Challenges in Solar and Stellar Model Physics

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50 Years of Seismology of the Sun and Stars

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Stars of nearly every evolutionary stage exhibit pulsations
This talk will focus on physics of lower main-sequence variables
Physics challenges

- Convection (mixing length+, semi-convection)
- Pulsation-convection interactions (time-dependence)
- Mixing processes (waves, shear, meridional circulation)
- Diffusion (thermal, chemical, gravitational); radiative levitation
- Magnetic fields
- Binarity, tidal effects
- Turbulent pressure and energy
- Oscillations, pulsations, waves (gravity, acoustic)
- Pulsation driving mechanisms (kappa effect, stochastic excitation, convective blocking, convective driving, epsilon mechanism)
- Adiabatic/nonadabatic
- Mode coupling, mode amplitudes (nonlinear effects)
- Viscosity (turbulent, molecular)
- Mass loss or accretion
- Rotation (differential, angular momentum transport)
- Dark matter

Core of 8.75 \( M_\text{sun} \) model + rotation (Deupree 1997)

Reese 2008
Input/databases

- Opacities (radiative, conductive, monochromatic, molecular)
- Equation of state (+relativistic effects, electron exchange, excitation as well as ionization, . . . )
- Diffusion coefficients
- Nuclear reaction rates (electron screening effects)

- Fundamental constants (G, sigma, solar mass, solar radius, . . . )
- Abundances and abundance mixtures
- Stellar atmosphere models

Fe concentration in 1.7 $M_{\text{sun}}$ model (Theado and Vauclair 2009)
Numerical challenges

- Disparate time and spatial scales for different processes
- 2D, 3D, zoning and rezoning, subgrid models
- Interpolation, extrapolation
- Timestep control (implicit, explicit)
- Eulerian, Lagrangian
- Boundary conditions (surface, center)
- Linear, nonlinear
- Viscosity treatment

Stein 1998

20 M$_{\text{Sun}}$ model

Shell H-burning

Smolec and Moskalik 2007

Deupree 2003
Observational tests and constraints

- Photometry (multicolor)
- Spectra (surface abundances and gravity, temperature, B fields, mass loss)
- Pulsation spectrum, amplitudes, variations with time
- Binaries (eclipsing)
- B fields, activity (spots, flares)
- Neutrinos

Spaceweather.com

Debosscher et al. 2011
A few challenges to consider

- Solar abundance problem; using solar models to examine physics
  - Mass loss, electron screening, dark matter
- Hybrid gamma Dor/delta Scuti (and SPB/beta Cep) stars
  - Why so many?
  - Alternate pulsation driving mechanisms
- Why are all of predicted low-degree modes in delta Scuti stars not observed?
  - 4 CVn

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- What is the cause of low-metallicity in lambda Boo stars?
  - Diffusion/accretion vs. intrinsic low Z
- Constant stars that should be pulsating?
Surface composition of the Sun by mass

- 73.2% Hydrogen
- 25% Helium
- 1.8% Other Elements

Proportions of elements heavier than H and He:
- Oxygen
- Carbon
- Ne
- Fe
- Si
- Mg
- N
- S

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Asplund et al. (2005) element abundances are lower than Grevesse & Sauval (1998) determination

| Element    | Percentage Decrease | Asplund et al. (2005) | Grevesse & Sauval (1998) |
|------------|---------------------|-----------------------|--------------------------|
| Oxygen     | 48% decrease        | 8.66 ± 0.05           | 8.83 ± 0.06              |
| Carbon     | 35% decrease        | 8.39 ± 0.05           | 8.52 ± 0.06              |
| Nitrogen   | 27.5% decrease      | 7.78 ± 0.06           | 7.92 ± 0.06              |
| Neon       | 74% decrease        | 7.84 ± 0.06           | 8.08 ± 0.06              |
| Argon      | 66% decrease        | 6.18 ± 0.08           | 6.40 ± 0.06              |

Na to Ca: lower by 0.05 to 0.1 dex (12 to 25%) (1D NLTE corrections)

Fe: 7.45 ± 0.05 (cf GS98 7.50 ± 0.05) 12% decrease

Revised mass fraction of ‘metals’ at Sun’s surface (Z) is only 0.0122 (instead of 0.018)
AGS05 abundances destroy the (possibly fortuitous) agreement with sound speed achieved with older abundances (The “solar abundance problem”)

Asplund, Grevesse, & Sauval 2005 mixture:

\[ R_{czb} = 0.7306; \]
\[ Y=0.227, Z=0.0124 \]

Grevesse & Noels 1993 mixture:

\[ R_{czb} = 0.7133; \]
\[ Y=0.242, Z=0.0181 \]
Observed - calculated frequency differences are smaller for old abundances

\[ \ell = 0, 2, 10, 20 \]

Observations from BiSON (Chaplin et al. 1998), LowL (Schou & Tomczyk 1996), or GOLF (Garcia et al. 2004)
Initial attempts to resolve solar abundance problem motivated us to reassess model physics

- Increased opacity below convection zone (11-20%)
  - (see, e.g., Serenelli et al., Monalban et al., Basu et al., Bahcall et al.)
- Increased abundances to upper uncertainty limits
- Increased Neon abundance (x 4)
  - see, e.g., Antia & Basu, et al., Bahcall et al, Turck-Chieze et al., Delahaye
    & Pinsonneault)
- Enhanced diffusive settling rates (x 1.5 or more)
  - see., e.g., Basu and Antia, Montalban et al., Guzik et al., Yang & Bi
- Accretion of lower-Z material at solar surface (Guzik; Castro et al.)
- Structure modification at CZ base from damping of gravity waves
  (Arnett et al.)
- Combinations of the above

It is difficult to match simultaneously new Z/X
and helioseismic constraints for
CZ helium abundance, CZ depth, & sound-speed profile
AGSS’09 abundances are a little higher than AGS’05, and mitigate disagreement.
Models with early mass loss were explored previously using the old higher abundances

Examined by Guzik, Willson & Brunish (1987), Swenson & Faulkner (1992), Guzik & Cox (1994), Sackmann & Boothroyd (2003) using old abundances.

Advantages
- Faint early sun problem, liquid water on Mars, early inner solar system bombardment
- Li destruction
- Solves some problems for other stars: Blue stragglers, early CN dredge-up on RGB

Disadvantages
- Too much mass loss destroys all surface Li
- Too much mass loss results in too much $^3$He at surface
- Too much mass loss gave discrepancy with seismology
We evolved mass-losing models with AGS05 abundances with initial masses 1.3 and 1.15 $M_{\text{sun}}$.

Mass-loss rate exponentially-decaying with e-folding time 0.45 Gyr.

Initial mass-loss rates 6.55 and 3.38 $\times 10^{-10}$ $M_{\text{sun}}$/yr.

Luminosities higher for the first 1-2 Gyr than for standard models.

Guzik and Mussack 2010
Early mass loss improves sound speed agreement for the new abundances

AGS05 Mixture model:

$R_{czb} = 0.7306$;
$Y=0.227, Z=0.0124$

Most extreme mass loss model:

$R_{czb} = 0.7195$;
$Y=0.233, Z=0.0131$
Unless mass is lost quickly, nearly all observed surface $^7$Li is destroyed

Temperature experienced by Li now present as surface vs. time.

Standard model surface layers do not reach 2.8 million K required for Li destruction
A small amount of mass loss improves small separations for AGS05 abundances

Data from BiSON 2007
Somewhat higher Caffau et al. ’08 or AGSS’09 abundances, + mass loss, improve agreement

![Graphs showing calculated vs observed frequency separations for different models and radial orders.](image)

1.1 $M_{\text{Sun}}$

Guzik and Mussack 2010
Generally, Salpeter’s approximation for screening is widely accepted.

Molecular dynamics simulations show that static screening is too high.

### Table: Electron Screening Treatment for Nuclear Reactions

| Case                  | $U_0(k_B T)$                  | Rate correction |
|-----------------------|-------------------------------|-----------------|
| Unscreened           | 0                             | 1               |
| Statically screened  | $-\left(Z Z_e e^2 / R_B\right) / k_B T$ | 1.05            |
| Dynamically Screened | $0.005 - 0.28 \left(\frac{E}{k_B T}\right)$ | 1               |

Mao, D. et. al. (2009)
Effects of screening for higher-mass or mass-losing solar models may be even larger

Wood, Guzik, Mussack 2011, 2013, in prep.
Dynamical screening improves small separation agreement for models with mass loss

Using dynamic screening + mass loss improves agreement in the core
Dark matter is predicted from current cosmological models

- Dark matter accounts for 23% of matter in the universe (dark energy 72%, baryonic matter only 5%)

- Various types of weakly interacting massive particles (WIMPs) proposed as the dark matter candidate

Could WIMPs have accumulated in the Sun, and would they have observable effects on solar structure?

(Some recent papers: Cumberbatsch et al. 2010; Turck-Chieze et al. ApJL 746 L12, 2012; Hamerly & Kosovichev ArXiv:111.1169 v1 6Oct 2012; More important in other stars? Iocco et al., PhysRvL108f301l, 2012)
We explored solar models with WIMP masses low enough and cross sections high enough to influence solar structure.

COUPP 2007 (purple)

PICASSO 2009 (blue)

upper limits
WIMPs are included in solar model by modifying the opacity

\[
\frac{1}{\kappa_{\text{total}}} = \frac{1}{\kappa_{\text{rad+cond}}} + \frac{1}{\kappa_{\text{WIMP}}}
\]

\( \kappa = \text{opacity (cm}^2/\text{g}) \)

\[
\frac{dT}{dT} = -\frac{3}{4ac} \frac{K}{T^3} \frac{L}{16\pi^2 r^4}
\]

WIMP energy transport is treated as a heat conduction process.
WIMPs orbiting through the center of the Sun and weakly interacting with matter transport energy from the inner to outer core.
WIMP energy transport produces a cooler isothermal core

Would change in temperature profile be detectable by pressure or gravity mode frequencies?

What effect does core temperature change have on solar neutrino output?

Lower-mass WIMPs have larger effect as they have larger orbits
Comparisons with inferred sound speed may rule out 5-10 GeV WIMP masses

Cumberbatch et al., *Light Wimps in the Sun: Constraints from Helioseismology*, Phys Rev D, 2010, http://arxiv.org/pdf/1005.5102v2
Small frequency separations may rule out 5-10 GeV strongly interacting WIMPS

\[ \ell = 0, 2 \]

Solar-cycle corrected frequency observations from BiSON (Chaplin et al. 2007)
Photometric and spectroscopic mode identifications obtained for highest-amplitude peaks (Castanheira et al. 2005)

18 modes observed; Breger et al. 1999

Dense frequency spectrum of stars with H-exhausted cores not observed

Predicted 336 \( \ell = 0, 1, 2 \) modes

18 modes observed; Breger et al. 1999
**B-V and Lamb frequencies determine cavities where modes propagate**

- Brunt Vaisalla (buoyancy) and Lamb (acoustic cutoff) frequency determine where p- and g-type nodes reside.

\[
N^2 = \frac{-g^2 \rho \chi_T}{P \chi_\rho} \left[ \nabla ad - \nabla + \frac{\chi_Y}{\chi_\rho} \left( \frac{d \ln Y}{d \ln P} \right) \right]
\]

- \( N = 0 \) in convection zones
- \( N \) high where steep composition gradients exist

\[
L^2 = \frac{l(l + 1)c^2}{r^2}
\]
For core H-exhausted delta Scuti stars, expect dense frequency spectrum with many g-type nodes.

4 CVn model: predict 332 $l=0$, 1, 2 modes.

Brunt-Vaissala frequency and $p_2$, $g_{25}$ eigenfunction vs. radius.

Growth rate per cycle

Frequency (cycles/day)

5/7/13
Could internal gravity modes cause mixing near convective core boundaries?

Most g modes are predicted to be stable, but damping rates are quite small for some (10^{-8} per period)

g modes could cause mixing of composition gradient outside convective core
4CVn models--extra mixing can extend core H burning phase and reduce number of predicted modes

Mixed model has
$X_{cc} = 0.0884$
$M_{cc} = 0.3738 \, M_{\odot}$
Age 1.6 Gyr

Normal model has
exhausted core H,
Age 0.878 Gyr

(Guzik et al. 2002, 2004)
**Number of predicted modes reduced significantly by extra mixing (to 30 from 332)**

|        | 2.05 $M_{\text{sun}}$ normal* | 2.50 $M_{\text{sun}}$ mixed |
|--------|-------------------------------|-------------------------------|
| $\ell = 0$ | 6 (6)                         | 1 (1)                         |
| $\ell = 1$ | 27 (81)                       | 3 (9)                         |
| $\ell = 2$ | 49 (245)                      | 4 (20)                        |

(Multiplied # modes by $2 \ell + 1$ to take into account rotational splitting)
Kepler light curve and periodogram for 50 days of data for KIC11445913
The δ Sct pulsations are driven by the ‘kappa’ effect from second ionization of He at about 50,000 K

[see J. P. Cox 1985; Chevalier 1971; Baker and Kippenhahn 1962]

$$\kappa \propto \frac{\rho}{T^3}$$

In ionizing region, temperature doesn’t increase much during compression as energy goes into ionization. Opacity therefore increases and heat is trapped.

The trapped heat produces relatively more pressure on expansion, ‘pumping’ the oscillations
The $\gamma$ Dor g modes can be driven by convective blocking at the base of the envelope convection zone

Luminosity fraction transported by radiation (red)

Work driving and damping (green)

Horizontal displacement (dashed black line)

$\gamma$ Dor g modes are driven best when T at convective envelope base is \( \sim 300,000 \) K

(Guzik et al. 2000; Dupret et al 2004, 2005)
Before Kepler, observations of gamma Dor and delta Scuti stars could mostly be explained by theoretical models.

Grigahcène et al. 2010; Uytterhoeven et al. 2011
Kepler data showed hybrid stars everywhere, and no clean separation by temperature.
Are there other pulsation driving mechanisms that could explain the hybrid behavior?

At summer 1999 Vienna and Budapest conferences, before γ Dor convective blocking mechanism was published, other driving mechanisms proposed:

- Convective driving at top of envelope convection zone, as in DA ZZ Ceti white dwarfs; see Wu & Goldreich; Goldreich & Wu 1999; Brickhill 1991
- Fe concentration due to settling and levitation, as in subdwarf O/B stars; see Turcotte et al. and Kaye et al. (2000): Richard et al. 2001 ApJ 558, 377; Theado & Vauclair 2009
- Interaction and phase offset between Fe and He ionization κ effect, plus open instead of reflecting surface boundary condition Gautschy & Loeffler 1996 DSN 10,13; Loeffler 1999 proceedings
- Stochastic excitation as in solar-like stars and red giants
Kepler first observed F4 V star (mag 4.48) \( \theta \) Cyg using a custom aperture June-Sept 2010

Data publicly available at http://keplergo.arc.nasa.gov/ArchivePublicDataThetaCygni.shtml (see also Haas et al. Seattle AAS 2011)
Power spectrum shows an excess in solar-like oscillation frequency range
11+ groups fit frequencies and produced $\theta$ Cyg echelle diagrams

Identified
20 $l=0$
20 $l=1$, and
20 $l=2$ modes

First Q6+Q8 result; Benomar January 2012
1.38 $M_{\text{sun}}$ (Z=0.017) and 1.29 $M_{\text{sun}}$ (Z=0.013) models were calculated to explore predictions for $\theta$ Cyg

- Z=0.017 (close to old solar GN93 abundance)
- Z=0.013 (close to new solar AGS05 abundance)
Pulsation analysis predicts one g mode for $1.38 \, M_{\text{sun}}$ model, but more g modes for $1.29 \, M_{\text{sun}}$ model

| T CZ base (K)       | $1.38 \, M_{\text{sun}}$ | $1.29 \, M_{\text{sun}}$ |
|---------------------|---------------------------|---------------------------|
|                     | 494,800                   | 456,600                   |
| Z                   | 0.017                     | 0.013                     |
| $\ell=1$ g modes    | $n = 22$                  | $n = 18$ to $25$          |
|                     | 0.77 days                 | 0.58 to 0.95 days         |
| $\ell=2$ g modes    | No unstable modes         | $n = 20$ to $28$          |
|                     |                           | 0.37 to 0.55 days         |
Models of θ Cyg with different mixing length and helium abundance can have very different CZ depths

\[ R = 1.51 R_\odot \quad M = 1.34 M_\odot \quad T_{\text{eff}} = 6650 \text{ K} \quad Z = 0.014 \]

| Model A | Model B |
|---------|---------|
| \( l=0 \) at \( \sim 1707 \mu \text{Hz} \) | \( l=0 \) at \( \sim 1748 \mu \text{Hz} \) |
| \( Y_{\text{init}} = 0.261 \) | \( Y_{\text{init}} = 0.247 \) |
| \( \alpha = 1.375 \) | \( \alpha = 1.84 \) |
| Age = 1.5 Gyr | Age = 2.1 Gyr |
| \( R_{\text{BCZ}} = 0.956 \) | \( R_{\text{BCZ}} = 0.898 \) |
| \( T_{\text{BCZ}} = 227,000 \text{ K} \) | \( T_{\text{BCZ}} = 540,000 \text{ K} \) |

Basu 2011
### Results from asteroseismic modeling portal (Metcalf) using Ligi et al. 2012 interferometric radius

\[
R = 1.503 \pm 0.007 \, R_\odot \quad L = 4.26 \pm 0.05 \, L_\odot
\]

| Scenario B                  | Scenario A                  |
|-----------------------------|-----------------------------|
| \( Y, Z = 0.267, 0.02168 \) | \( Y, Z = 0.285, 0.02239 \) |
| Mass= 1.45 \( M_\odot \); \( \alpha = 2.12 \) | Mass= 1.47 \( M_\odot \); \( \alpha = 1.18 \) |
| \( T_{\text{eff}} 6699 \, K, \, L = 4.21 \, L_\odot \) | \( T_{\text{eff}} 6846 \, K, \, L = 4.48 \, L_\odot \) |
| Age = 0.66 Gyr              | Age = 0.12 Gyr              |
| \( T_{\text{BCZ}} = 340,000 \, K \) | \( T_{\text{BCZ}} = 30,000 \, K \)

Diffusion nearly drains convection zone helium!
After removing 4 low frequencies, one low-frequency mode remains at 1.7 cycles/day (background binary?)

Four pre-whitened low frequency peaks

| freq d^{-1} | A mmag |
|-------------|--------|
| 0.0116000   | 1.159  |
| 0.0141000   | 0.307  |
| 0.0363000   | 0.105  |
| 0.0534000   | 0.076  |
New data from both ground and space observations (Kepler, CoRoT, . . .) are revealing new challenges to stellar model physics and providing new opportunities to test models.
Pressure (p) modes and gravity (g) modes travel in different regions of the stellar interior

(from Toomre 1984)
Because photometric variations are averaged over the (unresolved) stellar disk, pulsation amplitudes are most visible for degrees $\ell = 0, 1, 2$ modes (from Toomre 1984).