Themes for this talk

1. Stellar evolution: present state
2. The multi-dimensional star
3. Application of stellar evolution

Quo vadis stellar evolution

Falk Herwig
University of Victoria
Beautiful British Coloumbia

Wednesday, March 31, 2010
Extra-mixing aka “cool-bottom processing”

Several observations on the AGB as well as on the RGB indicate that a certain amount of mixing between the bottom of the giant convection envelope and the H-burning shell is needed, e.g.

• large \([N/Fe]\) in C-rich extremely metal poor stars
• lower \(^{12}\text{C}/^{13}\text{C}\) on the AGB then expected from standard models
• abundance correlations with L in RGB GC stars, e.g. C/N
• Li enhancements in RGB GC stars

Proposed scenarios include

• followed finally by “Is Extra Mixing Really Needed in Asymptotic Giant Branch Stars?” Karakas et al (2010) [best reproduction of observations with enhanced \(^{16}\text{O}\) intershell abundance]
Deep Mixing of $^3$He: Reconciling Big Bang and Stellar Nucleosynthesis

Peter P. Eggleton,* David S. P. Dearborn,1 John C. Lattanzio2

Low-mass stars, ~1 to 2 solar masses, near the Main Sequence are efficient at producing the helium isotope $^3$He, which they mix into the convective envelope on the giant branch and should distribute into the Galaxy by way of envelope loss. This process is so efficient that it is difficult to reconcile the low observed cosmic abundance of $^3$He with the predictions of both stellar and Big Bang nucleosynthesis. Here we find, by modeling a red giant with a fully three-dimensional hydrodynamic code and a full nucleosynthetic network, that mixing arises in the supposedly stable and radiative zone between the hydrogen-burning shell and the base of the convective envelope. This mixing is due to Rayleigh-Taylor instability within a zone just above the hydrogen-burning shell, where a nuclear reaction lowers the mean molecular weight slightly. Thus, we are able to remove the threat that $^3$He production in low-mass stars poses to the Big Bang nucleosynthesis of $^3$He.

Fig. 1. Evolution of a low-mass Pop I star in a luminosity-temperature diagram. The model was computed in 1D, that is, spherical symmetry was assumed, using the code of (20, 21) with updated equation of state, opacity, and nuclear reaction rates (22). Surface temperature is in kelvins, luminosity in solar units.

Fig. 3. The profile of reciprocal molecular weight ($1/\mu$), as a function of mass in solar units, at three successive times (red, then green 2 million years later, then blue 2 million years later still).

Fig. 4. A color-coded plot of $\mu$ on a cross-section through the initial 3D model. The shell where the $\mu$ inversion occurs is the yellow region sandwiched between a yellow-green and a darker green. The inversion is at a radius of ~5 $\times$ 10$^7$ m. The base of the SCZ is at ~2 $\times$ 10$^9$ m, well outside the frame, and the surface of the star is at ~2 $\times$ 10$^{10}$ m.

Fig. 5. The development with time of a contour surface of mean molecular weight near the peak in the blue curve of Fig. 3. The contour dimples, and begins to break up, on a time scale of only ~2000 s.
Thermohaline mixing: a physical mechanism governing the photospheric composition of low-mass giants

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ABSTRACT

\textbf{Aims.} Numerous spectroscopic observations provide compelling evidence for a non-canonical mixing process that modifies the surface abundances of Li, C and N of low-mass red giants when they reach the bump in the luminosity function. Eggleton and collaborators have proposed that a molecular weight inversion created by the \textsuperscript{3}He(\textsuperscript{4}He, 2p)\textsuperscript{4}He reaction may be at the origin of this mixing, and relate it to the Rayleigh-Taylor instability. We argue that one is actually dealing with a double diffusive instability referred to as thermohaline convection and we discuss its influence on the red giant branch.

\textbf{Methods.} We compute stellar models of various initial metallicities that include thermohaline mixing, which is treated as a diffusive process based on the prescription given originally by Ulrich for the turbulent diffusivity produced by the thermohaline instability in stellar radiation zones.

\textbf{Results.} Thermohaline mixing simultaneously accounts for the observed behaviour of the carbon isotopic ratio and of the abundances of Li, C and N in the upper part of the red giant branch. It significantly reduces the\textsuperscript{3}He production with respect to canonical evolution models as required by measurements of \textsuperscript{3}He/H in galactic HII regions.

\textbf{Conclusions.} Thermohaline mixing is a fundamental physical process that must be included in stellar evolution modeling.

\textbf{Key words.} instabilities – stars: abundances – stars: interiors – hydrodynamics
THERMOHALINE CONVECTION IN STELLAR INTERIORS

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ABSTRACT

A quantitative theory of mixing induced by an inverted gradient of mean molecular weight is presented. This theory is applied to three stellar problems, with the following results: (1) during $^3\text{He}$ burning in a $2\,M_\odot$ star the change of $X_3$ between the center and surface is 0.002; (2) the $\mu$-mechanism proposed by Stothers and Simon is too short-lived to explain the $\beta$ Cephei variables, and (3) after the initial ignition of $^4\text{He}$ burning in a degenerate shell flash, the $^4\text{He}$ core and the $^{12}\text{C}$ shell mix on a time scale greater than $10^5$ years. The theory is checked by comparison with the laboratory experiment by Stommel and Faller quoted by Stern. The agreement is satisfactory. An important uncertainty in the theory is the ratio of length to width of a moving finger of matter.

VI. APPLICATIONS

a) $^4\text{He}$ Burning (Case 1)

The entry for case 1 in the last column of Table 4 indicates that the mixing time is comparable to the time scale for depletion of $^3\text{He}$. Consequently, a detailed discussion of this case is necessary. I assume that the initial $^4\text{He}$ abundance is large and ask the question: What is the difference in $^4\text{He}$ abundance between the center and the surface of the star required to allow a uniform rate of depletion throughout?

Just prior to the arrival of a pre-main-sequence star on the $^1\text{H}$ burning main sequence, the reaction

$$^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + ^2\text{H} + 12.86 \text{ MeV}$$

(26)

can temporarily halt gravitational contraction. Furthermore, this reaction converts two particles into three and thus decreases the mean molecular weight. After the maximum gradient of $X_3$, the mass fraction of $^3\text{He}$, has been achieved, the thermohaline-convection mechanism discussed above permits $X_3$ to decrease at a uniform rate throughout the star. Thus,

$$\left( \frac{\partial X_3}{\partial t} \right)_{\text{actual}} = \left( \frac{\partial X_3}{\partial t} \right)_{\text{nue}} + \left( \frac{\partial X_3}{\partial t} \right)_{\text{diff}} = \frac{L_*}{QM_*},$$

(27)

where $Q$ is the energy released per unit mass of $^3\text{He}$ which undergoes reaction (26); its value is $2.07 \times 10^{18}$ ergs per g $^3\text{He}$ consumed. Also, $L_*$ and $M_*$ are the total luminosity and mass.
COMPULSORY DEEP MIXING OF $^3$He AND CNO ISOTOPE RATIOS IN THE ENVELOPES OF LOW-MASS RED GIANTS

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ABSTRACT

Three-dimensional stellar modeling has enabled us to identify a deep-mixing mechanism that must operate in all low-mass giants. This mixing process is not optional, and is driven by a molecular weight inversion created by the $^3$He($^3$He,$2p$)$^4$He reaction. In this paper we characterize the behavior of this mixing, and study its impact on the envelope abundances. It not only eliminates the problem of $^3$He overproduction, reconciling stellar and big bang nucleosynthesis with observations, but solves the discrepancy between observed and calculated CNO isotope ratios in low-mass giants, a problem of more than three decades standing. This mixing mechanism, which we call “$\delta\mu$ mixing,” operates rapidly (relative to the nuclear timescale of overall evolution, $\sim 10^8$ yr) once the hydrogen-burning shell approaches the material homogenized by the surface convection zone. In agreement with observations, Population I stars between 0.8 and 2.0 $M_\odot$ develop $^{12}$C/$^{13}$C ratios of 14.5 $\pm$ 1.5, while Population II stars process the carbon to ratios of 4.0 $\pm$ 0.5. In stars less than 1.25 $M_\odot$, this mechanism also destroys 90%–95% of the $^3$He produced on the main sequence.

Subject headings: hydrodynamics — stars: abundances — stars: chemically peculiar — stars: evolution — stars: interiors — stars: Population II
Mass loss and opacities in AGB stars

An important new ingredient for AGB stellar evolution are new low-T opacities and - ideally matching - mass loss rates, e.g. from hydrodynamic wind models (see Susanne Hoefner’s presentation for details).

Goal: correctly and predictively describe the loss of the envelope when the star becomes C-rich through 3rd dredge-up, and the surface temperature evolution.

Routinely employed now, e.g.:
Mass loss and opacities in AGB stars
Mattson, Herwig, Hoefner, Wahlin, Lederer, Paxton

Effects of Carbon-excess Dependent Mass Loss and Molecular Opacities on Models of C-star Evolution

A Mass loss according to Blöcker for both M-star phase and C-star phase. Low-temperature opacities by Alexander & Ferguson (1994) without dependence on the carbon excess.

B Mass loss according to Blöcker for M-star phase and according to Mattsson et al. (2009) for the C-star phase, and low-temperature opacities as in A.

C Mass loss as in A, but the new low-temperature opacities as described in Sect. 2.3.

D Mass loss as in B and low-temperature opacities as in C, i.e., the new opacities and the new mass-loss prescription implemented simultaneously.

mass loss vs. age

“forward-modeling” superwind?!!

mass vs. age

total mass vs. age
Rotation and magnetic fields

- Rotation in 1D stellar evolution, e.g. Maeder & Meynet, Heger et al., Langer et al.
- plus magnetic fields, e.g. Taylor & Spruit dynamo, questioned by Zahn et al. (2007)

Compare to observations in late phases:
- Rotation rates of neutron stars and white dwarfs
- Implications from nucleosynthesis, e.g. s-process in TP-AGB stars (Herwig et al. 2003)

“Seismic evidence for the loss of stellar angular momentum before the white-dwarf stage”
• Implications from nucleosynthesis, e.g. s-process in TP-AGB stars (Herwig et al 2003)
Rotation and magnetic fields

Fig. 1. Modelling strategy to study dynamical stellar evolution. The diagram presents timescales of the typical physical processes as a function of the angular resolution necessary to properly describe these processes. The angular resolution is expressed in terms of the $l$ index of the spherical harmonics $Y_{l,m} (\theta, \phi)$. $l_{\text{num}} \approx 600$ indicates the maximum angular resolution (in term of spherical harmonics nodes) presently achieved in global numerical simulations.


“A Model of Magnetic Braking of Solar Rotation That Satisfies Observational Constraints”
Denissenkov (2010)

• improving on Charbonneau & MacGregor (1993)
• strongly anisotropic rotation-driven turbulent diffusion with dominating horizontal components
• numerical solution of the azimuthal components of the coupled momentum and magnetic induction equations in 2D

“Numerical Simulations of a Rotating Red Giant Star. I. Three-dimensional Models of Turbulent Convection and Associated Mean Flows” Brun & Palacios, 2009
Stellar evolution in the early Universe

The ratio of the mixing time scale and the reaction time scale is called the Damköhler number:

\[ D_\alpha = \frac{\tau_{\text{mix}}}{\tau_{\text{react}}}. \]


- \( D_\alpha \ll 1 \): fully mixed burning, MLT appropriate
- \( D_\alpha \sim 1 \): combustion regime, MLT and 1D spherical symmetry assumption inappropriate
- combustion in low- and zero-metallicity stars common, including both low-mass and massive, rotating and non-rotating stars
- examples of papers which have not observed this physics requirement: e.g. Herwig et al. 1999, Herwig 2001 plus ca. 10-20 since then.
- check our poster and arXiv:1002.2241 for details
MESA: modules for experiments in stellar evolution
A new, modern, modular, open, fast community stellar evolution code

PMS of Brown dwarfs, VLM and LM stars

MS to WD through He-core flash < 1 day on my laptop

IM$_{\odot}$ internal evolution

Wednesday, March 31, 2010
MESA: modules for experiments in stellar evolution

A new, modern, modular, open, fast community stellar evolution code

low-/intermediate mass evolution

massive star evolution

C-star formation on the AGB
MESA: modules for experiments in stellar evolution

A new, modern, modular, open, fast community stellar evolution code
MESA: modules for experiments in stellar evolution

A new, modern, modular, open, fast community stellar evolution code

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★ Jon Tomshine
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Some features:
• versatile compilation of EOS, allowing VLM stars, brown dwarfs, degenerate stars
• full coupling of mixing, burning and structure operators
• both hydrodynamic and hydrostatic option
• range of networks, including those needed for massive star collapse
• convection MLT (different versions), overshooting, Ledoux criterion, semi-convection
• mass transfer, accretion, mass loss, binary stars (Roche Lobe overflow)
• several atmosphere options, including atmosphere tables, e.g. from Phoenix code
• verified (as in code comparison with established research codes) for low mass stars, the sun, advanced phases (AGB), massive stars, including nucleosynthesis predictions
• passed Stellar Code Calibration (Achim Weiss etal) project test cases
• individual module level verification for eos, kap, atm, mlt by running in DSEP code and EVOL code
• diffusion/gravitational settling via Thoul et al. (1994); recently verified against VandenBerg’s code with diffusion treated according to Michaud & Proffit.
• pulsation module (LAWE according to Jørgen Christensen-Dalsgaard’s ADIPLS, 1997)
• thermohaline mixing
• compatible with NuGrid nucleosynthesis codes.
NuGrid: Nucleosynthesis for a wide range of (M,Z)

A new, parallel, comprehensive nucleosynthesis code for large-scale post-processing computations

The PPN code

- physics package
- solver package

1 nuclear network time step

There are three drivers that use the same physics/solver package:

- SPPN: Single-zone Post-Processing Network
- MPPN: Multi-zone Post-Processing Network
- TPPN: Trajectory Post-Processing Network
NuGrid: Nucleosynthesis for a wide range of (M,Z)

Application examples

25M\textsubscript{sun} nucleosynthesis
NuGrid: Nucleosynthesis for a wide range of (M,Z)

Application examples

2.0$M_{\text{sun}}$ nucleosynthesis

Cycle=0032010, Mass=0.189E+01, Age=0.153E+10, $T_{9,\text{max}}=0.183E+00$, proc. shells=853
NuGrid: Nucleosynthesis for a wide range of (M,Z)

Application examples

2.0\(M_{\odot}\) nucleosynthesis
NuGrid: Nucleosynthesis for a wide range of \((M,Z)\)

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★ JINA
Multi-dimensional stars

Convection (vs. secular instabilities) of the stellar interiors:

α_{MLT} is different in different convection zones


ii. “Abundances in intermediate-mass AGB stars undergoing third dredge-up and hot-bottom burning” McSaveney, J. A.; Wood, P. R.; Scholz, M.; Lattanzio, J. C.; Hinkle, K. H., MN (2007) \( \alpha_{MLT} \sim 2.3 - 2.6 \)

iii. “Three-dimensional Simulations of Turbulent Compressible Convection”, Porter & Woodward (2000) \( \alpha_{MLT} \sim 2.68 \)
Multi-dimensional stars

Stellar interior simulations:

i. massive stars:
“Turbulent convection in stellar interiors”
Meakin & Arnett (2007)

ii.“The core helium flash revisited” Mocák et al
Multi-dimensional stars

He-shell flash convection

i. 2D and 3D plane-parallel box-in-a-star (Herwig et al. 2006)

2D entropy fluctuations (2400x800), realistic heating rate
Courant time scale at this resolution: \(\sim 3 \times 10^{-3} \text{sec} \rightarrow 1.6 \text{M cycles}\)

\[\text{lc0gi: time=4000 s } v_{\text{rms, max}}=14.4 \text{ km/s}\]

quantify “overshooting” - develop models for 1D stellar evolution (cf. Karakas et al. 2010.)

\[\text{k-}\omega \text{ diagrams for various heights of benchmark run lc0gg}\]
Multi-dimensional stars

Next generation He-shell flash convection

i. 3D $4\pi$ star-in-a-box simulations (e.g. Herwig et al. 2010, poster outside)

ii. compressible gas dynamics PPM code
   Paul Woodward (http://www.lcse.umn.edu)

iii. high accuracy PPB advection scheme

iv. 2 fluids, with individual, realistic material densities

v. $576^3$ cartesian grid, simulated time total 60ks

vi. $\text{Ma} \sim 0.03$, $1\text{l}H_p$ in conv. zone

abundance of H-rich material entrained from above into convection zone at $\sim 20\text{ks}$

Multi-dimensional stars

3D 4π star-in-a-box simulations

horizontal and vertical $v_{\text{rms}}$

comparison 1D and 3D averaged profiles
Multi-dimensional stars

3D 4π star-in-a-box simulations

How expensive is it? $576^3$ for 60ks (several M cycles):

- $18 \times 8 \times 10 \times 24 \approx 34,000$ CPU hrs
- factor 2 up in resolution = factor 8 in effort: $\approx 270,000$ CPU hrs for $1152^3$
- another factor 2 up: $2.2M$ CPU hrs
- another one up 17M CPU hrs ($4608^3$, corresponding to $\Delta r=6\text{km}, \Delta r_{\text{eff}}=3\text{km}$)

How does this compare to availability?
- 256 cluster: $2.2M$ CPU hrs
- regional facilities: $> \text{dozen CPU hrs}$
- peta-scale computing now deployed: $\approx 1,500 \text{ M CPU hrs}$
Applications of stellar evolution

• stellar populations
• first stars/near-field cosmology
• high-z Universe, especially AGB stars (e.g. how well can we describe C-star formation?)
• grains, nucleosynthesis
• SN progenitors
Adding another argument to the solar abundance puzzle:
Applications of stellar evolution

• first stars/near-field cosmology

![Graphs](image-url)
Applications of stellar evolution

• high-z universe, especially AGB stars (e.g. how well can we describe C-star formation?)

AGB Stars Have Huge Implications for Measuring Masses of High-z Galaxies

Melbourne et al (2010)
Marasont et al (2009)
Tonini et al (2009)