STARS: INTERNAL STRUCTURE AND EVOLUTION

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1- Introduction: objectives & tools
2- Stellar modeling: assumptions & equations
3- Observational constraints for stellar interior models
4- A few examples: Sun, binary stars, cluster stars, oscillating stars
5- Perspectives
STELLAR STRUCTURE & EVOLUTION: OBJECTIVES

STARS

\[ \Downarrow \]

EXTREME PHYSICAL CONDITIONS

\[ \Downarrow \]

MEANS to UNDERSTAND FUNDAMENTAL PHYSICS and VALIDATE THEORY

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STARS

\[ \Downarrow \]

ACTORS and TRACERS

\[ \Downarrow \]

MEANS to UNDERSTAND HISTORY and EVOLUTION of GALAXIES, & CONSTRAIN COSMOLOGY

- CHEMICAL EVOLUTION OF THE GALAXY, OF GALAXIES
  - helium abundance: from primordial helium abundance to present helium-metallicity relation?

- DYNAMICS OF THE GALAXY
  - stellar ages: thin and thick disc, bulge, halo

- COSMOLOGY
  - luminosity calibration and the distance scale
  - age of the oldest stars \[ \Rightarrow \] minimum age of the Universe
STELLAR STRUCTURE & EVOLUTION: TOOLS

STARS ➔ EXTREME PHYSICAL CONDITIONS + ACTORS and TRACERS

TOOLS

- theory, 2 & 3D (M)HD simulations
- astronomic observations
  - global parameters: \( L, R, M, T_{\text{eff}} \)
  - distances, surface abundances, \( v_{\text{ROT}} \)
- seismic: frequencies, amplitudes...
- laboratory experiments
  - high-energy-density facilities
  - particle accelerators
  - fluid experiments...

MODELING STARS: ASSUMPTIONS FOR STANDARD MODELS

SPHERICAL SYMMETRY

NEGLECT
EXTERNAL FORCES, ROTATION & MAGNETIC FIELDS

QUASI-STATIC EQUILIBRIUM

1-D DESCRIPTION ➔ variable: radius \( r \) or mass \( m = M(r) \) in sphere of radius \( r \)

4 EQUATIONS FOR STELLAR STRUCTURE +
N EQUATIONS for the TEMPORAL EVOLUTION of CHEMICAL COMPOSITION
STANDARD 1D-MODELS: INTERNAL STRUCTURE

4 EQUATIONS FOR STELLAR STRUCTURE (here written in Lagrangian form)

\[
\frac{\partial r}{\partial m} = -\frac{1}{4\pi r^2 \rho} \quad \text{mass conservation}
\]

\[
\frac{\partial P}{\partial m} = \frac{Gm}{4\pi r^4} \quad \text{hydrostatic equilibrium}
\]

\[
\frac{\partial L}{\partial m} = \epsilon_{\text{nuc}} - \epsilon_{\nu} + \epsilon_{\text{g}}
\]

\[
\frac{\partial T}{\partial m} = -\frac{GmT}{4\pi r^4 P} \nabla \quad \text{with} \quad \nabla = \frac{d \ln T}{d \ln P} \quad \text{energy transport}
\]

- 3 possibilities for energy transport:
  - transport by RADIATION, CONVECTION ➤ classical stars
  - transport by CONDUCTION ➤ important in dense degenerate media

\[
\nabla = \nabla_{\text{rad}} = \frac{3}{16\pi acG} \frac{\kappa LP}{mT^4} \quad \text{or} \quad \nabla = \nabla_{\text{conv}} \quad \text{or} \quad \nabla = \nabla_{\text{cond}}
\]

STANDARD 1D-MODELS: CONVECTIVE STABILITY

Gas blob accidentally displaced by \( dr \) upwards from equilibrium position

If the displacement over \( dr \) is \textit{adiabatic} & \textit{pressure equilibrium} is maintained

- the blob moves to lower pressures: it expands and cools off adiabatically
- at \( r+dr \): if the blob has a lower density than its surroundings the \textit{buoyancy} pushes it upwards: it continues to rise ➤ \textit{INSTABILITY}

\[
\text{SCHWARZSCHILD’s criterium (1906)}
\]

\[
\nabla_{\text{rad}} \geq \nabla_{\text{ad}}
\]

\[
\nabla_{\text{ad}} = 1 - \frac{1}{\Gamma_2} \quad \nabla_{\text{rad}} = \frac{3}{16\pi acG} \frac{\kappa LP}{mT^4}
\]

lower blob density ⇔ higher temperature
STANDARD 1D-MODELS: CONVECTIVE STABILITY

Gas blob accidentally displaced upwards from equilibrium position

➤ if the blob has a higher density than its surroundings restoring force (gravity) ➤ the blob will fall back: STABILITY

\[
N_{BV}^2 = g \left( \frac{1}{\Gamma_1} \frac{d\ln P}{dr} - \frac{d\ln \rho}{dr} \right)
\]

Brunt-Väisälä frequency

STANDARD 1D-MODELS: INTERNAL STRUCTURE

4 EQUATIONS FOR STELLAR STRUCTURE

\[
\begin{align*}
\frac{\partial r}{\partial m} &= -\frac{1}{4\pi r^2 \rho} \\
\frac{\partial P}{\partial m} &= Gm \\
\frac{\partial L}{\partial m} &= \epsilon_{\text{nuc}} - \epsilon_{\nu} + \epsilon_g \\
\frac{\partial T}{\partial m} &= -\frac{GmT}{4\pi r^4 P} \nabla \quad \text{with} \quad \nabla = \frac{d\ln T}{d\ln P}
\end{align*}
\]

mass conservation

hydrostatic equilibrium

energy conservation

energy transport

VARIABLES: \( P=P(m), r(m), L(m), T(m) \) pressure, radius, luminosity, temperature

BOUNDARY CONDITIONS:

center: \( m=0 \Rightarrow r=0, L=0 \)

surface: \( M=M_{\text{star}}-m_{\text{atm}} \Rightarrow \text{junction with a model atmosphere } m_{\text{atm}} \Rightarrow R_{\text{star}}, L_{\text{star}}, P_s, T_s \)

INITIAL CONDITIONS: \( M & X, Y, Z \); star assumed to be homogeneous
STANDARD 1D STELLAR MODELS: TEMPORAL EVOLUTION

**GRAVITATIONAL CONTRACTION**

\[ \frac{\partial L}{\partial m} = \epsilon_{\text{nuc}} - \epsilon_{\nu} + \epsilon_{g} \]

with \( \epsilon_{g} = -T \frac{\partial S}{\partial t} \)

**TEMPORAL EVOLUTION OF CHEMICAL SPECIES & MIXING**

\[ \left( \frac{\partial X_{i}}{\partial t} \right) = \left( \frac{\partial X_{i}}{\partial t} \right)_{\text{nucl}} + \left( \frac{\partial X_{i}}{\partial t} \right)_{\text{conv}} \]

\( i = 1, \ldots, I \)

**Creating and/or destruction by nuclear reactions**

\[ \left( \frac{\partial X_{i}}{\partial t} \right)_{\text{nucl}} = \frac{m_{i}}{\rho} \left( \sum_{j} r_{ji} - \sum_{k} r_{ik} \right) \]

**MIXING HOMOGENIZING CONVECTION ZONES**

Standard model treatment:

- Convection zone boundaries: Schwarzschild’s criterion
- Assumption: instantaneous mixing in turbulent convection zones

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STANDARD MODELS: INPUT PHYSICS - MICROSCOPIC & MACROSCOPIC PROCESSES

**Microscopic Processes**

<table>
<thead>
<tr>
<th>( \frac{\partial r}{\partial m} )</th>
<th>( \frac{\partial P}{\partial m} )</th>
<th>( \frac{\partial L}{\partial m} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( -\frac{1}{4\pi r^{2}\rho} )</td>
<td>( -\frac{Gm}{4\pi r^{4}} )</td>
<td>( \epsilon_{\text{nuc}} - \epsilon_{\nu} - \frac{T}{\partial t} \frac{\partial S}{\partial t} )</td>
</tr>
</tbody>
</table>

**CONVECTION ZONE BOUNDARIES**

\( \frac{\partial T}{\partial m} = -\frac{GmT}{4\pi r^{4}P} \nabla \) with \( \nabla = \nabla_{\text{rad}} = \frac{3}{16\pi a_{e}GmT^{4}} \) or \( \nabla = \nabla_{\text{conv}} \) or \( \nabla_{\text{cond}} \)

**\( \left( \frac{\partial X_{i}}{\partial t} \right)_{\text{nucl}} \)**

\[ \left( \frac{\partial X_{i}}{\partial t} \right)_{\text{nucl}} = \frac{m_{i}}{\rho} \left( \sum_{j} r_{ji} - \sum_{k} r_{ik} \right) \]

**Opacities, Equation of State**

- Radiative opacity, conduction, thermodynamical quantities

**Nuclear and Particle Physics**

- Nuclear reaction rates, neutrino losses

**Rather good knowledge**

Improvement still needed: Sun, cold or dense stars, advanced stages

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CONVECTION

description generally remains crude in stellar evolution codes but much progress in theory, 2-3D simulations

MIXING LENGTH THEORY (Böhm-Vitense 58), FST (Canuto & Mazitelli 91, 96)

phenomenology: l is the characteristic length (mixing-length), the gas blob rises through before it loses its identity and merges with the surroundings

it requires to fix/adjust the mixing-length parameter: α_{MLT}=l/H_p

NON STANDARD 1D STELLAR MODELS

INTRODUCE ROTATION, TRANSPORT PROCESSES

MICROSCOPIC ⇒ ATOMIC DIFFUSION

MACROSCOPIC ⇒ OVERSHOOTING, SEMICONVECTION

ROTATION, MAGNETIC FIELDS, INTERNAL GRAVITY WAVES

REQUIRES to MODIFY STELLAR STRUCTURE EQUATIONS

centrifugal force modifies equation of hydrostatic equilibrium...

ADD TERMS in the EQUATIONS for EVOLUTION of CHEMICALS

ADD EQUATION for TRANSPORT of ANGULAR MOMENTUM

etc.
NON STANDARD 1D STELLAR MODELS

TRANSPORT OF ANGULAR MOMENTUM

CURRENT TREATMENT: ≠ transport processes related to differential rotation

- large scale meridional circulation ⇒ advection of angular momentum
- hydrodynamical (shear) instabilities ⇒ diffusion of angular momentum

ASSUMPTION: highly anisotropic turbulence: \( D_h \gg D_v \)

shellular rotation \( \Omega(r, \theta) = \Omega(r) \)

see lecture by S. Talon, 2007

\[
\frac{d}{dt} \left[ r^2 \Omega \right] = \frac{1}{5r^2} \frac{\partial}{\partial r} \left[ \rho r^4 \Omega u \right] + \frac{1}{r^4} \frac{\partial}{\partial r} \left[ \rho \nu_v r^4 \frac{\partial \Omega}{\partial r} \right]
\]

- \( u \) ⇒ vertical component of the meridional circulation velocity
- \( \nu_v = D_v \) ⇒ vertical component of the turbulent viscosity

formalism: Zahn 92, Maeder & Zahn 98 ; coefficients: Zahn 74, Maeder & Meynet 96, Talon & Zahn 97

BUT role of magnetic field, role of internal gravity waves ??? not clear

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NON STANDARD 1D STELLAR MODELS

TRANSPORT OF CHEMICAL SPECIES & MIXING

\[
\left( \frac{\partial X_i}{\partial t} \right) = \left( \frac{\partial X_i}{\partial t} \right)_{\text{nuc}} + \left( \frac{\partial X_i}{\partial t} \right)_{\text{conv, diff}} \quad i = 1, \ldots, I
\]

SEAT in CONVECTIVE ZONES, RADIATIVE ZONES and THEIR INTERFACES

CONVECTIVE ZONES + RADIATIVE/CONVECTIVE ZONES INTERFACES

\[
\left( \frac{\partial X_i}{\partial t} \right)_{\text{conv}} = \frac{\partial}{\partial m} \left( 4\pi r^2 \rho \right)^2 D \frac{\partial X_i}{\partial m}
\]

CONVECTIVE MIXING MAY BE TREATED AS A DIFFUSIVE PROCESS \( (D=10^{13} \text{ cm}^2.\text{s}^{-1}) \)

EXTRA MIXING DUE TO OVERSHOOTING, SEMICONVECTION

crude modeling BUT progress in theory, numerical simulations

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OVERSHOOTING OF CONVECTIVE CORES

2D hydrodynamic simulations,
2.25 $M_\odot$ on the MS, Deupree 00

Schwarzschild: $a=0$

overshooting: $v=0$

CRUDE MODELING: OVERSHOOTING DISTANCE $l = \alpha_{OV} H_p$ ($\alpha_{OV}$ to be adjusted)

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SEMI-CONVECTION

composition gradient
receeding convective core

CONVECTIVELY UNSTABLE LAYER
➤ SLOW MIXING

NO SATISFACTORY TREATMENT ➤ OFTEN NEGLECTED

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NON STANDARD STELLAR MODELS

TRANSPORT OF CHEMICAL SPECIES & MIXING

RADIATIVE ZONES

\[
\left( \frac{\partial X_i}{\partial t} \right) = \left( \frac{\partial X_i}{\partial t} \right)_{\text{nucl}} + \left( \frac{\partial X_i}{\partial t} \right)_{\text{diff}} \quad i = 1, \ldots, I
\]

\[
\left( \frac{\partial X_i}{\partial t} \right)_{\text{diff}} = \frac{\partial}{\partial m} \left( 4\pi r^2 \rho V_i X_i \right) + \frac{\partial}{\partial m} \left( (4\pi r^2 \rho)^2 D_{\text{tot}} \frac{\partial X_i}{\partial m} \right)
\]

ATOMIC DIFFUSION ➤ (SLOW) TRANSPORT of CHEMICALS resulting from

1) PRESSURE (GRAVITATIONAL SETTLING), TEMPERATURE, CONCENTRATION GRADIENTS included as standard process in much codes for solar model uncertainties in diffusion velocities \(V_i\)

2) RADIATIVE FORCES included in the Montreal code, other codes: in progress

theory: Burgers 69, Chapman & Cowling 70
formalism to include in models: Michaud & Proffitt 93, Thoul et al. 94

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NON STANDARD STELLAR MODELS

TRANSPORT OF CHEMICAL SPECIES & MIXING

RADIATIVE ZONES

\[
\left( \frac{\partial X_i}{\partial t} \right) = \left( \frac{\partial X_i}{\partial t} \right)_{\text{nucl}} + \left( \frac{\partial X_i}{\partial t} \right)_{\text{diff}} \quad i = 1, \ldots, I
\]

ROTATIONAL MIXING ➤ MERIDIONAL CIRCULATION + SHEAR INSTABILITIES ➤ vertical transport

diffusion equation

\[
\left( \frac{\partial X_i}{\partial t} \right)_{\text{diff}} = \frac{\partial}{\partial m} \left( (4\pi r^2 \rho)^2 D_{\text{tot}} \frac{\partial X_i}{\partial m} \right)
\]

formalism: Chaboyer & Zahn 92,
coefficients: Zahn 92, Chaboyer & Zahn 92, Maeder & Meynet 96, Talon & Zahn 97, Maeder 03, Mathis & Zahn 04,

still under validation, many assumptions parallel progress in theory, 2-3D simulations, laboratory experiments

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OTHER PROCESSES...

- MASS LOSS
- ACCRETION
- PERTURBATION by a COMPANION...

MULTI-DIMENSIONAL STELLAR EVOLUTION CODES

ESTER PROJECT: 2D STELLAR EVOLUTION CODE INCLUDING ROTATION
Rieutord et al. 05

presently: polytropic rotating models

DJEHUTY: A 3D STELLAR EVOLUTION CODE
Turcotte et al 01, Lattanzio et al 06

- FULLY EXPLICIT HYDRODYNAMICS CODE
  suited to evolutionary calculations on the shortest timescales

  first application: calculation of the core helium flash
STELLAR MODELS: INTERFACES

INTERFACES : INTERIOR-ATMOSPHERE-ISM

➤ MODEL ATMOSPHERES provide boundary conditions for the interior model

standard stellar models often based on very simple atmospheres:
➤ assumptions: radiative equilibrium, 1D, grey atmosphere...

\[
\kappa_\nu \equiv \kappa \\
T^4(\tau) = \frac{3}{4} T_{\text{eff}}^4 (\tau + q(\tau)) \\
L = 4 \pi R^2 \sigma T_{\text{eff}}^4 \\
d\tau = -\kappa \rho \, dr
\]

or include results (T- \tau laws) from 1D model atmospheres
➤ Kurucz’s ATLAS models
➤ MARCS, PHOENIX model atmospheres...

OBSERVATION PROVIDES INPUTS/CONSTRAINTS for MODELS

BUT FUNDAMENTAL PARAMETERS HAVE TO BE EXTRACTED FROM OBSERVATIONS

NOT STRAIGHTFORWARD, FOR INSTANCE...

➤ ASTROMETRIC MEASUREMENTS \Leftrightarrow \ldots \Leftrightarrow DISTANCES
+ ADDITIONAL OBSERVATIONS: PHOTOMETRY, SPECTROSCOPY, INTERFEROMETRY...
+ (MODEL ATMOSPHERES)
\Leftrightarrow \ldots \Leftrightarrow LUMINOSITIES, MASSES, RADI

➤ OBSERVED SPECTRA
+ MODEL ATMOSPHERES \Leftrightarrow \ldots \Leftrightarrow T_{\text{eff}}, ABUNDANCES, GRAVITY, VELOCITIES...

MODEL ATMOSPHERES are CRUCIAL! NEXT LECTURE by A. KORN...

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BEST OBSERVATIONS: SMALL INTERNAL ERRORS but SYSTEMATIC ERRORS!

GOOD ACCURACY for a number of A-K DWARFS & GIANTS

- $\sigma_\pi / \pi < 10\%$
- $\sigma_{F_{bol}} / F_{bol} \sim 2\%$
- $\sigma_{T_{eff}} \sim 50-100$ K
- $\sigma_{[Fe/H]} \sim 0.02-0.10$ dex
- $\sigma_{\text{mass}} \sim 1-2\%; \sigma_{\text{radius}} \sim 1-2\%$
- Seismic data (frequencies, amplitudes)

$2 \times 10^4$ stars: astrometry with Hipparcos

$5 \times 10^2$ stars: multicolor photometry

$10^3$ stars: IRFM, SBM, SEDF, spectroscopy

$10^5$ stars: spectroscopy, photometry

$10^2$ stars: spectro, photometry, interferometry

Sun + a few stars: spectroscopy, photometry

BUT LARGER ERRORS FOR COOL and HOT STARS ... AND SYSTEMATIC ERRORS

for instance...

ABUNDANCES & $T_{eff}$-SCALE

- Cool giants - metal poor dwarfs $\Rightarrow$ [Fe/H]: typ. 0.2-0.3 dex - $T_{eff}$: 200-400 K

BOLOMETRIC CORRECTIONS, COLOR-TEMPERATURE CONVERSIONS...

$\Rightarrow$ Robichon et al 99, Lebreton 00, Gustafsson 04, Vandenberg 05, Allende Prieto 06, etc.

CONFRONTING MODELS with the BEST OBSERVATIONS $\Rightarrow$ CALIBRATORS

CALIBRATORS = RELATIVELY FEW STARS

$\Rightarrow$ strong/complete observational constraints $\Rightarrow$ LEARN on the PHYSICS

- Sun, close single/binaries, stars in clusters, oscillating stars...

... FROM CALIBRATORS TO OTHER STARS

ALL STARS

$\Rightarrow$ few, less accurate data $\Rightarrow$ FIND AGES, HELIUM ABUNDANCE, DISTANCE SCALE...

$\Rightarrow$ apply knowledge from calibrators (theoretical/empirical)

$\Rightarrow$ correct for $\neq$ composition, mass, evolution stage
Oscillations now seen in many different types of stars:
solar-type, delta Scuti, β Ceph, γ Dor, Cepheids, RR Lyrae, SPB, WD etc.
detection: photometry (intensity changes); spectroscopy (changes in $v_{\text{rad}}$ or eq. widths)
nature: acoustic p-modes, gravity g-modes
depending on mass, evolutionary state, composition, excitation mechanism

Solar-like oscillations observed in several main sequence, subgiants, giant stars
**Critical Acoustic Frequency (Lamb)**

\[
S_l^2 = \frac{\ell (\ell + 1) c^2}{r^2}
\]

- characterizes medium compressibility
- \( S_l^2 \): time it takes a sound wave to travel a characteristic distance (√(λ/2π)).

**Buoyancy (Brunt-Väisälä Frequency)**

\[
N_{BV}^2 = g \left( \frac{1}{\Gamma_1} \frac{d \ln P}{dr} - \frac{d \ln \rho}{dr} \right)
\]

- \( N_{BV}^2 > 0 \): radiation
- \( N_{BV}^2 < 0 \): convection

In a convectively stable medium (\( N_{BV}^2 > 0 \)), \( N_{BV} \): frequency of oscillation associated with a perturbed parcel of fluid.

**Different Waves** can propagate depending on the value of \( nlm \)

- \( nlm > N_{BV}^2, S_l^2 \)
  - **Standing Sound Waves**
  - **Acoustic p-Modes**

- \( nlm < N_{BV}^2, S_l^2 \)
  - **Standing Gravity Waves**
  - **Gravity g-Modes**

**Calibrators: Seismic Data and Related Constraints**

- SOLAR INTERIOR
  - propagation of acoustic waves

- \( l = 0, 2, 20, 25, 75 \); \( v = 3 \text{ mHz} \)

**Spherical Symmetry:** \( nlm \) independent of \( m \) ➔ **rotation lifts degeneracy** \( nlm (\Omega) \)
SEISMIC DIAGNOSTICS BASED on FREQUENCIES or their COMBINATION

SUN: A LOT OF OSCILLATION MODES ARE OBSERVED (>10^5 eigenmodes)

> INVERSION of OSCILLATIONS

SOUND SPEED, DENSITY, ROTATION PROFILE

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SUN: SOUND SPEED PROFILE

\[
c = \left( \frac{\partial P}{\partial \rho} \right)_{\text{ad}}^{1/2} = \left( \frac{\Gamma \mu P}{\rho} \right)^{1/2} \propto \left( \frac{T}{\mu} \right)^{1/2}
\]

from data by Basu et al. 00

VERY ACCURATE OUTPUTS:
CONVECTION ZONE DEPTH, HELIUM ABUNDANCE...

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SEISMIC DIAGNOSTICS BASED on FREQUENCIES or their COMBINATION

SOLAR-LIKE OSCILLATORS: a few low degree p-modes are observed

frequencies may be combined ⇒ exemple: large & small frequency separation

\[
\Delta \nu_{n,l} = \nu_{n,l} - \nu_{n-1,l}
\]

\[
\delta \nu_{n,l} = \nu_{n,l} - \nu_{n-1,l+2}
\]

sound speed travel time from centre to surface
⇒ sensitive to stellar density ⇒ mass

integral of the sound speed gradient weighted by (1/r)
⇒ sensitive to core structure ⇒ age
SEISMIC DIAGNOSTICS BASED on FREQUENCIES or their COMBINATION

SOLAR-LIKE OSCILLATORS: a few low degree p-modes are observed

frequencies may be combined ⇒ exemple: large & small frequency separation

OUTPUTS:
- MASS, AGE,...

BUT the ANALYSIS REQUIRES ACCURATE CLASSICAL DATA
- PARALLAX, magnitude
- [Fe/H], $T_{\text{eff}}$...

GAIA,...

Christensen-Dalsgaard, 88, 93

THE SOLAR MODEL CALIBRATION

INPUT PARAMETERS
- OBSERVATIONAL CONSTRAINTS
  - SOLAR MASS + AGE
- CHOSEN INPUT PHYSICS

OUTPUTS at SOLAR AGE
- OBSERVATIONAL CONSTRAINTS
  - SOLAR LUMINOSITY + RADIUS
  - $(Z/X)$ PHOTOSPHERIC VALUE
  - DETAILED ELEMENT MIXTURE

TO BE ADJUSTED:
- INITIAL HELIUM ABUNDANCE + INITIAL $(Z/X)$ VALUE
- MIXING-LENGTH PARAMETER

OUTPUTS of the MODEL WITH CALIBRATED VALUES of INITIAL $Y$, $(Z/X)$ and $\alpha_{\text{MLT}}$

TO BE COMPARED WITH ALL OTHER OBSERVATIONAL CONSTRAINTS
- SOUND SPEED PROFILE, DEPTH & HELIUM in OUTER CONVECTION ZONE, etc.

SHOWS WHETHER THE INPUT PHYSICS IS SUITABLE OR NOT
BINARY SYSTEMS CALIBRATION

MODELS INPUT PARAMETERS

- OBSERVATIONAL CONSTRAINTS
  - Masses \( M_A, M_B \)
- CHOSEN INPUT PHYSICS

OUTPUTS at PRESENT AGE

- OBSERVATIONAL CONSTRAINTS
  - Luminosities \( L_A, L_B \), Radii \( R_A, R_B \),
  - \( T_{\text{eff},A}, T_{\text{eff},B} \), \( \log g_A, \log g_B \), \([\text{Fe}/\text{H}]_A, B\),
  - \([\alpha/\text{Fe}]_A, B\), Seismic Data (\( \Delta \nu, \delta \nu \)...

THE MORE NUMEROUS and ACCURATE CONSTRAINTS, THE MORE PARAMETERS CAN BE ADJUSTED

- System age, initial helium abundance, initial \((Z/X)\)
- Physical parameters: mixing-length, overshooting...

THE CALIBRATION METHOD and OUTPUTS DEPEND ON THE PARTICULAR SYSTEM STUDIED (mass & evolutionary stage, number and quality of observational constraints...)

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CALIBRATORS - SUN: AGS05 MIXTURE, SISMOLOGY and SOLAR MODEL

REVISION OF SOLAR PHOTOSPHERIC ABUNDANCES

- 3D radiative-hydrodynamics model atmospheres, NLTE effects
- C, N, O, Ne, Ar to 30-40%, \( Z_\odot \approx 0.0173 \rightarrow 0.0122 \)

Asplund et al 05, Allende Pietro, Grevesse et al 07

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MAIN EFFECT

- DECREASE of THE OPACITY
  - SOLAR MODEL NO MORE SATISFIES HELIOSEISMIC CONSTRAINTS
    - Convection zone depth & helium
    - Sound speed, density profiles...

Bahcall et al 04, Montalban et al 04, Turck Chièze et al 04, Basu et al, Antia et al...
PROBLEMS where $r/R \in [0.3,0.7]$:
below the convective zone:
tachocline and radiative region

BAD PHYSICS in RADIATIVE ZONE?

OPACITIES? uncertainties remain
but OPAL vs. OP: 2% (Badnell 05)
testable in the future with lasers

ATOMIC DIFFUSION COEFFICIENTS?
$V_{\text{diff}}$ for O, Fe uncertain by ~35%
but it’s not enough
Montalban et al 06

MISSING PROCESSES?
convective penetration?
Zahn 07

$\text{BAD PHYSICS in RADIATIVE ZONE?}$

$\text{NEON} \Rightarrow$ many determinations
$\odot$ corona, SW, SEP, active stars...

$\text{NO DEFINITE ANSWER} \text{ Grevesse et al. 07}$

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MODEL 2 STARS in a BINARY SYSTEM ASSUMING SAME AGE, INITIAL ABUNDANCES

THE SB2/EB BINARY SYSTEM RS CHA: 2 A-stars, PMS, metal rich, oscillations

NEW OBSERVATIONS: accurate masses, radii, [Fe/H] (Alecian et al. 05)

MODELING: no agreement with GN93 $\odot$ mixture even if reasonable changes in physics

agreement requires a DECREASE of C, N abundances to delay onset of convective core

AMONG OTHERS, THE AGS05 MIXTURE MAKES IT (Alecian et al. 06,07)
CALIBRATORS - RS CHA BINARY SYSTEM: AGS05 MIXTURE and MODELS

QUALITY OBSERVATIONS BRING CONSTRAINTS for the MODELS

BUT WEAKNESSES

[Fe/H] ➔ 1D model atmosphere ⇒ differences between 3D/1D for α Cen A, Bigot et al. 07

need for detailed mixture: C, N, O...

oscillation data scarce ⇒ but new observations have just been made, Böhm et al. 07

OUTPUTS NOT FIRM: AGE=9.13 ± 0.13 Myr, INITIAL HELIUM ABUNDANCE Y=0.255

MORE GENERALLY, TO GET VALUABLE INFORMATION (physics, astrophysics), WE NEED

⇒ AT LEAST VERY ACCURATE CLASSICAL DATA

L, T_eff, M, R, abundances (individ. elements)

parallax, magnitude,[Fe/H], T_eff ➔ GAIA,...

⇒ IDEALLY SEISMIC DATA

CALIBRATORS - STARS in OPEN CLUSTERS: HYADES ⇒ AGE, HELIUM

STARS in an OPEN CLUSTER: SAME AGE, INITIAL COMPOSITION, DIFFERENT MASSES

HYADES DATA after Hipparcos: the only cluster with individual distances to ≈ 100 members

π, B, V, [Fe/H]: σ_π/π ≈ 2.5%, σ_B~V=0.05 mag, σ_[Fe/H]=0.01 mag, σ_[Fe/H]=0.05 dex

FIT of the H-R DIAGRAM

⇒ PARALLAX, colors/T_eff [Fe/H]⇒ GAIA

WHAT CAN WE INFERENCE?

HELIUM ⇒ lower MS position

AGE ⇒ turn-off position

BUT

Y-[Fe/H] degeneracy

physics not well-known

⇒ convection & overshooting

⇒ rotational mixing, ...
CALIBRATORS - BINARIES in OPEN CLUSTERS ⇝ HYADES, PLEIADES

MASS-LUMINOSITY/MASS-RADIUS PLANES: CAN WE GET MORE?

HELUM
FROM LOW MASS UNEVOLVED MEMBERS
HIGH ACCURACY REQUIRED
ON LUMINOSITY
ON MASS (<-1%)
ON [Fe/H] ➞ Y-[Fe/H] degeneracy
⇒ ΔY/Δ[Fe/H]=0.3

CONSTRAINTS ON PHYSICS
POSSIBLE BUT NEEDS SEVERAL BINARIES SPANNING A LARGE MASS RANGE
STILL NOT AVAILABLE

HYADES DATA:

vB22 (SB2/EB) : σM/M, σR/R<1%
4 SB2 SYSTEMS : σM/M=5-25%

CALIBRATORS in the NEXT DECADE: HELIUM from SEISMIC DATA

HELUM in CONVECTION ZONE ➞ He⁺ ionisation ➞ Γ₁ depression ➞ when Y ➞ affects acoustic modes ➞ sismic analysis ➞ ΔY_CZ=0.01-0.02 for M : 0.8→1.4 M☉

REQUIREMENTS:

ACCURATE SEISMIC AND CLASSIC DATA:
- LOW DEGREE p-MODES, l=0-3; σν/ν=10⁻⁴
- MASS or RADIUS ➞ binaries, HRA

BUT! Y_CZ≠ Y_initial ➞ TRANSPORT PROCESSES
ATOMIC DIFFUSION, ROTATIONAL MIXING...

SEISMOLOGY CAN/WILL ALSO PROVIDE

CONVECTION ZONE BOUNDARY, COMPOSITION, MASS (Mazumdar et al. 02,, Piau et al. 04)

Y. Lebreton
MIXED CORE SIZE ⇒ determines STRUCTURE & available FUEL ⇒ \( L, T_{\text{eff}}, \text{AGE} \)

\[ R_{\text{mixed}}? \]

2/3D MAGNETO HYDRODYNAMIC SIMULATIONS of STELLAR CORES
nonlinear convection + rotation + magnetism

SHOW:
PROLATE SHAPE, DIFFERENTIAL ROTATION, CONVective OVERSHOOTING

BUT TODAY NO FULL SATISFACTORY HYDRODYNAMICAL DESCRIPTION

CURRENT MODELING of OVERSHOOTING:
\[ R_{\text{mixed}} = R_{\text{Schwarzschild}} + \alpha_{ov} H_D \] but \( \alpha_{ov} \) (mass, composition, age) ???

EMPIRICAL CALibrATIONS: MS WIDTH, BINARIES, THEORY
▷ order of magnitude of core extent + possibility of a METALLICITY DEPENDANCE

Zahn 91, Kuhfuß 86, Roxburgh 89, Ribas et al 00, Cordier et al 01, Young et al 02

CURRENT MODELING of ROTATION:
MAINLY 1D MODELING, assuming SHELLULAR ROTATION \( \frac{\Omega}{\Omega} = \Omega(r) \)

THEORY:
ROTATION ▷ large scale meridional circulation, shear-induced turbulence,...
▷ MACROSCOPIC TRANSPORT OF ANGULAR MOMENTUM AND CHEMICALS

SEVERAL DIFFERENT TREATMENTS/ASSUMPTIONS
Zahn 92-07, Maeder 98-07, Talon 97-07, Meynet 00-07, Mathis 04-07, Palacios 04-07...
DIFFICULTIES: INTERNAL MIXING → OVERSHOOTING, ROTATION...

MODELS INCLUDING OVERSHOOTING and/or ROTATION

OVERSHOOTING and ROTATION

MODIFY

CHEMICAL COMPOSITION PROFILES

&

TRACKS/ ISOCHRONES/ STELLAR POSITION

DISTINCT PROCESSES

but SIMILAR SIGNATURES in the HRD

→ HOW TO DISCRIMINATE ?

→ UNCERTAINTY on AGE ?

DIFFICULTIES: INTERNAL MIXING

OVERSHOOTING, ROTATION, ...

Goupil & Talon 02

ROTATIONAL MIXING or OVERSHOOTING?

DIFFERENT PROFILES of \( \nabla \mu \)

DIFFERENCES in OSCILLATION FREQUENCIES

(low degree, low frequencies mixed and g modes)

SEISMIC ANALYSIS of \( \delta \) Scuti

ALLOWS to PROBE the CORE

\( \nabla \mu \),

size of mixed region...

REQUIREMENTS:

ACCURATE SISMIC + CLASSIC DATA

PARALLAX, ABUNDANCES

Goupil & Talon 02

Y. Lebreton

ELSA School - Leiden 10-19-07

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CALIBRATORS in the NEXT DECADE - A-F STARS : AGE & MIXING

A-F STARS: CONVECTIVE CORES - ROTATORS - OSCILLATORS: δ Scuti instability strip

AGE of a TYPICAL A-F STAR

AT PRESENT
at $d = 200$ pc $\sigma_\nu / \pi = 10\%$
$\alpha_{OV} = 0.20 \pm 0.15 \Rightarrow \Delta \alpha / \alpha = 75\%$
$\Rightarrow \Delta \text{age}(\alpha_{OV}) = 13-24\%$

MICRO ARC SECOND ASTROMETRY
at $d = 1$ kpc $\sigma_\nu / \pi = 0.5\%$
$\Delta L / L < 2\% + \sigma_\nu = 0.1 \mu$Hz $\Rightarrow$
$\Delta \alpha_{OV} = \pm 0.03 \Rightarrow \Delta \alpha / \alpha = 15\%$
$\Rightarrow \Delta \text{age}(\alpha_{OV}) = 3-5\%$

PRESENT STATE and FUTURE

CONFRONTATIONS between THEORY and OBSERVATION
major impact of atmosphere modeling + observed parameters accuracy

RECENT CONSIDERABLE PROGRESS for the SUN & other CALIBRATORS MODELS
BUT many models remain very uncertain : physics, boundary conditions...

HIGH QUALITY OBSERVATIONAL MATERIAL is REQUIRED ... and EXPECTED
OBSERVATIONS : WHAT is EXPECTED in the NEXT DECADE?

- MOST MASSES/EVOLUTION STAGES will be UNPRECEDENTEDLY DOCUMENTED
- ENLARGED SAMPLES of FIELD STARS & OPEN & GLOBULAR CLUSTERS

ASTROMETRY: GAIA, SIM...

GAIA: all kinds of stars, all populations even rare or particular objects
high accuracy for $\mu$, $\pi$, $V$, flux, $T_{\text{eff}}$, $M$, [Fe/H]
7 $10^5$ stars $\Rightarrow \sigma/\pi \leq 0.1$
120 open clusters: $\sigma_{m-M, G<15} \leq 0.02$ mag $\Rightarrow$ 1kpc; $\sigma_{m-M} \leq 0.01$ mag
17 000 binaries $\Rightarrow \sigma/M \leq 1\%$; $\sim 10$ binaries/cluster
a lot of halo subdwarfs and subgiants, globulars: $\sigma/\pi = 10\%$ for 20 GC

INTERFEROMETRY, HIGH RESOLUTION SPECTROSCOPY

VLT- VLTI, JWST...

SEISMOLOGY: MOST, CoRoT, Kepler,... SIAMOIS, SONG, PLATO

2006: CoRoT seismology $\Rightarrow$ 50 main targets
2008: Kepler seismology $\Rightarrow$ $10^5$ stars

COROT TARGETS

- 50 MAIN TARGETS $\Rightarrow$
solar-like, $\delta$ Scuti, $\beta$ Cephei, giants
5 Long Runs are planned, $T = 150$ days each
$\sigma_V = 0.1$ $\mu$Hz to $0.5 -1$ $\mu$Hz
CONFRONTATIONS between THEORY and OBSERVATION
major impact of atmosphere modeling + observed parameters accuracy

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HIGH QUALITY OBSERVATIONAL MATERIAL is REQUIRED ... and EXPECTED

PARALLEL FONDAMENTAL IMPROVEMENTS ALSO REQUIRED
- theory, hydrodynamic simulations, laboratory experiments

LABORATORY: HIGH-ENERGY-DENSITY FACILITIES

ZONE UNDER REACH of the
NEXT GENERATION of
INTENSE LASERS
LMJ, NIF

BETTER
OPACITIES
THERMONUCLEAR
REACTIONS
EQUATION of STATE
In the future high quality spectra will have to be analysed

Several 2 & 3D atmosphere codes are being developed/improved

(magneto)hydrodynamics simulations/ LTE $\rightarrow$ NLTE: convection, shocks, oscillations

Stein, Nordlund, Asplund, Allende Prieto Freitag, Steffen, Ludwig, Khochukov, Bigot et al., etc.

SUN

A star

Betelgeuse

NEXT LECTURE by A. KORN...