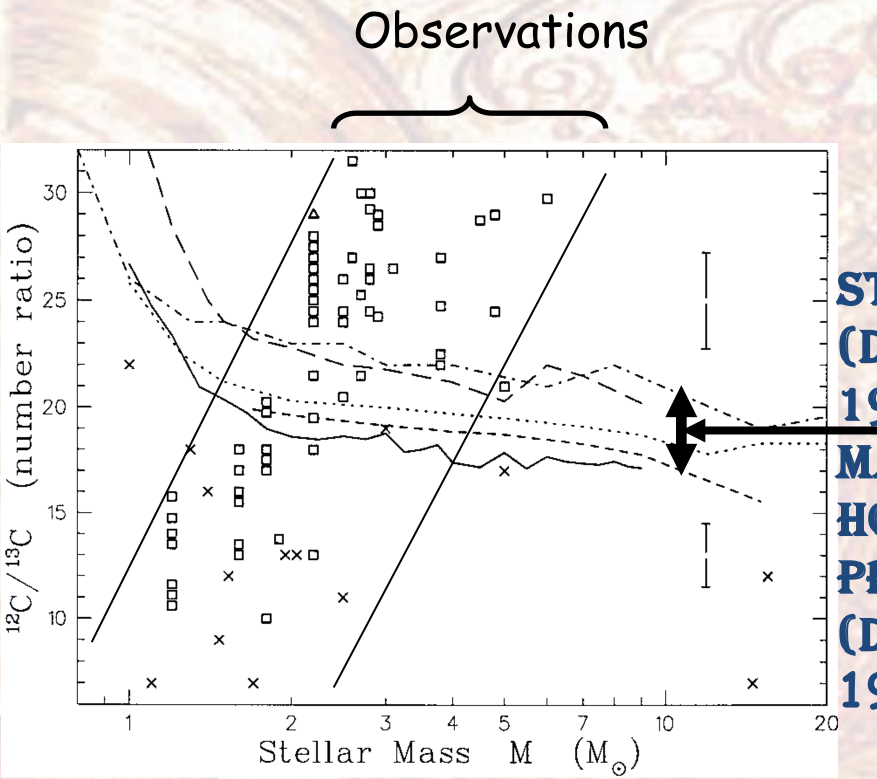
NEWS ON NON-CONVECTIVE TRANSPORT IN STARS. THERMOHALINE & MAGNETIC MIXING

M. BUSSO – UNIVERSITY OF PERUGIA

1. OBSERVATIONAL EVIDENCE
2. THERMOHALINE MIXING: DOUBTS AND POSSIBLE WAYS OUT FROM PLASMA PHYSICS
3. MIXING ON THE AGB FOR FORMING THE NEUTRON SOURCE
4. MAGNETIC BUOYANCY & ITS BASIS ON EXACT MHD
5. TOWARD NON-PARAMETRIC SOLUTIONS FOR n-CAPTURES
6. PRELIMIARY CONCLUSIONS

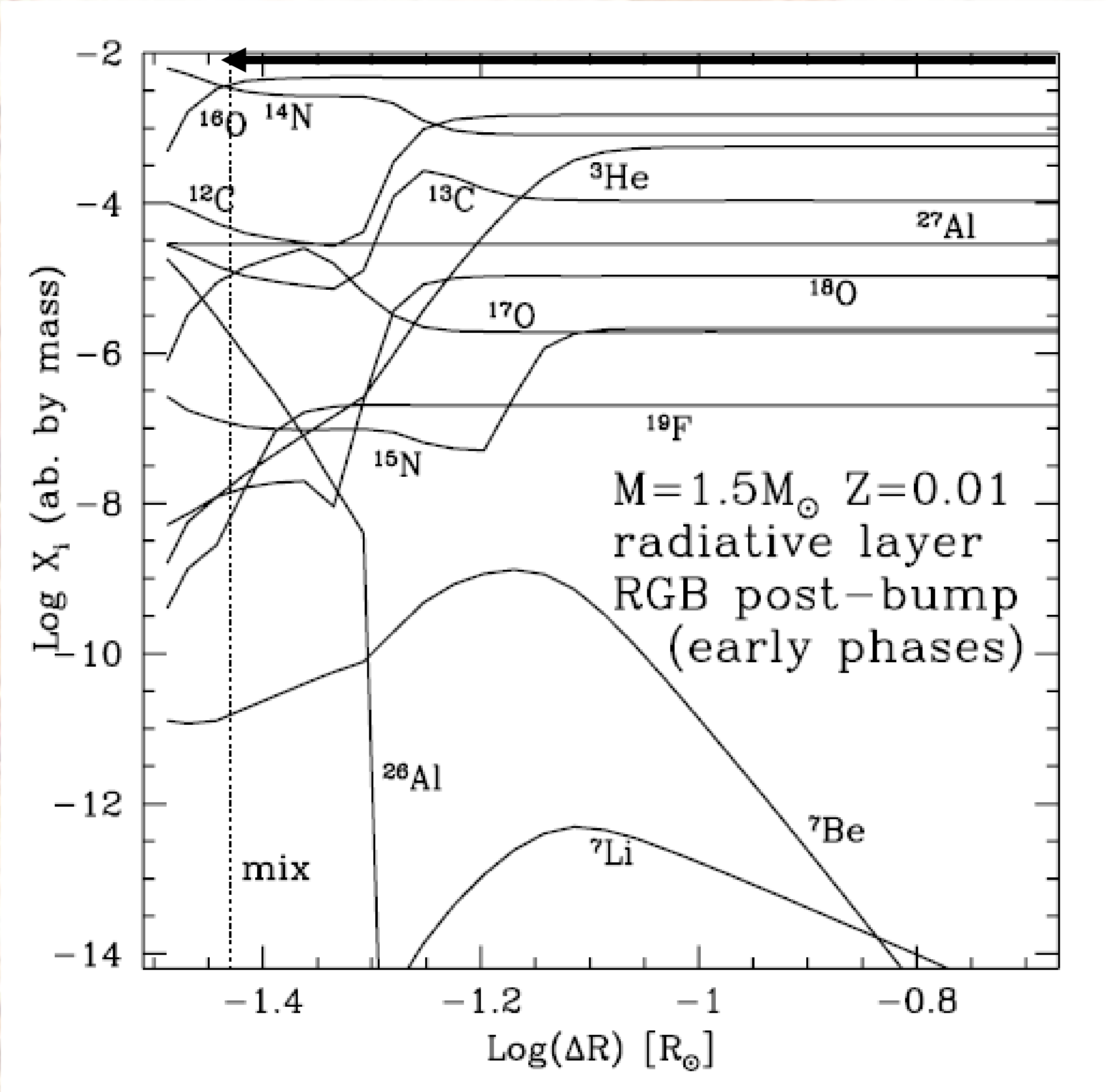
OLD OBSERVATIONAL EVIDENCE



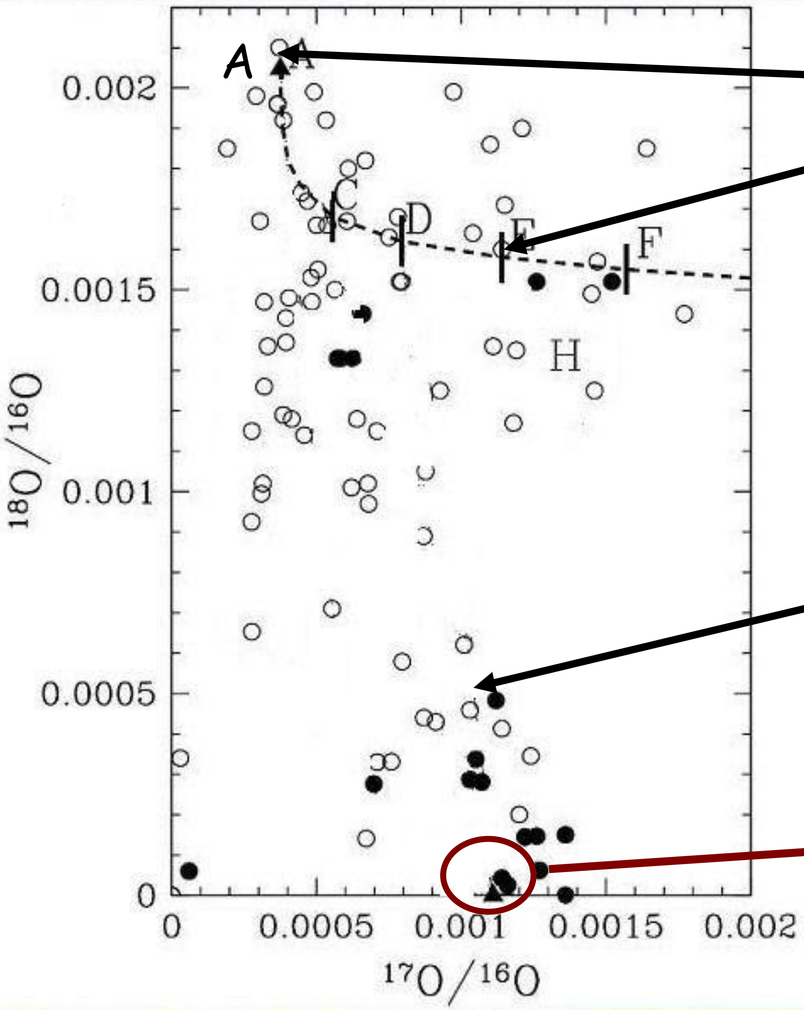
STANDARD MODELS AFTER FIRST D.-UP (DISCREPANCY ADRESSED BY GILROY 1989; GILROY AND BROWN 1991; THEN MANY OTHERS)

HOWEVER, THE NEED FOR "SOME OTHER PROCESS" HAD BEEN NOTED PREVIOUSLY (DEARBORN ET AL. 1975; TOMKIN ET AL. 1976).

ALSO CONNECTED WITH LI PRODUCTION/DESTRUCTION (SEE E.G. CHARBONNEL & DONASCIMIENTO 1998). CANNOT BE CURED BY EXTENDING FIRST DREDGE-UP


M=1.5M☉ Z=0.01
radiative layer
RGB post-bump
(early phases)
Log X_i (ab. by mass)
Log(ΔR) [R☉]
mix
^{16}O
^{14}N
^{12}C
^{13}C
^{3}He
^{27}Al
^{18}O
^{17}O
^{19}F
^{15}N
^{26}Al
^{7}Be
^{7}Li
−2
−4
−6
−8
−10
−12
−14
−1.4
−1.2
−1
−0.8

PRESOLAR AL_2O_3 GRAINS



SOLAR RATIOS → POINT A;
RATIOS AFTER FIRST DREDGE-UP FOR MASSES 1.1 – 2.0 $M_{\odot}$: C-F

PRESOLAR GRAINS: NITTLER ET AL. 1997

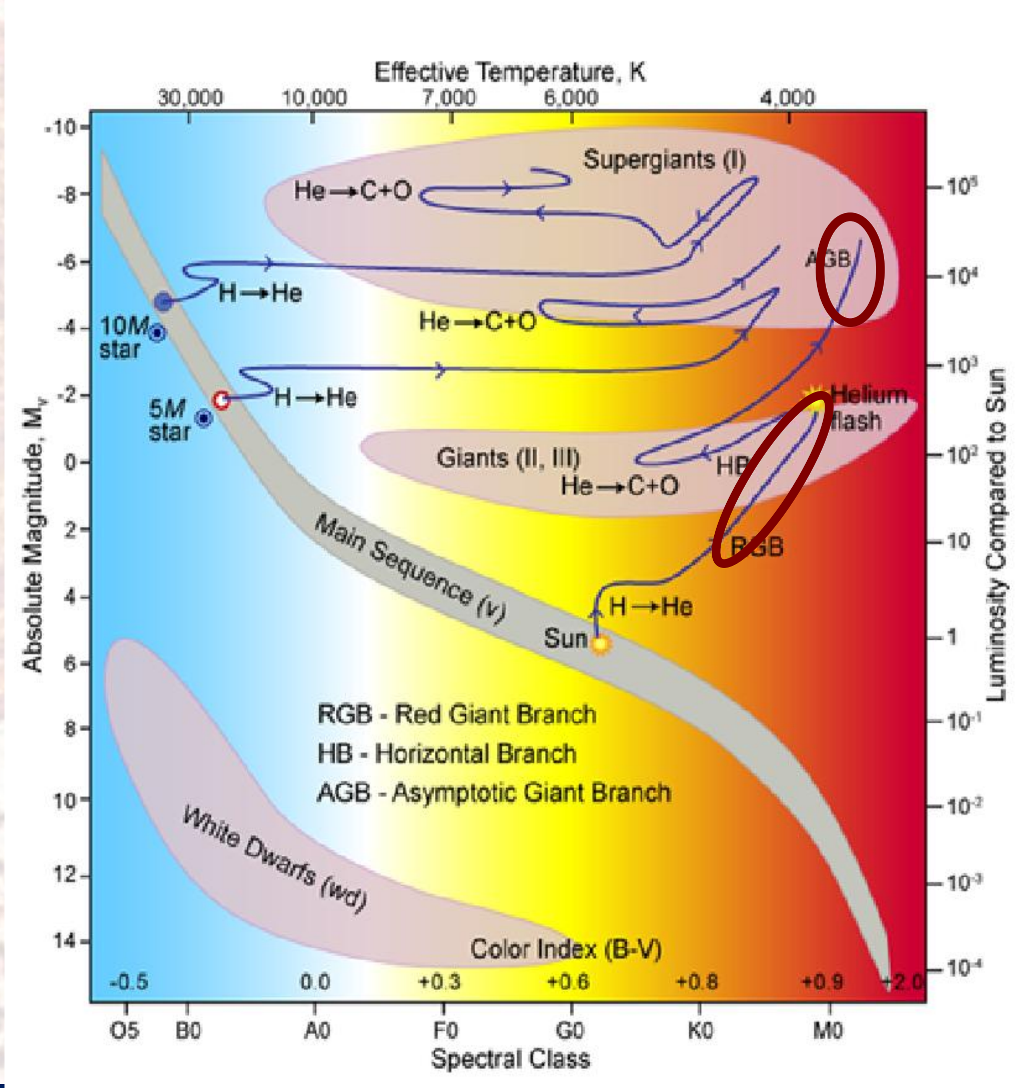
DOTS: OXIDE GRAINS, OF GROUP 2, CURRENTLY ATTRIBUTED TO FURTHER MIXING OCCURRING IN RED GIANTS AND AGB STARS.

CNO EQUILIBRIUM AT HIGH T (DEPENDENCE ON T!!)

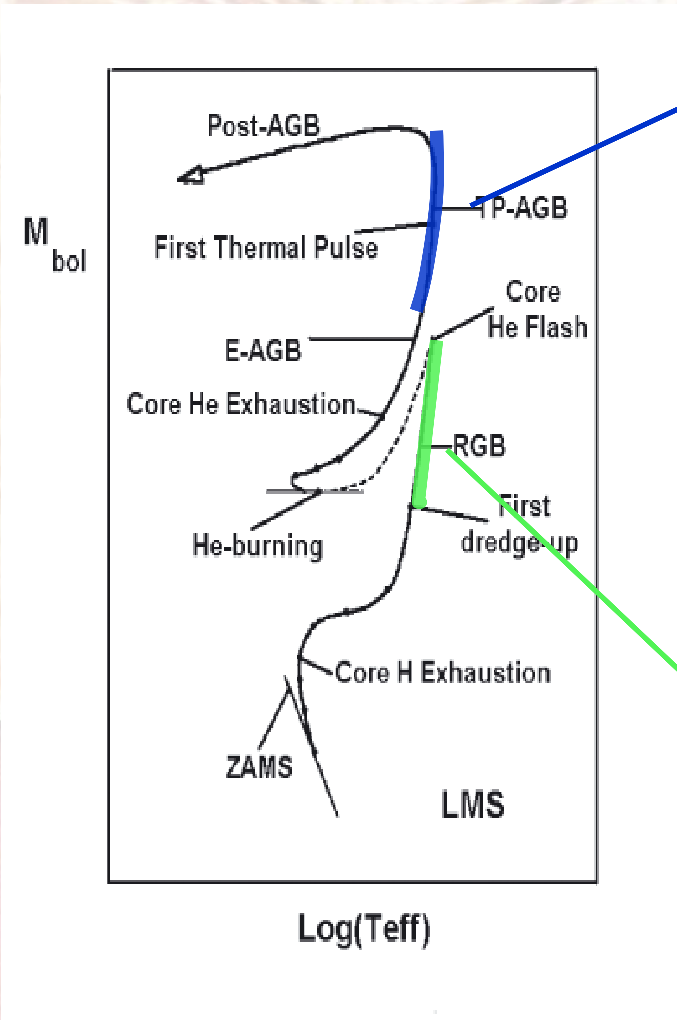
WHERE MIXING IS NEEDED

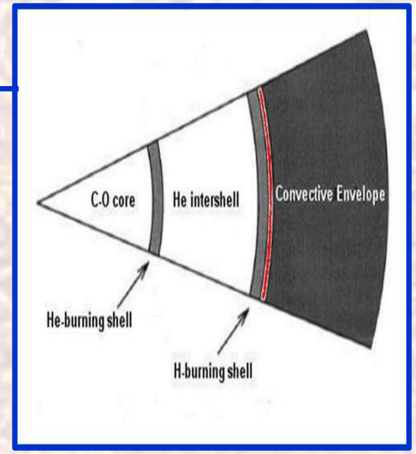
I) IN RGB PHASES AFTER THE BUMP OF THE L-FUNCTION (MANY AUTHORS, E.G. CHARBONNEL & BALACHANDRAN 2000)

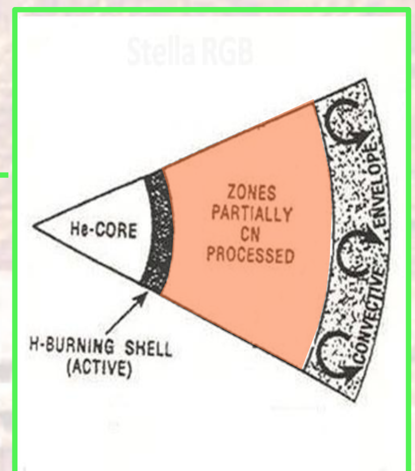
II) IN TP-AGB PHASES (E.G. BUSSO ET AL. 2010; PALMERINI ET AL. 2011 A,B)

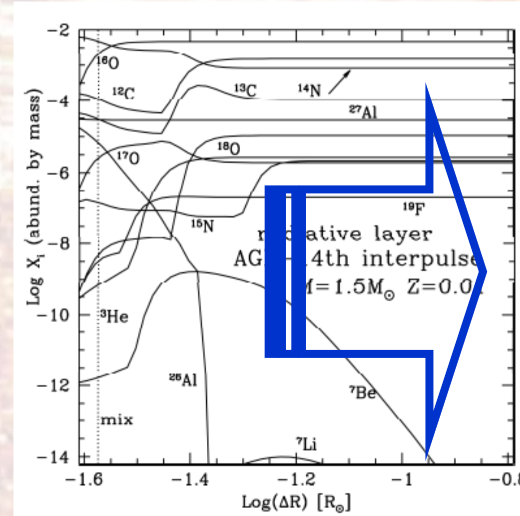


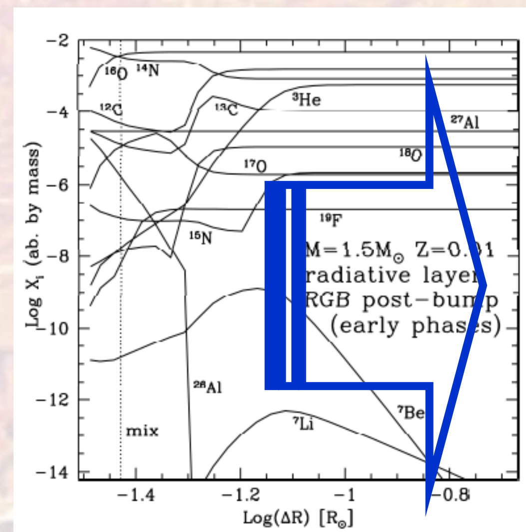
RADIATIVE ZONES ABOVE THE H-SHELL



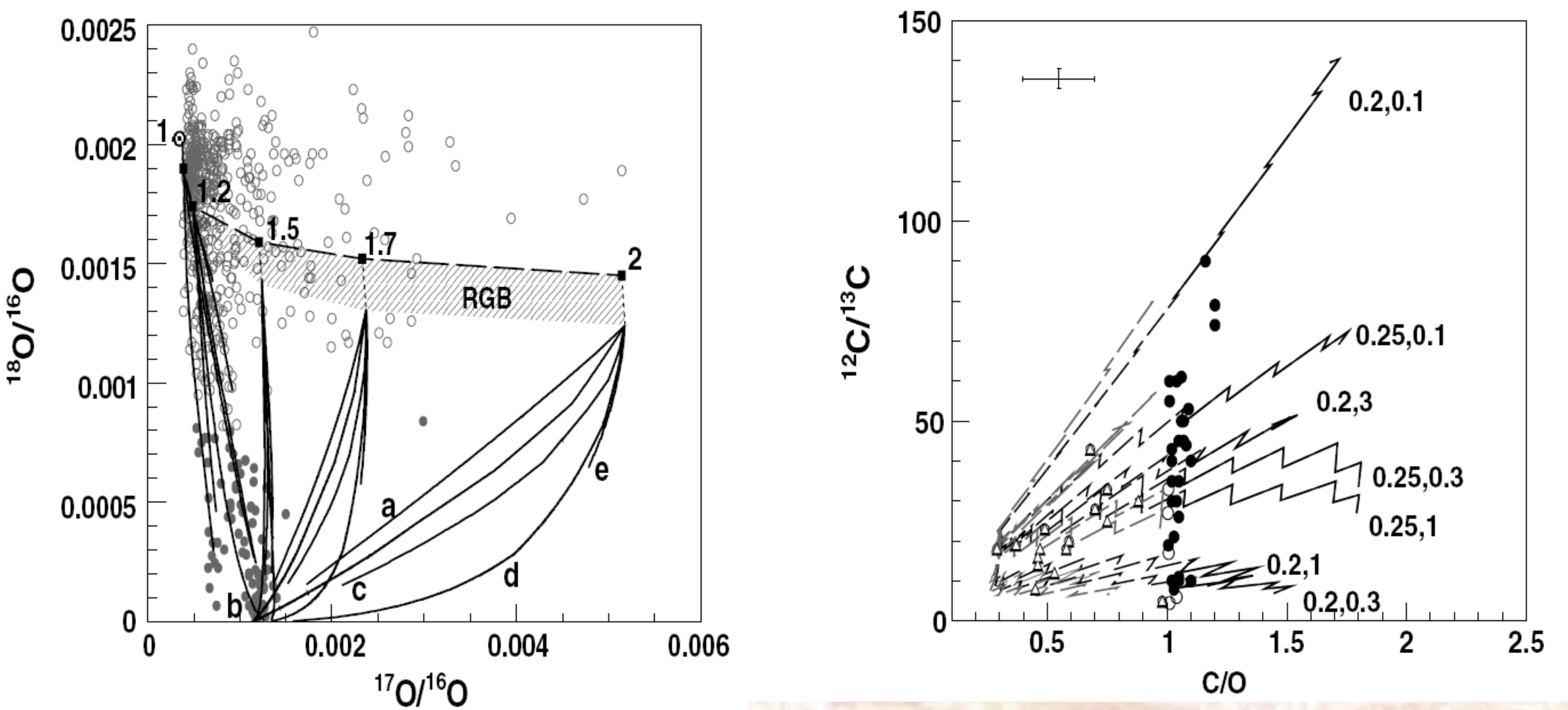




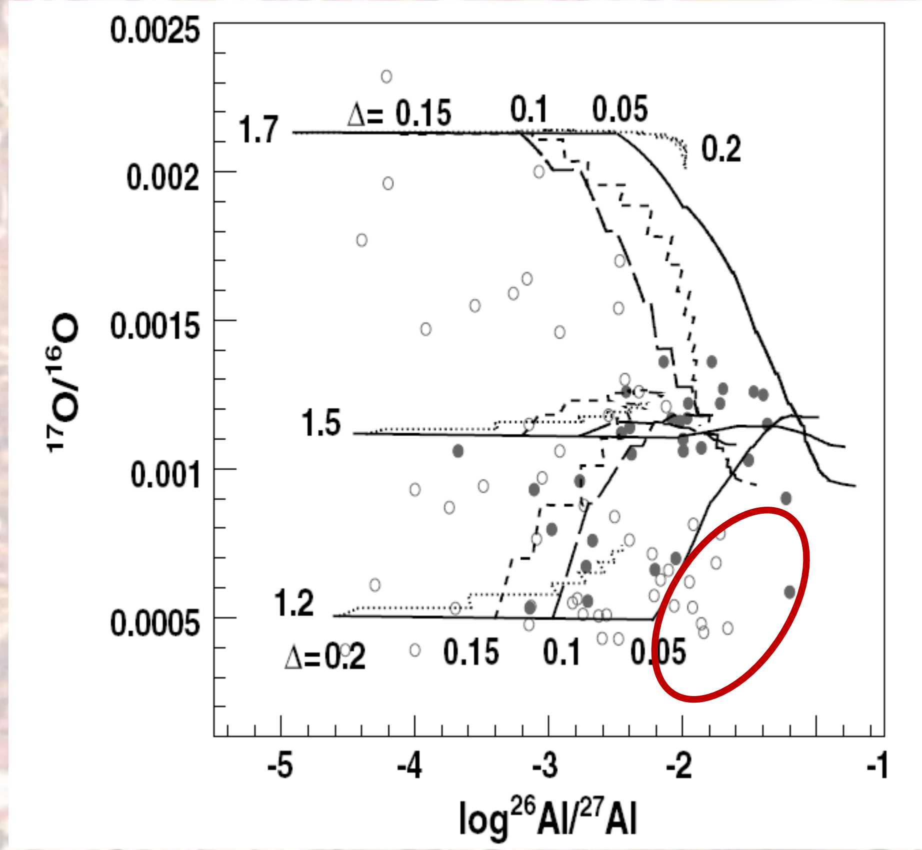




TYPICAL RESULTS FROM PARAMETRIC MIXING MODELS



- ISOTOPIC ABUNDANCES IN PRESOLAR GRAINS & C-STARS WELL EXPLAINED
- REMAINING PROBLEMS FOR ^{26}AL


0.0025
0.002
0.0015
0.001
0.0005
$^{17}O/^{16}O$
1.7
Δ= 0.15
0.1
0.05
0.2
1.5
1.2
Δ=0.2
0.15
0.1
0.05
-5
-4
-3
-2
-1
$\log^{26}Al/^{27}Al$

"OLD" DEEP MIXING MODELS (≥ 10YR)

P A R A M E T R I C

BOOTHROYD, SACKMANN, WASSERBUG 1994-1995: 'CBP'→ CIRCULATION- LIKE TRANSPORT OF MATTER. THEN SHOWN TO BE EQUIVALENT TO A DIFFUSIVE MIXING (NOLLETT ET AL. 2003)
→ $^{12}C/^{13}C$, ^{26}Al AND O ISOTOPIC RATIOS IN PRESOLAR GRAINS

SACKMANN & BOOTHROYD 1999→CREATION/ DESTRUCTION OF LI DUE TO DEEP MIXING IN RED-GIANTS

P H Y S I C A L

CHARBONNEL & DO NASCIMIENTO 1998, DENISSENKOV & VAN DEN BERG 2003 ; PALACIOS ET AL. 2003 →PROCESSES DUE TO ROTATION (SHEAR AND DIFFUSION, MERIDIONAL CIRCULATION) → $^{12}C/^{13}C$, LI + ^{3}He DEPLETION.
OTHER SUGGESTIONS I) GRAVITATIONA WAVES DENISSENKOV & TOUT (2003); II) DIFFUSION IN FLUIDS WITH VARIABLE μ (Δμ MIXING OR THERMOHALINE DIFFUSION). STOTHERS & SIMON (1969); ULRICH 1972; KIPPENHAN 1980; → EGGLETON ET AL. (2006)

EXTRAMIXING: RECENT SUGGESTIONS

$$\rho \propto \frac{P}{T}\mu$$

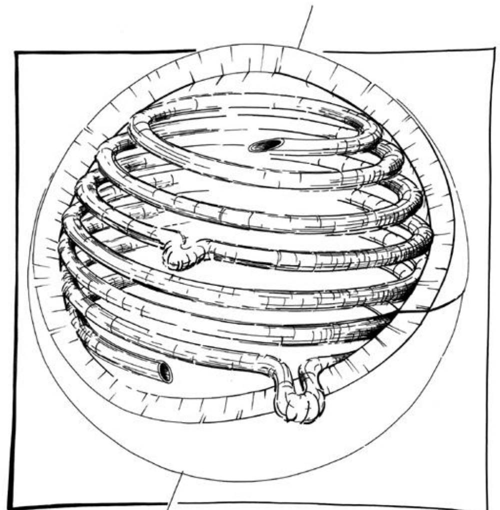
THERMOHALINE MIXING

DIFFUSION DUE TO THE MOLECULAR WEIGHT INVERSION INDUCED BY $^3He + ^3He \rightarrow ^4He + 2p$ (EGGLETON ET AL. 2006, 2008. A FIRST-PRINCIPLE-BASED PROCESS?). SLOW MIXING, V< 1 CM/SEC.

$$\frac{\partial \mathbf{B}}{\partial t} = \lambda \nabla^2 \mathbf{B} + \nabla \times (\mathbf{v} \times \mathbf{B}).$$

MAGNETIC BUOYANCY

DYNAMO MECHANISMS MIGHT PERSIST IN RED GIANTS (BUSSO ET AL. 2007; NORDHAUS ET AL. 2008. DENISSENKOV ET AL. 2009; NUCCI & BUSSO 2013)



A SECTION OF THE 'FLUX-TUBE' SYSTEM.

MAGNETIC DOMAINS HAVE A LOWER GAS PRESSURE:

$$P^G_E = P^G_I + B^2/8\pi$$

$$\Delta P^G_{(I-E)}\ (<0) = -B^2/8\pi$$

THEY ARE LIGHTER &MOVE OUTWARD!

Molecular weight inversion

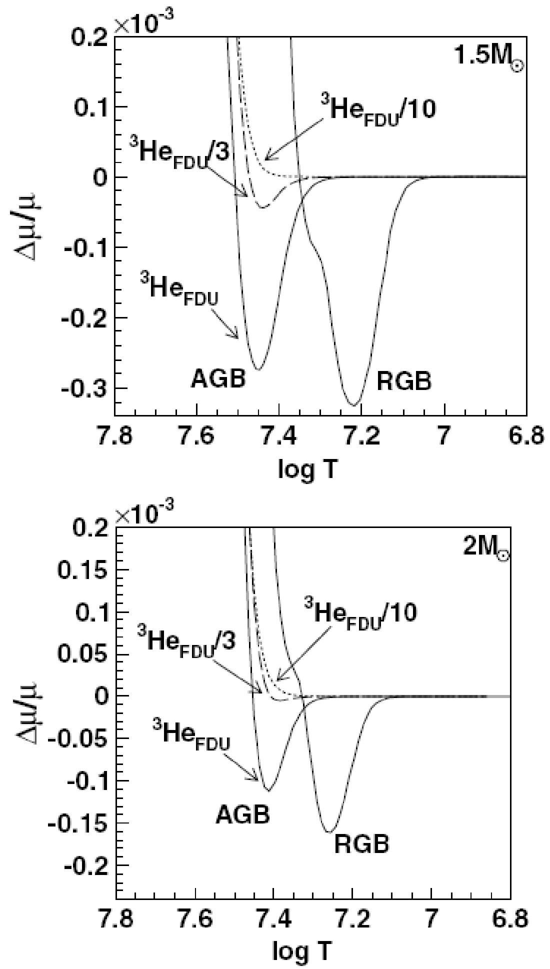


Figure 1. Relative variation of the molecular weight ($\Delta\mu/\mu$) for a 1.5 and a 2.0 $M_\odot$ star with solar metallicity in the layers hosting ^{3}He burning above the H shell. The μ inversion, present on the RGB, is also preserved on the AGB only if a sufficient supply of ^{3}He remains. For the AGB, different lines refer to different abundances of ^{3}He resulting from the previous RGB phase, as indicated by the labels.

In the H-burning region:

$$^3He + ^3He \rightarrow ^4He + 2p$$

Induces a small inversion of μ; this lets the matter above that layer be heavier than that in the burning region and sink down, promoting a mixing mechanism in the form of "fingers". The more these are elongated, the more efficient and fast the mixing is.

This is a form of thermohaline mixing (Charbonnel &Zahn 2007).

THE DEBATE ON THEMOHALINE MIXING

DIFFERENT AUTHORS FIND DIFFERENT RESULTS ABOUT THE EFFECTIVENESS OF THERMOHALINE MIXING.

EXAMPLES (SEE MAEDER ET AL. 2013):

I) CHARBONNEL & LAGARDE (2010) AND LAGARDE ET AL (2013) FIND IT ADEQUATE TO EXPLAIN RED GIANT ABUNDANCES (AND ALSO THE EVOLUTION OF ^{3}HE IN THE GALAXY)

II) DENISSENKOV (2010), DENISSENKOV & MERRYFIELD (2010), PALMERINI ET AL. (2011), ANGELOU ET AL. (2011), CANTIELLO & LANGER (2010) FOUND IT TOO SLOW BY A LARGE FACTOR (THERE IS NO TIME ON THE RGB TO ACHIEVE THE OBSERVED ABUNDANCES).

Thermohline mixing on the RGB?

1. Eggeleton et al. (2006, 2008) suggested that the molecular weight inversion be at the origin of abundance anomalies in red giants.
2. Subsequently, the same group (Angelou et al. 2011) found the mixing velocity (a fraction of a cm/sec) to be too small and showed that abundances in GC red giants needed a much larger "$\Delta\mu$" effect.
3. Is there any possibility to increase the ^{3}He consumption, hence the extent to which μ is varied reconciling those different results?

EFFECTS OF MICROSCOPIC PLASMA PHYSICS ON THERMOHALINE MIXING?

THE ASTROPHYSICAL JOURNAL, 764:118 (12pp), 2013 February 20 doi:10.1088/0004-637X/764/2/118

THEORETICAL ESTIMATES OF STELLAR e^- CAPTURES. I. THE HALF-LIFE OF ^{7}Be IN EVOLVED STARS

S. SIMONUCCI[1,2], S. TAIOLI[2,3,4,5], S. PALMERINI[6], AND M. BUSSO[2,7]
[1] Department of Physics, University of Camerino, Camerino, Italy
[2] Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, Perugia, Italy; stefano.simonucci@unicam.it
[3] Interdisciplinary Laboratory for Computational Science, FBK-CMM and University of Trento, Trento, Italy; taioli@fbk.eu
[4] Department of Physics, University of Trento, Trento, Italy
[5] Department of Chemistry, University of Bologna, Bologna, Italy
[6] Departamento de Física Teórica y del Cosmos, Universidad de Granada, Spain
[7] Department of Physics, University of Perugia, Perugia, Italy
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IN AFFORDING A VERY DIFFERENT ISSUE, NAMELY TRYING TO FIGURE OUT A RATE FOR ^{7}BE DECAY IN CONDITIONS DIFFERENT FROM SOLAR, WE DISCOVERED SOMETHING THAT MIGHT BE OF SOME USE!

Where we started from

There is no rate for ^{7}Be decay outside solar conditions.

I don't understand how people can calculate Li abundances. The rates available (from Bahcall, or from Adelberger et al) cannot and should not be extrapolated (Nollett, private communication, 2 days ago!).

Hence virtually all calculations (EHM, including ours: Palmerini et al. 2011) are somehow wrong!!!

Problem: The Coulomb force lets electrons crowd around a Be nucleus in RGB stars. Matter is locally partly degenerate, even for Maxwellian plasmas!

DYNAMICS OF E-CAPTURES FROM AB-INITIO CALCULATIONS

$$\sigma_{i\to f} = \int \frac{d^3k}{(2\pi)^3}\frac{2\pi}{v}\left|\langle\psi^-_{f,k}|W|\phi^+_{i,p}\rangle + \langle\phi^-_{f,k}|V|\phi_{i,p}\rangle\right|^2 \times \delta\left(\frac{p^2}{2m_e} + E_i - E_f - ck\right)$$
$$= \int \frac{d^3k}{(2\pi)^3}\frac{2\pi}{v}\left|\langle\phi^-_{f,k}|T_w|\phi^+_{i,p}\rangle\right|^2 \times \delta\left(\frac{p^2}{2m_e} + E_i - E_f - ck\right).$$

WEAK INTERACTIONS AS EXAMPLES OF QUANTUM SCATTERING UNDER TWO POTENTIALS. TREATED WITH A HARTREE-FOCK APPROACH IN THE POTENTIAL OF BE PLUS THAT OF A MEAN FIELD, CREATED BY ALL OTHER IONS.

MAIN RESULTS:

I) THE ELECTRON DENSITY IN THE DEBYE SPHERE IS HIGHER THAN USUALLY ESTIMATED WITH THE DEBYE-HUECKEL CLASSICAL APPROACH (HIGHER E-CAPTURE RATES THAN EXPECTED)

II) THE EFFECT IS LARGE FOR REGIONS OF LOW ρ AND T, LIKE ABOVE A H-BURNING SHELL (WHILE IS ONLY 1% IN THE SUN: BAHCALL'S RESULTS FOR SOLAR NEUTRINOS OK).

III) NUCLEAR REACTIONS OCCURRING AT LOW T,ρ VALUES SHOULD BE FASTER, FOR INCREASED E-SCREENING!!

IV) ^{3}HE+^{3}HE MIGH BE MORE EFFECTIVE, BOTH IN CONSUMING ^{3}HE AND IN PROMOTING μ GRADIENTS.

→ THEMORHALINE MIXING MORE EFECTIVE? (WORK IN PROGRESS!)

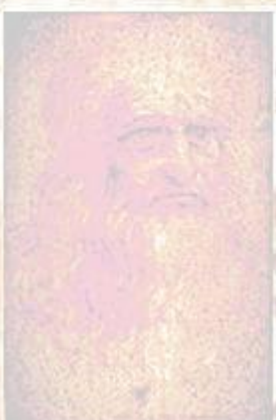
RESULTS FOR LI ON THE AGB

THE BASIC IDEA IS VERY SIMPLE AND OBVIOUS. WE ONLY SAY THAT UNDER ELECTROSTATIC ATTRACTION (I.E. INSIDE THE DEBYE SPHERE) , A GAS IS NOT MAXWELLIAN BUT ACTUALLY….. NOT EXEMPT FROM FORCES (MR DE LAPALISSE)

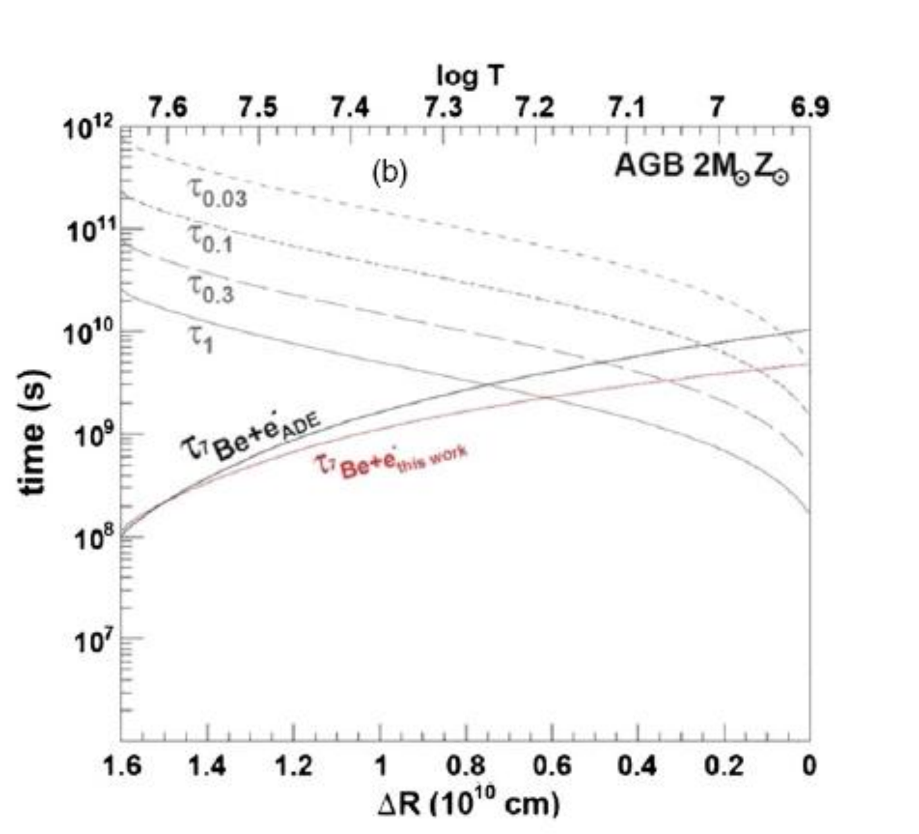
THE CALCULATIONS HOWEVER ARE NOT THAT SIMPLE!

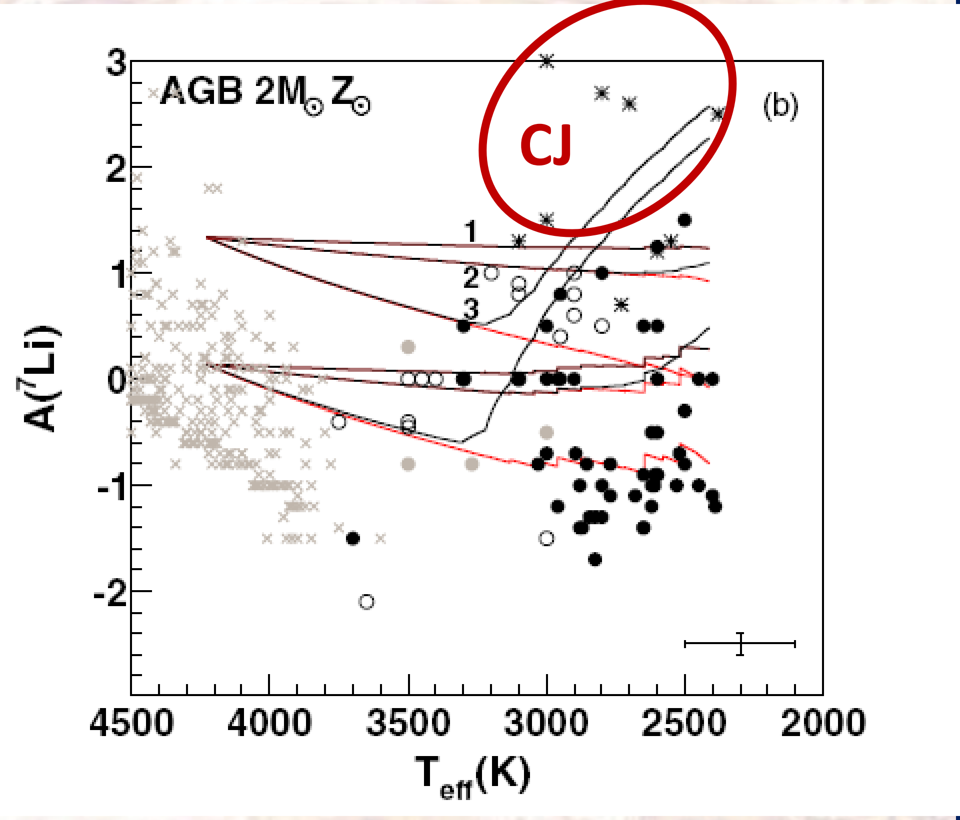
FOR YOUR CURIOSITY I CAN SHOW YOU OUR SIMPLEST FORM FOR THE HAMILTONIAN OF THE INTERACTION…….

$$
\begin{aligned}
H = & \sum_{j=1}^{N_e}\left(-\frac{1}{2m_e}-\frac{1}{2M_{\mathrm{Be}}}\right)\nabla'^2_{e,j} \\
& + \sum_{J=1}^{N_p}\left(-\frac{1}{2m_p}-\frac{1}{2M_{\mathrm{Be}}}\right)\nabla'^2_{p,J} - \sum_{j=1}^{N_e}\frac{Z_{\mathrm{Be}}}{|\boldsymbol{r}'_{e,j}|} + \sum_{J=1}^{N_p}\frac{Z_{\mathrm{Be}}}{|\boldsymbol{R}'_{p,J}|} \\
& - \sum_{j=1}^{N_e}\sum_{J=1}^{N_p}\frac{1}{|\boldsymbol{r}'_{e,j}-\boldsymbol{R}'_{p,J}|} + \sum_{j=1}^{N_e}\sum_{k=j+1}^{N_e}\frac{1}{|\boldsymbol{r}'_{e,j}-\boldsymbol{r}'_{e,k}|} \\
& + \sum_{J=1}^{N_p}\sum_{K=J+1}^{N_p}\frac{1}{|\boldsymbol{R}'_{p,J}-\boldsymbol{R}'_{p,K}|} - \frac{1}{2M_{\mathrm{Be}}}\nabla'^2_{\mathrm{Be}} \\
& - \sum_{\substack{J,J'=1 \\ J\neq J'}}^{N_p}\left(\frac{1}{M_{\mathrm{Be}}}\boldsymbol{\nabla}'_{p,J}\cdot\boldsymbol{\nabla}'_{p,J'}\right) \\
& - \sum_{\substack{j,j'=1 \\ j\neq j'}}^{N_e}\left(\frac{1}{M_{\mathrm{Be}}}\boldsymbol{\nabla}'_{e,j}\cdot\boldsymbol{\nabla}'_{e,j'}\right) \\
& - \frac{1}{M_{\mathrm{Be}}}\sum_{j=1}^{N_e}\sum_{J=1}^{N_p}\boldsymbol{\nabla}'_{p,J}\cdot\boldsymbol{\nabla}'_{e,j} \\
& + \sum_{j=1}^{N_e}\left(\frac{1}{M_{\mathrm{Be}}}\boldsymbol{\nabla}'_{e,j}\cdot\boldsymbol{\nabla}'_{\mathrm{Be}}\right) + \sum_{J=1}^{N_p}\left(\frac{1}{M_{\mathrm{Be}}}\boldsymbol{\nabla}'_{p,J}\cdot\boldsymbol{\nabla}'_{\mathrm{Be}}\right).
\end{aligned}
\tag{A3}
$$



RESULTS FOR LI





COMPARISONS OF RESULTS FROM PALMERINI ET AL. (2011B) AND SIMONUCCI ET AL. (2013).

CJ STARS ARE NOT NORMAL AGB STARS, EVEN FOR LI!!

Consequences for mixing?

1. Thermohaline mixing in red giants might be considerably more effective than estimated by Denissenkov & others (and… us!)

2. D, ^{3}He & Li production/destruction & their nucleosynthesis in general must be re-computed from scratch with improved weak interactions and e-screening. No existing result can be trusted!!!!

3. However, we need deep mixing also on the AGB, and also in He-rich layers, to explain the formation of the ^{13}C neutron source. There we have no μ–gradient, no thermohaline mixing.

THE TRADITIONAL PICTURE

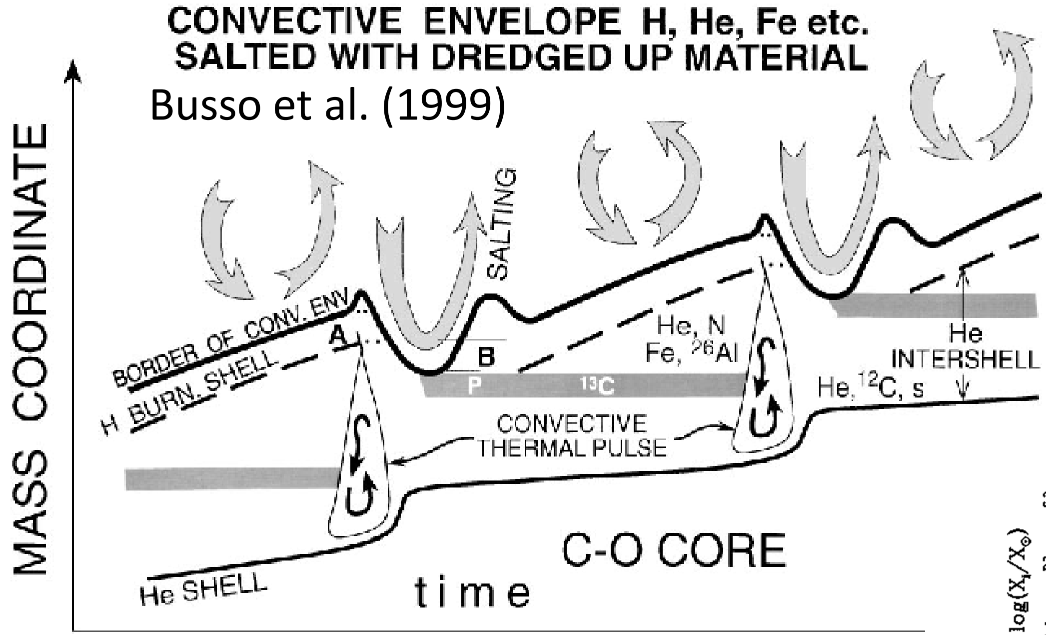
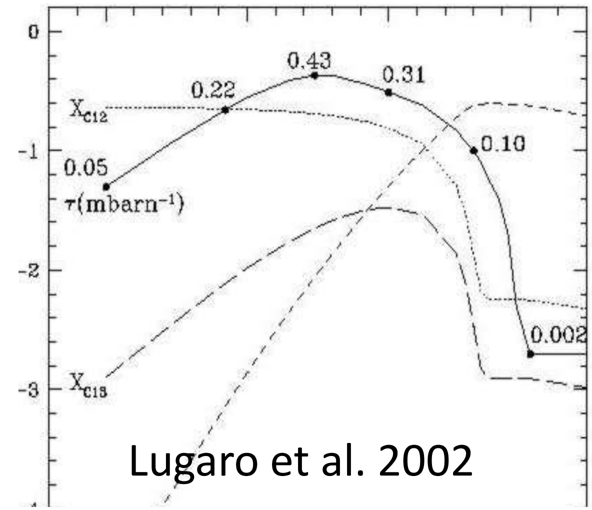
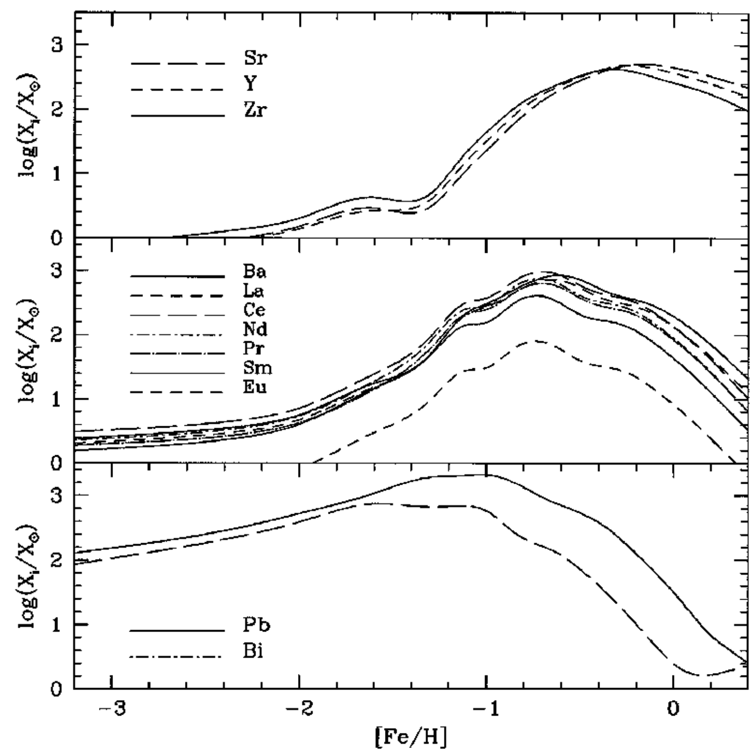
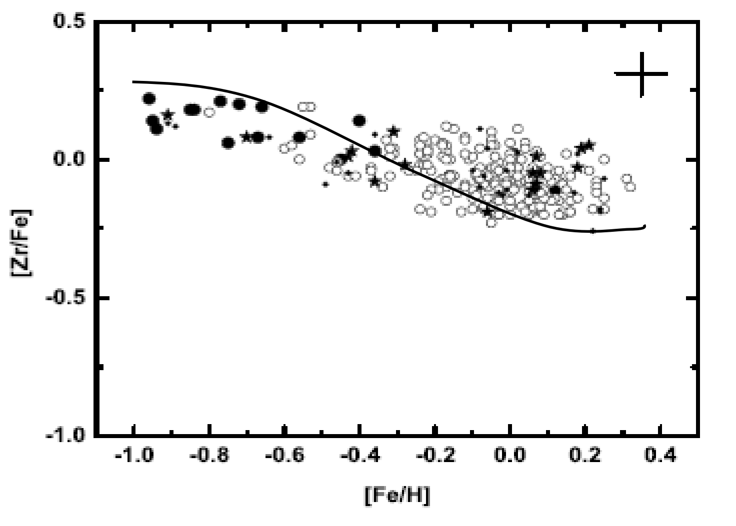


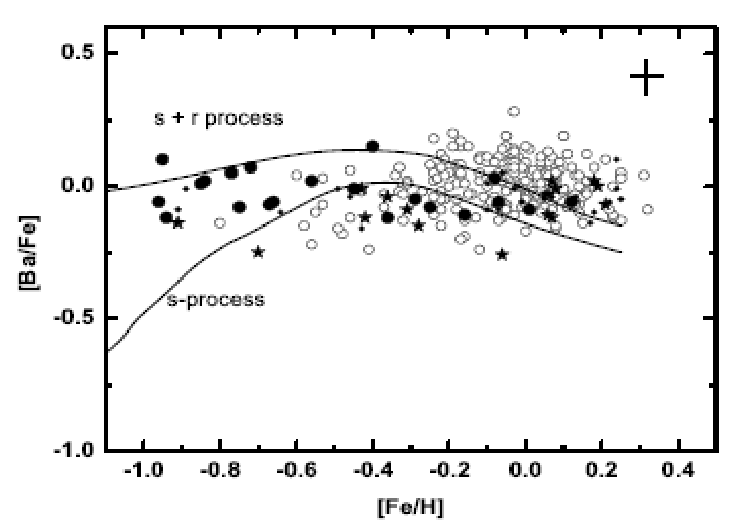
Figure 5 Illustration of the structure of a thermal pulse-asymptotic giant branc
time, showing the border of the convective envelope, the H-burning shell, ar
burning shell. The region between the H and He shells is the He intershell. *Horiz*
bars represent zones where protons are assumed to be ingested to make ^{13}C. In
models, ^{13}C was not allowed to burn until the region was engulfed in a convec
In the newer models, ^{13}C is naturally burned under radiative conditions in the
before ingestion because of the progressive heating of the region. The slow neutr
(*s*) products are then engulfed by the thermal pulse, and further processing occu
neutrons from the $^{22}Ne(\alpha,n)^{25}Mg$ source. Region *A* between the H shell and the
the convective zone and region *B* in the He intershell are mixed into the convectiv
during TDU, and these regions salt the envelope with freshly synthesized ma
remaining part of the He intershell region below B is also enriched in *s*-proces
and is partly mixed over subsequent cycles. Note that the convective thermal puls
reach the H-burning shell, as found by Iben (1977).





BUT…

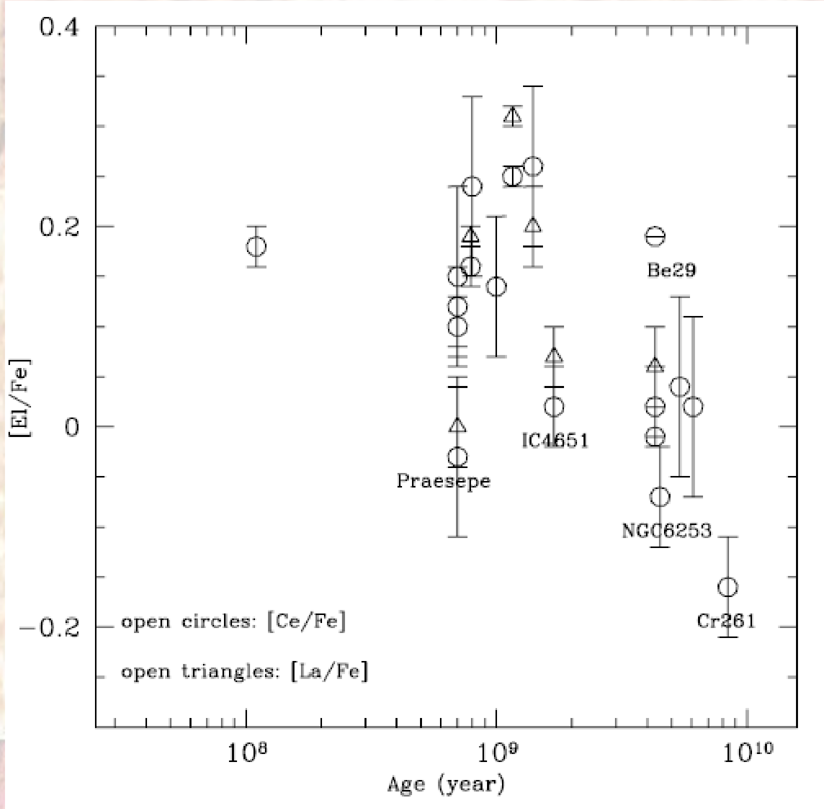


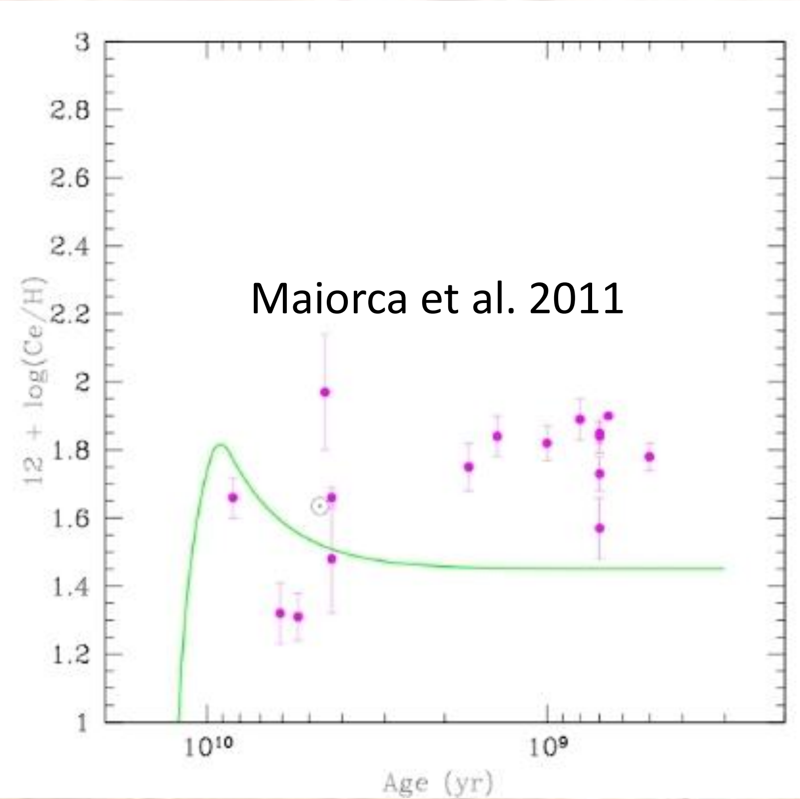


Adapted from Mishenina et al. 2013 (stars older than 2 Gyr)

More neutrons are neded. The chemical evolution at high metallicities not reproduced

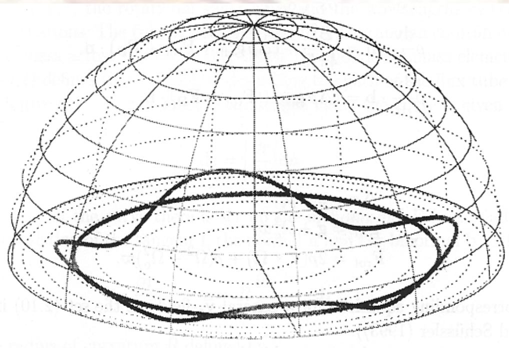
EVIDENCE FROM YOUNG (τ< 1.5GYR) OPEN CLUSTERS

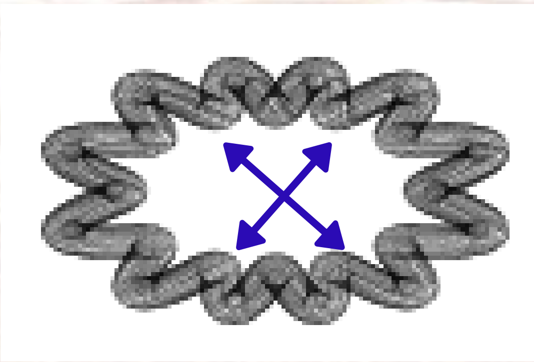


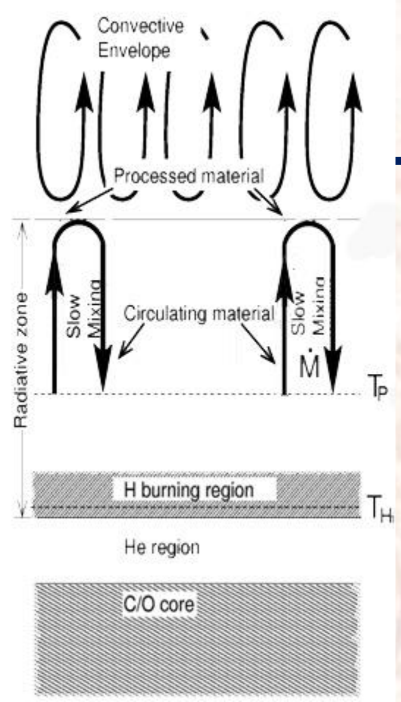


RECENT DATA (D'ORAZI ET AL. 2009; MAIORCA ET AL. 2011; JACOBSON & FRIEL 2013) SHOW THAT THE ABUNDANCES OF S ELEMENTS ARE ACTUALLY INCREASING IN THE GALAXY

MAGNETIC BUOYANCY (BUSSO ET AL. 2007)







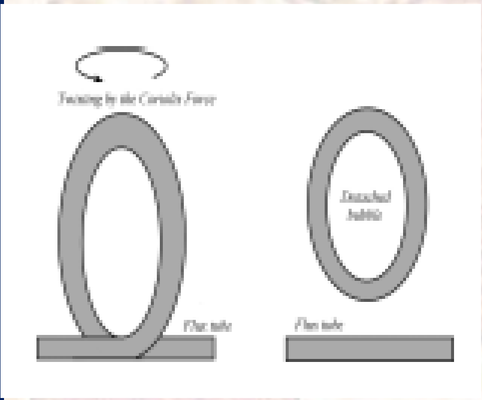
CASE 1 SLOW: "COMMON" DEEP MIXING.

MIXING VEL. DEPENDS ON HEAT EXCHANGES (DENISSENKOV ET AL 2009; PARKER 1974).

$V = 3X10^{14}/A^2$ (PARKER '74)

FOR A = 0.3KM, V = 3KM/SEC

FOR A=100KM, V= 3CM/SEC



CASE 2 FAST: DETACHED BUBBLES

SLOW (CM/SEC):AS WELL AS FAST (KM/SEC) MIXING IS POSSIBLE BY MAGNETIC MODELS

FAST MIXING, DUE TO SMALL INSTABILITIES WOULD BE INTERMITTENT: V AND DM/DT DECOUPLED!!

DO VELOCITY ISSUES EXIST ALSO FOR MAGNETIC BUOYANCY??

ON THE AGB WE HAVE A SHORT TIME FOR MIXING AT TDU: FEW HUNDRED YEARS!

MHD EQUATIONS: 2D EXACT SOLUTIONS

Nucci & Busso 2013, ApJ submitted

NO DRAG:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \tag{1}$$

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} + \frac{1}{\rho}\nabla p - \mathbf{F} + \frac{1}{4\pi\rho}\mathbf{B} \times (\nabla \times \mathbf{B}) - \eta \Delta \mathbf{v} = 0 \tag{2}$$

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) - \nu_m \Delta \mathbf{B} = 0 \tag{3}$$

$$\frac{\partial \epsilon}{\partial t} + \mathbf{v} \cdot \nabla \epsilon + \frac{P}{\rho}\nabla \cdot \mathbf{v} - \frac{1}{\rho}\nabla \cdot (K \nabla T) + \frac{\nu_m}{4\pi\rho}(\nabla \times \mathbf{B})^2 = 0 \tag{4}$$

WITH DRAG:

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} + \frac{1}{\rho}\nabla P - \mathbf{F} - \frac{1}{\rho}\alpha_D^2 \mathbf{v} + \frac{1}{4\pi\rho}\mathbf{B} \times (\nabla \times \mathbf{B}) - \eta \Delta \mathbf{v} = 0 \tag{2b}$$

IN POLAR COORDINATES

$$\varrho\left(\frac{\partial v_r}{\partial t}+v_r\frac{\partial v_r}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_\theta}{\partial \theta}-\frac{v_\theta^2}{r}+\frac{\partial p}{\partial r}+F_r\right)$$
$$-\eta\left(\frac{\partial^2 v_r}{\partial r^2}+\frac{1}{r^2}\frac{\partial^2 v_\theta}{\partial \theta^2}+\frac{1}{r}\frac{\partial v_r}{\partial r}-\frac{2}{r^2}\frac{\partial v_\theta}{\partial \theta}-\frac{v_r}{r^2}\right)+\frac{1}{4\pi\mu}\frac{B_\theta}{r}\left(\frac{\partial(rB_\theta)}{\partial r}-\frac{\partial B_r}{\partial \theta}\right)=0 \quad (1)$$

$$\varrho\left(\frac{\partial v_\theta}{\partial t}+v_r\frac{\partial v_\theta}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_\theta}{\partial \theta}+\frac{v_r v_\theta}{r}+\frac{1}{r}\frac{\partial p}{\partial \theta}+F_\theta\right)$$
$$-\eta\left(\frac{\partial^2 v_\theta}{\partial r^2}+\frac{1}{r^2}\frac{\partial^2 v_\theta}{\partial \theta^2}+\frac{1}{r}\frac{\partial v_\theta}{\partial r}+\frac{2}{r^2}\frac{\partial v_r}{\partial \theta}-\frac{v_\theta}{r^2}\right)-\frac{1}{4\pi\mu}\frac{B_r}{r}\left(\frac{\partial(rB_\theta)}{\partial r}-\frac{\partial B_r}{\partial \theta}\right)=0 \quad (2)$$

$$\frac{\partial \varrho}{\partial t}+\frac{\partial(\varrho v_r)}{\partial r}+\frac{1}{r}\frac{\partial(\varrho v_\theta)}{\partial \theta}+\frac{\varrho v_r}{r}=0 \quad (3)$$

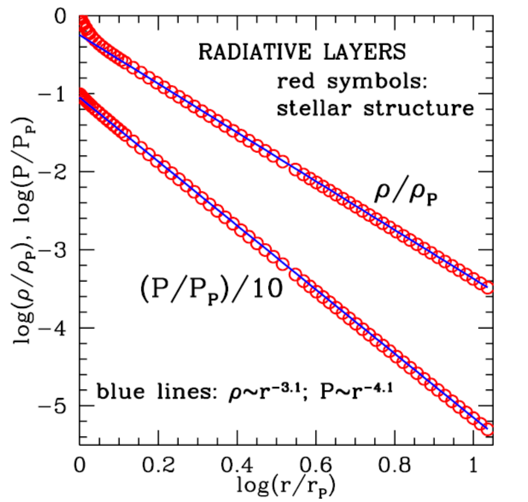
$$\frac{\partial B_r}{\partial t}-\frac{1}{r}\frac{\partial(v_r B_\theta - v_\theta B_r)}{\partial \theta}-\nu_m\left(\frac{\partial^2 B_r}{\partial r^2}+\frac{1}{r^2}\frac{\partial^2 B_r}{\partial \theta^2}+\frac{1}{r}\frac{\partial B_r}{\partial r}-\frac{2}{r^2}\frac{\partial B_\theta}{\partial \theta}-\frac{B_r}{r^2}\right)=0 \quad (4)$$

$$\frac{\partial B_\theta}{\partial t}+\frac{\partial(v_r B_\theta - v_\theta B_r)}{\partial r}-\nu_m\left(\frac{\partial^2 B_\theta}{\partial r^2}+\frac{1}{r^2}\frac{\partial^2 B_\theta}{\partial \theta^2}+\frac{1}{r}\frac{\partial B_\theta}{\partial r}+\frac{2}{r^2}\frac{\partial B_r}{\partial \theta}-\frac{B_\theta}{r^2}\right)=0 \quad (5)$$

$$\frac{\partial B_r}{\partial r}+\frac{1}{r}\frac{\partial B_\theta}{\partial \theta}+\frac{B_r}{r}=0 \quad (6)$$

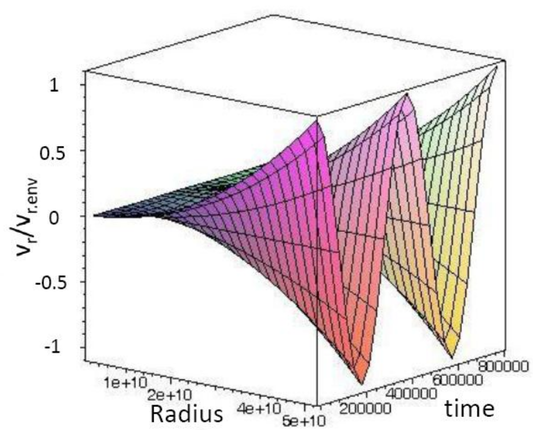
2D! ONLY THE MAGNETIC BUOYANCY OF TOROIDAL STRUCTURES IS VERIFIED TO BE AN EXACT SOLUTION OF MHD EQUATIONS

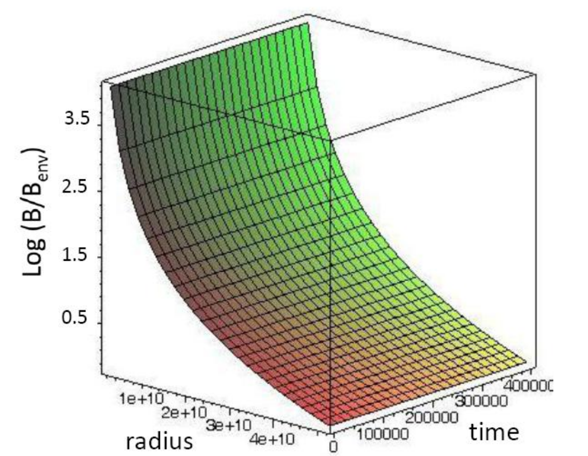
AGB. Magnetic mixing always fast?



$$v_r = \frac{\mathrm{d}w(t)}{\mathrm{d}t} r^2, \qquad B_\theta = \frac{\Phi(\xi)}{r^2}, \qquad \left[\xi = w(t) + \frac{1}{r}\right]$$

$$\varrho = \frac{\varrho_P}{(r/r_P)^3};$$

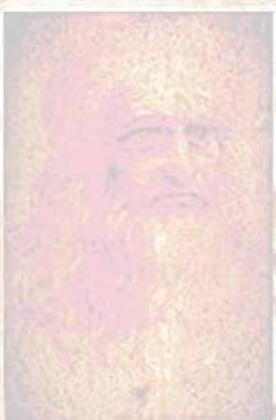




According to Nucci & Busso 2013, in TP-AGB stars the radiative layer above the H-shell is a polytrope of index 3 (a "bubble of radiation"), with very little mass (0.001 $M_\odot$ in 1 $R_\odot$).

Virtually no drag & no thermal exchanges, fast (parabolic) rising velocity. Then in the huge envelope: no escape, matter trapped there (mixing!!)

Magnetic flux is preserved for "traditional" choices of the arbitrary functions!



A NON-PARAMETRIC MODEL FOR THE ^{13}C SOURCE FORMATION

- Assuming steady state conditions, using the flux conservation discussed before and a sort of transport equation for the magnetic structures generated, in crossing a layer dr we have:

$$d\dot{N} = -\dot{N}\alpha^* dr^* + \frac{\varepsilon^*}{r^{*4}} dr^*$$

were $\varepsilon^* = \gamma F_B^2$ and F_B is the magnetic flux.

- The rate of buoyant structures (N) is diminished by dissipative phenomena, described by an absorption coefficient α* and is increased by the number of structures born in the same layer dr*.
- By substituting $r = r^*/r_0^*$, we can obtain:

$$d\dot{N} = -\dot{N}\alpha dr + \frac{\varepsilon}{r^4} dr$$

A NON-PARAMETRIC MODEL FOR THE ^{13}C SOURCE FORMATION

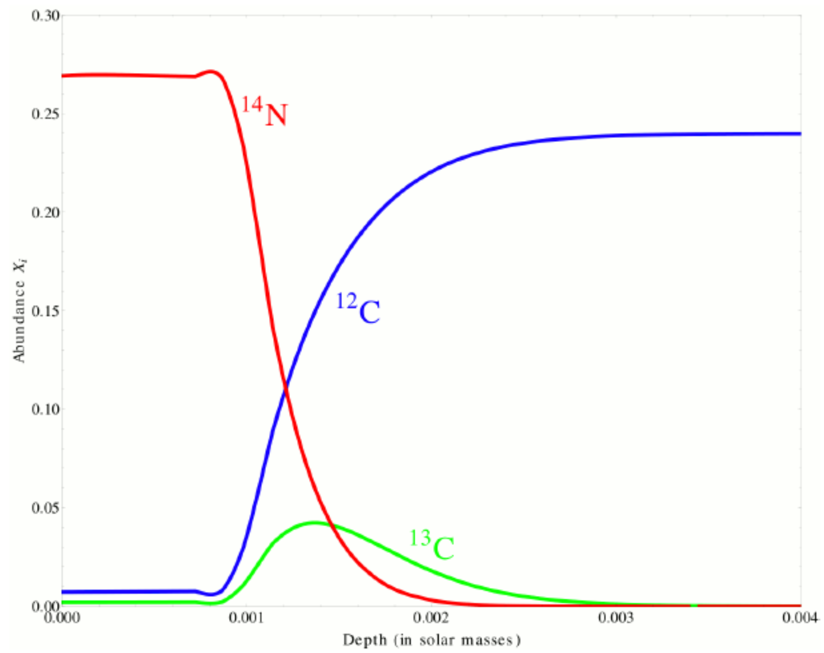
- We have to solve the linear, but non-homogeneous, equation:

$$R = R_0 e^{-\alpha(r-r_0)} + \varepsilon \alpha^3 e^{-\alpha r} \int_{(\alpha r_0)}^{(\alpha r)} \frac{e^{\alpha r}}{(\alpha r^4)} d(\alpha r)$$

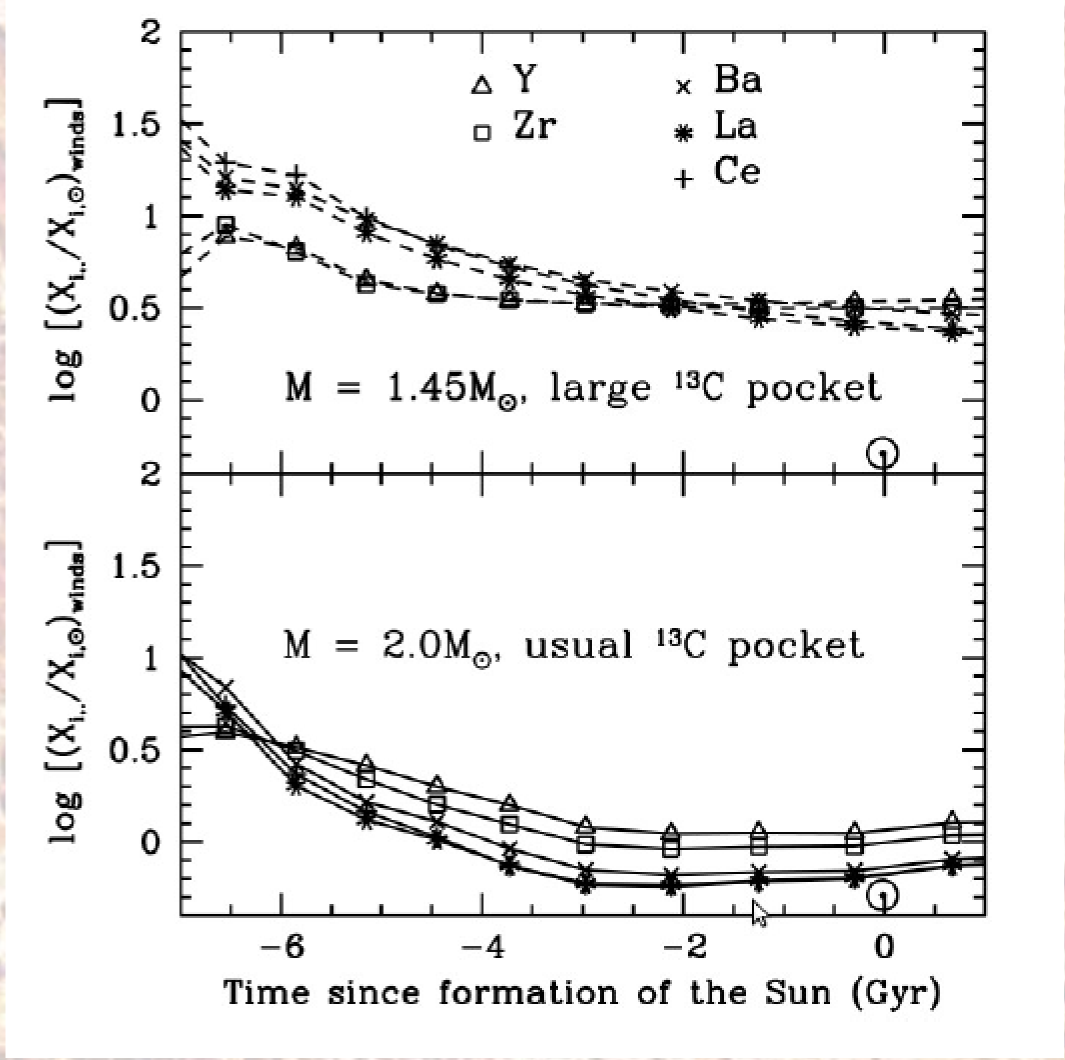
- where α refers to different dissipation phenomena: thermal diffusivity, viscosity and magnetic diffusivity.
- The profile of proton penetration, neglecting the second term in the equation and assuming the conservation of mass, is roughtly EXPONENTIAL.
- This shape is used in most parameterized approaches, but now we starts to have a physical interpretation, based on MHD.

A NON-PARAMETRIC MODEL FOR THE ^{13}C SOURCE FORMATION

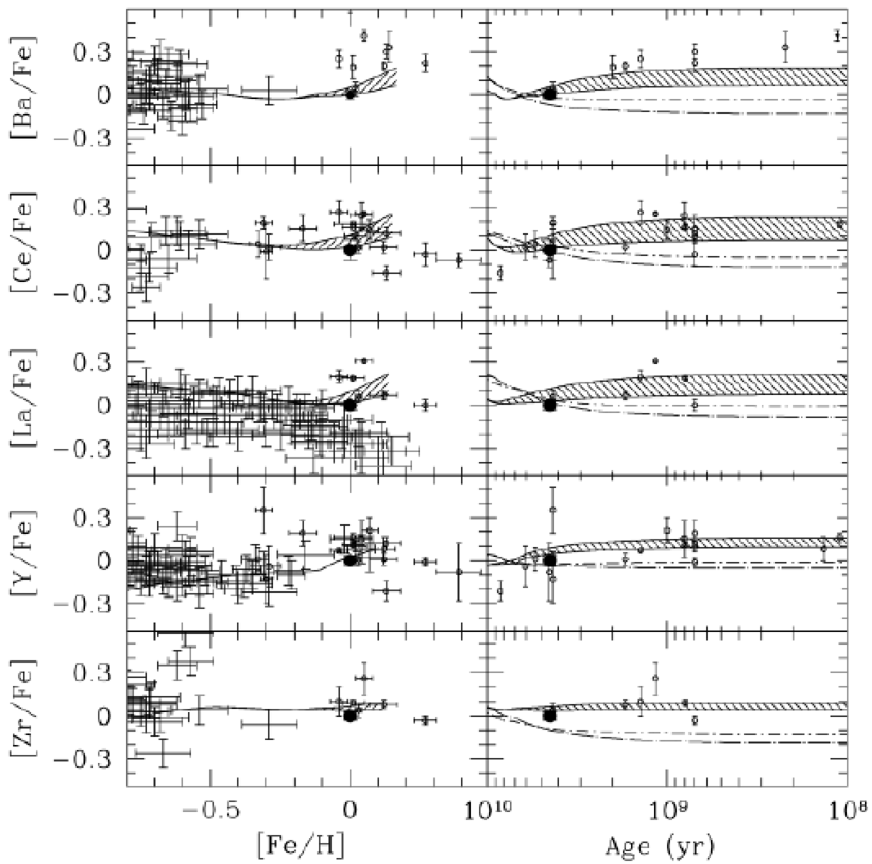
- The ^{13}C-pocket is more extended than the standard one. The average value is 4×10^{-3} solar masses, as the extension of intershell region.
- Neutron fluences larger than those so far assumed in literature.
- The ^{13}C-pocket is where the green line overcomes the red one.
- There is a limited neutron production in the ^{14}N-rich region, because ^{14}N is the main neutron absorber.



The effect of expanding the 13C reservoir on the stellar yields



RESULTS FOR THE CHEMICAL EVOLUTION OF THE GALAXY WITH THE NEW ^{13}C POCKET



Percentage of Contribution to Solar *s*-only Nuclei

Isotope	Case A	Case B	Arlandini et al. (1999)
^{100}Ru	95	93	95
^{110}Cd	97	95	97
^{124}Te	94	92	91

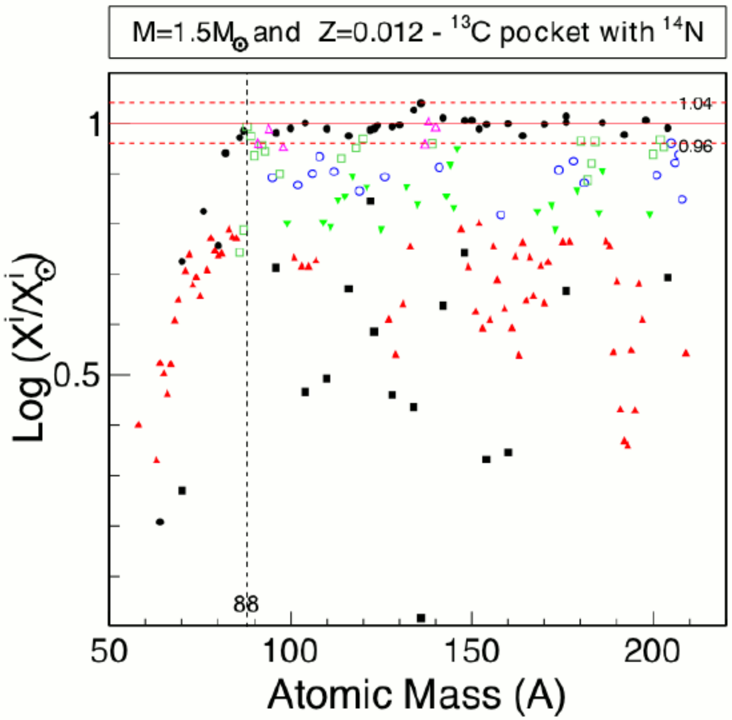
Percentage of Contributions to Solar Heavy Elements from LMS

Element	This Work (A)	This Work (B)	This Work (C)	Literature
Strontium	90	89	86	55[1]
Yttrium	81	80	84	62[1]
Zirconium	80	78	80	55[2]
Barium	89	86	85	84[2]
Lanthanum	72	70	70	70[2]
Cerium	79	78	76	81[2]

Maiorca et al. 2012

REPRODUCING THE SOLAR S-PROCESS ABUNDNCES

- The figure shows the solar distribution as obtained by an average single model performed using the extended ^{13}C-pocket.
- The figure represents over-abundances of several isotopes normalized to the average over-abundances of *s*-only elements.
- Different points refer to nuclei with a different percentage of *s*-process production. Full black circles are *s*-only isotopes.
- The orizontal red lines bracket a good, almost flat fit (constant production factor for all *s*-only nuclei).
- The spread is less than 4%.



CONCLUSIONS

- EVEN MORE THAN FOR CONVECTION (SEE TALK BY THE OTHER MAURIZIO), DEEP MIXING UNCERTAINTIES PREVENT US SO FAR TO GET FINAL CONCLUSIONS
- RECENT WORK UNDERLINES THE NEED TO PAY ATTENTION TO DETAILED PLASMA PROCESSES.
- THERMOHALINE DIFFUSION MIGHT BE MORE EFFECTIVE THAN IMAGINED; THIS APPROACH REQUIRES A REVISION OF ELECTRON SCREENING &WEAK INTERACTIONS.
- MAGNETIC BUOYANCY OF TOROIDAL STRUCTURES (FORESEEN BY APPROXIMATE 3D DYNAMO MODELS) GIVE AN EXACT SOLUTION TO (2D) MHD EQUATIONS , W. FAST MIXING IN THE RADIATIVE LAYERS (ESPECIALLY ON THE AGB)
- IT MIGHT PROVIDE AN EXTENDED ^{13}C RESERVOIR, SUITABLE TO ACCOUNT FOR S-PROCESS DATA IN OPEN CLUSTERS

Everything is still so uncertain that we need probably to spend much more time learning some physics, before drawing any real conclusion!