The light elements in a helio- and astero-seismic perspective

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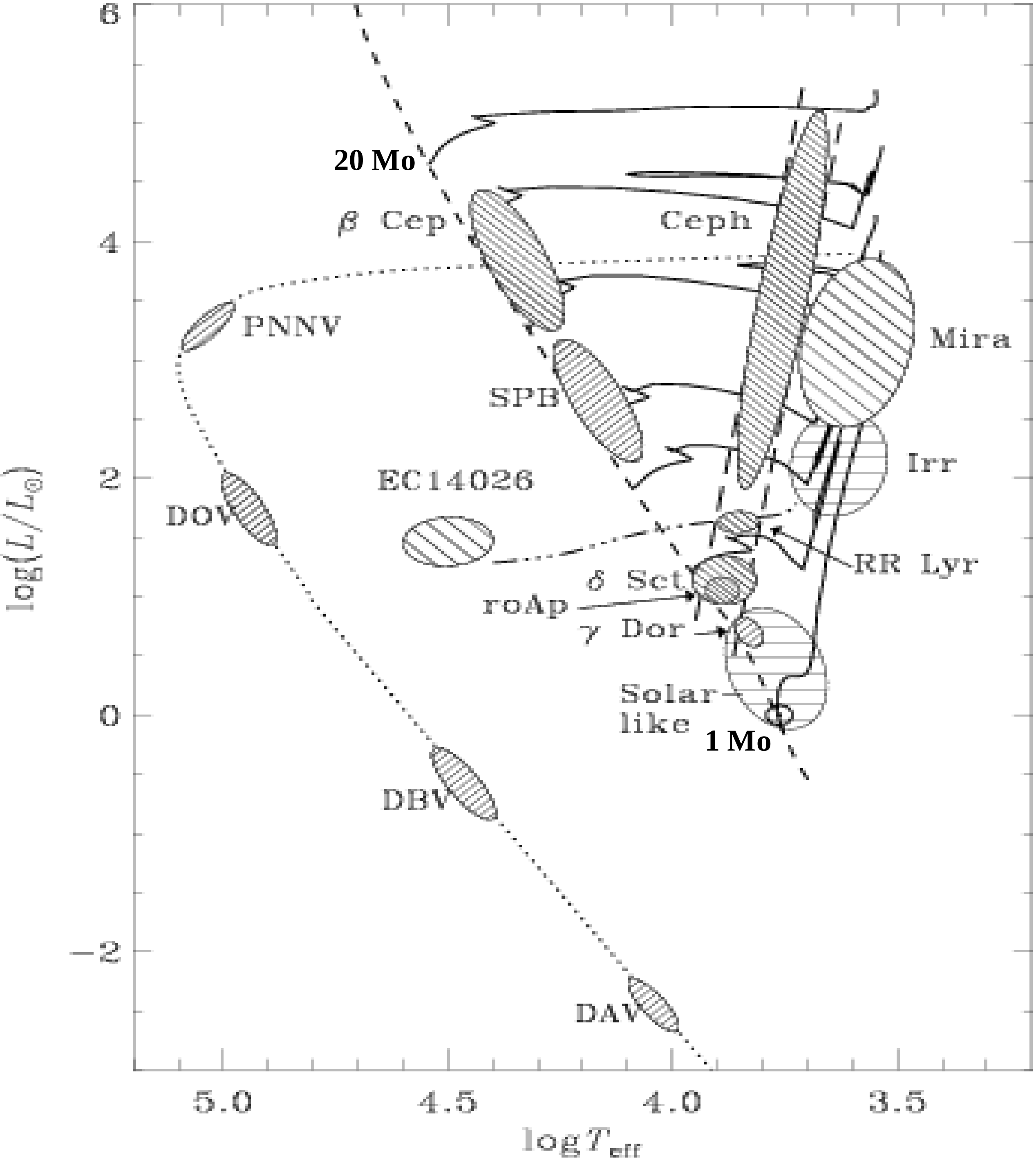
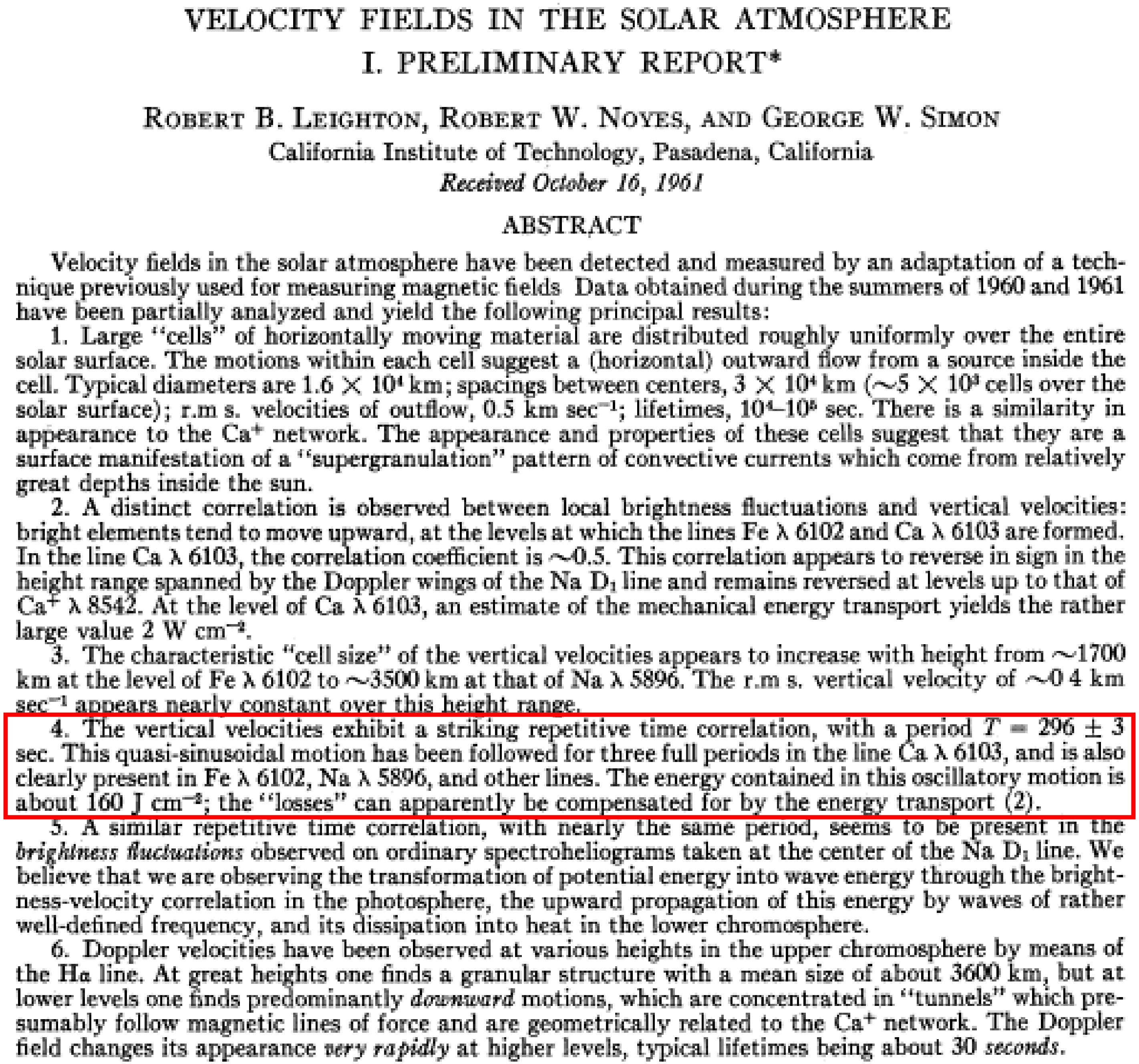

20 Mo
β Cep
Ceph
PNNV
Mira
SPB
Irr
EC14026
DOV
RR Lyr
δ Sct
roAp
γ Dor
Solar like
1 Mo
DBV
DAV
6
4
2
0
−2
log(L/L☉)
5.0
4.5
4.0
3.5
log T_eff

Light elements and seismology

Helium 4 is directly related to asteroseismology as its abundance modifies stellar structure.
-> it may lead to κ mechanism
-> Y may be determined from seismology
-> internal helium gradients have seismic signatures

LiBeB and **He3** are indirectly related to asteroseismology through the determinations of macroscopic motions (convective zones, internal mixing) which have seismic signatures



VELOCITY FIELDS IN THE SOLAR ATMOSPHERE

I. PRELIMINARY REPORT*

ROBERT B. LEIGHTON, ROBERT W. NOYES, AND GEORGE W. SIMON
California Institute of Technology, Pasadena, California

Received October 16, 1961

ABSTRACT

Velocity fields in the solar atmosphere have been detected and measured by an adaptation of a technique previously used for measuring magnetic fields Data obtained during the summers of 1960 and 1961 have been partially analyzed and yield the following principal results:

1. Large "cells" of horizontally moving material are distributed roughly uniformly over the entire solar surface. The motions within each cell suggest a (horizontal) outward flow from a source inside the cell. Typical diameters are 1.6×10^4 km; spacings between centers, 3×10^4 km ($\sim 5 \times 10^3$ cells over the solar surface); r.m s. velocities of outflow, 0.5 km sec^{-1}; lifetimes, 10^4–10^5 sec. There is a similarity in appearance to the Ca^+ network. The appearance and properties of these cells suggest that they are a surface manifestation of a "supergranulation" pattern of convective currents which come from relatively great depths inside the sun.

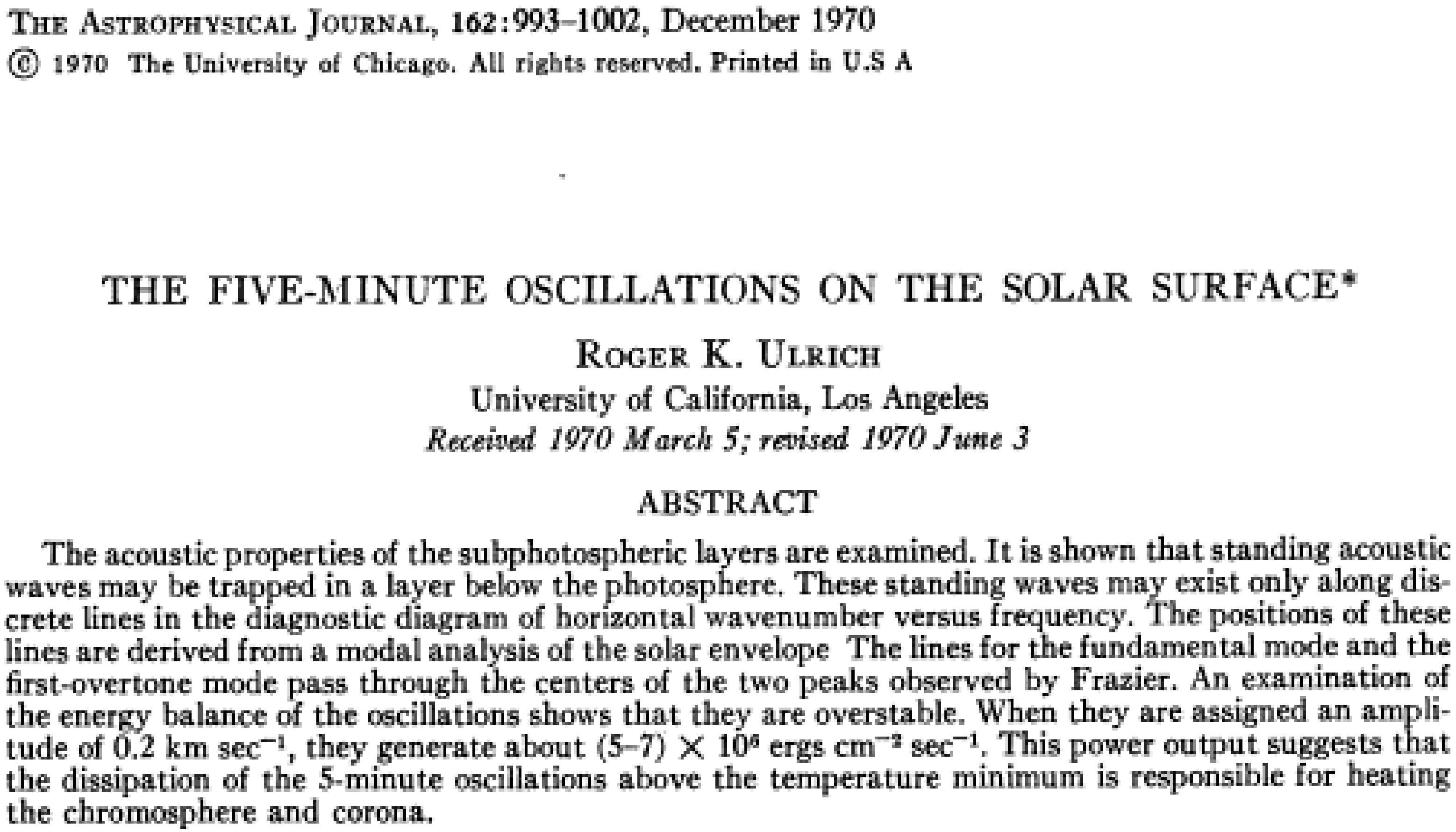
2. A distinct correlation is observed between local brightness fluctuations and vertical velocities: bright elements tend to move upward, at the levels at which the lines Fe λ 6102 and Ca λ 6103 are formed. In the line Ca λ 6103, the correlation coefficient is $\sim$0.5. This correlation appears to reverse in sign in the height range spanned by the Doppler wings of the Na D_1 line and remains reversed at levels up to that of Ca^+ λ 8542. At the level of Ca λ 6103, an estimate of the mechanical energy transport yields the rather large value 2 W cm^{-2}.

3. The characteristic "cell size" of the vertical velocities appears to increase with height from $\sim$1700 km at the level of Fe λ 6102 to $\sim$3500 km at that of Na λ 5896. The r.m s. vertical velocity of $\sim$0 4 km sec^{-1} appears nearly constant over this height range.

4. The vertical velocities exhibit a striking repetitive time correlation, with a period $T = 296 \pm 3$ sec. This quasi-sinusoidal motion has been followed for three full periods in the line Ca λ 6103, and is also clearly present in Fe λ 6102, Na λ 5896, and other lines. The energy contained in this oscillatory motion is about 160 J cm^{-2}; the "losses" can apparently be compensated for by the energy transport (2).

5. A similar repetitive time correlation, with nearly the same period, seems to be present in the *brightness fluctuations* observed on ordinary spectroheliograms taken at the center of the Na D_1 line. We believe that we are observing the transformation of potential energy into wave energy through the brightness-velocity correlation in the photosphere, the upward propagation of this energy by waves of rather well-defined frequency, and its dissipation into heat in the lower chromosphere.

6. Doppler velocities have been observed at various heights in the upper chromosphere by means of the Hα line. At great heights one finds a granular structure with a mean size of about 3600 km, but at lower levels one finds predominantly *downward* motions, which are concentrated in "tunnels" which presumably follow magnetic lines of force and are geometrically related to the Ca^+ network. The Doppler field changes its appearance *very rapidly* at higher levels, typical lifetimes being about 30 *seconds*.



THE ASTROPHYSICAL JOURNAL, 162:993–1002, December 1970

THE FIVE-MINUTE OSCILLATIONS ON THE SOLAR SURFACE*

ROGER K. ULRICH
University of California, Los Angeles

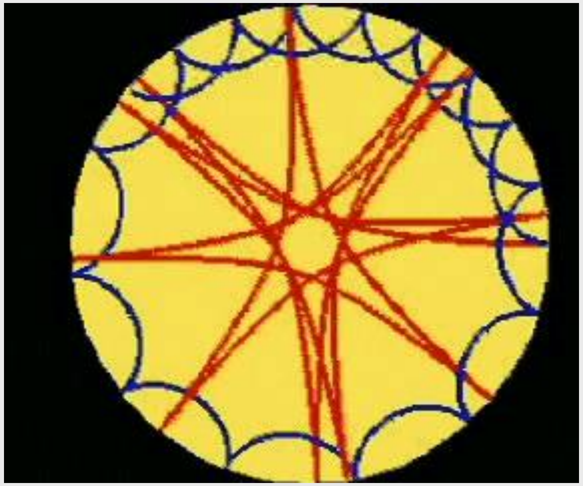
Received 1970 March 5; revised 1970 June 3

ABSTRACT

The acoustic properties of the subphotospheric layers are examined. It is shown that standing acoustic waves may be trapped in a layer below the photosphere. These standing waves may exist only along discrete lines in the diagnostic diagram of horizontal wavenumber versus frequency. The positions of these lines are derived from a modal analysis of the solar envelope The lines for the fundamental mode and the first-overtone mode pass through the centers of the two peaks observed by Frazier. An examination of the energy balance of the oscillations shows that they are overstable. When they are assigned an amplitude of 0.2 km sec^{-1}, they generate about (5–7) × 10^6 ergs cm^{-2} sec^{-1}. This power output suggests that the dissipation of the 5-minute oscillations above the temperature minimum is responsible for heating the chromosphere and corona.

Also Leibacher and Stein 1971, Astrophys Lett 7, 191

Helioseismology



Special case for the Sun compared to other stars due to the spatial resolution.
Spatial filter: generalised 2D Fourier transform

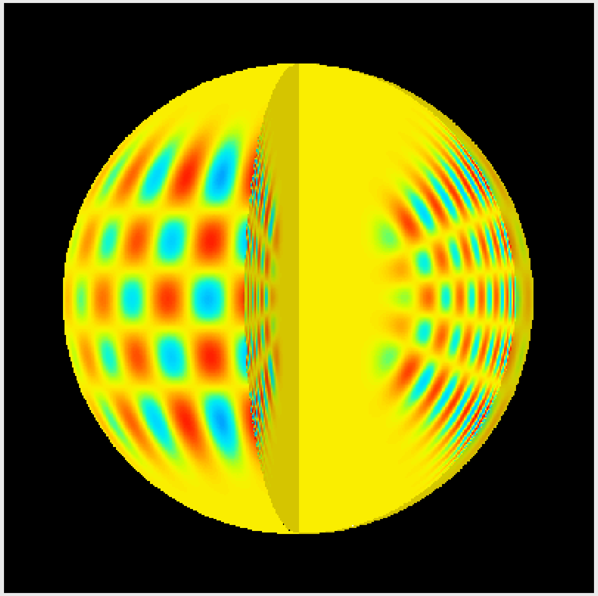
Spherical harmonics:

$$Y_l^m(\theta,\phi)=(-1)^m c_{lm} P_l^m(\cos\theta)\exp(im\phi)$$

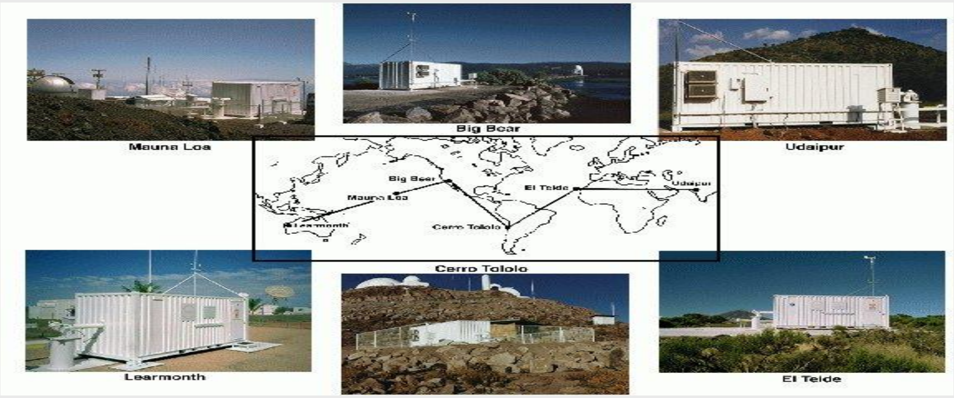
$P_l^m(\cos\theta)$ is a Legendre polynomial

c_{lm} is a normalisation factor, so that the integral of $|Y_l^m|^2$ on the sphere is 1.

$$c_{lm}=\frac{(2l+1)(l-m)!}{4\pi(l+m)!}$$



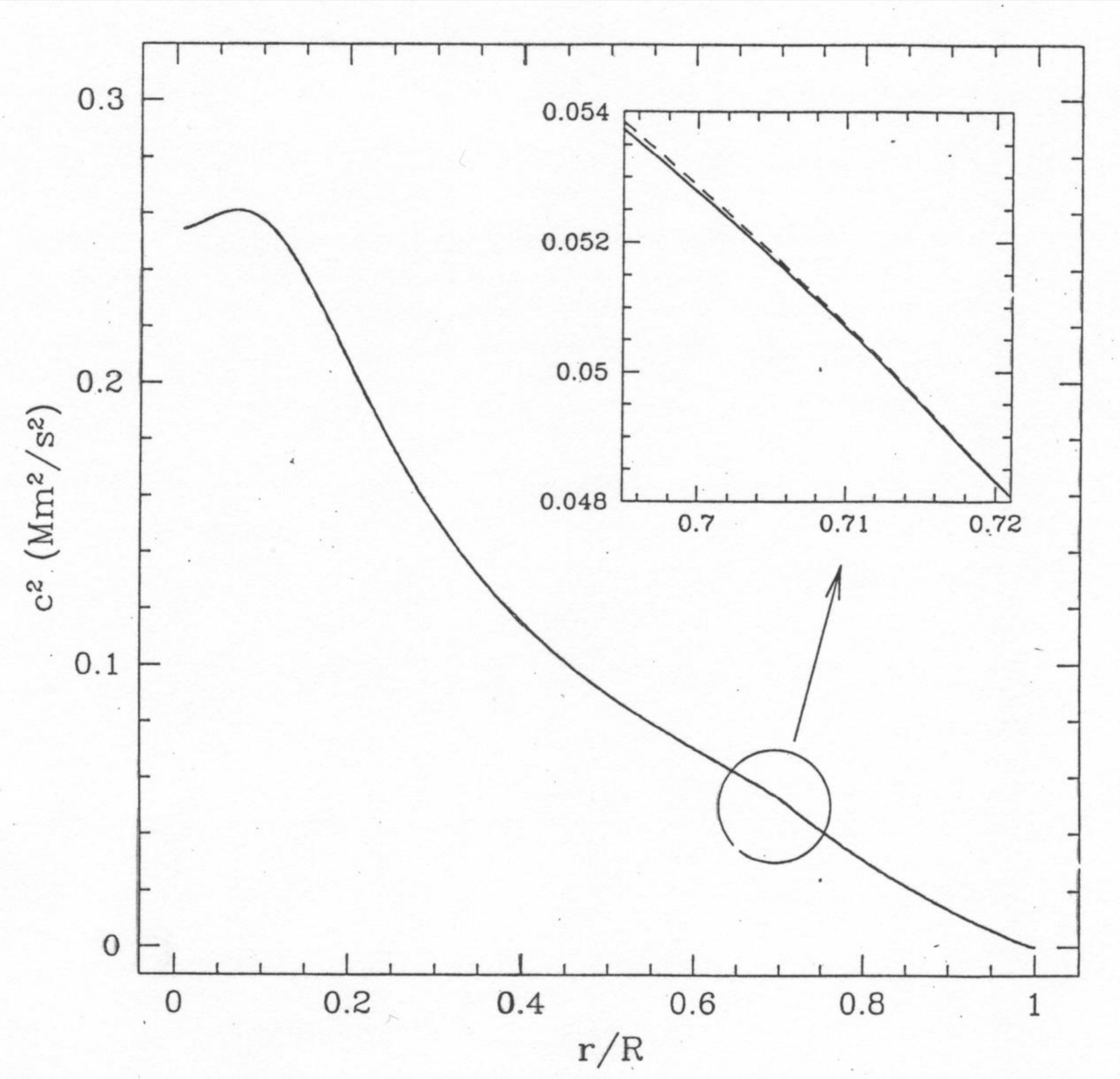
Helioseismology



* Beginnings : south pole (Grec, Fossat, Pomerantz, 1980)
* Observation networks: GONG+ (Doppler), BiSON (integrated light), etc.
* Space : SoHO-Solar and Heliospheric Observatory

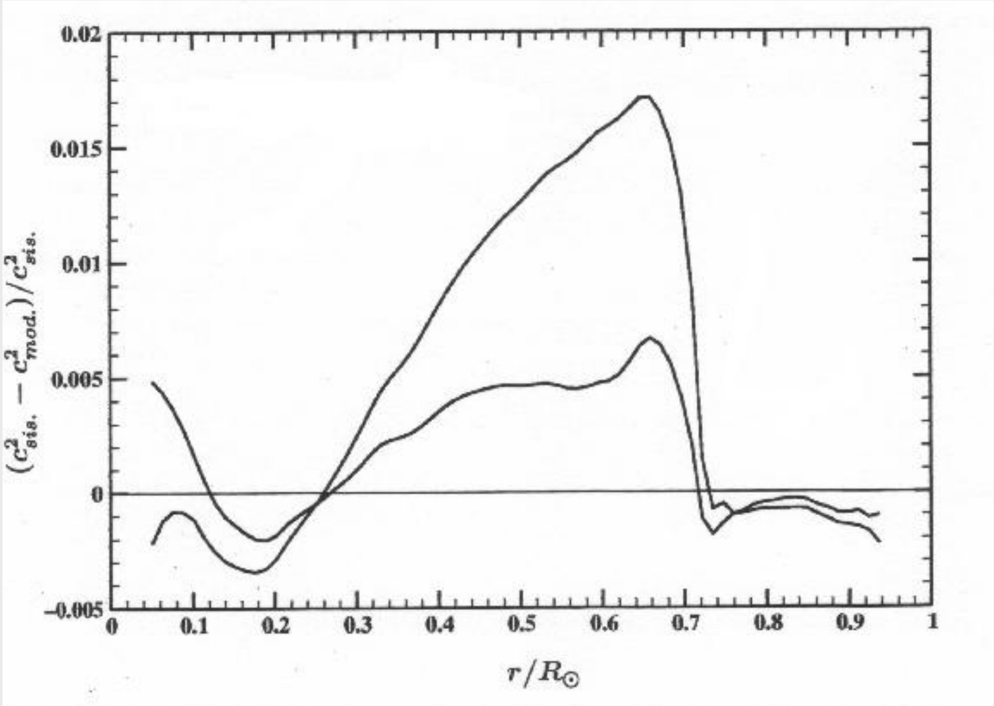
* 10 millions of p-modes
* Frequencies around 2 to 4 mhz (5min.)
* Velocity amplitudes : about 1 $\mathrm{cm.s^{-1}}$ (max:20 $\mathrm{cm.s^{-1}}$)
* Relative light variations : 10^{-7}
* Lifetime of modes :
    a few hours for large l (~ 250) and small n (~ 1)
    a few months for small l (~ 0) and large n(~ 10)

*For $l < 180$: global modes (lifetime larger than the propagation time around the Sun)



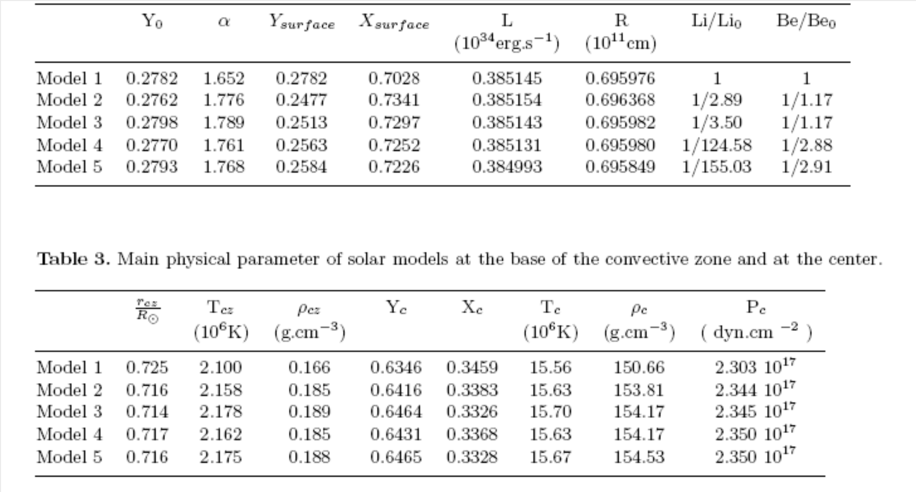
Bottom convective zone : r/R = .713   .003

(science, 1996)



Effects of atomic diffusion
and turbulence below the convective zone
(cf Richard et al. A&A, 1996)

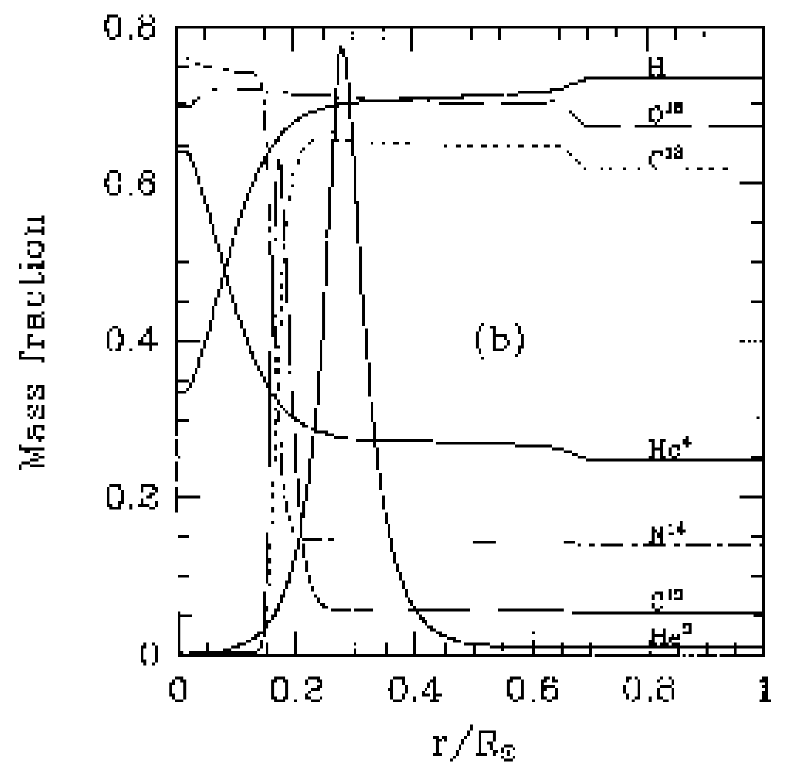
Ys from seismic inversions (from Γ1)
0.248 +/- 0.02 (Dziembowski et al. 1998)



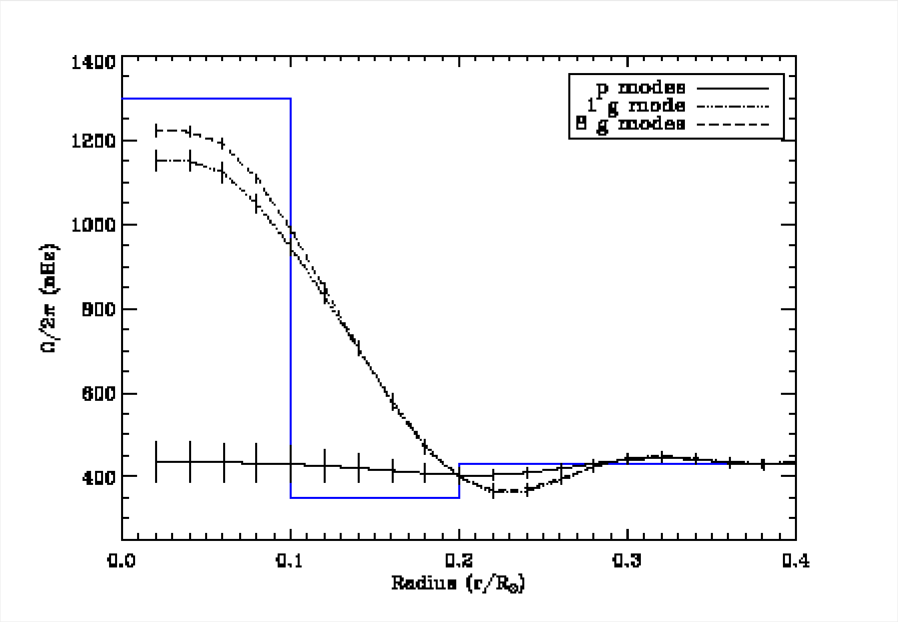
	Y_0	α	$Y_{surface}$	$X_{surface}$	L (10^{34}erg.s^{-1})	R (10^{11}cm)	Li/Li$_0$	Be/Be$_0$
Model 1	0.2782	1.652	0.2782	0.7028	0.385145	0.695976	1	1
Model 2	0.2762	1.776	0.2477	0.7341	0.385154	0.696368	1/2.89	1/1.17
Model 3	0.2798	1.789	0.2513	0.7297	0.385143	0.695982	1/3.50	1/1.17
Model 4	0.2770	1.761	0.2563	0.7252	0.385131	0.695980	1/124.58	1/2.88
Model 5	0.2793	1.768	0.2584	0.7226	0.384993	0.695849	1/155.03	1/2.91

Table 3. Main physical parameter of solar models at the base of the convective zone and at the center.

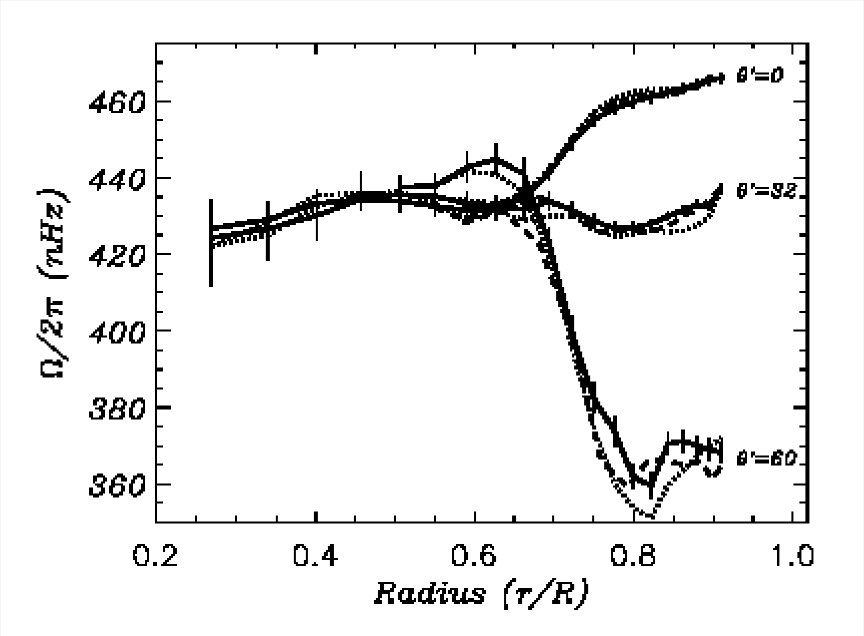
	$\frac{r_{cz}}{R_\odot}$	T_{cz} (10^6K)	ρ_{cz} (g.cm^{-3})	Y_c	X_c	T_c (10^6K)	ρ_c (g.cm^{-3})	P_c (dyn.cm $^{-2}$)
Model 1	0.725	2.100	0.166	0.6346	0.3459	15.56	150.66	$2.303\ 10^{17}$
Model 2	0.716	2.158	0.185	0.6416	0.3383	15.63	153.81	$2.344\ 10^{17}$
Model 3	0.714	2.178	0.189	0.6464	0.3326	15.70	154.17	$2.345\ 10^{17}$
Model 4	0.717	2.162	0.185	0.6431	0.3368	15.63	154.17	$2.350\ 10^{17}$
Model 5	0.716	2.175	0.188	0.6465	0.3328	15.67	154.53	$2.350\ 10^{17}$



Solar internal rotation



Garcia et al. 2008



Eff-Darwich et al. 2002

Shallow tachocline, solid body rotation in most of the Sun…
Gravity waves? Magnetic field? Other? Cf Charbonnel, Talon, Zahn, Gough et al….

THE CRISIS!
New solar abundances
Asplund et al 2005
Revised
(here: Serenelli et al. 2009)

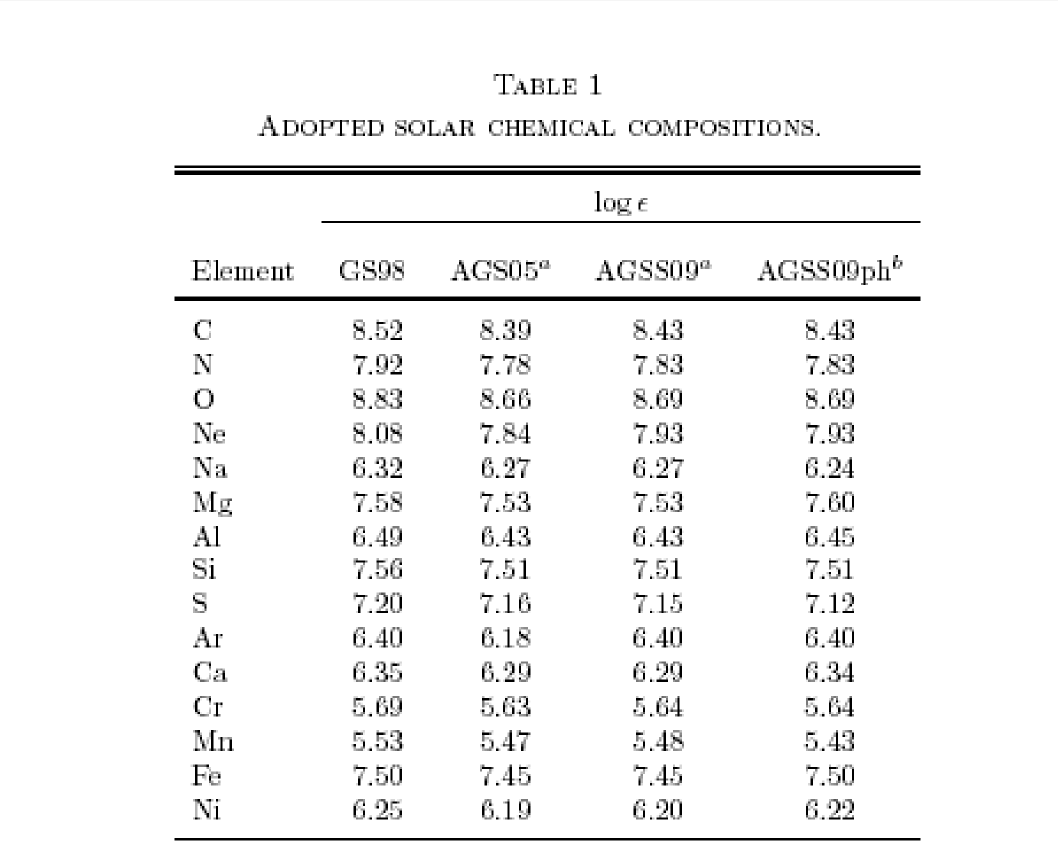


TABLE 1
ADOPTED SOLAR CHEMICAL COMPOSITIONS.

	$\log \epsilon$			
Element	GS98	AGS05[a]	AGSS09[a]	AGSS09ph[b]
C	8.52	8.39	8.43	8.43
N	7.92	7.78	7.83	7.83
O	8.83	8.66	8.69	8.69
Ne	8.08	7.84	7.93	7.93
Na	6.32	6.27	6.27	6.24
Mg	7.58	7.53	7.53	7.60
Al	6.49	6.43	6.43	6.45
Si	7.56	7.51	7.51	7.51
S	7.20	7.16	7.15	7.12
Ar	6.40	6.18	6.40	6.40
Ca	6.35	6.29	6.29	6.34
Cr	5.69	5.63	5.64	5.64
Mn	5.53	5.47	5.48	5.43
Fe	7.50	7.45	7.45	7.50
Ni	6.25	6.19	6.20	6.22

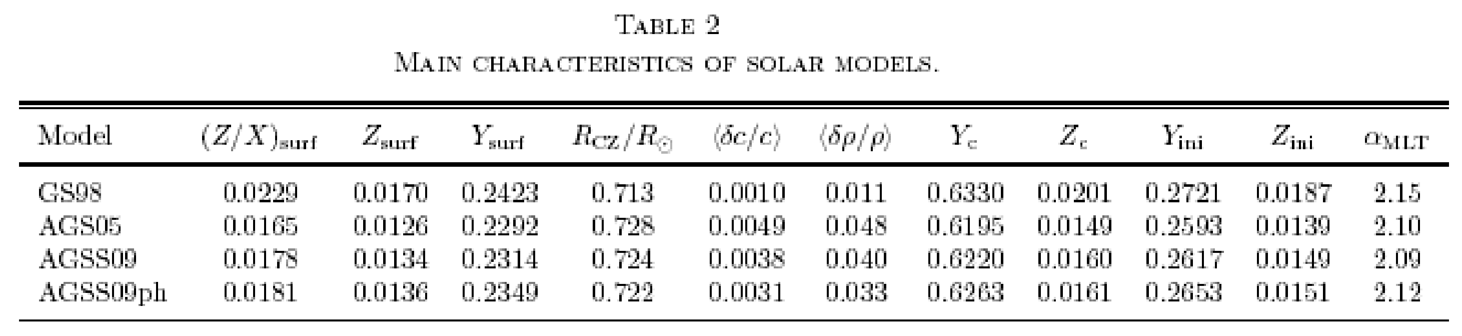


TABLE 2
MAIN CHARACTERISTICS OF SOLAR MODELS.

Model	$(Z/X)_{\rm surf}$	$Z_{\rm surf}$	$Y_{\rm surf}$	$R_{\rm CZ}/R_{\odot}$	$\langle \delta c/c \rangle$	$\langle \delta \rho/\rho \rangle$	$Y_{\rm c}$	$Z_{\rm c}$	$Y_{\rm ini}$	$Z_{\rm ini}$	$\alpha_{\rm MLT}$
GS98	0.0229	0.0170	0.2423	0.713	0.0010	0.011	0.6330	0.0201	0.2721	0.0187	2.15
AGS05	0.0165	0.0126	0.2292	0.728	0.0049	0.048	0.6195	0.0149	0.2593	0.0139	2.10
AGSS09	0.0178	0.0134	0.2314	0.724	0.0038	0.040	0.6220	0.0160	0.2617	0.0149	2.09
AGSS09ph	0.0181	0.0136	0.2349	0.722	0.0031	0.033	0.6263	0.0161	0.2653	0.0151	2.12

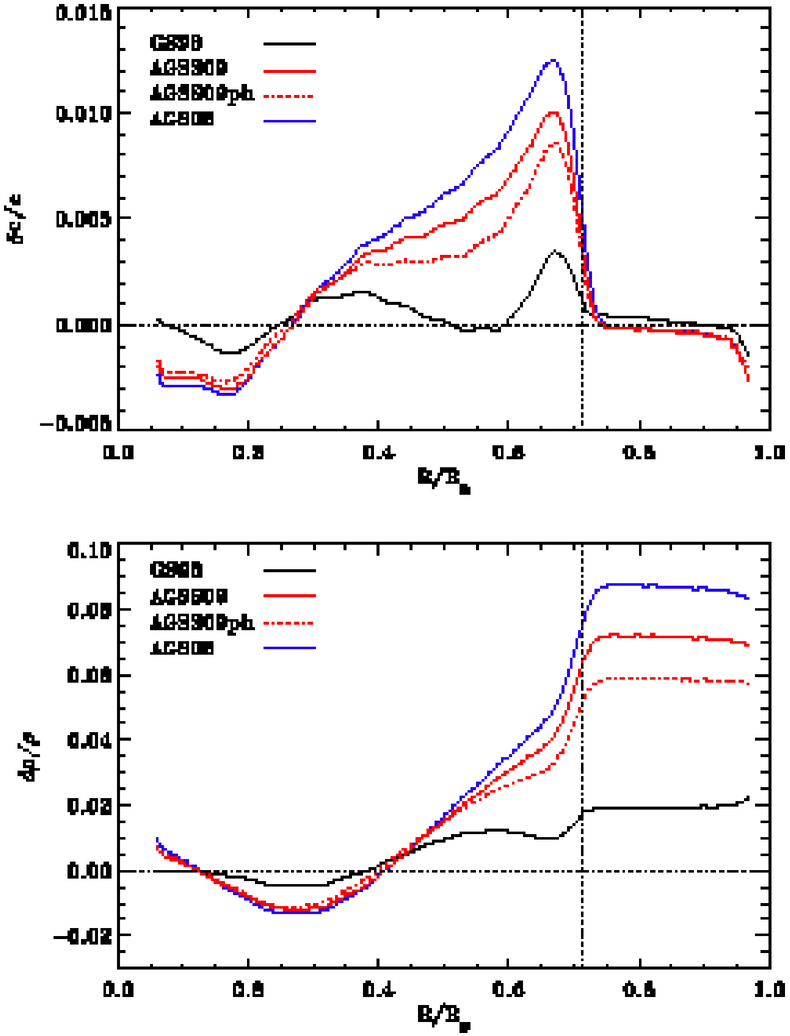


Fig. 1.— Relative sound speed $\delta c/c$ and density $\delta\rho/\rho$ differences, in the sense (Sun - Model)/Model, between solar models and helioseismological results. Details on the inversion procedure and data used, as well as the reference sound speeds and densities are given in Basu et al. (2009).

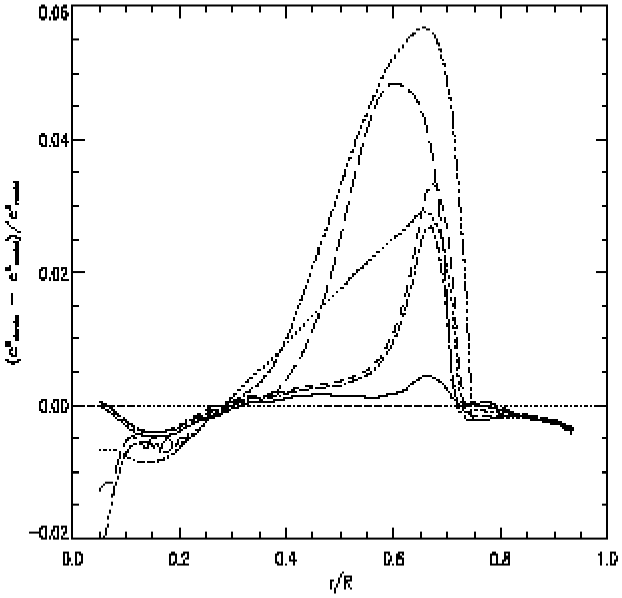


Fig. 1. Comparison between the profile of sound velocity of the different models (S1 : solid line, S2 : dotted line, S3 : dashed line, S4 : dot-dashed line, S5 : three dot-dashed line, S6 : long dashed line) and the one deduced from the helioseismology

Castro et al 2007
Accretion of metal poor matter
(Cf. Nordlund 2009)

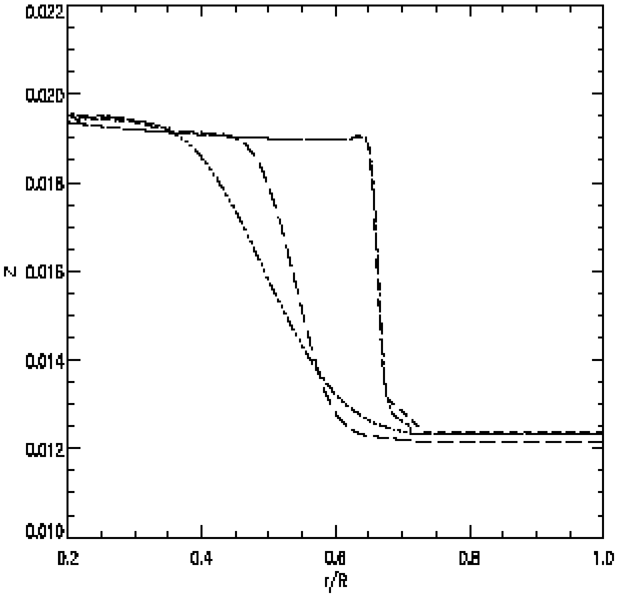
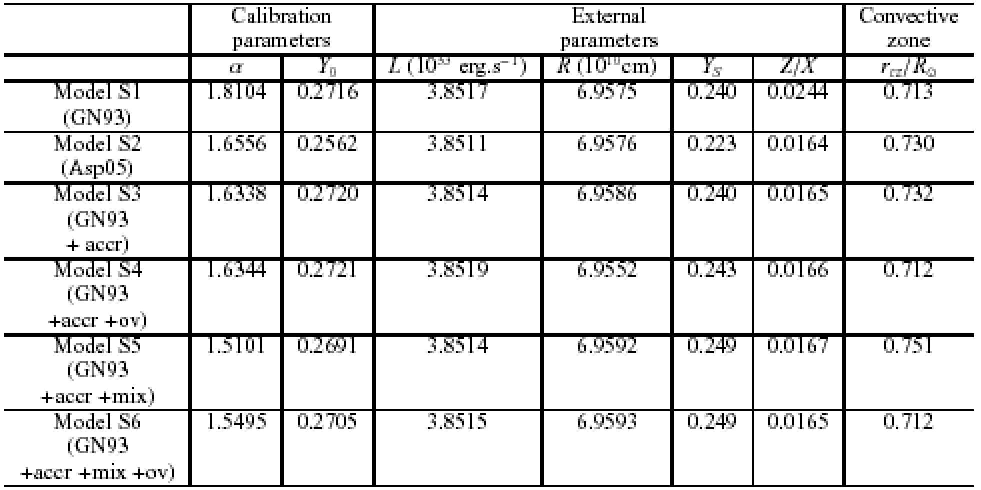
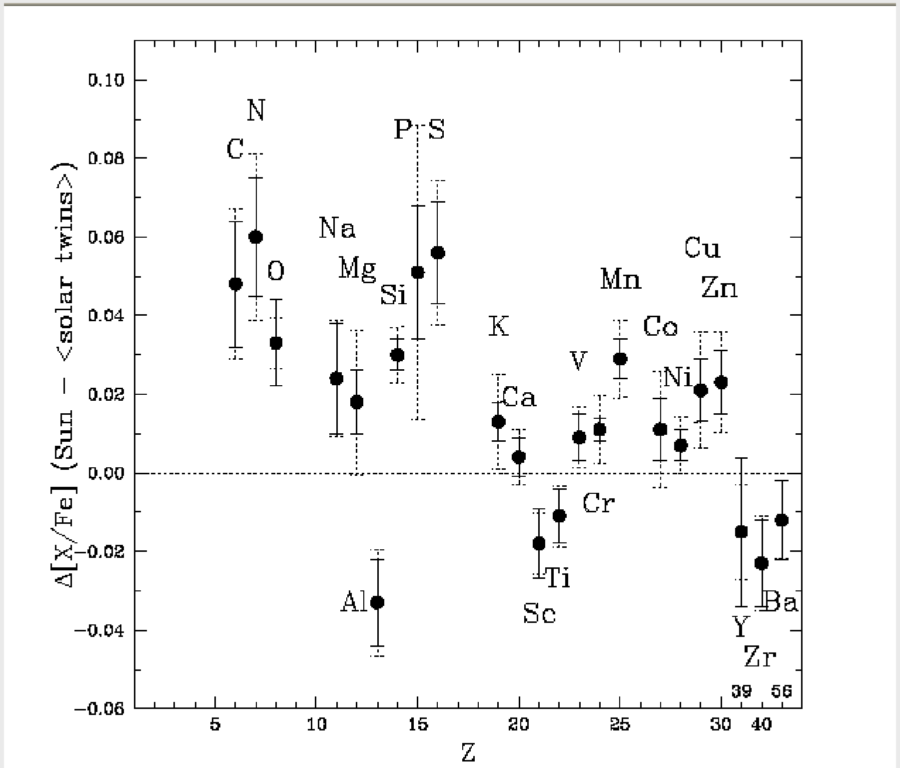


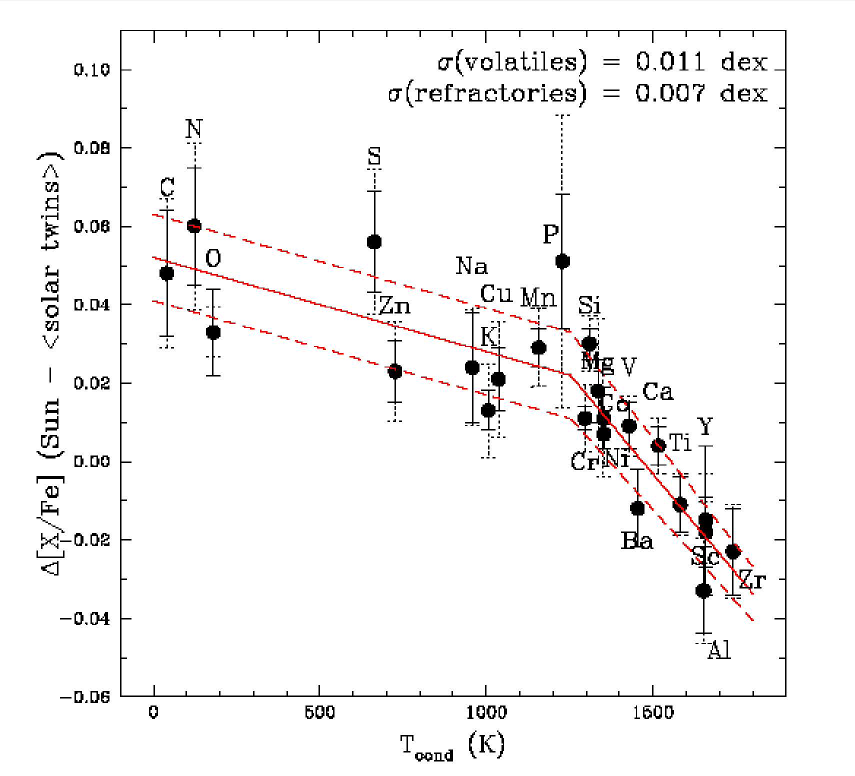
Fig. 2. Metal profile below the convective zone of models S3 (dashed line), S4 (dot-dashed line), S5 (three dot-dashed line), and S6 (long dashed line)

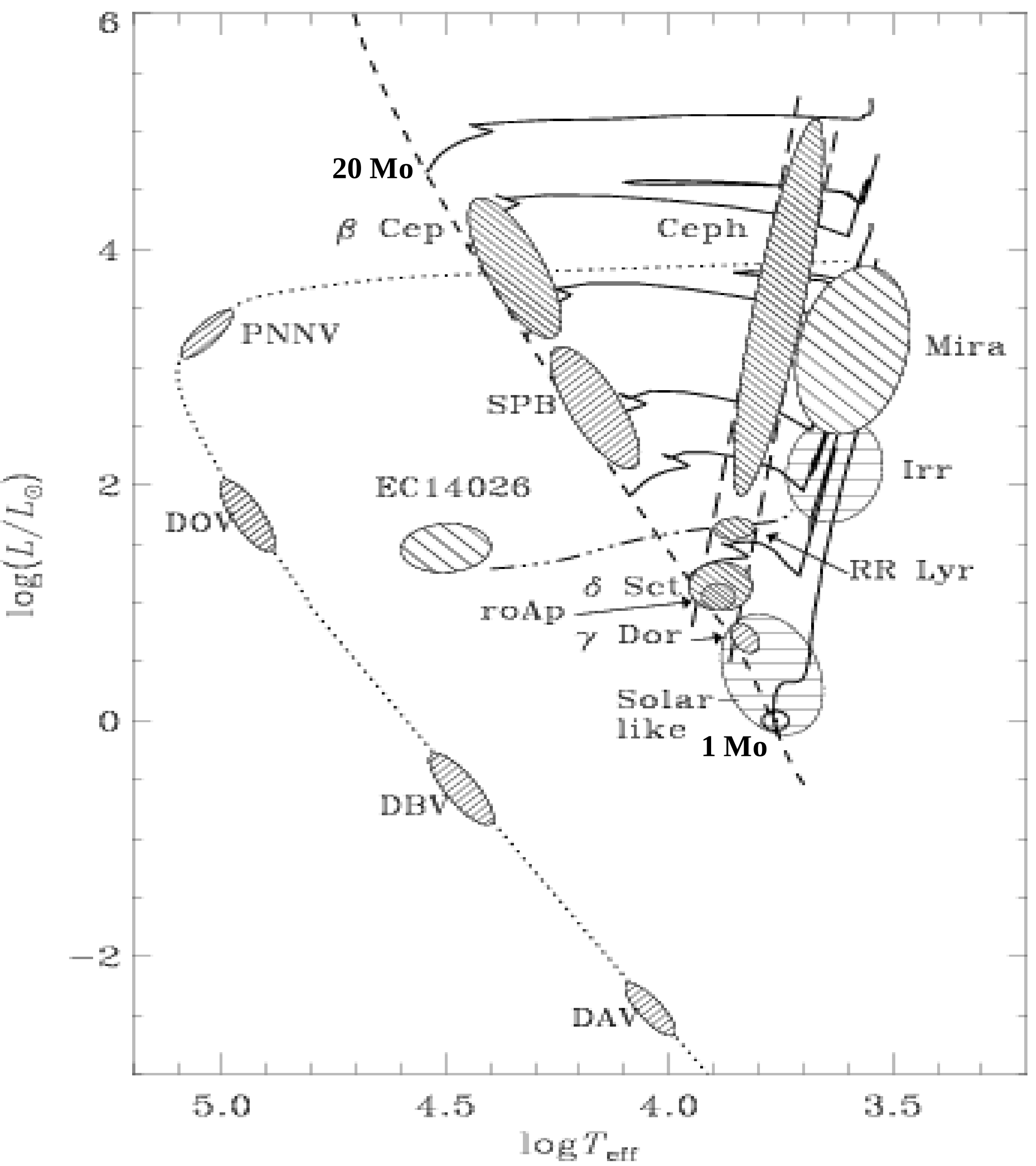


	Calibration parameters		External parameters				Convective zone
	α	Y_0	L (10^{33} erg.s^{-1})	R (10^{10}cm)	Y_S	Z/X	$r_{cz}/R_\odot$
Model S1 (GN93)	1.8104	0.2716	3.8517	6.9575	0.240	0.0244	0.713
Model S2 (Asp05)	1.6556	0.2562	3.8511	6.9576	0.223	0.0164	0.730
Model S3 (GN93 + accr)	1.6338	0.2720	3.8514	6.9586	0.240	0.0165	0.732
Model S4 (GN93 +accr +ov)	1.6344	0.2721	3.8519	6.9552	0.243	0.0166	0.712
Model S5 (GN93 +accr +mix)	1.5101	0.2691	3.8514	6.9592	0.249	0.0167	0.751
Model S6 (GN93 +accr +mix +ov)	1.5495	0.2705	3.8515	6.9593	0.249	0.0165	0.712

Meléndez et al. 2009

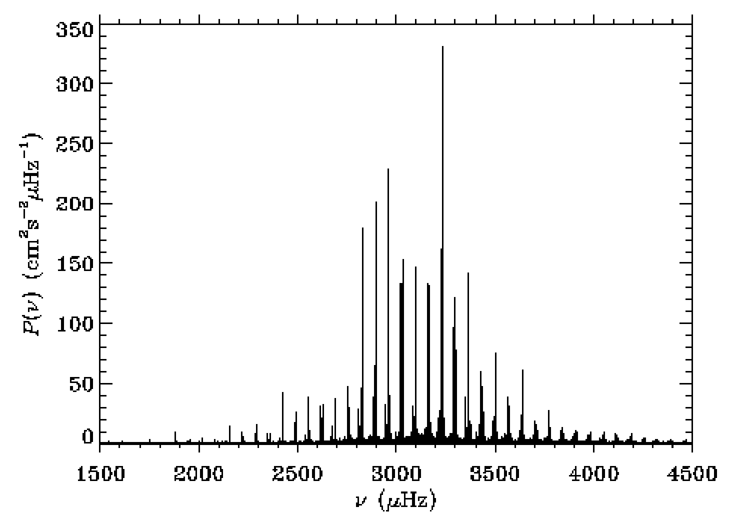






20 Mo
β Cep
Ceph
PNNV
Mira
SPB
Irr
EC14026
DOV
RR Lyr
δ Sct
roAp
γ Dor
Solar-like
1 Mo
DBV
DAV
log(L/L⊙)
log Teff
6
4
2
0
−2
5.0
4.5
4.0
3.5

sun


350
300
250
200
150
100
50
0
P(ν) (cm²s⁻²μHz⁻¹)
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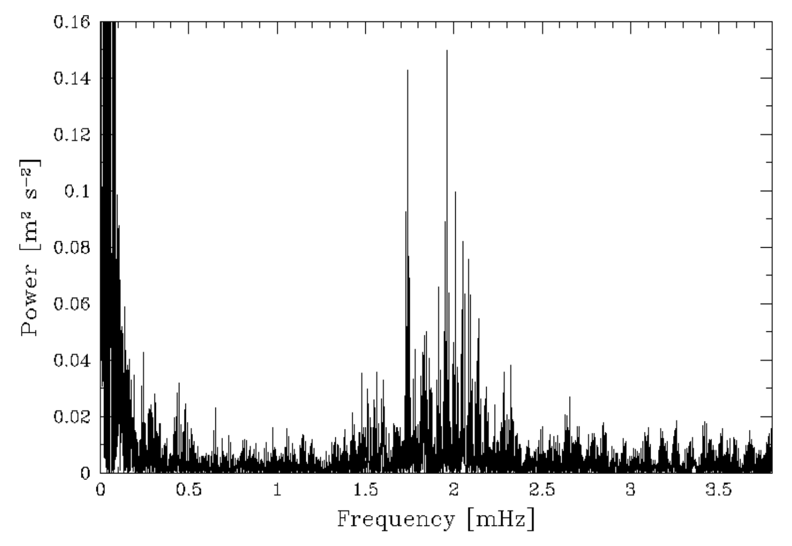
2000
2500
3000
3500
4000
4500
ν (μHz)


0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Power [m² s⁻²]
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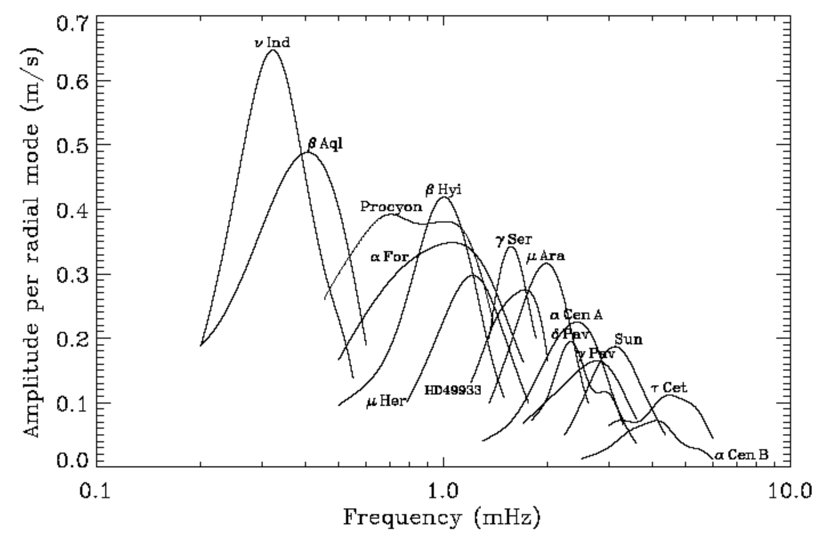
0.5
1
1.5
2
2.5
3
3.5
Frequency [mHz]


0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Amplitude per radial mode (m/s)
ν Ind
β Aql
Procyon
β Hyi
α For
γ Ser
μ Ara
α Cen A
δ Pav
Sun
γ Pav
μ Her
HD49933
τ Cet
α Cen B
0.1
1.0
10.0
Frequency (mHz)

mu Arae

Basics of asterosismology
(for slowly rotating stars)

« asymptotic theory » (Tassoul 1980) :

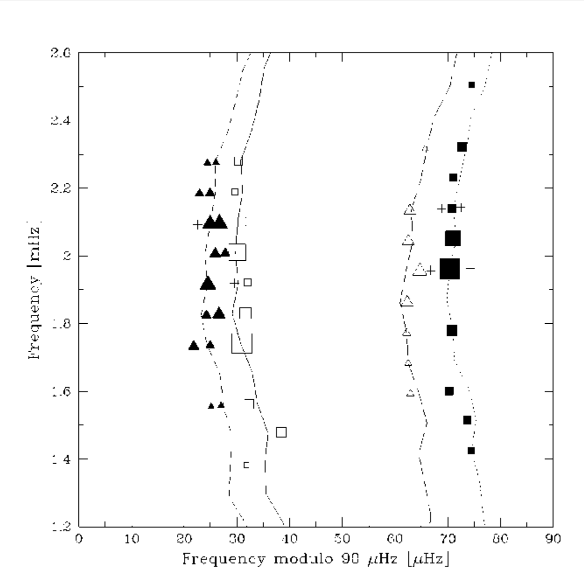
$$\nu_{n,l} \simeq (n+\frac{l}{2}+\frac{1}{4}+\alpha)\Delta\nu_l - \frac{l(l+1)\Delta\nu_l}{4\pi^2\nu_{n,l}}\left[\frac{c(R)}{R} - \int_{r_l}^{R}\frac{1}{r}\frac{dc}{dr}dr\right] - \delta\frac{\Delta\nu_l^2}{\nu_{n,l}}$$

Large separations : $\Delta\nu\,(n,l) = \nu\,(n+1, l) - \nu\,(n,l)$

$\Delta\nu_1 \sim \Delta\nu_0 \sim 1/2t_{\mathbf{a}}$

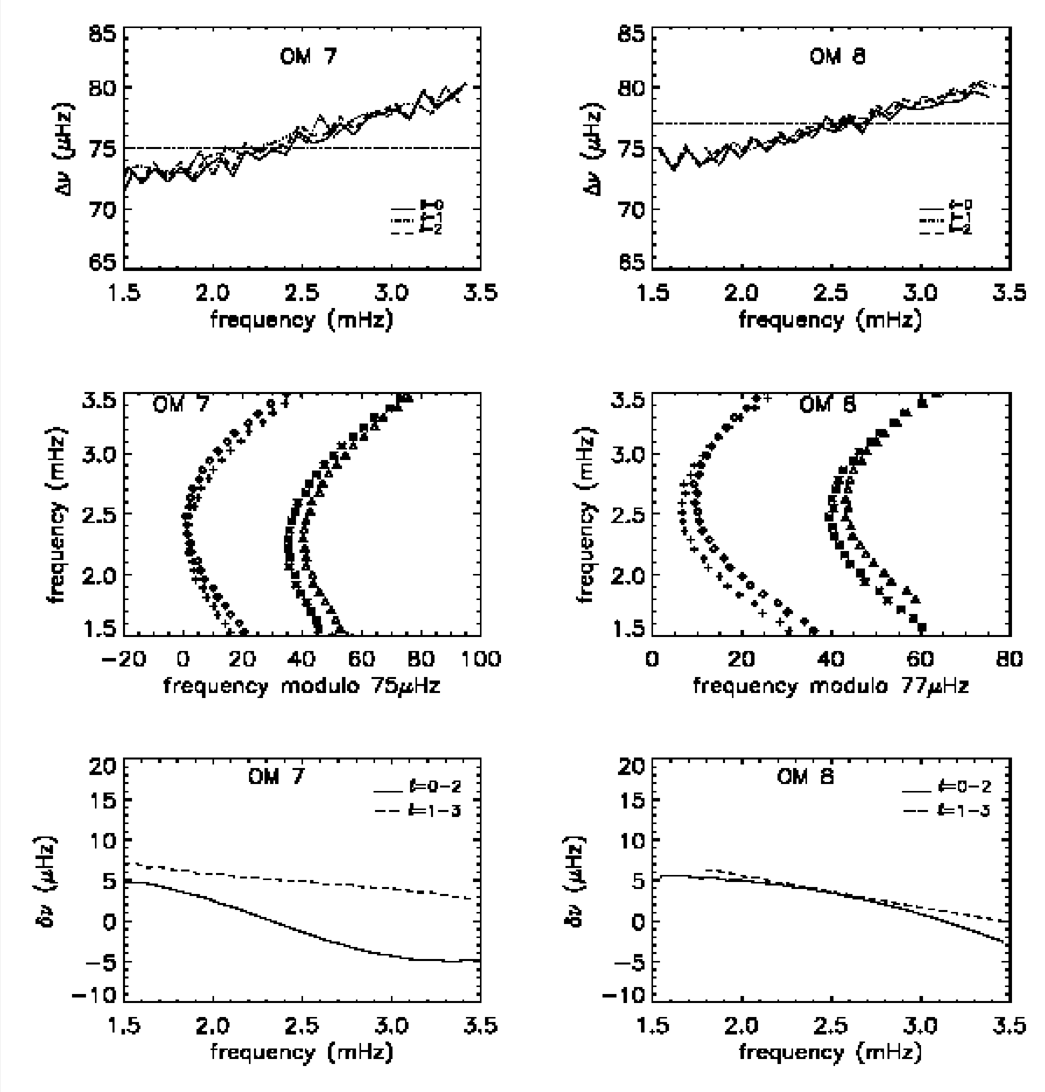
Small separations :

$$\delta\nu = \nu_{n,l} - \nu_{n-1,l+2} \simeq -(4l+6)\frac{\Delta\nu}{4\pi^2\nu_{n,l}}\int_0^R \frac{1}{r}\frac{dc}{dr}dr$$



échelle diagram

Negative small separations

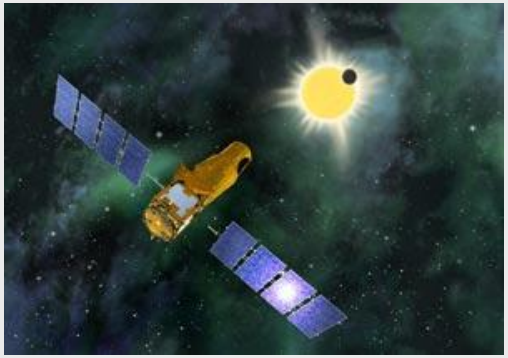


Example: HD 52265 (« Corot Star ») Left : Main Sequence ; right : Subgiant

Asterosismology :
ground based and space observations

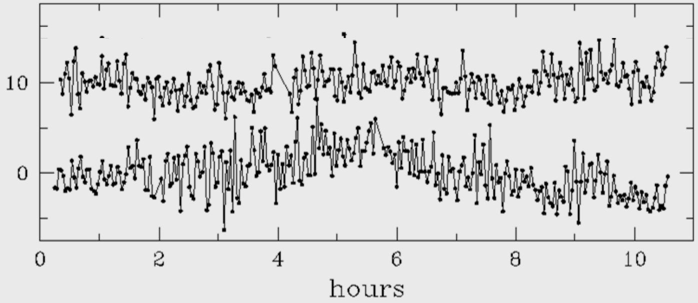
Same instruments as for the detection of exoplanets

Ground: radial velocity methods
HARPS (La Silla), SOPHIE (OHP),
AAT, VLT, Keck, etc…future: SONG

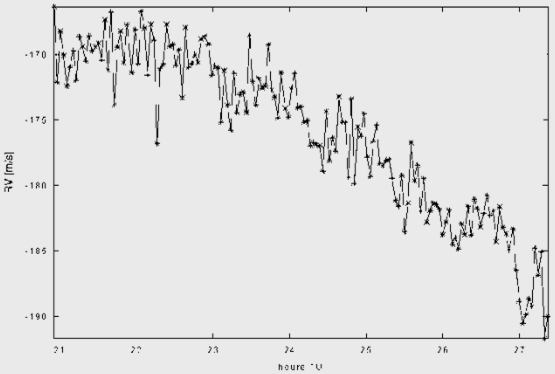


Space: photometric methods
MOST, COROT, KEPLER…

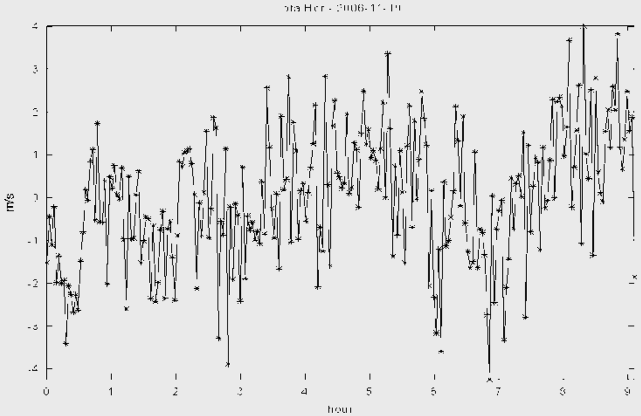
At least 4 planets-host stars already observed on large periods (8 or 9 consecutive nights) + HD52265 (CoRoT star) :



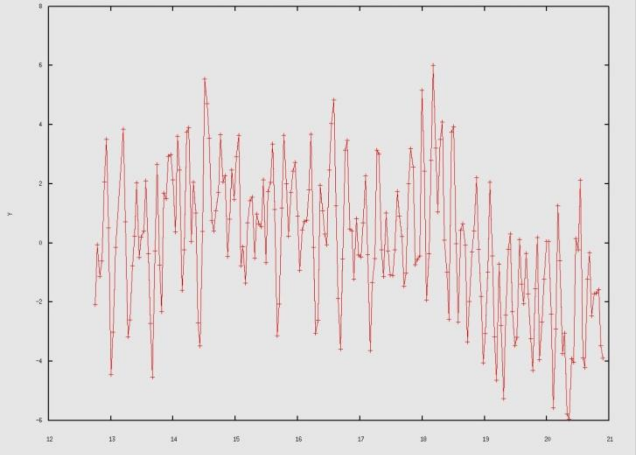
mu Arae, HARPS 2004



51 Peg, SOPHIE 2007



iota Hor, HARPS 2006

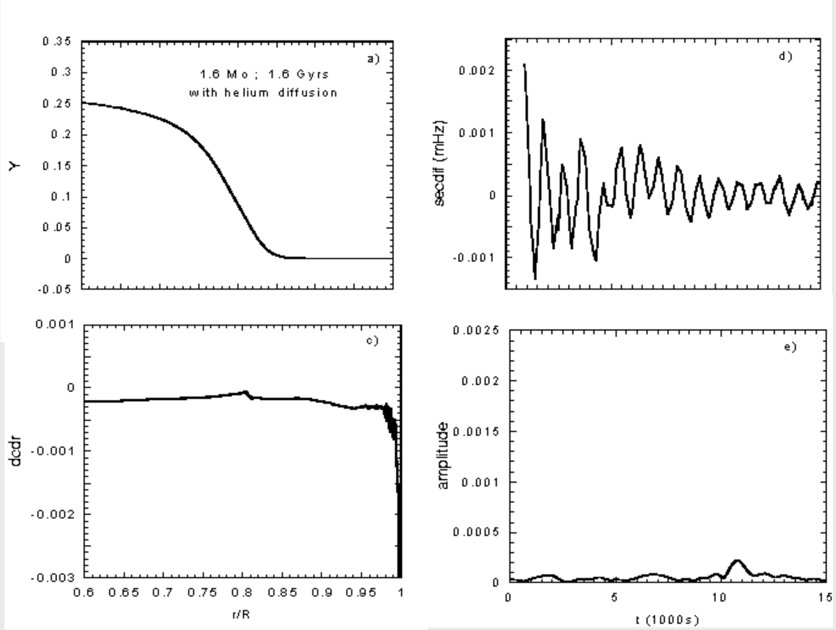


94 Cet, HARPS 2007

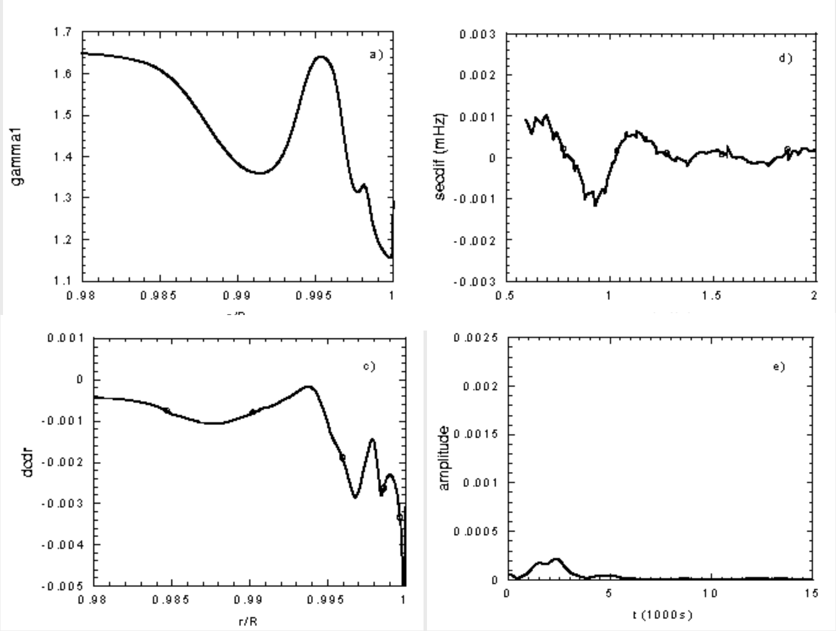
Caracterisation of Ysurf and helium gradients

Frequency fluctuations due to wave partial reflexion in regions of rapid variations of c

Second differences : $\delta_2 \nu_n = \nu_{n+1} + \nu_{n-1} - 2\,\nu_n$



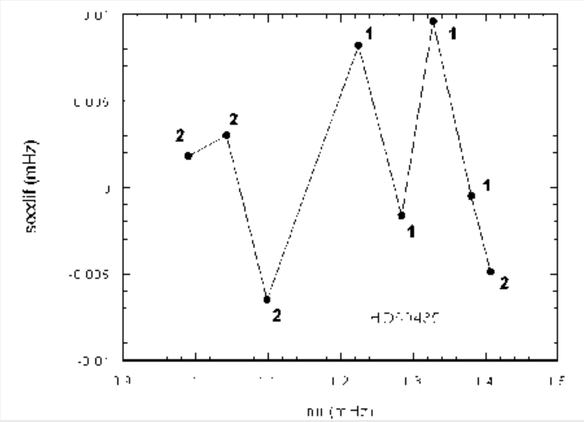
with diffusion

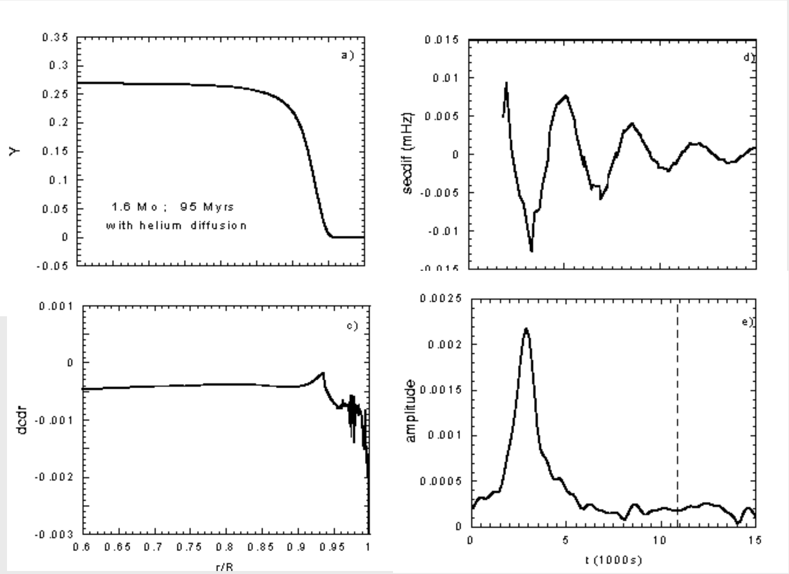


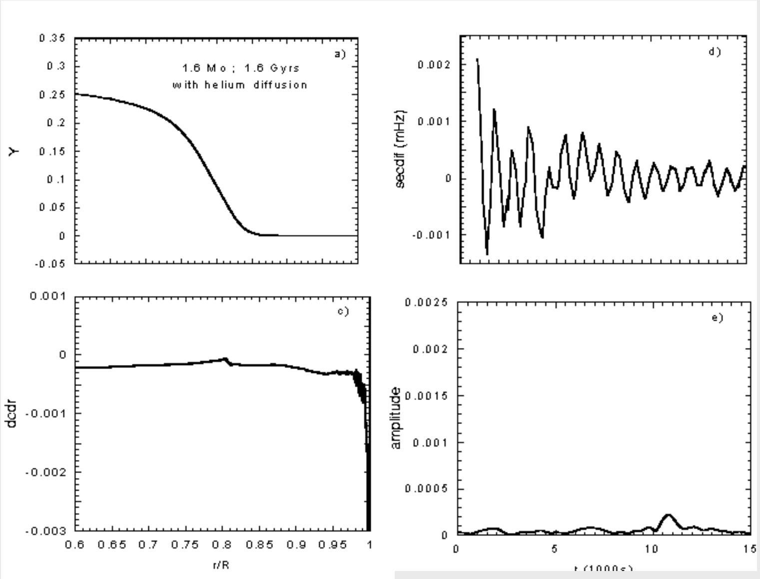
without diffusion

1.6Mo , 1.6 Gyr

Example: The roAp star HD 60435,
Possible helium gradient at r/R = 0.93



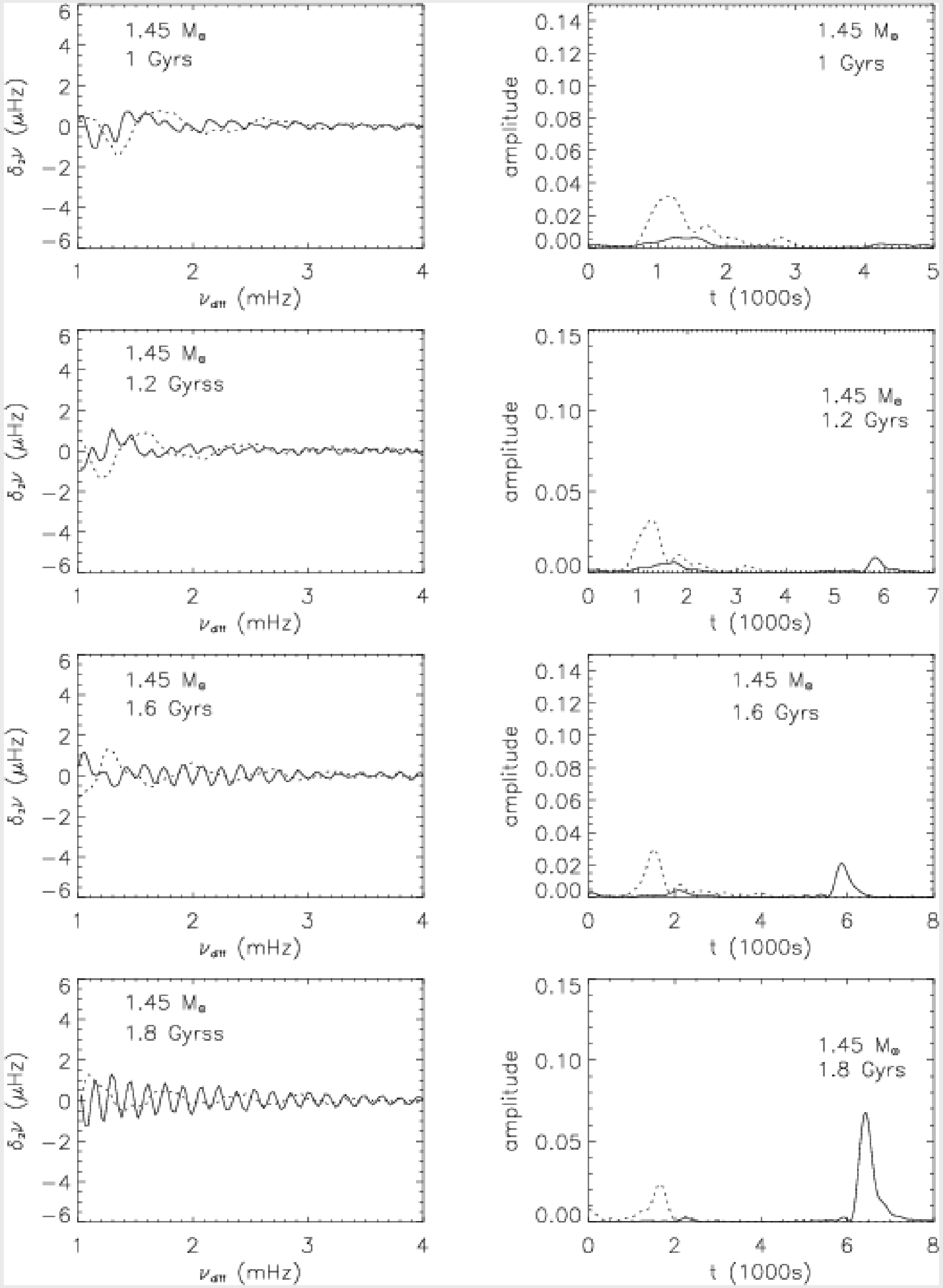




(Vauclair et Théado 2004)

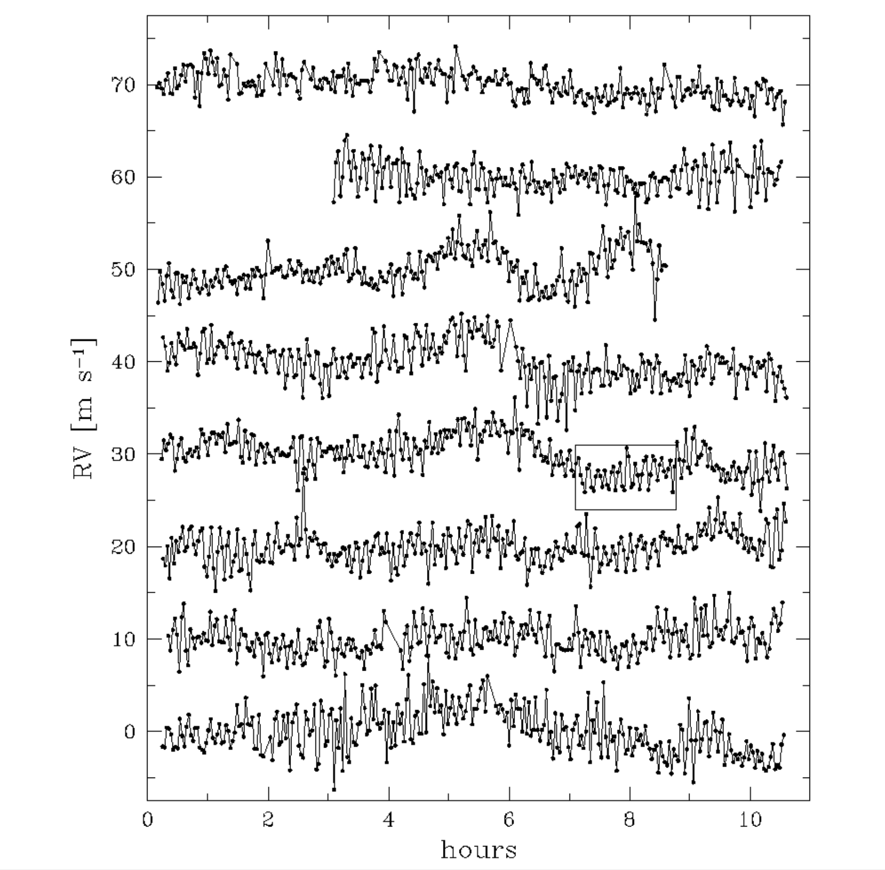
second example (theoretical) :
Helium gradients in solar type stars
Castro et Vauclair 2006

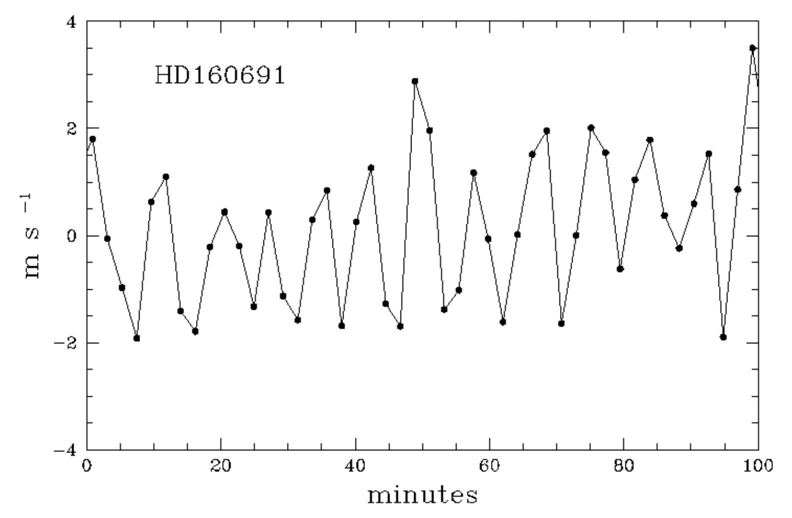
solid lines: with diffusion
dashed lines: without diffusion

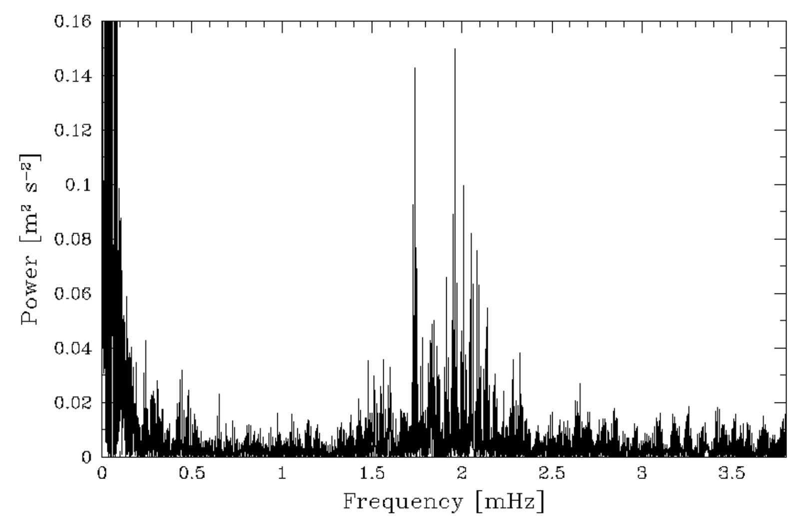


Y_{init} determinations

1st ex: mu Arae, HD 160691

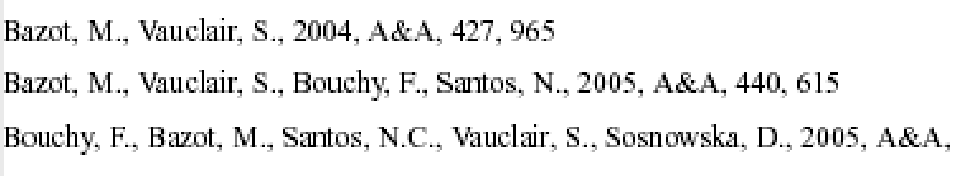






43 detected modes , l = 0 to 3

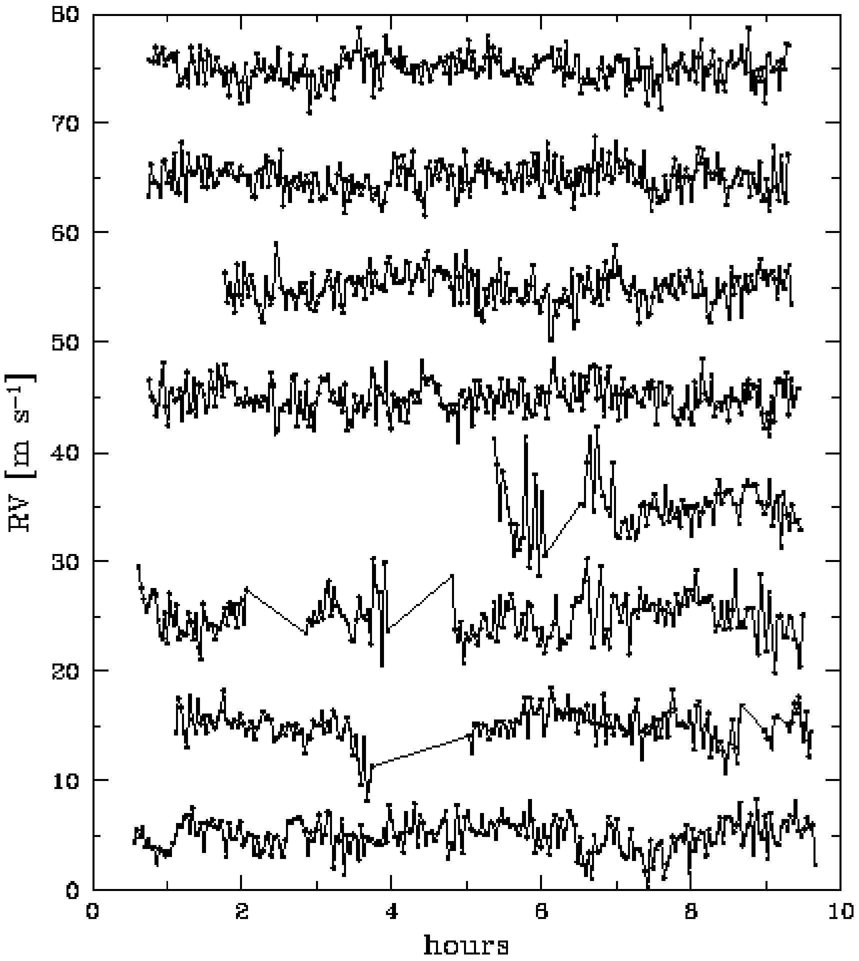
Ages from chromospheric index:
6.41 Gyr (Donahue 93)
1.45 Gyr (Rocha Pinto and Maciel 98)
(Cf. Saffe, Gomez & Chavero 2008)

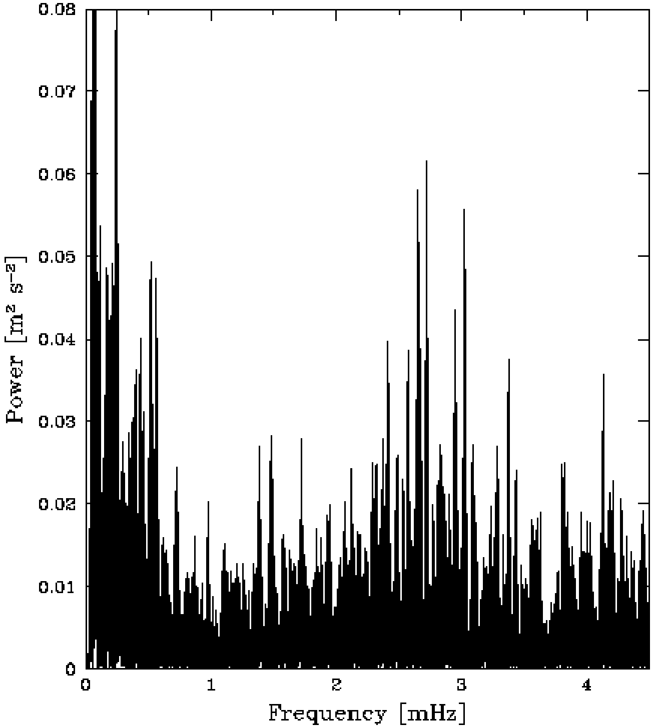

Bazot, M., Vauclair, S., 2004, A&A, 427, 965

Bazot, M., Vauclair, S., Bouchy, F., Santos, N., 2005, A&A, 440, 615

Bouchy, F., Bazot, M., Santos, N.C., Vauclair, S., Sosnowska, D., 2005, A&A,

2nd ex: iota Horologii

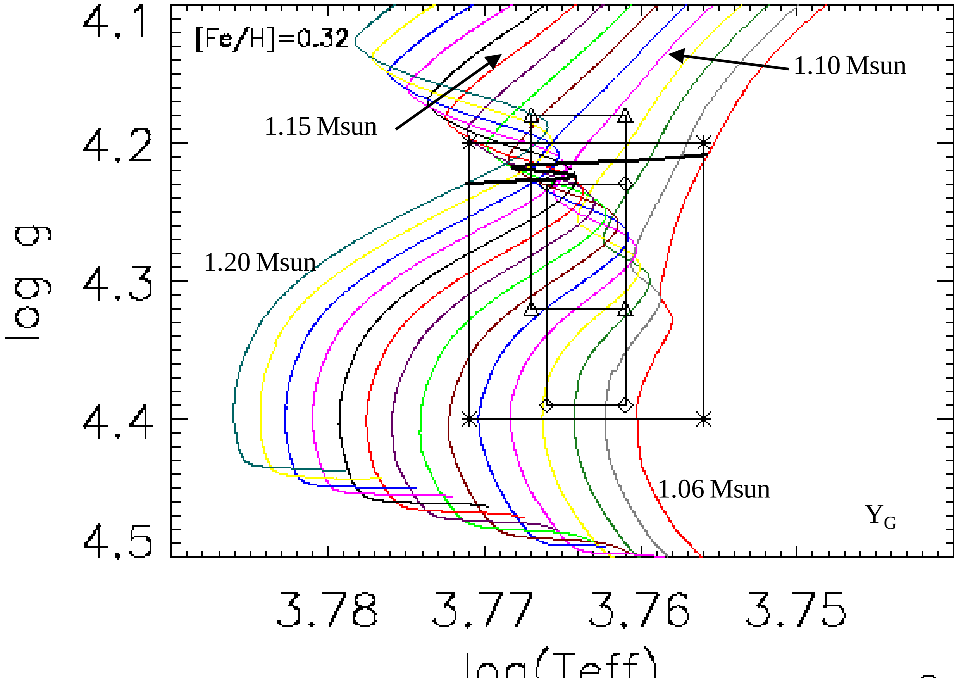




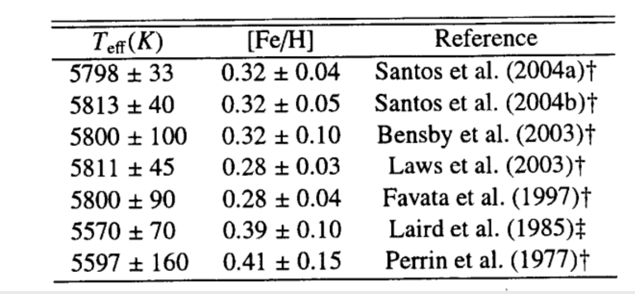
8 nights with HARPS, November 2006
25 identified modes

Ages (Gyr): 1.47 (D93); 0.43 (RPM98)
Isochrones: 3.6 (1.1 to 6.7) ; (Saffe et al.)

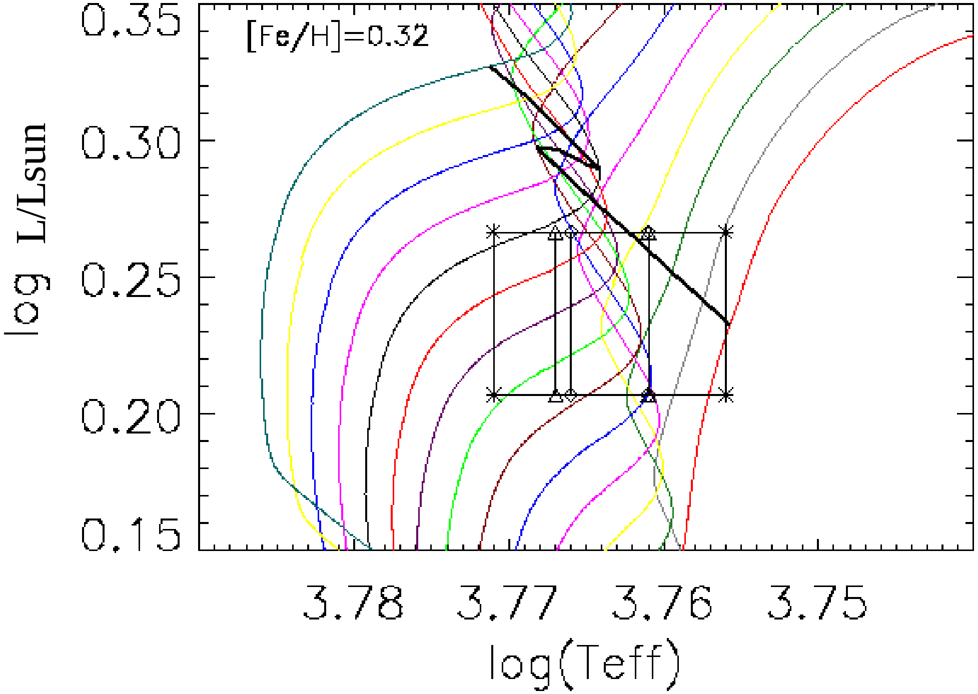
Laymand, Bouchy, Vauclair et al.

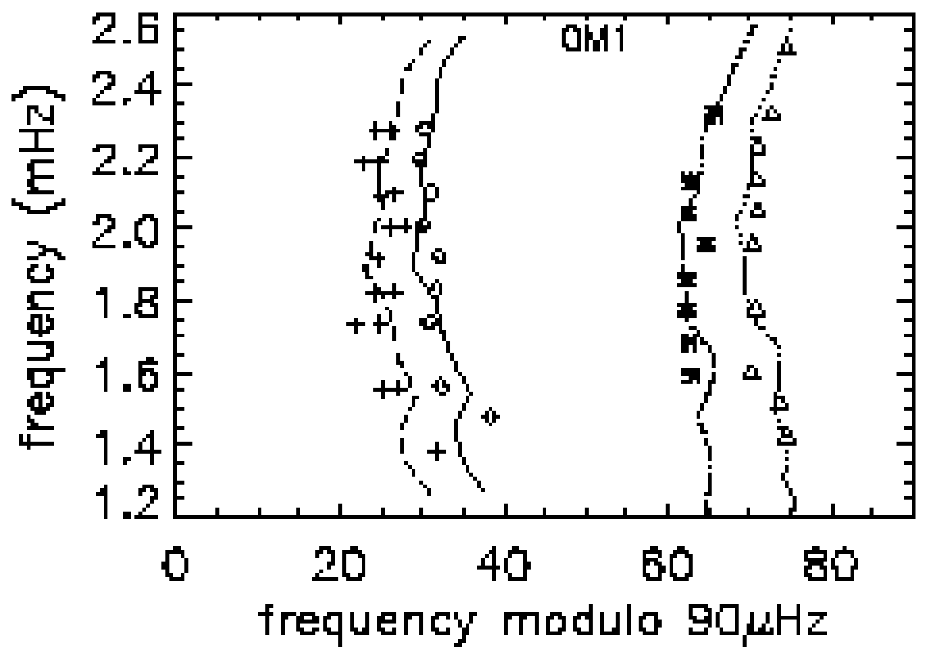


Ex of model computations:
μ Arae
(Soriano et al. 2009)



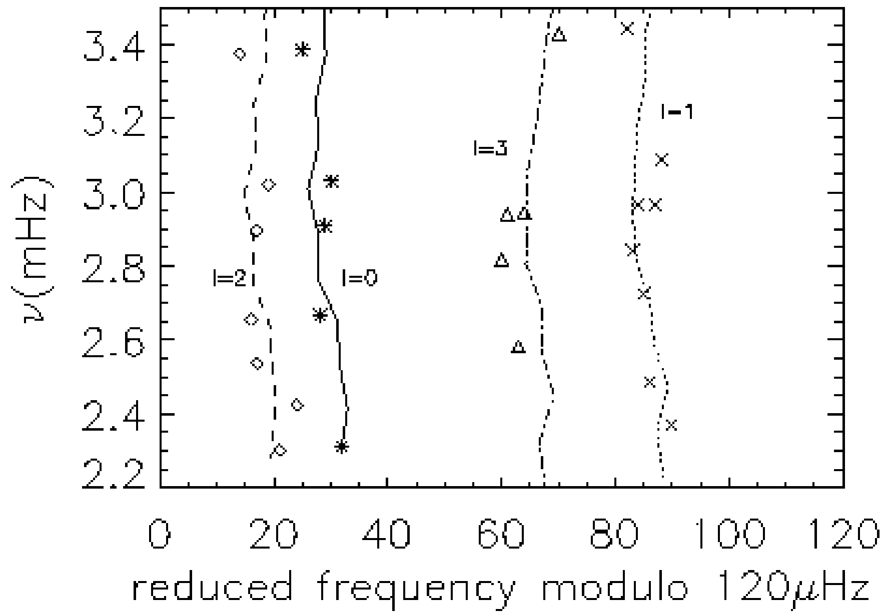
$T_{\mathrm{eff}}(K)$	[Fe/H]	Reference
5798 ± 33	0.32 ± 0.04	Santos et al. (2004a)†
5813 ± 40	0.32 ± 0.05	Santos et al. (2004b)†
5800 ± 100	0.32 ± 0.10	Bensby et al. (2003)†
5811 ± 45	0.28 ± 0.03	Laws et al. (2003)†
5800 ± 90	0.28 ± 0.04	Favata et al. (1997)†
5570 ± 70	0.39 ± 0.10	Laird et al. (1985)‡
5597 ± 160	0.41 ± 0.15	Perrin et al. (1977)†

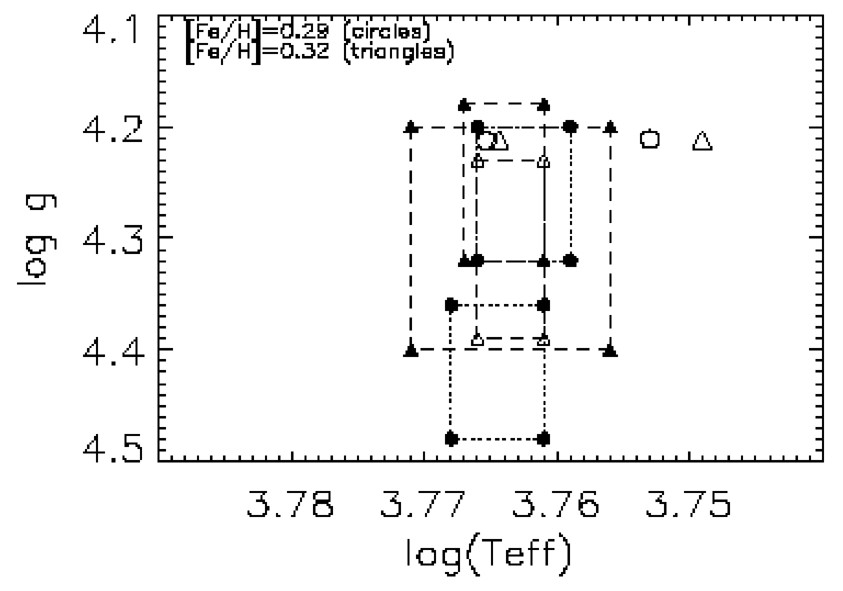




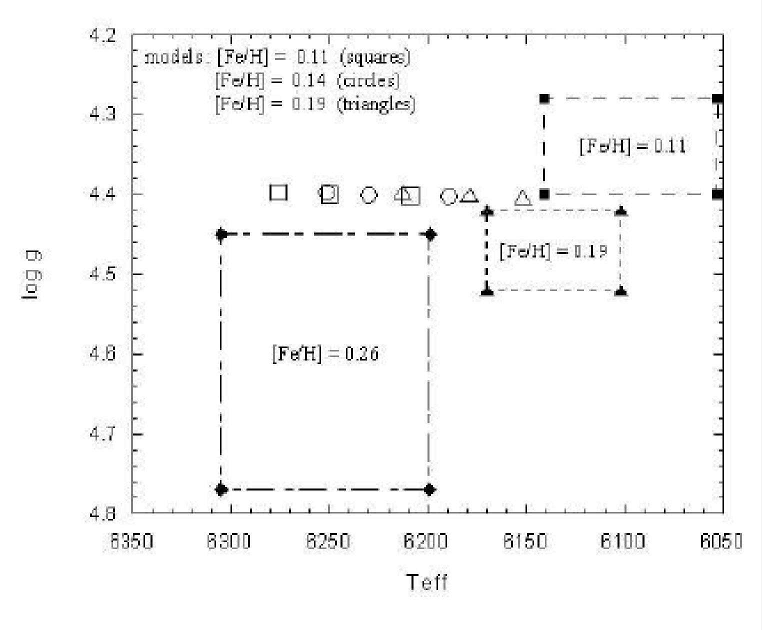
<- mu Arae

iota Hor ->





M/Mo = 1.10+/- 0.01
Log g = 4.215+/- 0.01
Y = 0.30+/- 0.01
[Fe/H] = 0.30 +/- 0.03
Age = 6.34+/- 0.4 Gyr



M/Mo = 1.25 +/- 0.01
Log g = 4.40 +/- 0.01
Y = 0.255 +/- 0.015
[Fe/H] = 0.16 +/- 0.03
Age = 625 +/- 5 Myr

Note: does not include uncertainties on physics: opacities, EOS, nuclear reactions rates, etc.

conclusions

- Crisis for the Sun

-It is just beginning for solar type stars

-Determinations of Y in progress

-Other elements… non standard mixing? (cf Eggenberger)

-Improvements with CoRoT and Kepler.