Solar models: Helioseismic comparisons vs. the solar neutrino problem

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Physics of Standard Solar Models

- **Opacities**

  OPAL (Iglesias & Rogers 1996); OP (Seaton 1996)

- **Low-temperature Opacities**

  Kurucz 1992; Alexander & Ferguson 1995; Neuforge 1993

- **Equation of State**

  OPAL (Rogers, Swenson & Iglesias 1996), MHD (Dappen, Mihalas, Hummer, & Mihalas 1988); CEFF (Christensen-Dalsgaard & Dappen 1992)

- **Nuclear Reaction Rates**

  Caughlan & Fowler 1988; Bahcall & Pinsonneault 1995; Adelberger et al. 1998; NACRE (Angulo et al. 1999)

- **Element Diffusion Treatment**

  Thoul, Bahcall & Loeb 1994; Cox, Guzik & Kidman 1989

- **Convection Treatment**

  Bohm-Vitense 1958; Canuto, Mazzitelli, & Goldman (1991, 1992, 1996)

Boundary Conditions and Assumptions

Radius **6.9599×10^{10} cm** (Allen 1973)

$6.95508 \pm 0.026 \times 10^{10}$ cm

(Brown & Christensen-Dalsgaard 1998)

Luminosity **$3.846 \pm 0.005 \times 10^{33}$ erg/s** (Willson et al. 1986)

Mass **$1.9891 \pm 0.0004 \times 10^{33}$ g**

Age **4.52 ± 0.04 Gyr** (Guenther 1989)

Element mixture and surface Z/X

0.0245 ± 0.0015 (Grevesse & Noels 1993)

0.0230 ± 0.0023 (Grevesse & Sauval 1998)

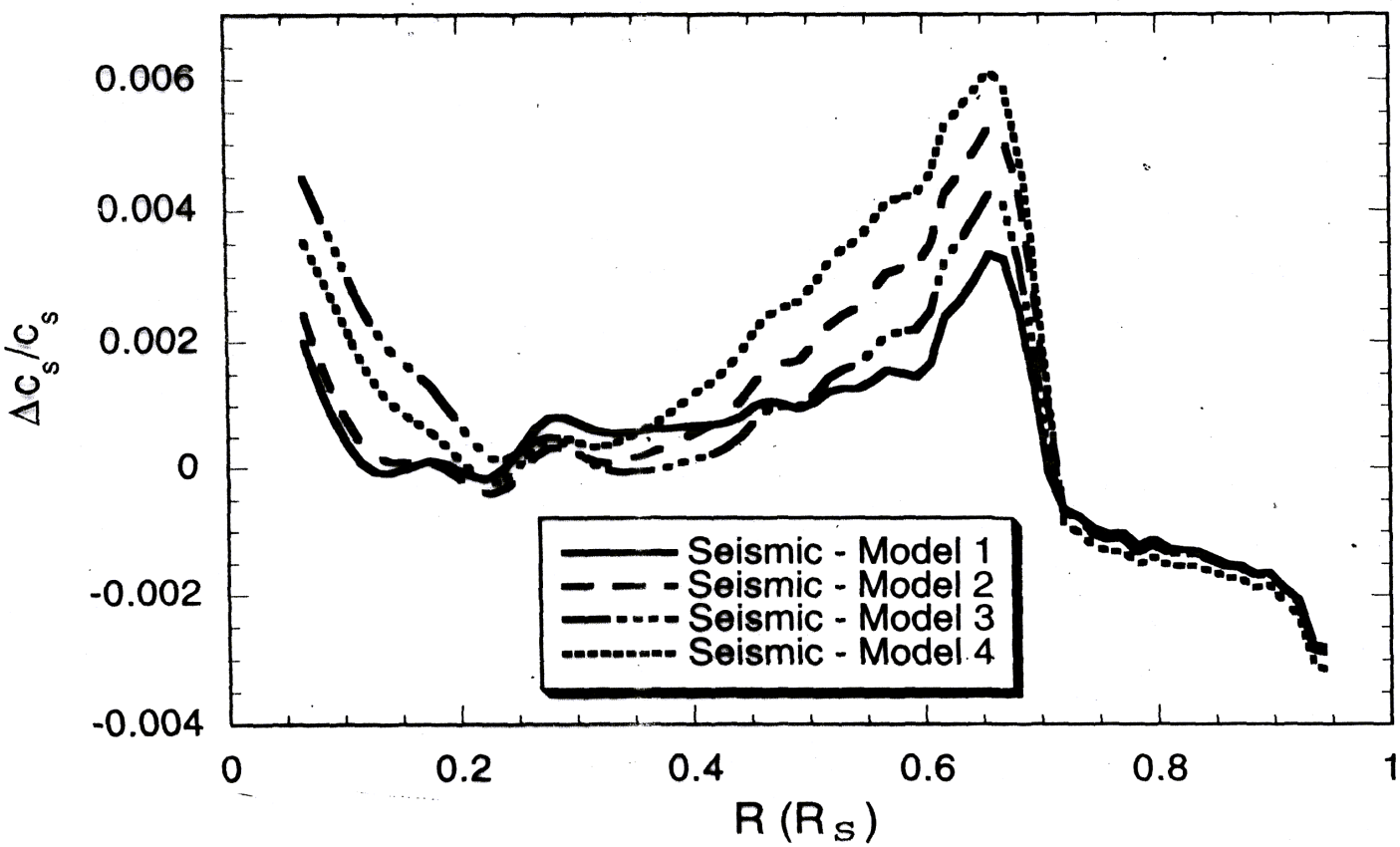
Initial homogeneous composition

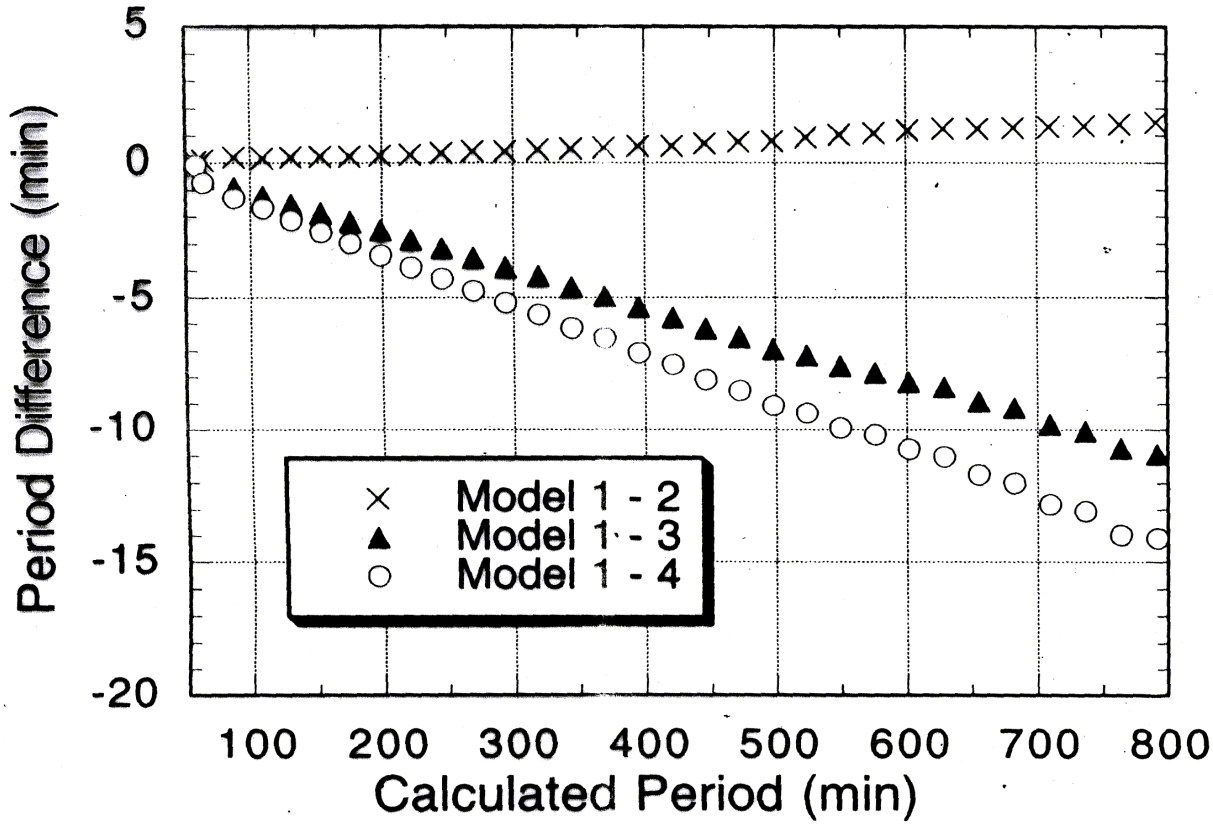
Negligible mass loss or accretion

X_0 (Y_0) ?

Z_0 ?

α ?


0.006
0.004
0.002
0
-0.002
-0.004
$\Delta c_s / c_s$
0
0.2
0.4
0.6
0.8
1
R (R_S)
Seismic - Model 1
Seismic - Model 2
Seismic - Model 3
Seismic - Model 4


5
0
-5
-10
-15
-20
Period Difference (min)
100
200
300
400
500
600
700
800
Calculated Period (min)
Model 1 - 2
Model 1 - 3
Model 1 - 4

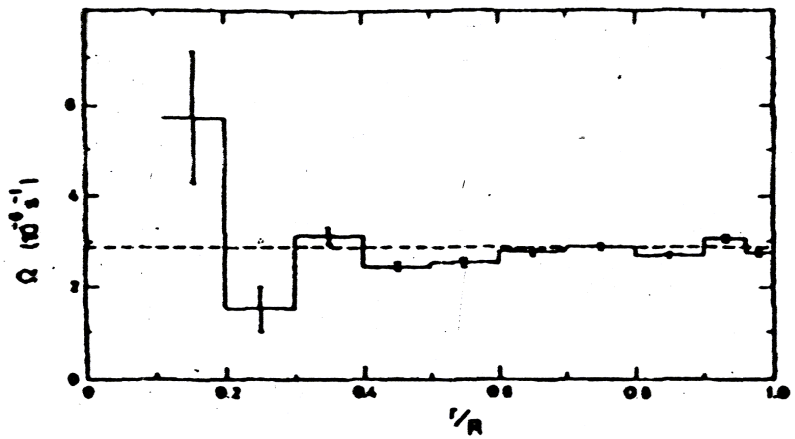


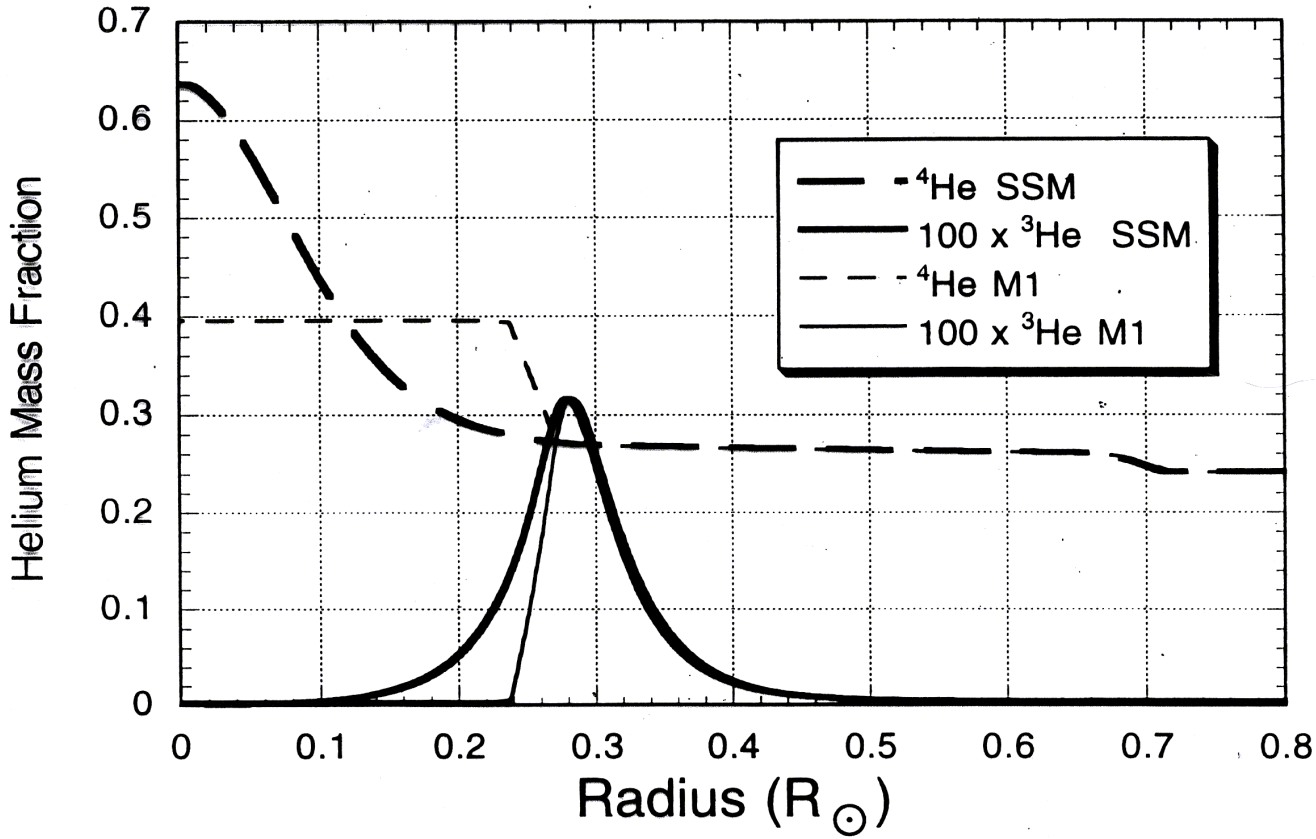
Fig.7. Fit of a piecewise-constant function to the angular velocity Ω in the Sun, averaged in the vicinity of the equatorial plane (after Duvall *et al.*, 1984). The vertical bars represent formal standard errors.

Nonstandard Models: Core Mixing + Opacity Decrease?

- **Cumming & Haxton (1996) propose that slow mixing of ^{3}He into the core (on the timescale of ^{3}He burning to equilibrium) could simultaneously decrease the ^{7}Be and ^{8}B neutrino flux, and also the ^{7}Be/^{8}B flux ratio.**

- **As pointed out by, e.g., Christensen-Dalsgaard (1995, 1997), mixed core models increase small frequency separations, and low-opacity models decrease small frequency separations.**

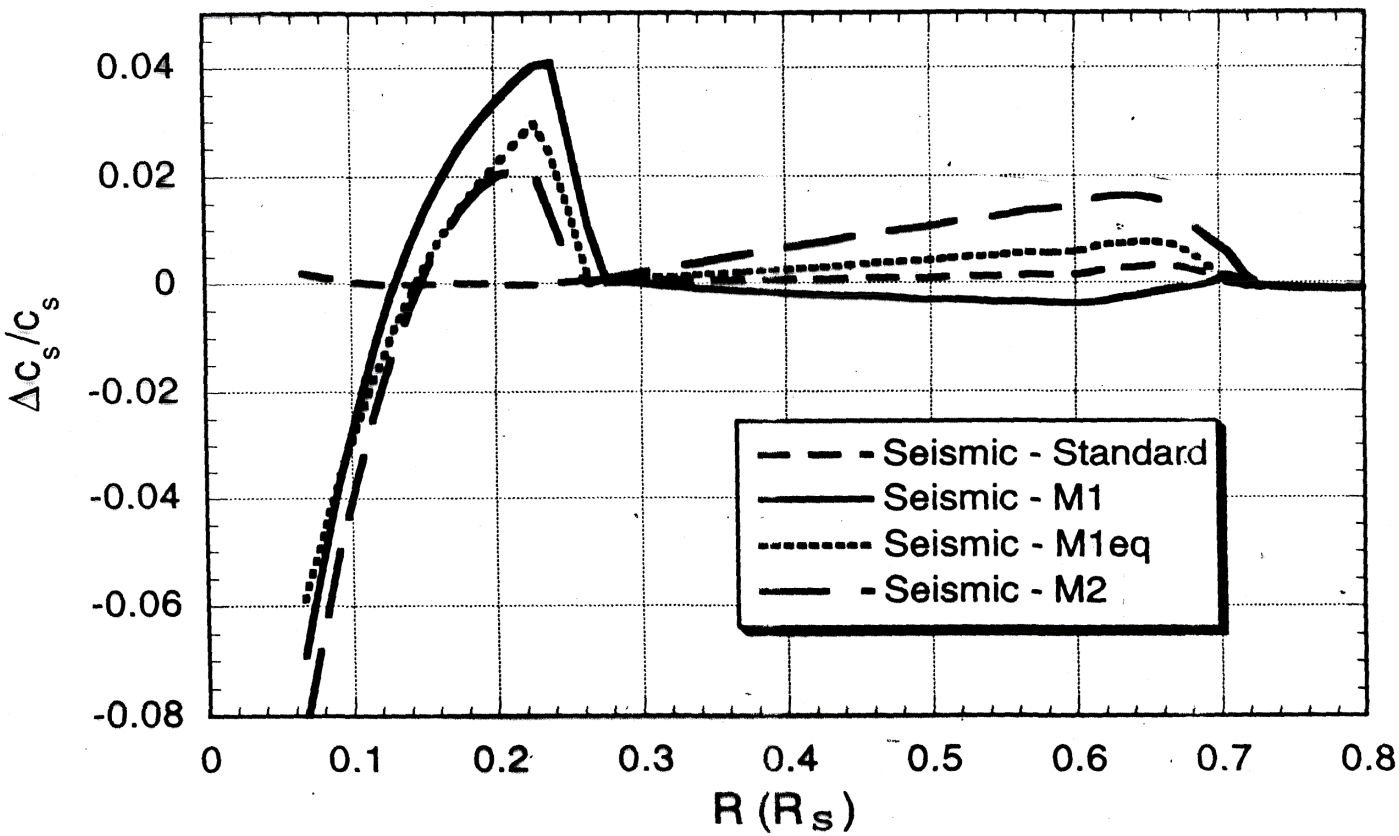
- **Can one contrive a model with both modifications applied simultaneously that satisfies helioseismic constraints?**


0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Helium Mass Fraction
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Radius (R⊙)
⁴He SSM
100 x ³He SSM
⁴He M1
100 x ³He M1

Standard vs. Mixed Core Models

	GN93 SSM	Mixed Core eq	Mixed Core neq	Mixed eq +κ*0.7	Mixed neq +κ*0.7	
Y_{core}	0.6375	0.3661	0.3955	0.3151	0.3939	
R_{czb} ($R_\odot$)	0.7135	0.7187	0.7055	0.7203	0.7314	0.713:
T_c (10^6 K)	15.66	14.94	16.28	14.28	15.63	
ρ_c (g/cc)	152.2	97.5	78.4	102.3	94.53	
^{37}Cl νs	7.85	3.40	10.08	1.55	5.33	
^{7}Be/^{8}B	2.69	3.96	1.62	6.92	2.78	
^{71}Ga νs	128.8	104.3	128.7	93.0	113.3	

8/15/00


0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
$\Delta c_s / c_s$
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
R (R_s)
Seismic - Standard
Seismic - M1
Seismic - M1eq
Seismic - M2