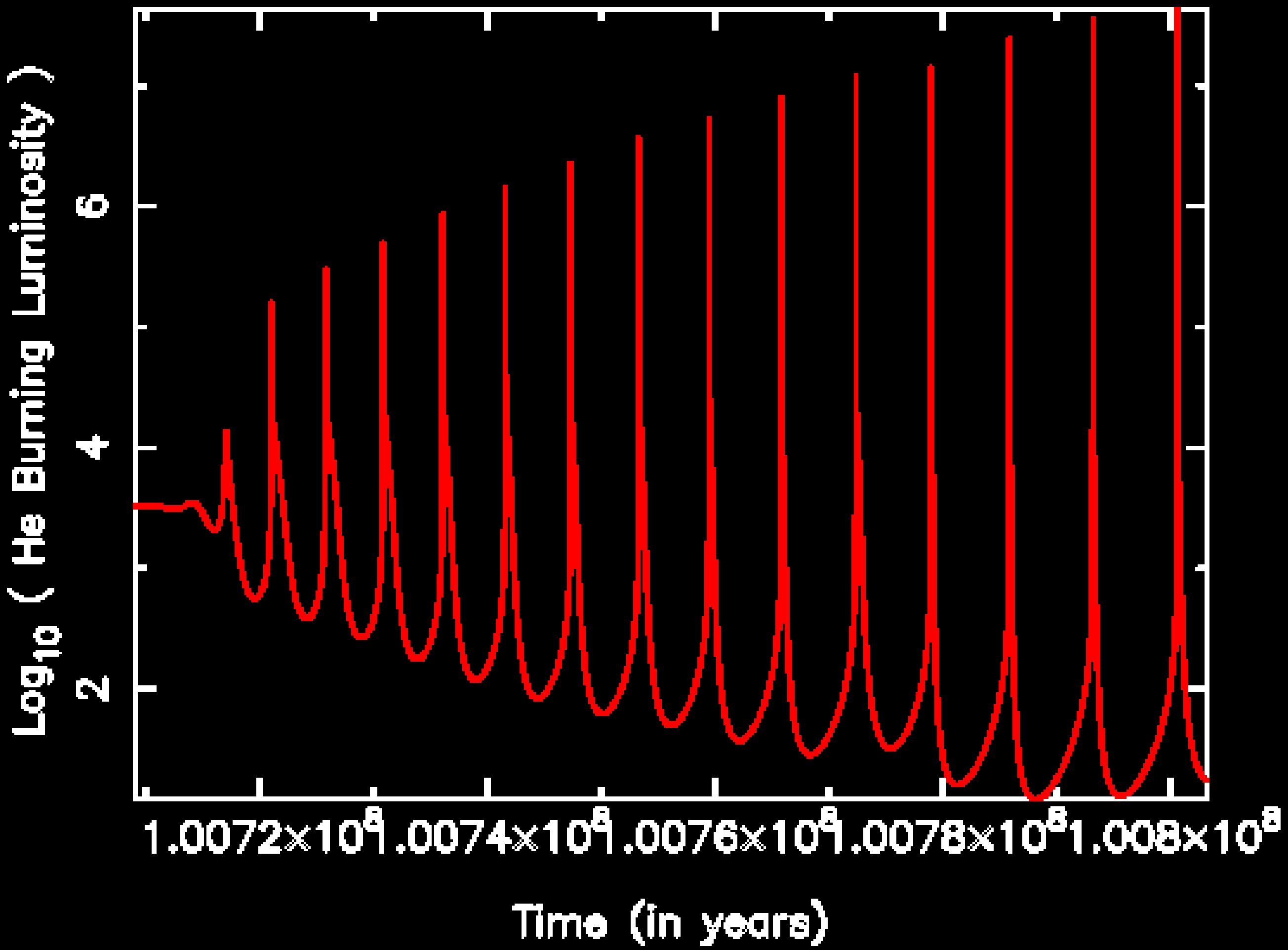
- No Fe variations
- Slower winds, so gas is kept in cluster
- Hot Bottom Burning provides high T for H processing by NeNa and MgAl cycles…

AGB Star nucleosynthesis

- Thermal pulses (He burning)
- H shell
- Repeated mixing of both regions
- Hot Bottom Burning...

- Could be ideal?

AGB Summary



Log10 (He Burning Luminosity)
2
4
6
1.0072×10^8
1.0074×10^8
1.0076×10^8
1.0078×10^8
1.008×10^8
Time (in years)

AGB Summary

- Energy sources
- Shell movement
- Mixing Zones

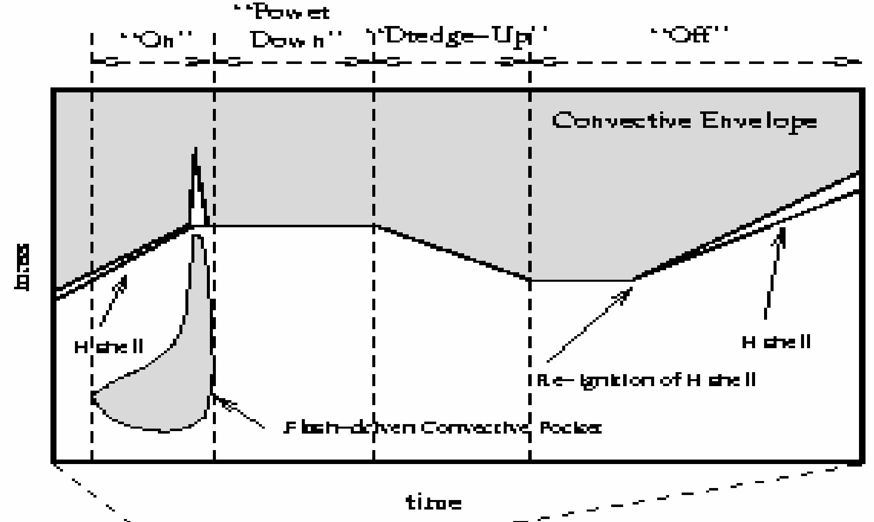


FIGURE 2 (a).-- One thermal pulse.

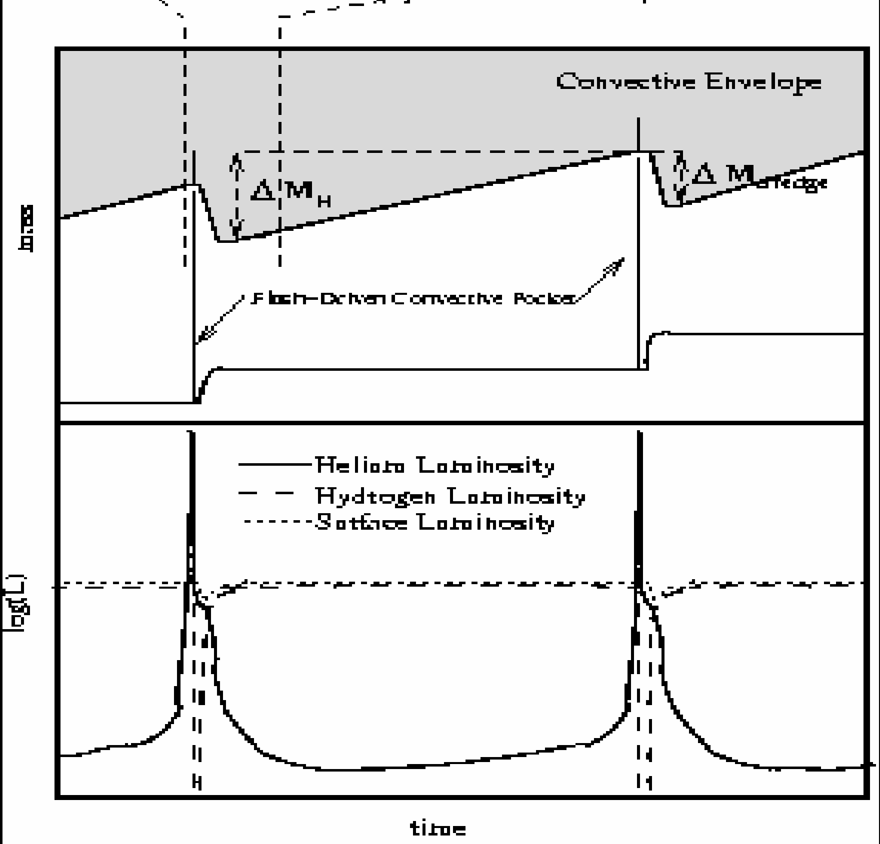
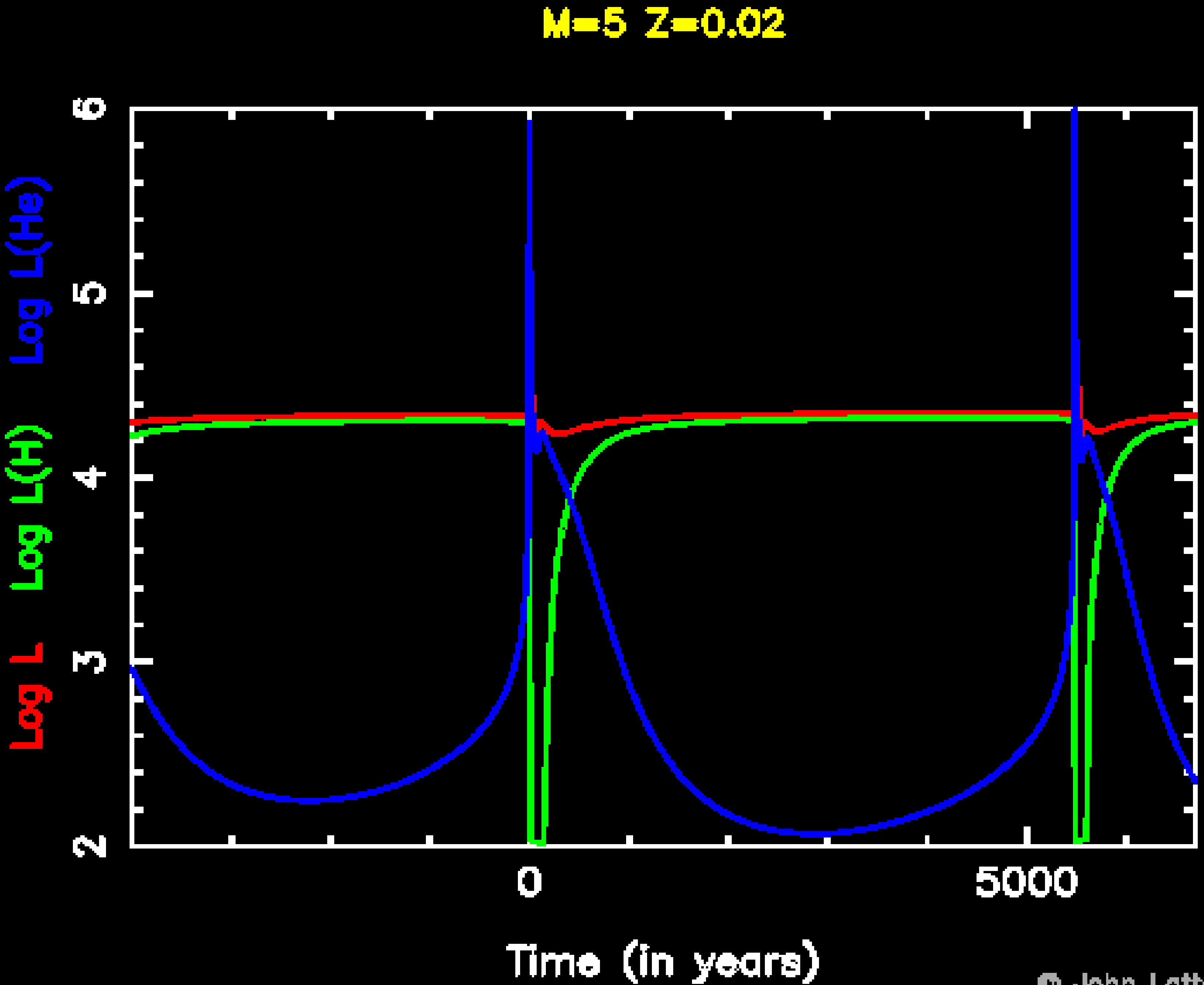
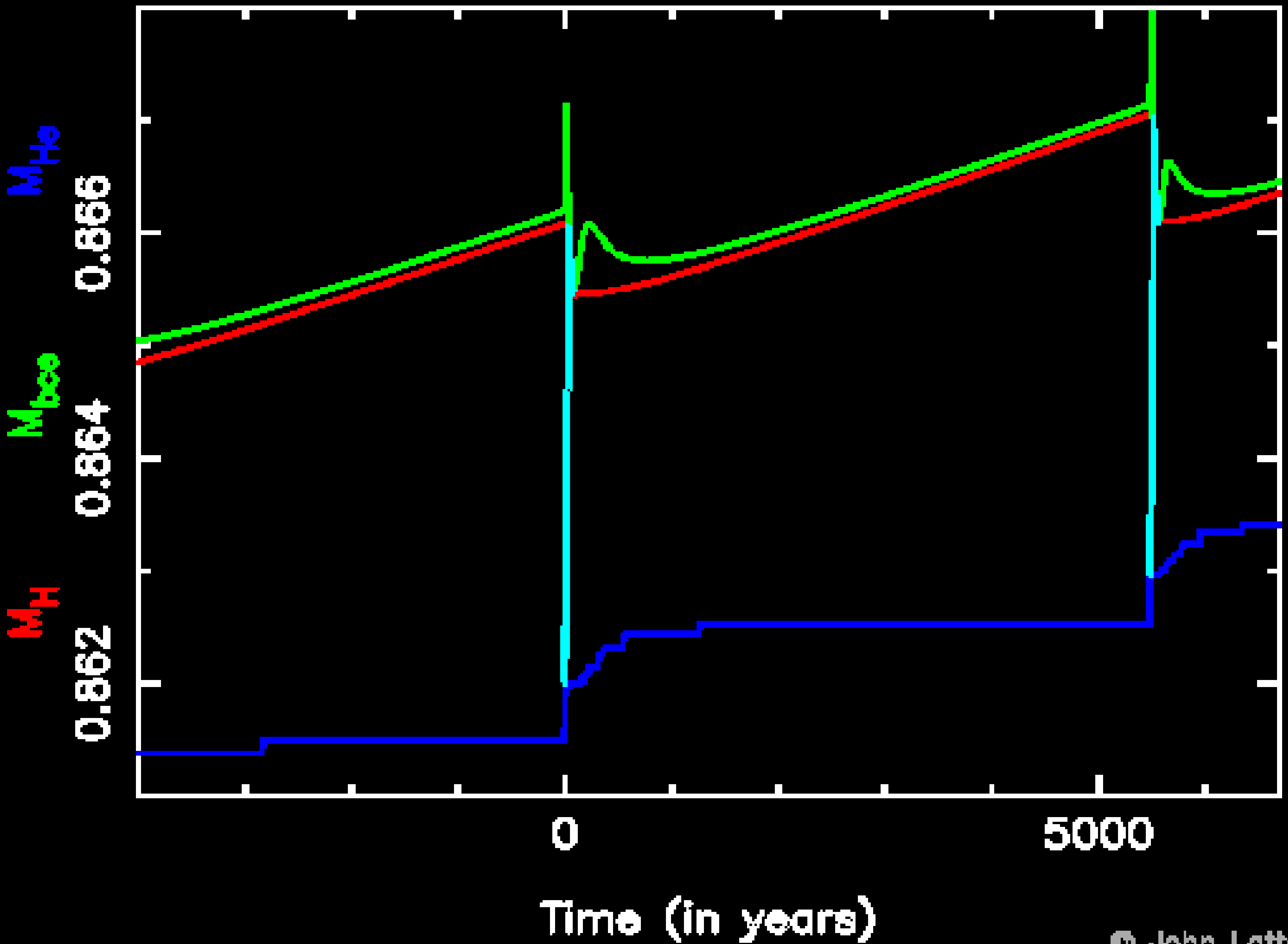


FIGURE 2 (b). Two consecutive thermal pulses


M=5 Z=0.02
Log L
Log L(H)
Log L(He)
6
5
4
3
2
0
5000
Time (in years)

M=5 Z=0.02



AGB Summary

Mixing Zones →

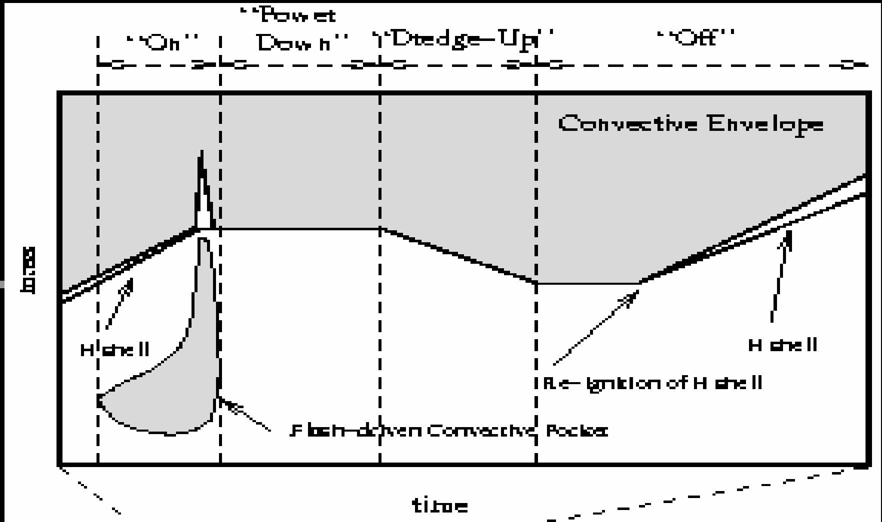


FIGURE 2 (a).– One thermal pulse.

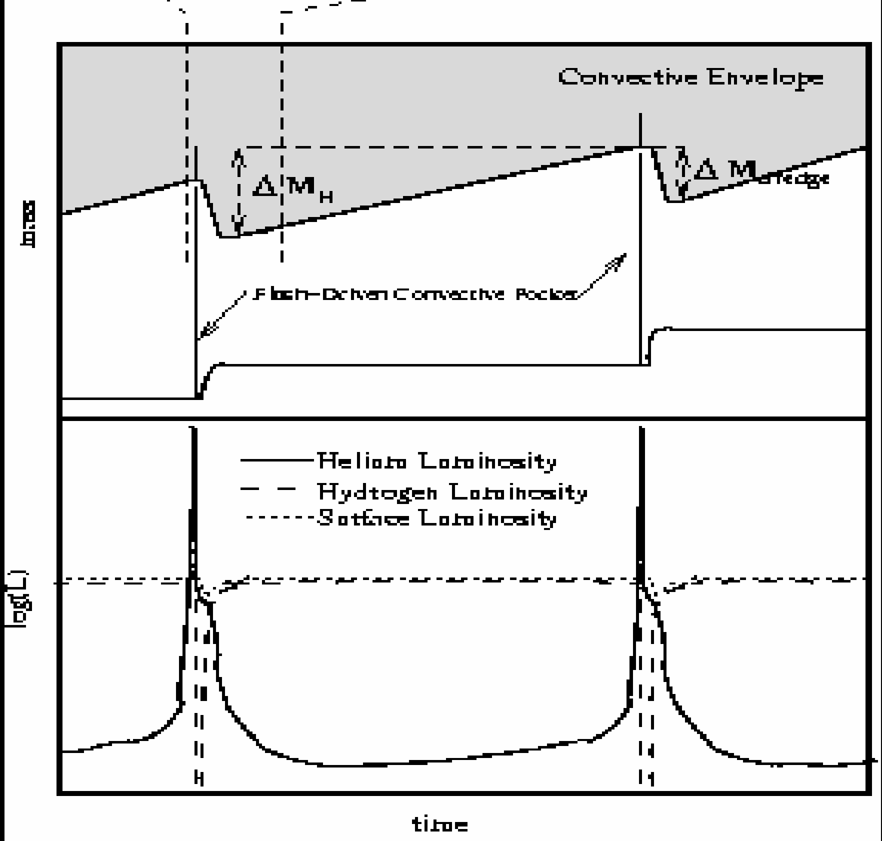
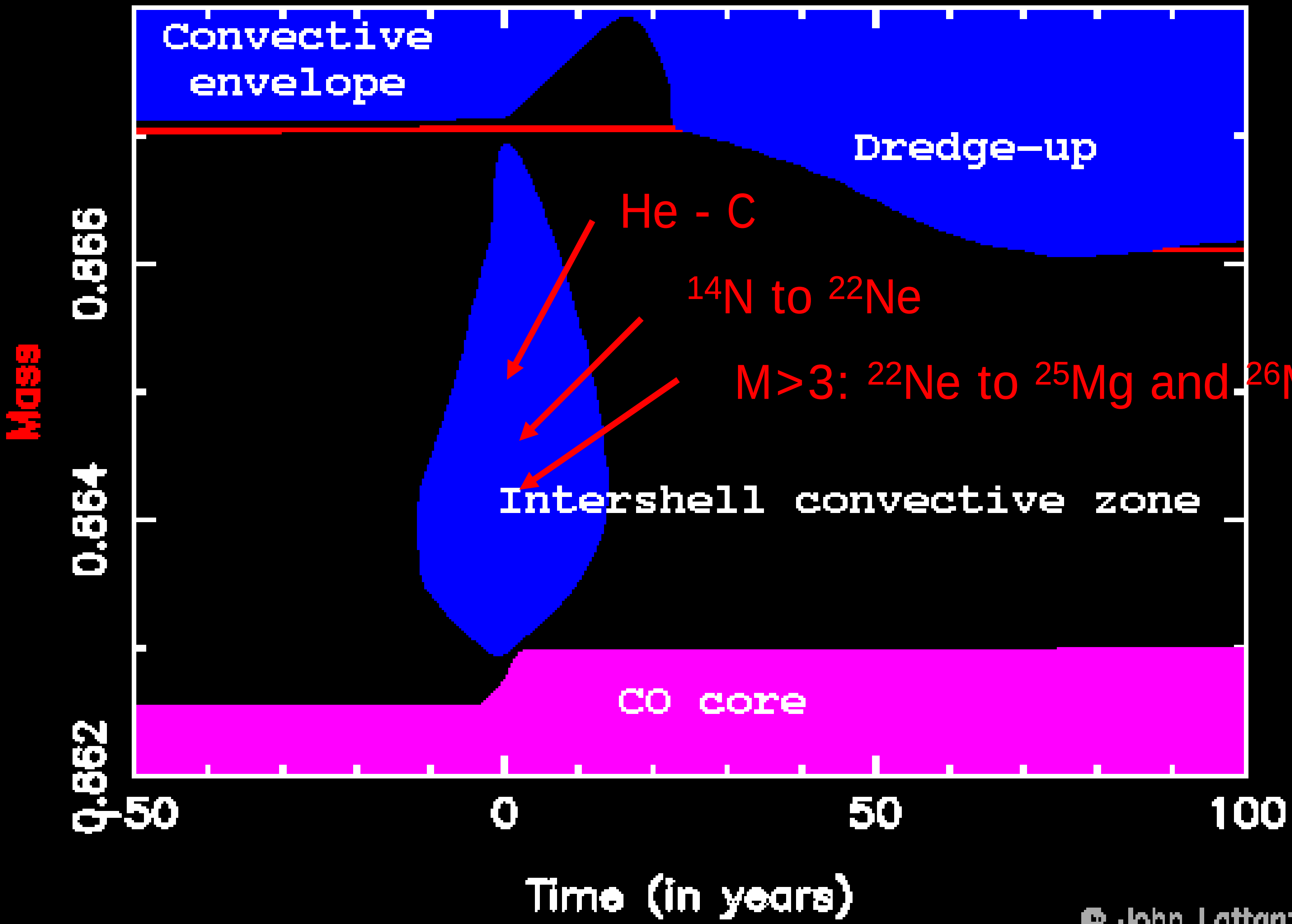


FIGURE 2 (b). Two consecutive thermal pulses

M=5 Z=0.02



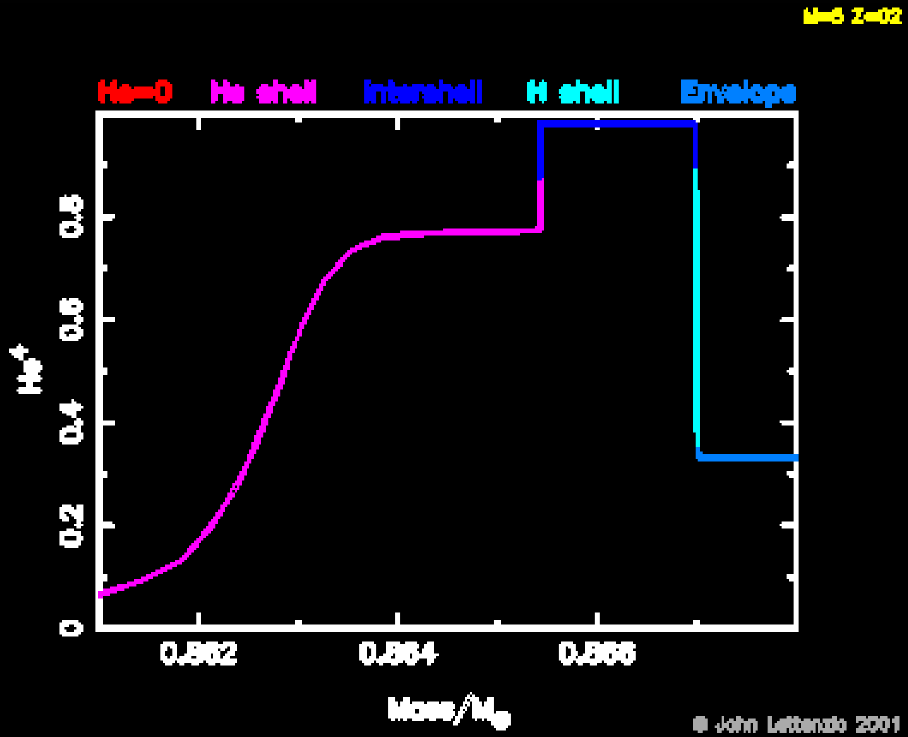
He - C

^{14}N to ^{22}Ne

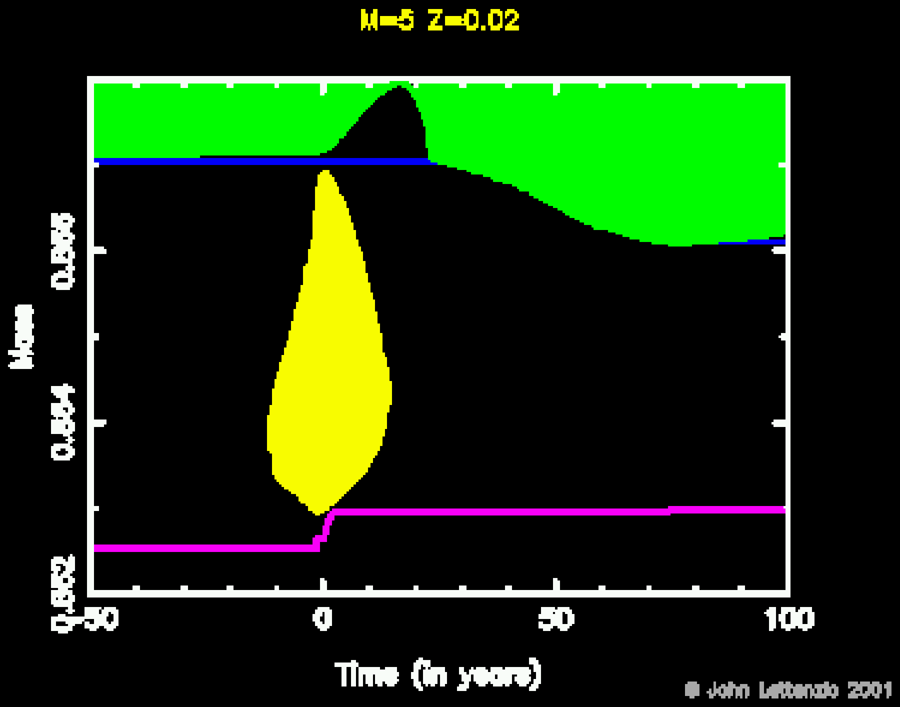
M>3: ^{22}Ne to ^{25}Mg and ^{26}Mg

© John Lattanzio 2001

AGB movies

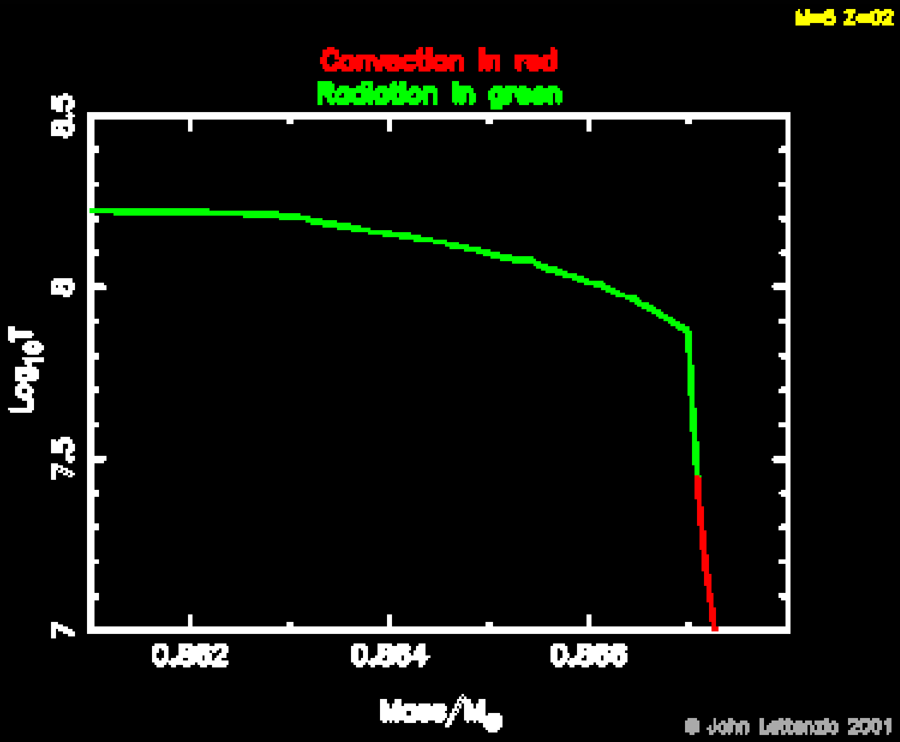


© John Lattanzio 2001

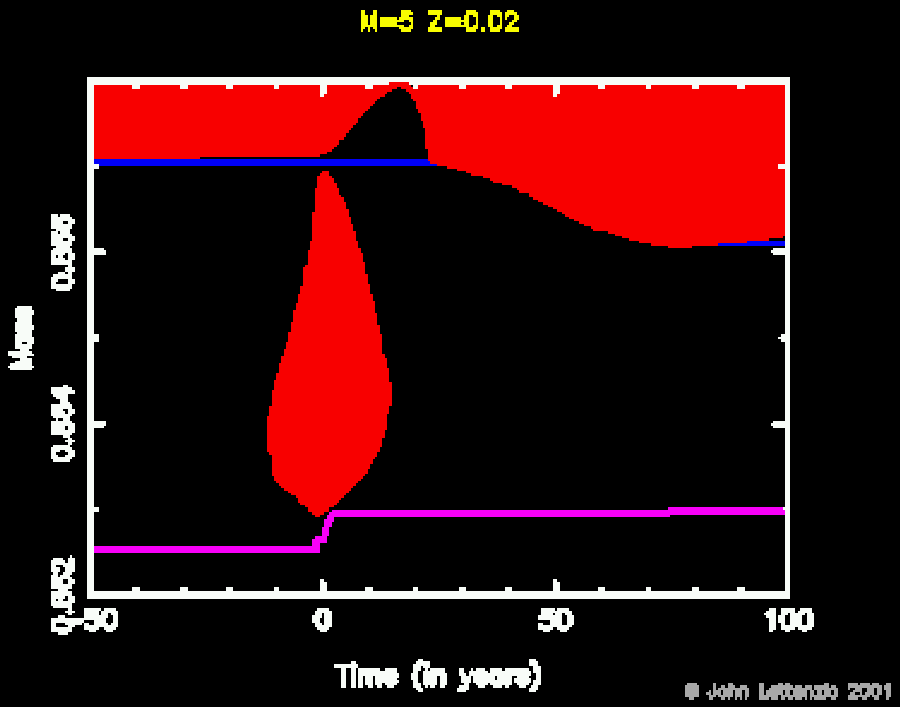


© John Lattanzio 2001

AGB movies



© John Lattanzio 2001

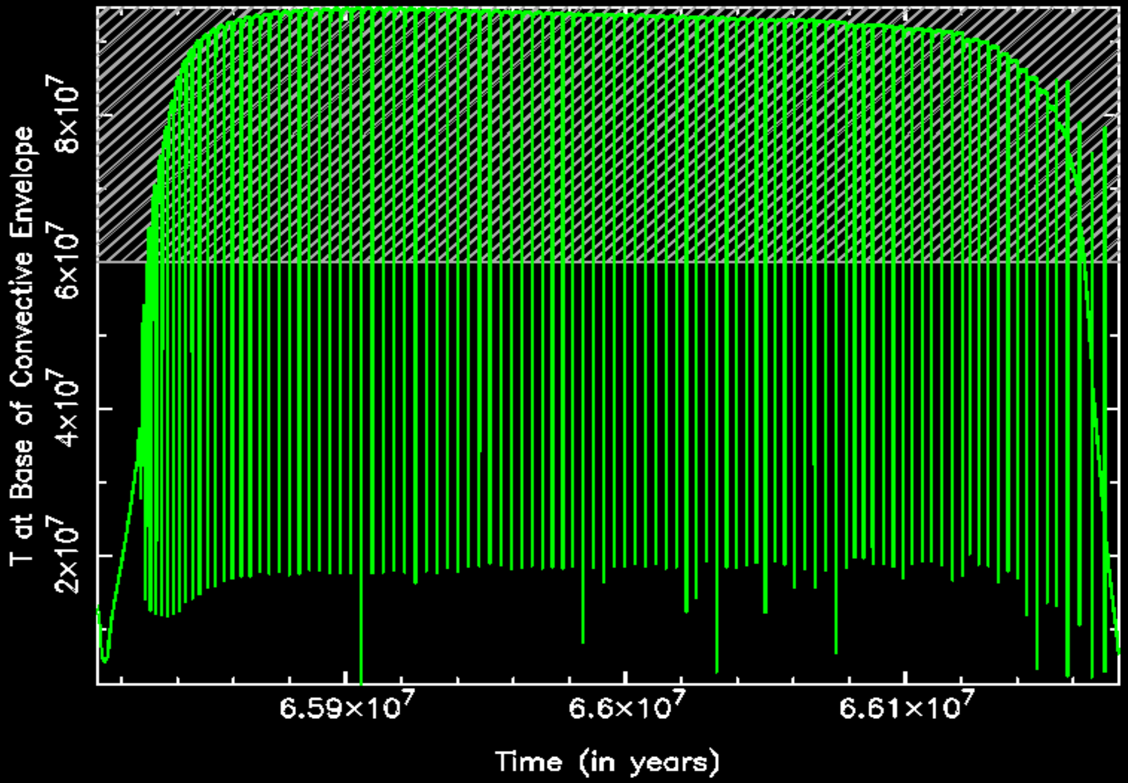


© John Lattanzio 2001

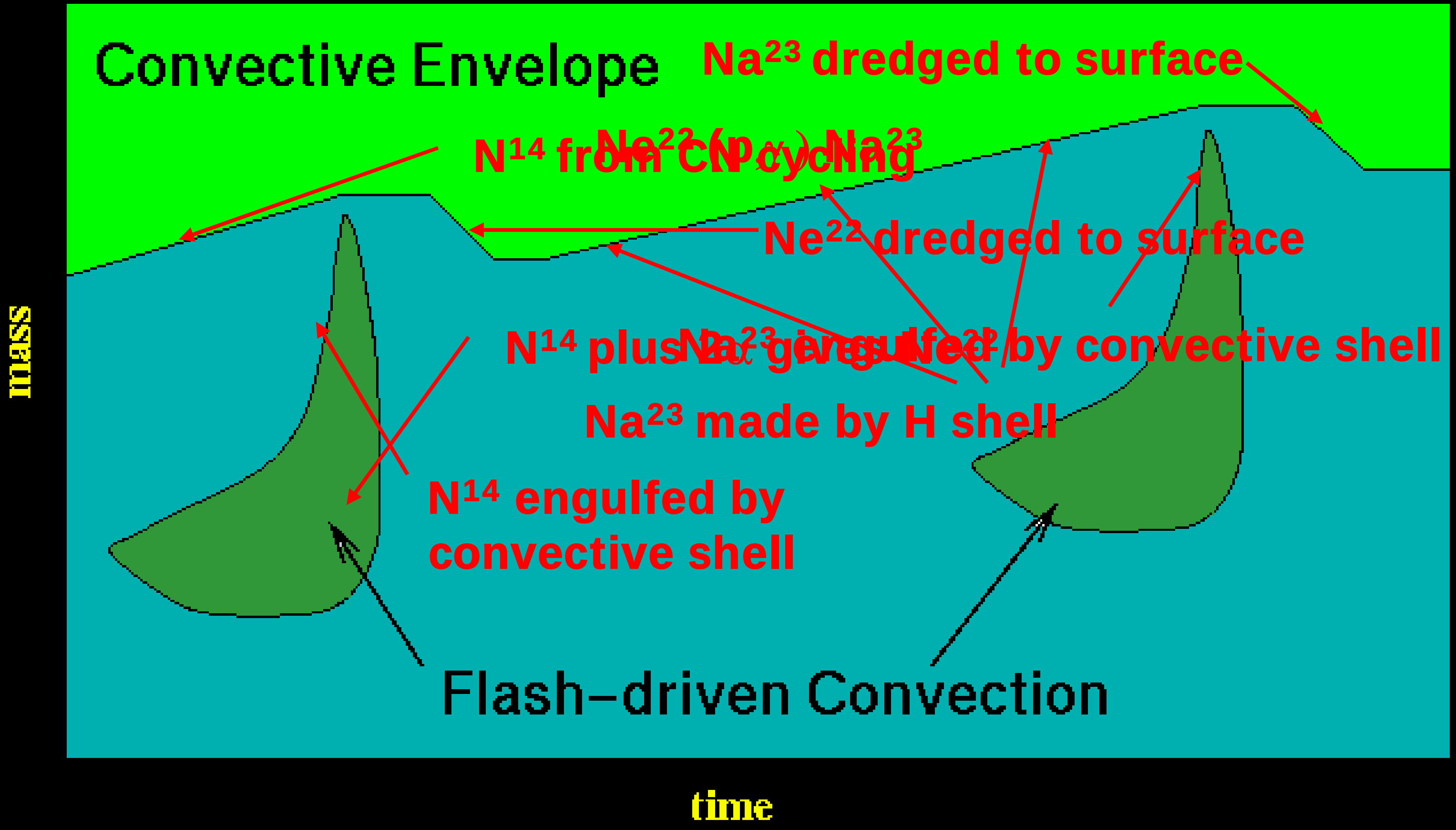
MONASH
UNIVERSITY

Hot bottom burning

M = 6, Z = 0.004: temperature at the base of the envelope ≈ 94 million K!

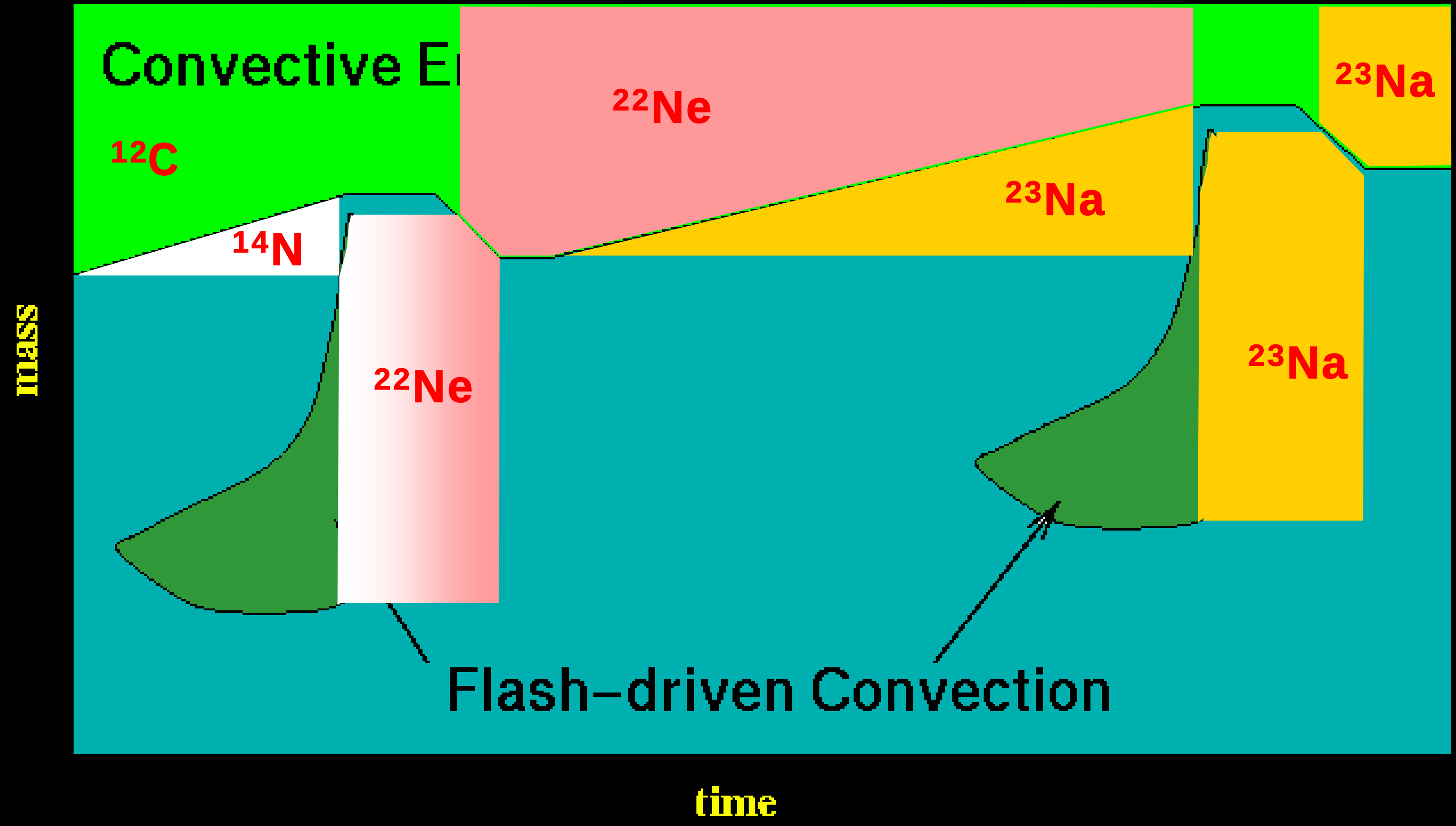


Advanced H Burning: Making Na^{23}



Note: some 23Na is primary and some is secondary!

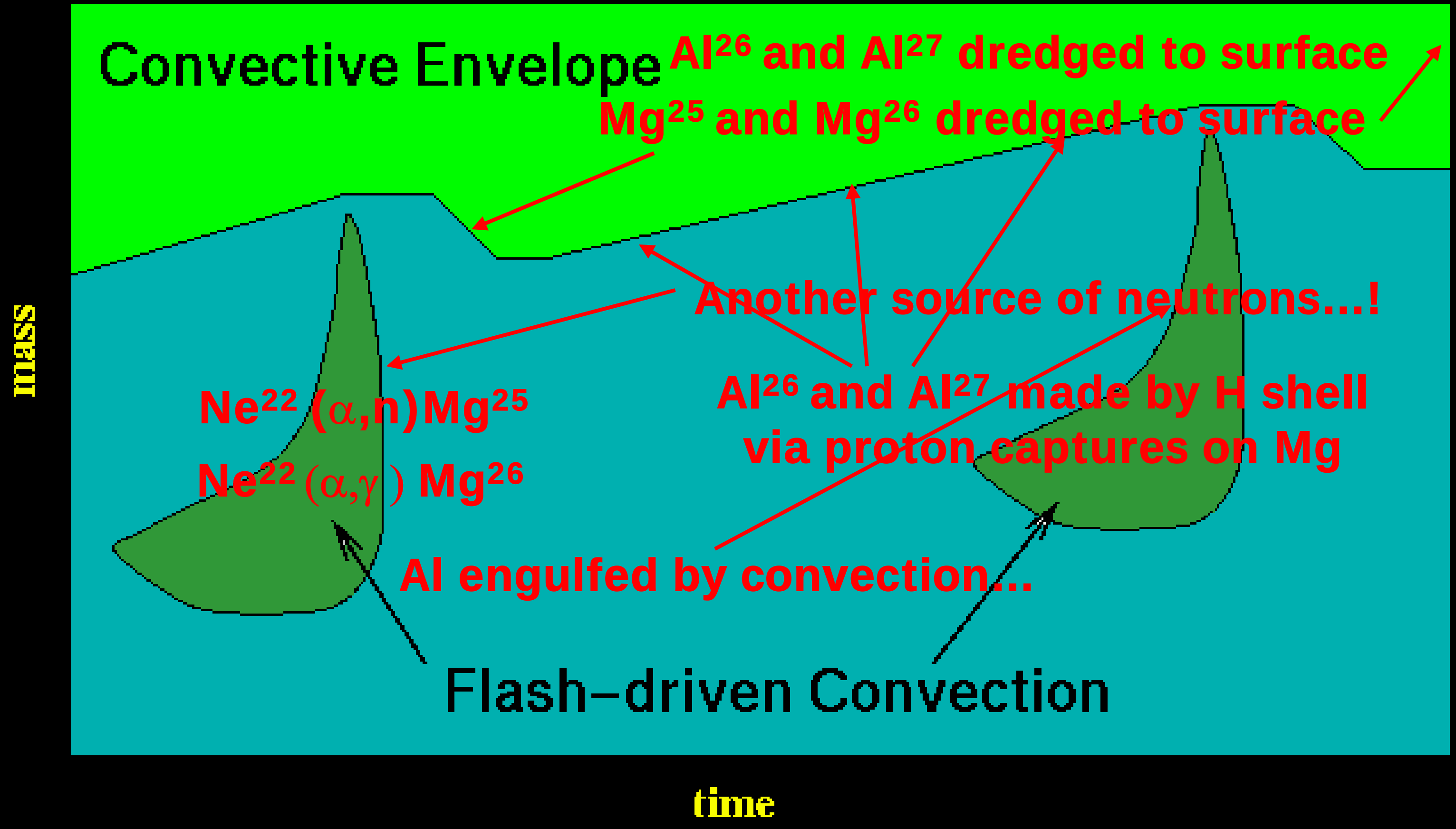
Advanced H Burning: Making Na^{23}



Note: some ^{23}Na is primary and some is secondary!

Advanced H Burning: $Mg^{25,26}$, $Al^{26,27}$

For T > 300 million (M > 2.5)



Al^{26} and Al^{27} dredged to surface

Mg^{25} and Mg^{26} dredged to surface

Another source of neutrons…!

$Ne^{22}(\alpha,n)Mg^{25}$

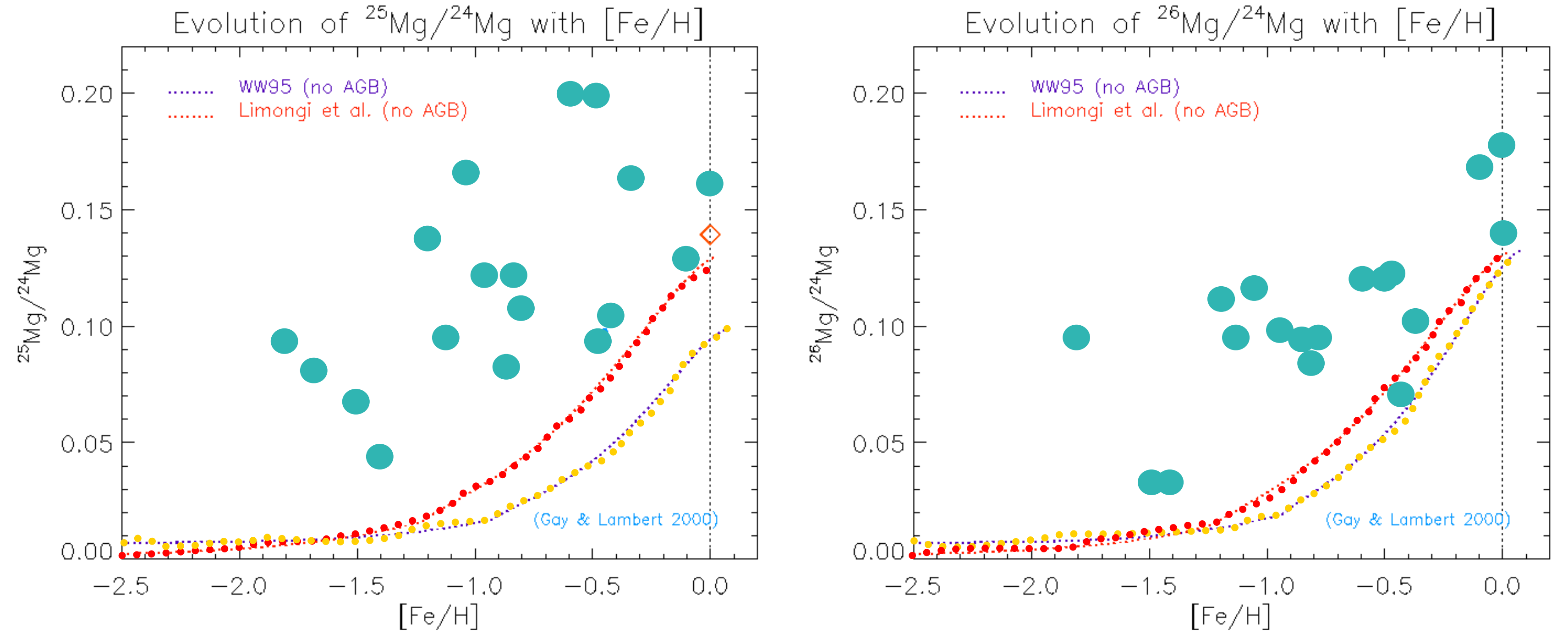
$Ne^{22}(\alpha,\gamma)Mg^{26}$

Al^{26} and Al^{27} made by H shell via proton captures on Mg

Al engulfed by convection…

Example: Mg isotopes in field stars

- Gay and Lambert looked at Mg isotopes in field stars
- Found some enhancements in heavy isotopes
- Does not fit SN yields...

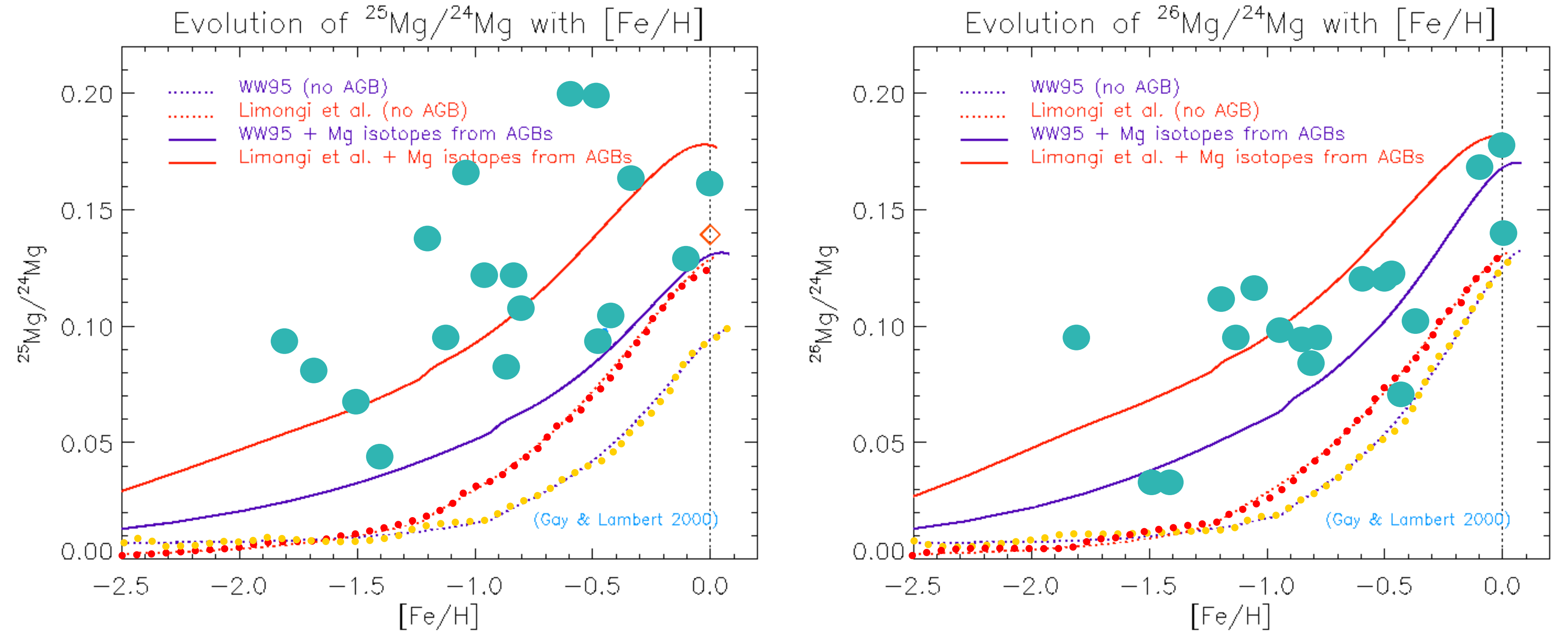


Massive stars produce most of the galactic magnesium, which is primarily ^{24}Mg at low Z

But 3 - 6 M_{sun} AGB stars can produce large amounts of the heavy magnesium isotopes

(Y. Fenner, A. Karakas, B. Gibson, J. Lattanzio)

MONASH UNIVERSITY



AGB stars are needed to recover the observed ^{25,26}M/^{24}Mg ratios at low metallicity

Limongi et al. (2002) calculations generate more ^{25,26}Mg than Woosley & Weaver (1995)

(Y. Fenner, A. Karakas, B. Gibson, J. Lattanzio, PASA, 2003)

MONASH
UNIVERSITY

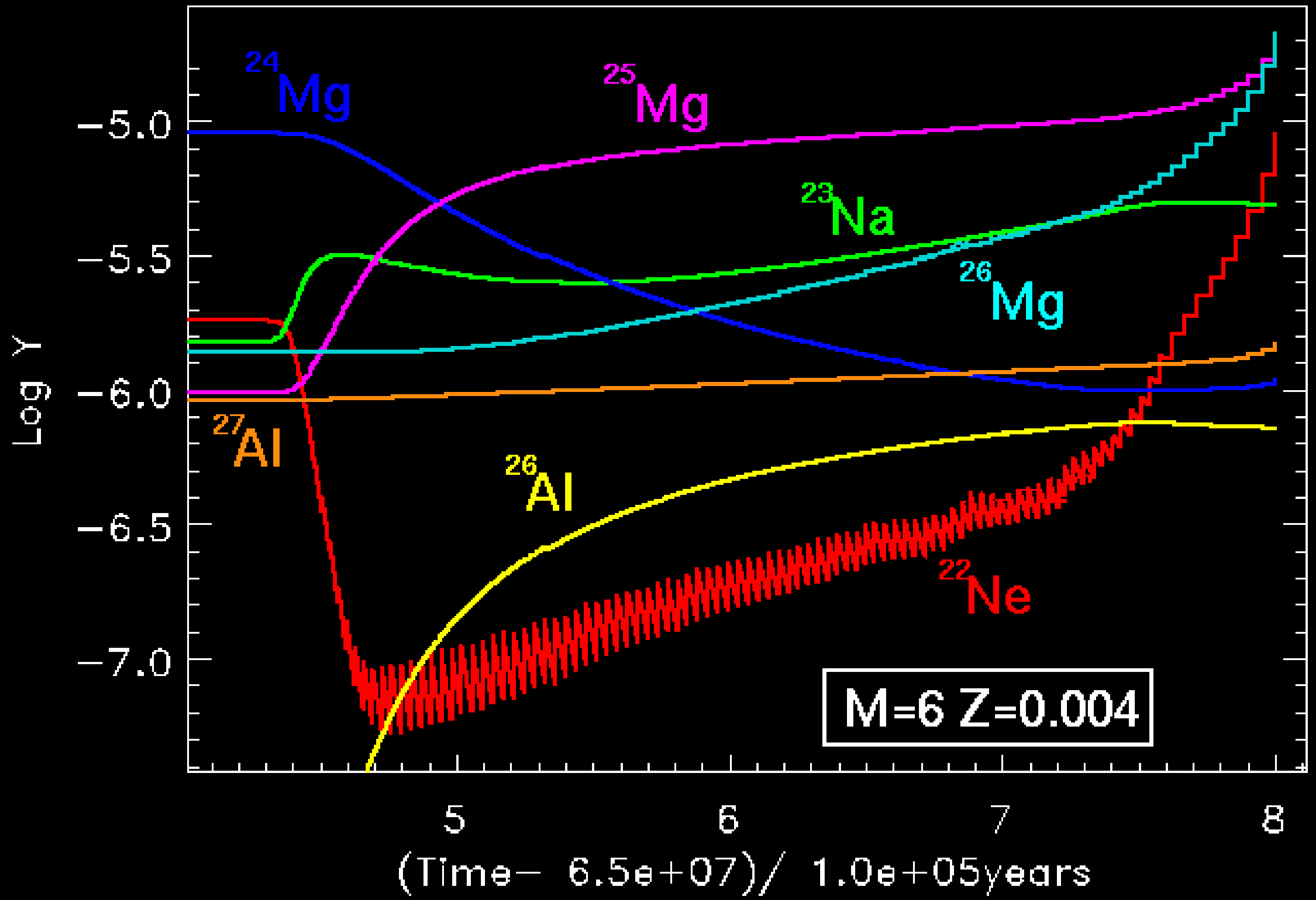
Nucleosynthesis in intermediate mass AGB stars

- Dredge-up increases: C, Ne22, Mg25, Mg26
- HBB burns
  1) C and O into N: O down and N up
  2) Ne22 into Na23: Na up
  3) Mg25 and Mg26 made: Mg25,26 increased
- More massive stars
  1) Mg24 burned into Al27: Mg24 down Al27 up

- Overall
  1) Increases in N, Na, heavy Mg, Al
  2) Decreases in O, Mg24

MONASH
UNIVERSITY

An example...



MONASH UNIVERSITY

What we need

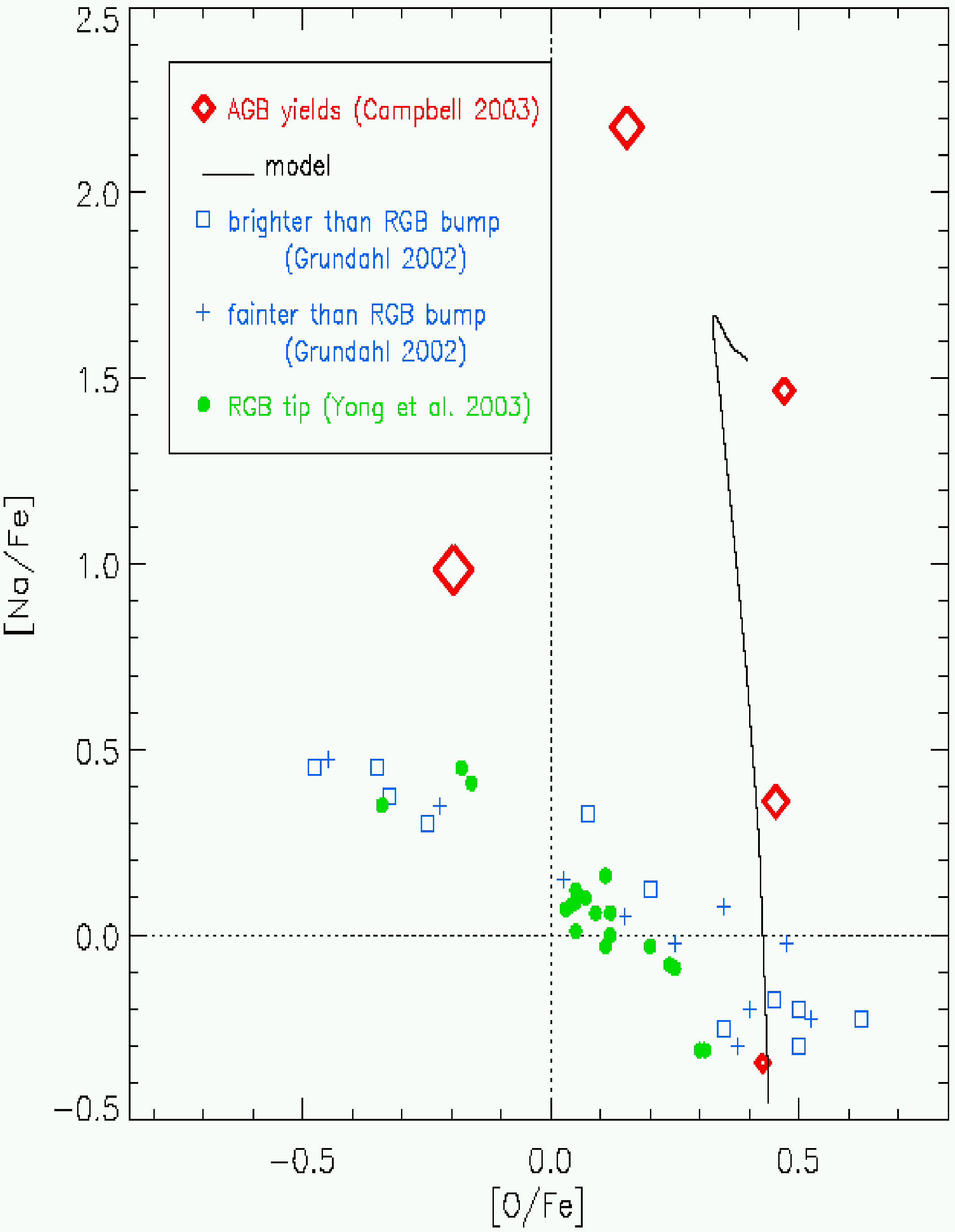
- Calculations for very low [Fe/H]
- Including species up to Al
- s-process? Probably not...
- Simon Campbell thesis...

Consistent model for NGC6752

- First generation of stars at Z=0
    1) Yields from Chieffi & Limongi 2002 for M=13-80Msun
    2) Yields from Umeda & Nomoto 2002 for M=150-270Msun
    3) Bimodal IMF from Nakamura and Umemura 2001
- Mix with primordial gas till [Fe/H] = -1.4 (observed)
- Second Generation at [Fe/H]=-1.4
    1) Evolve with EXACT composition for all elements
    2) M=1.25 – 6.5 Msun models
    3) No SNIa as Fe does not vary

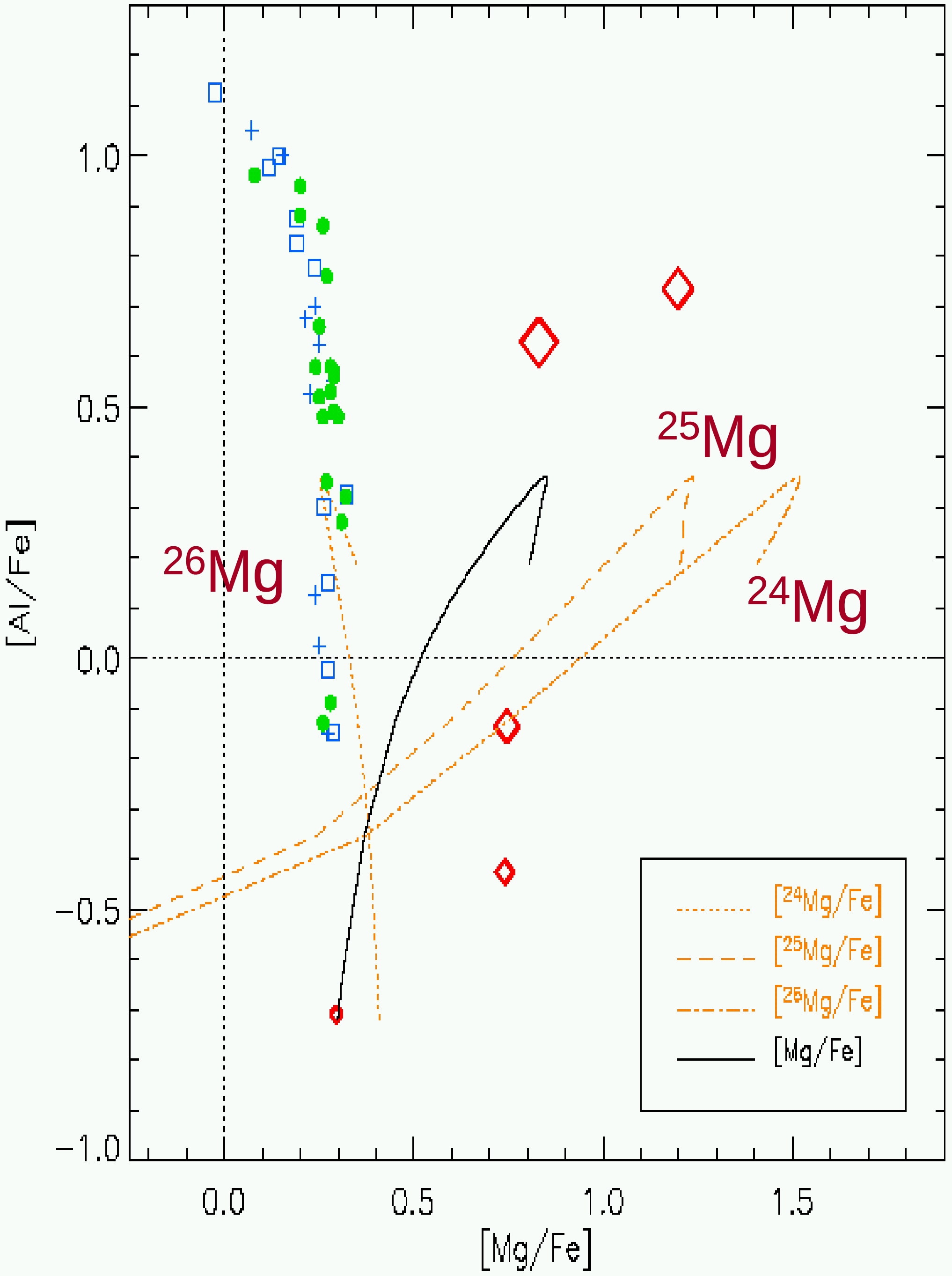
Bad News ☹ for Na vs O

- Diamonds are individual AGB stars yields
  1) size indicates mass of star
  2) M=1.25, 2.5, 3.5, 5.2, 6.5
- Nowhere near enough O depletion...
- Too much Na production...
- Problem is its primary Na



Bad News ☹ for Al vs Mg

- Not enough Al...
- Too much Mg...
- Its primary Mg...
- Mg^{26}? Yong et al...



Mg isotopes: still bad news ☹

Models: heavy Mg isotopes correlated

Data: no they are not!

^{25}Mg independent of everything…

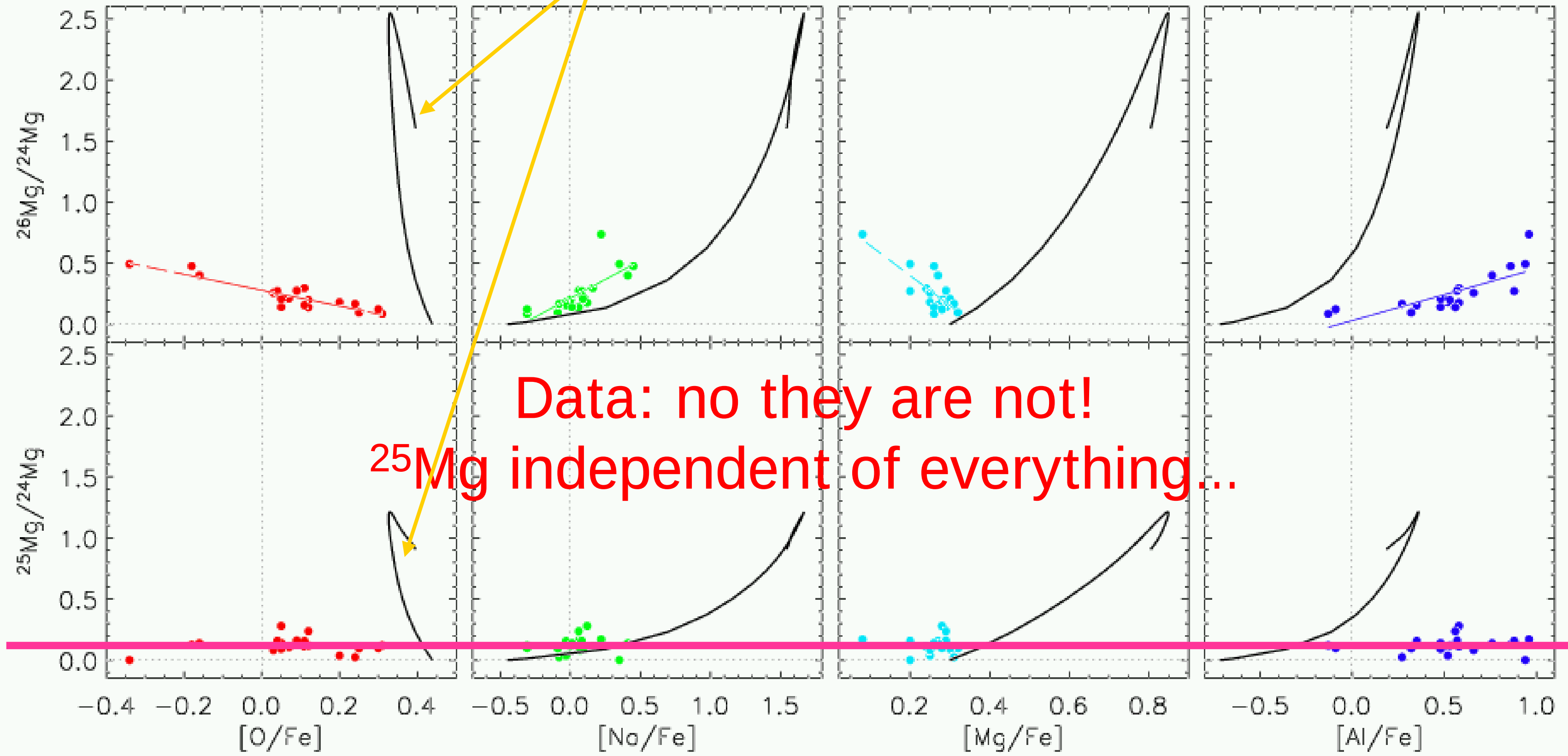
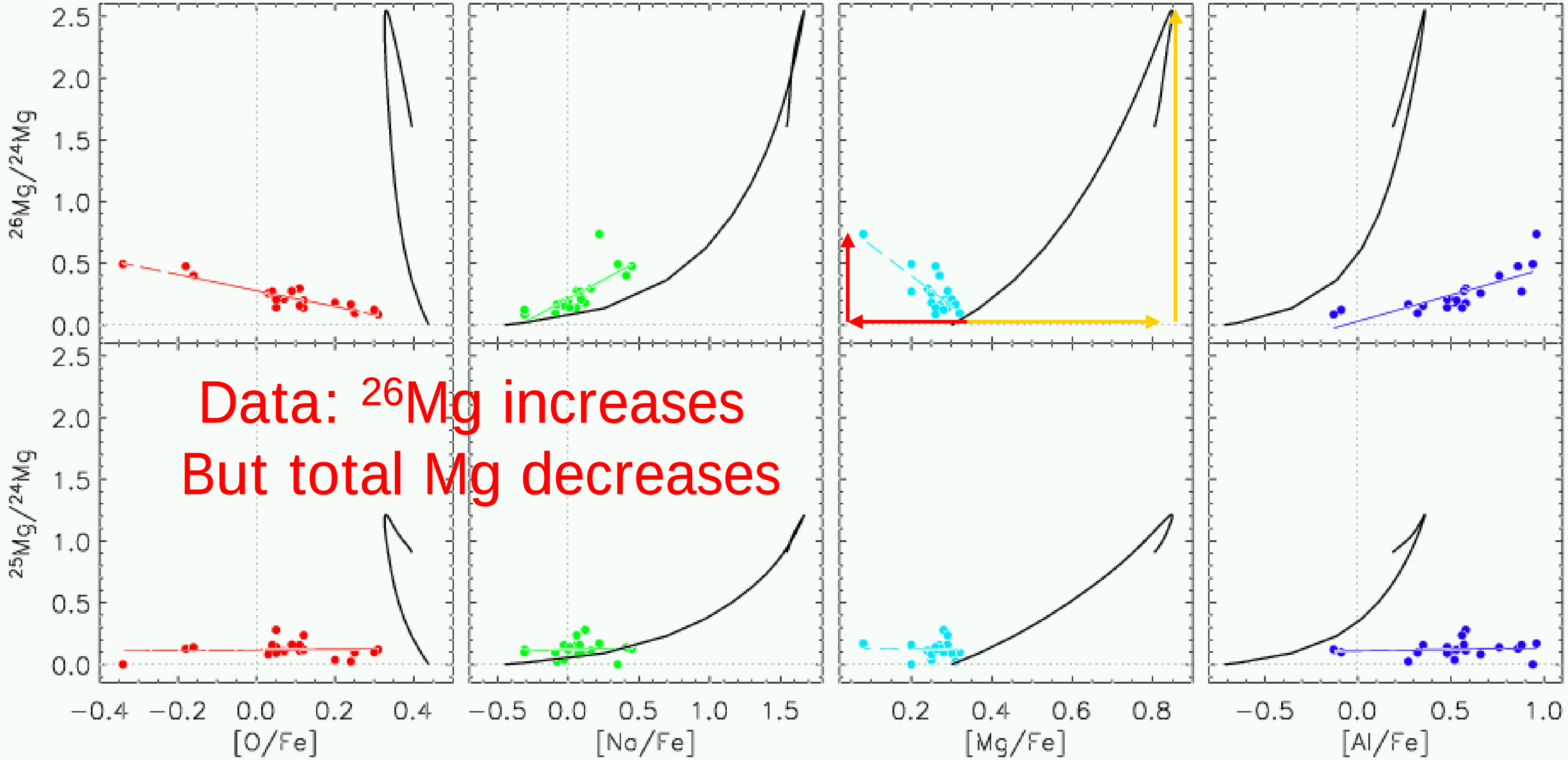


Fig. 2. The trend of Mg isotopic ratios with O, Na, Mg, and Al abundance predicted by the NGC 6752 model presented in this paper. The thick solid lines show predictions for ^{25}Mg/^{24}Mg (*top panels*) and ^{26}Mg/^{24}Mg (*bottom panels*). Circles correspond to data from Yong et al. 2003 showing positive correlations between ^{26}Mg/^{24}Mg and [Na,Al/Fe]; anticorrelations between ^{26}Mg/^{24}Mg and [O,Mg/Fe]; and no correlation for ^{25}Mg/^{24}Mg. The lines of best fit to the data are represented by thin lines.

Mg isotopes: still bad news ☹

Models: ^{26}Mg increases as does total Mg



Data: ^{26}Mg increases
But total Mg decreases

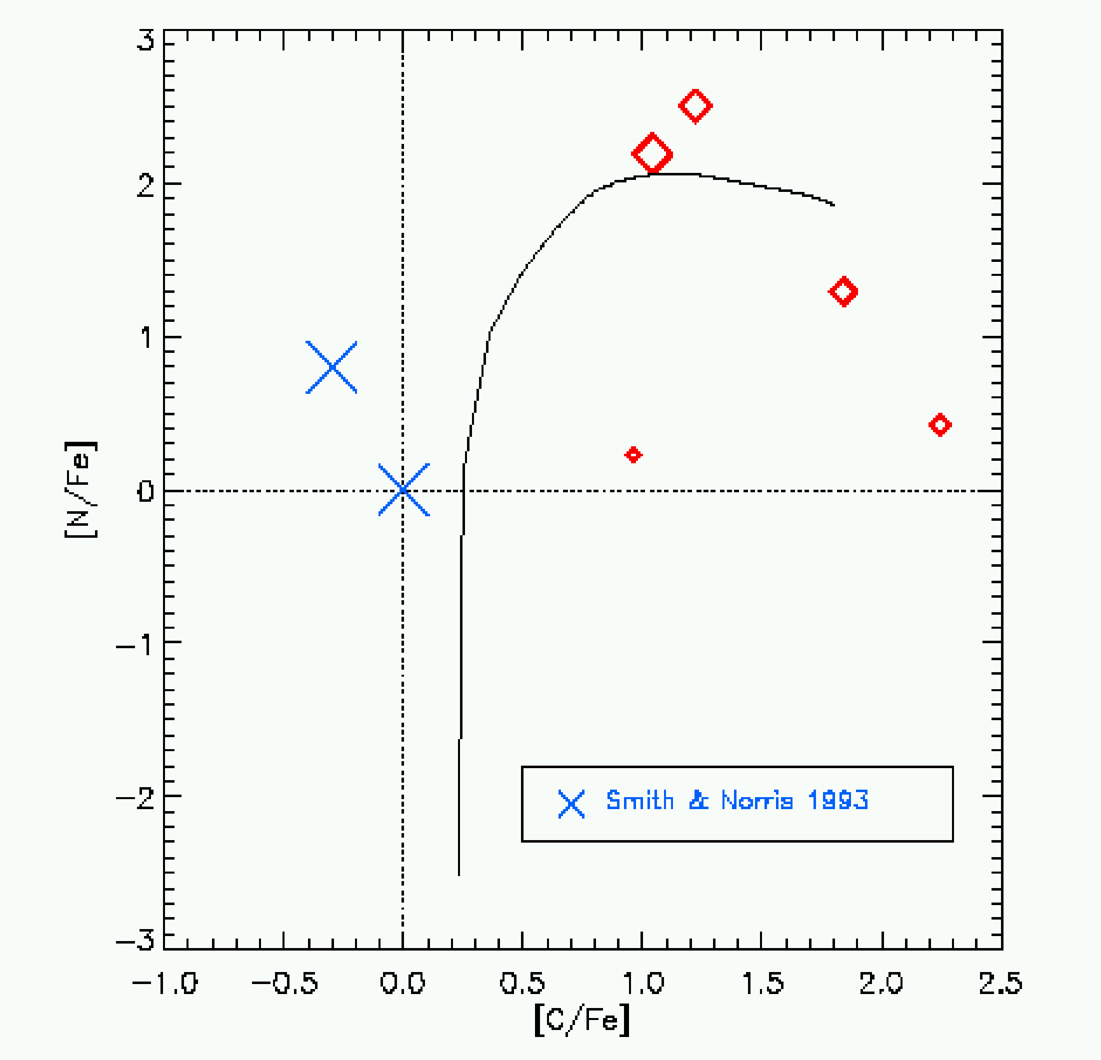
Fig. 2. The trend of Mg isotopic ratios with O, Na, Mg, and Al abundance predicted by the NGC 6752 model presented in this paper. The thick solid lines show predictions for ^{25}Mg/^{24}Mg (*top panels*) and ^{26}Mg/^{24}Mg (*bottom panels*). Circles correspond to data from Yong et al. 2003 showing positive correlations between ^{26}Mg/^{24}Mg and [Na,Al/Fe]; anticorrelations between ^{26}Mg/^{24}Mg and [O,Mg/Fe]; and no correlation for ^{25}Mg/^{24}Mg. The lines of best fit to the data are represented by thin lines.

C and N...

- Too much C...
- Too much N...

- The model shows a POSITIVE correlation!

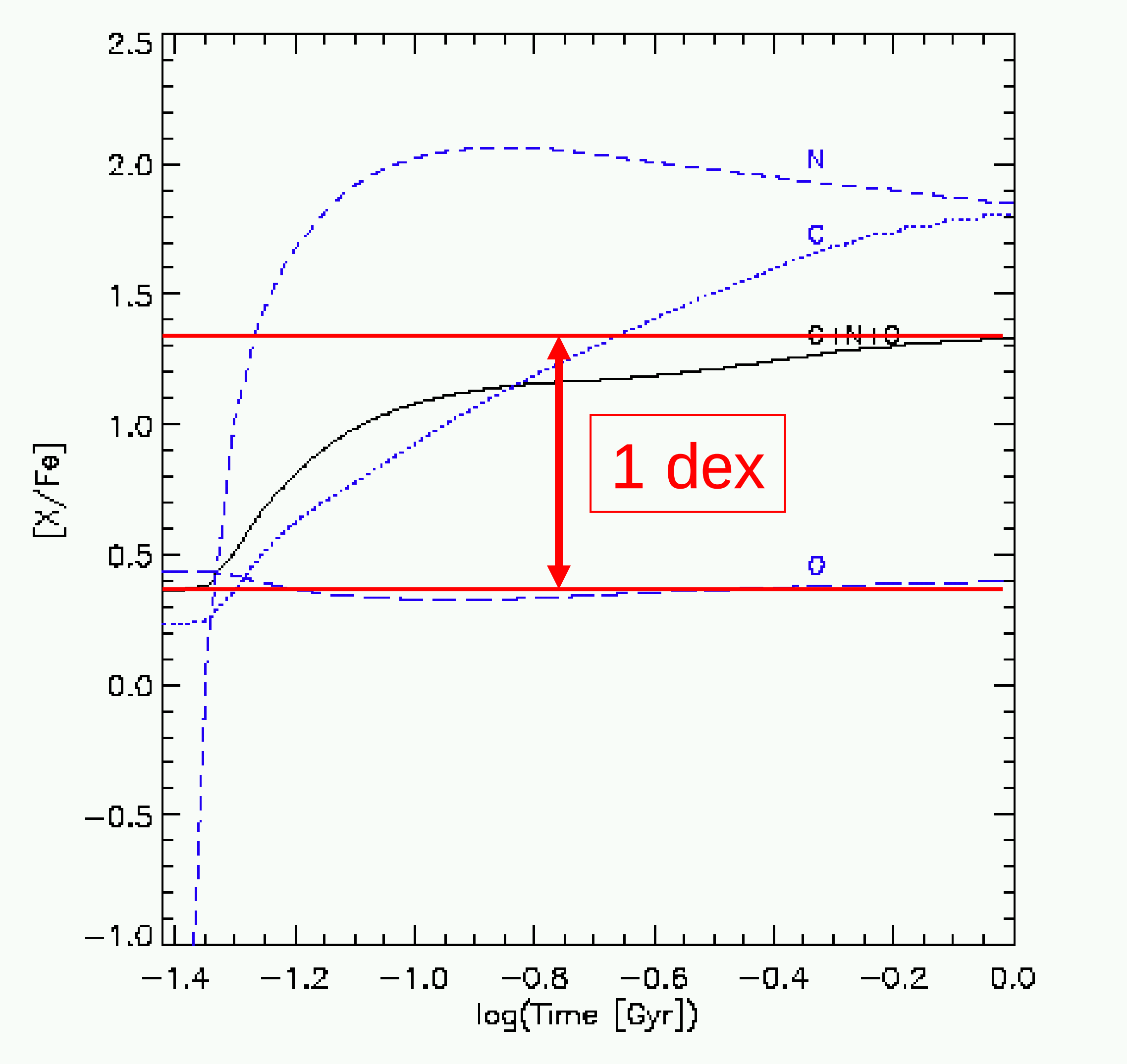
- Problem is primary C and N



C+N+O observed “constant” but…

- C: too much
- N: too much
- O: too much

- C+N+O increases by an order of magnitude! We would see that?!



Summary for NGC6752

- O not depleted enough by AGB stars
- Mg not depleted enough by AGB stars
- C+N+O is not constant, but increases by 1 dex
- Mg^{25} and Mg^{26} are correlated, in contradiction with Yong et al observations

NGC6752 and AGB pollutants...

- Hard to make it work...
- Need hot H burning, yes...
- But not the accompanying He burning
  1) Which makes primary C
  2) Hence primary N (ruining C+N+O)
  3) And primary ^{22}Ne, ^{23}Na, ^{25}Mg, and ^{26}Mg
- Do we need AGB stars with HBB but no dredge-up?
- Or maybe not AGB stars at all...

MONASH UNIVERSITY

And on that happy (?) thought……

The End