Helioseismology
Low degree oscillations of the Sun : From the South Pole to SoHO

(the point of view of an observer)

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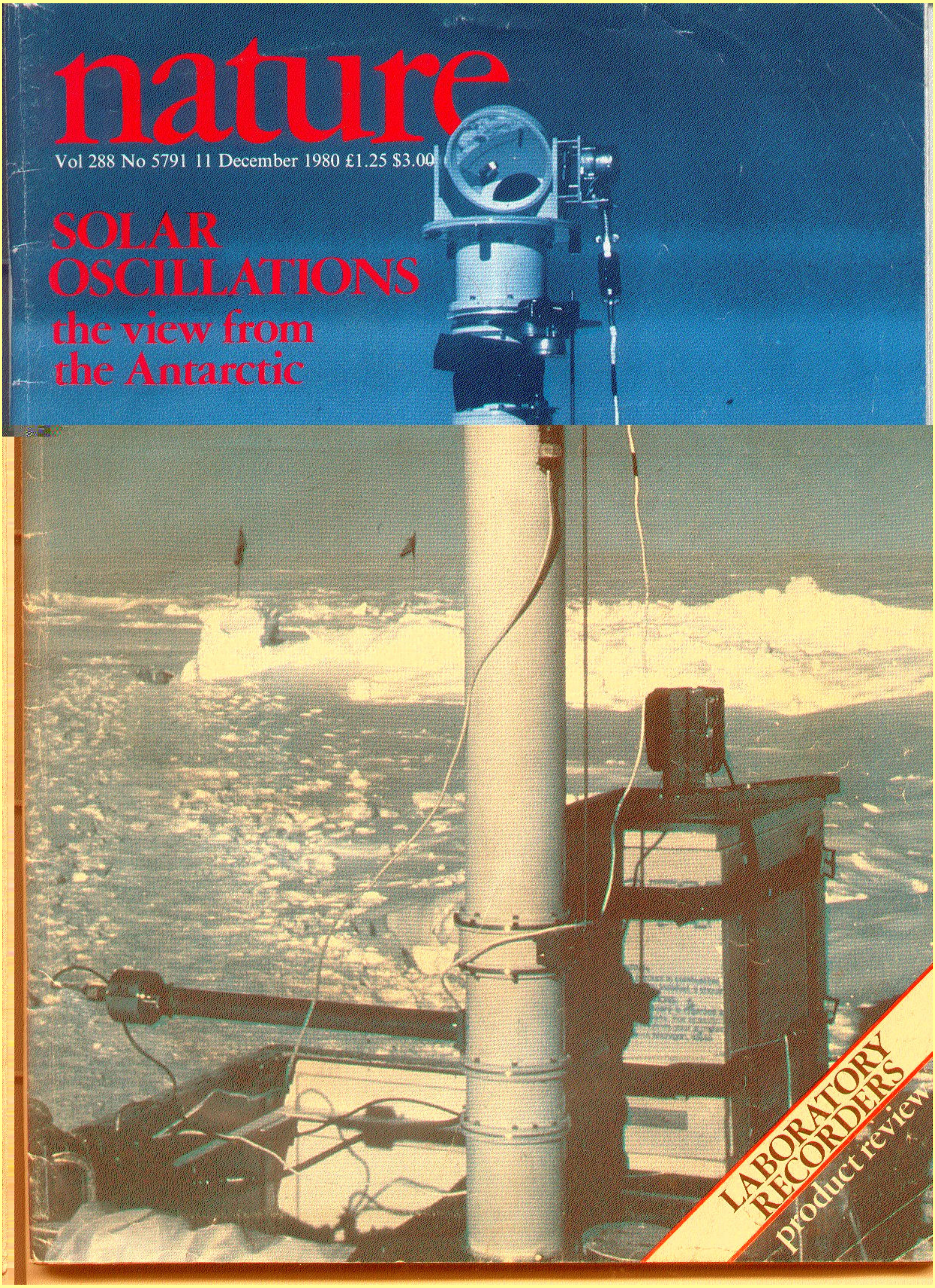
For the GOLF data analysis collaboration with:
E. Fossat, M. Lazrek, C.Renaud
Calculation of numerical solar models due to:
G. Berthomieu, T. Corbard, P. Morel,
J. Provost, A. Zaatri

The south pole observations:

originally,
an experiment to improve the observation
of the 160 min oscillation

A spectrophotometer using the optical
resonance in sodium vapor to measure
the Doppler shift related
to the photospheric velocity field
averaged on the solar disk



nature

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SOLAR OSCILLATIONS the view from the Antarctic

LABORATORY RECORDERS product review

1979: First observations at the south pole G. Grec, E. Fossat, M. Pomerantz

The first spectrum showing separately the p modes from *l* =0 to *l* =3

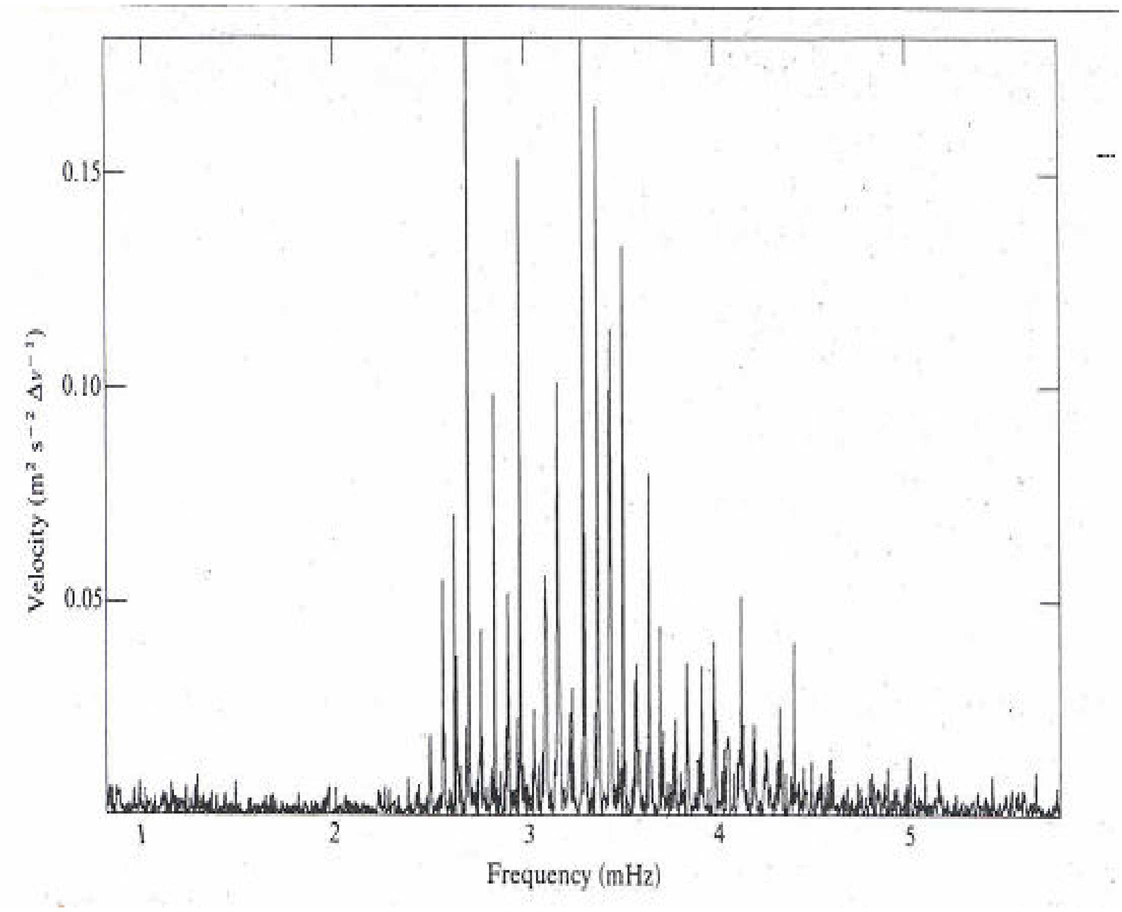


Fig. 1 Power spectrum of the continuous 5-day full-disk Doppler shift measurements recorded at the South Pole from 31 December, 1979 to 5 January, 1980. The resolution of the power in 3-mHz range into many discrete equidistant lines separated by 68 µHz indicates that global *p*-modes corresponding at least to *l* values of 0 and 1 are observed. Note that the small peaks around 2.4 mHz represent global oscillations with an amplitude <10 cm s-1, corresponding to motion of the solar radius <5 m, or 7×10-6 arc s.

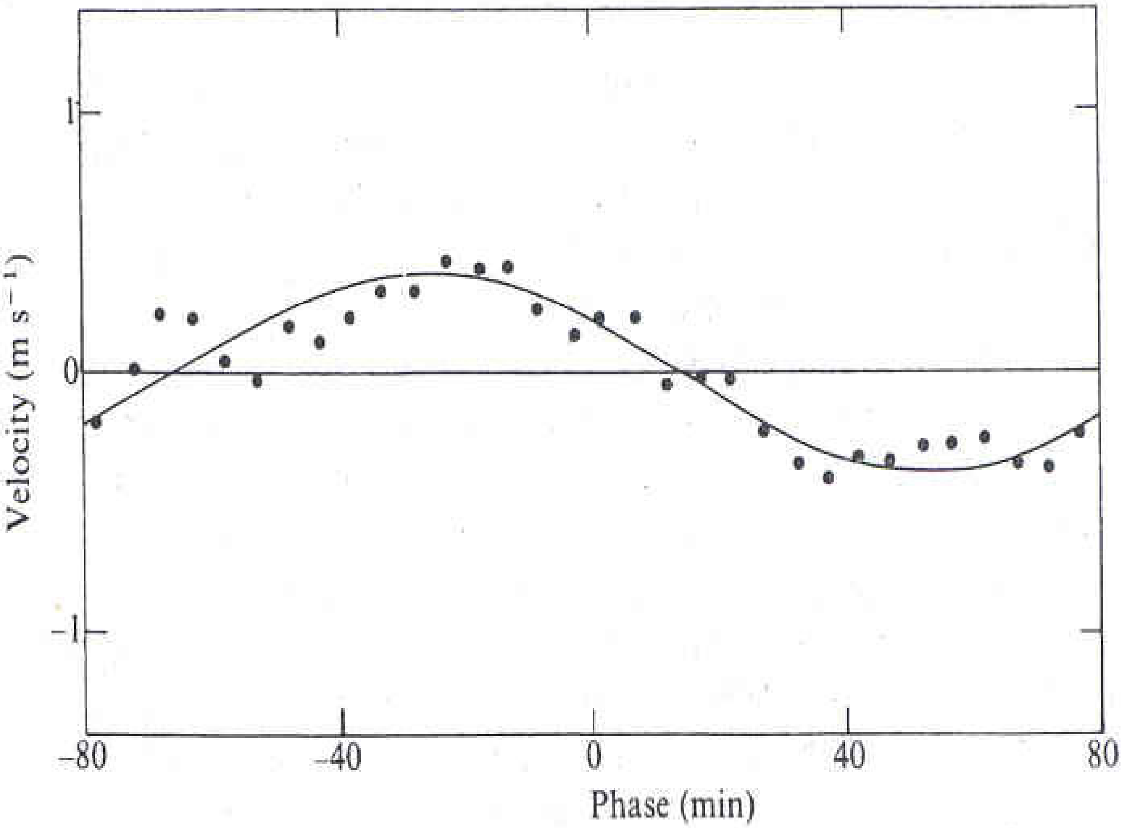


Fig. 4 The superposed epoch analysis of a data sample extending over 5 days (45 periods of 160 min). The points represent the South Pole data, and the solid line is the average based upon the observations obtained at the Crimean Observatory and Stanford.

Helioseismology in space

“After the impressive progress resulting
from 7 days of uninterrupted observation
of the Sun made at the south pole,
I was convinced of the strong interest to
have uninterrupted observations from space,
possibly lasting several years“

R.M. Bonnet,
former scientific director of ESA,
(Orsay, 10 y of SoHO meeting)

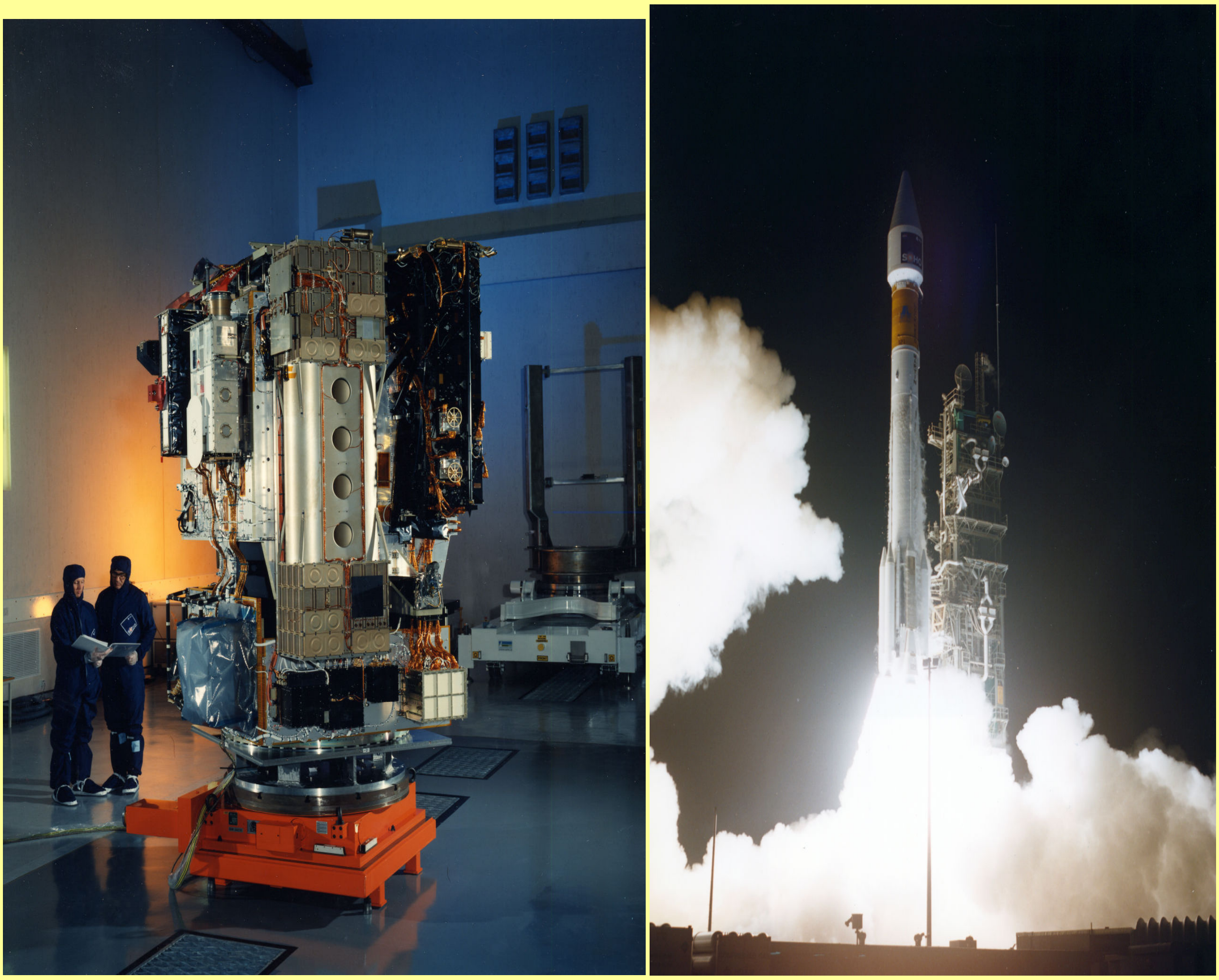
SoHO is a solar observatory, on a halo orbit circling the L1 Lagrange point.
It carries 11 instruments, 3 of those are dedicated to helioseismology :

- MDI, imaging the photospheric velocity field with a resolution of 1 mega pixel.
(and imaging the magnetic field)

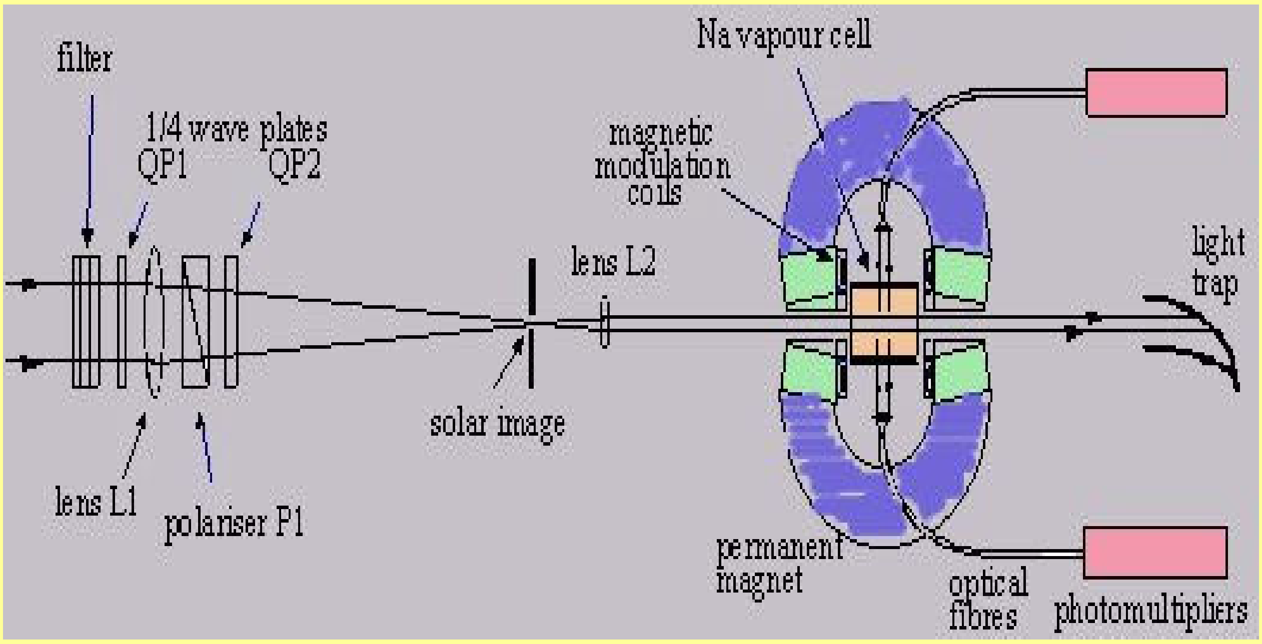
- GOLF, measuring the photospheric velocity averaged over the solar disk

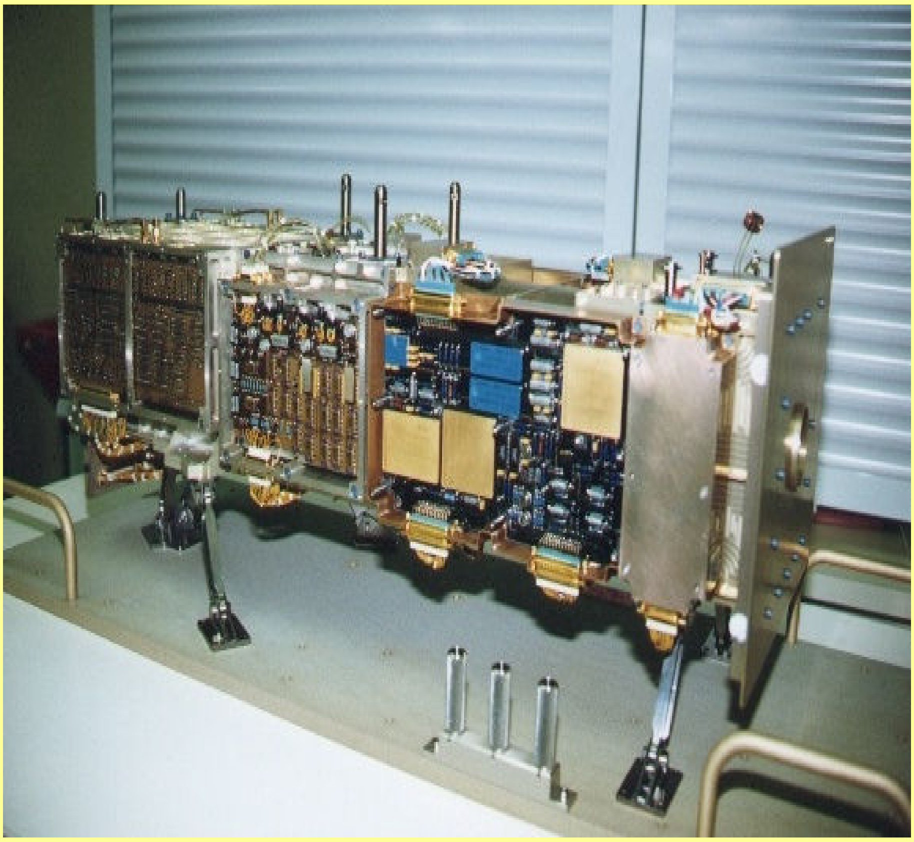
- VIRGO, measuring the solar irradiance.
(and low resolution imaging of luminosity)

The initial mission was 3 y.
Today, several additional years of operations are still foreseen, the helioseismic data will cover more than a 11 y solar cycle, probably until the SDO launch.



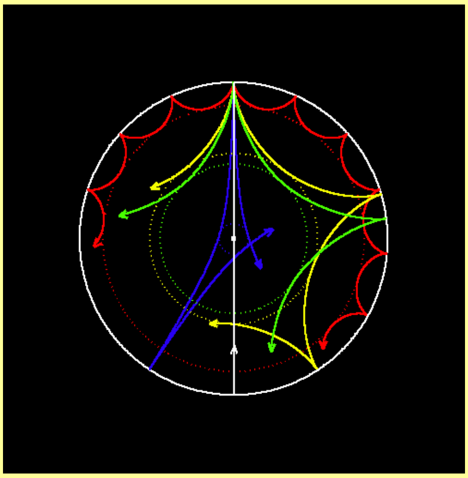
GOLF: Helioseismology aboard SoHO. Launch, December 1995



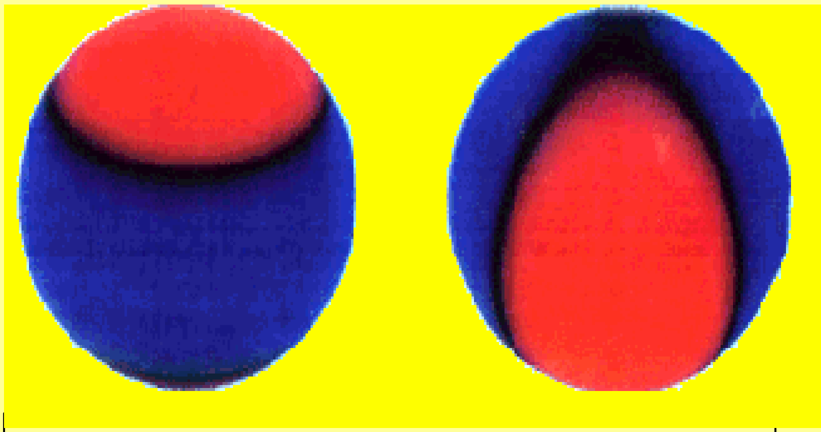


The GOLF instrument: a monochromatic filter select a narrow band to measure the Doppler shift averaged over the full solar disk

The Sun observed as a star : Low degree resonant modes

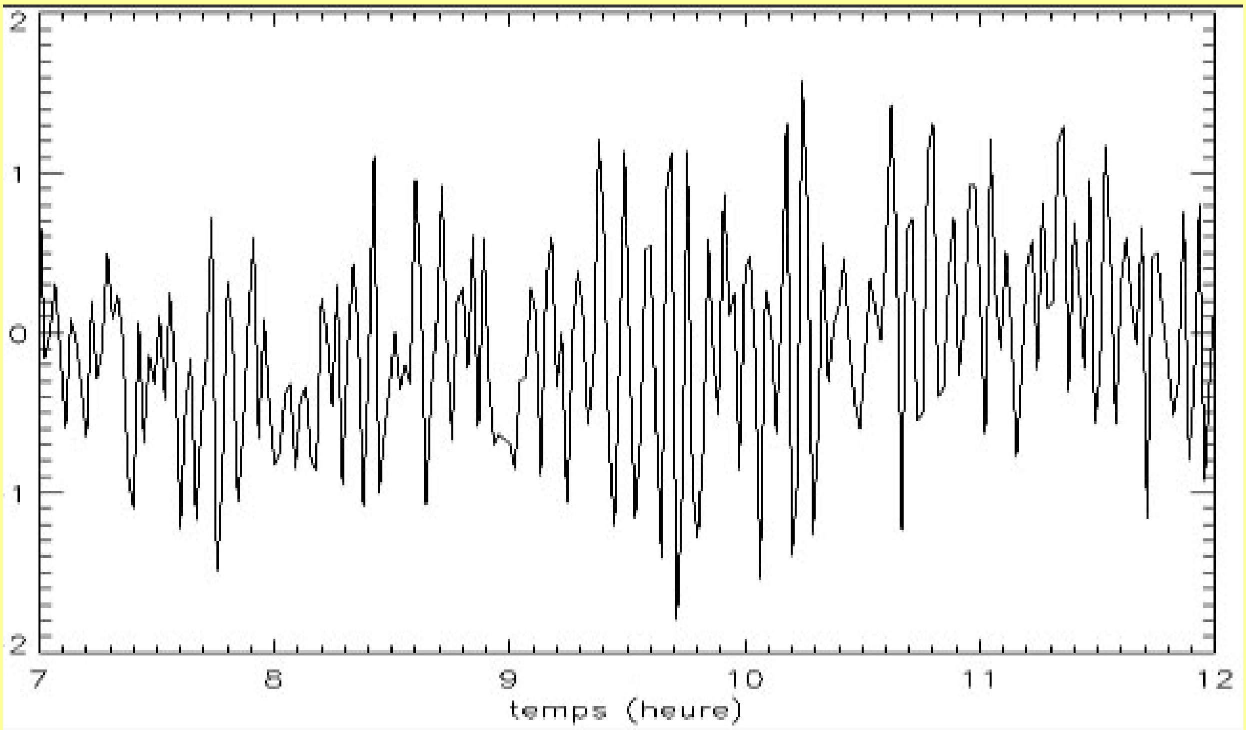


Propagation of an acoustical perturbation



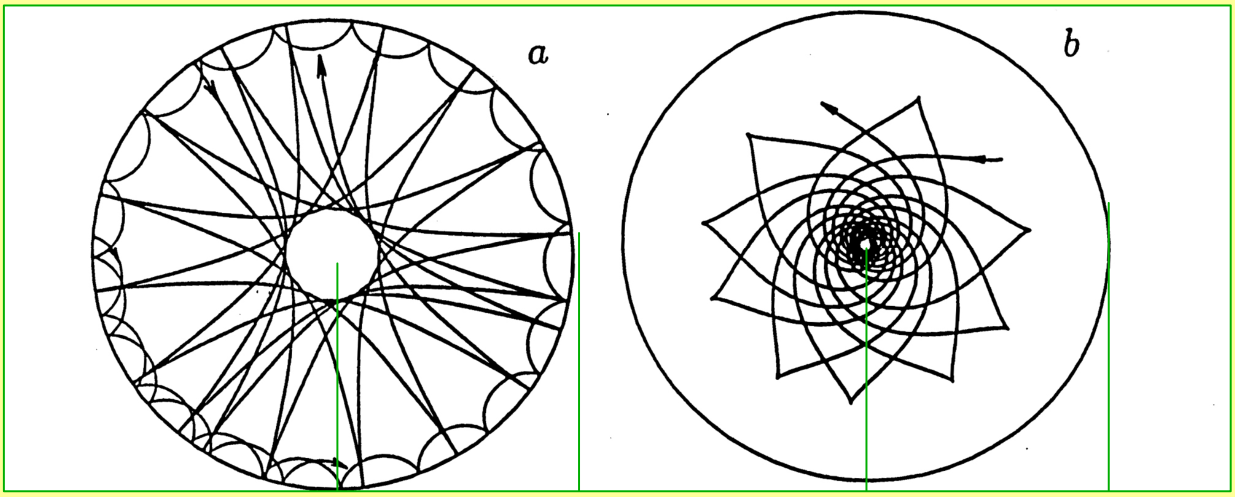
***l*=1 *m*=0** **l=1 m=±1**

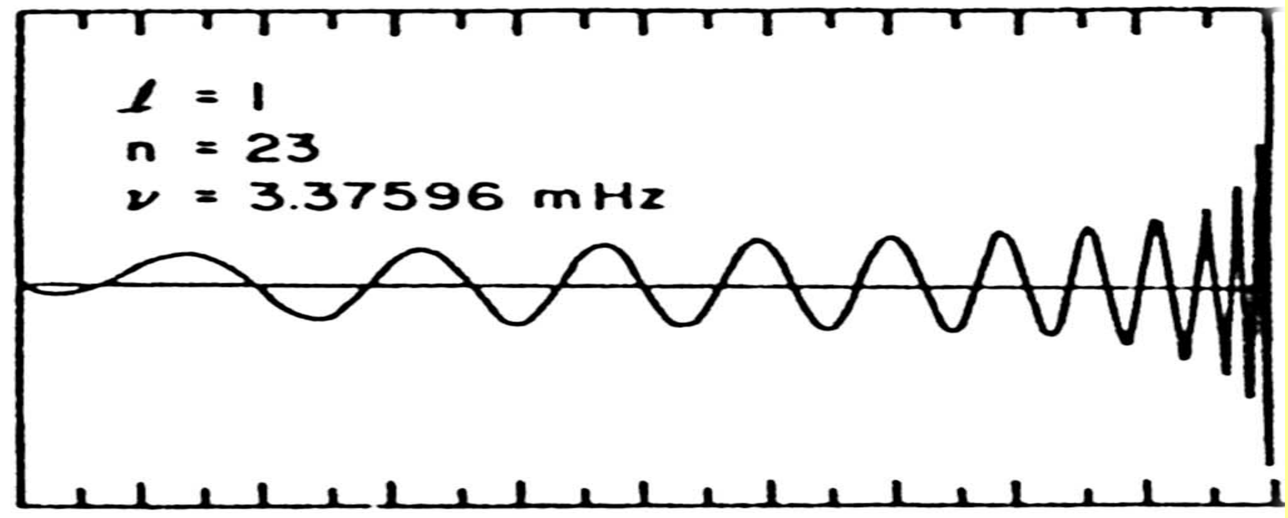
degree *l*, tesseral order *m*, radial order *n*

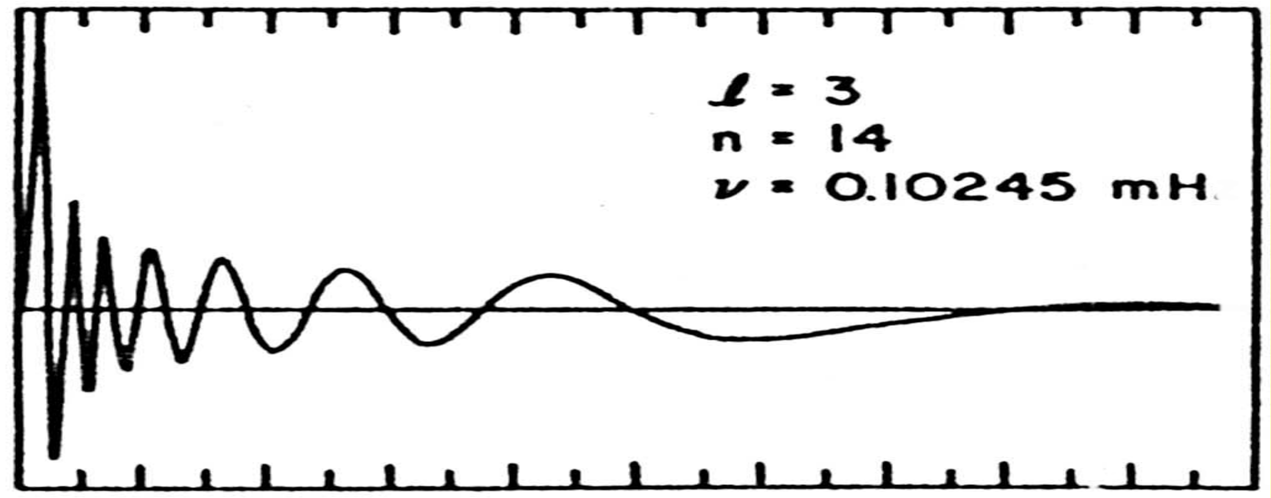


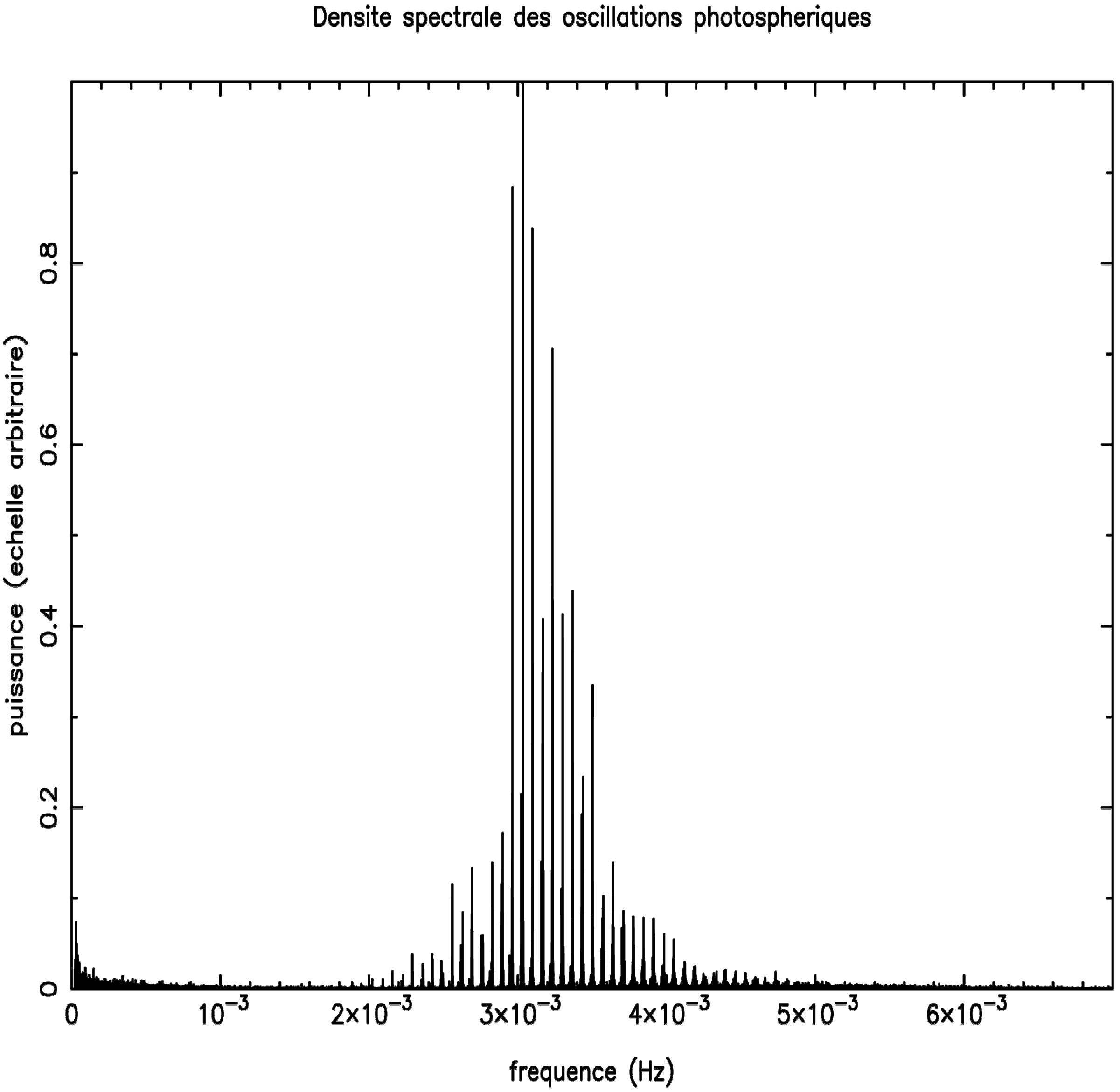
temporal series

Pressure modes / gravity modes









a solar spectrum calculated from several years of GOLF data

The frequency of the low degree modes follow a periodical law, depending on the radial order n and on the degree l, (Tassoul, 1980).

$$\nu_{n,l} = (n + \frac{l}{2} + \epsilon)\ \nu_0 \ - \ \frac{l\ (l+1) + \delta}{n + l/2 + c}\ A$$

where

$$\nu_0 = \left(2 \int_0^{R_S} \frac{dr}{c}\right)^{-1}$$

is proportional to $\sqrt{\frac{GM}{R_S^3}}$
R_S being the solar radius, $1/\nu_0$ is the time needed to an acoustical perturbation to cross the solar sphere.

At the first order a p-mode frequency is

$$\nu_{n,l} = (n + \frac{l}{2} + \epsilon)\ \nu_0$$

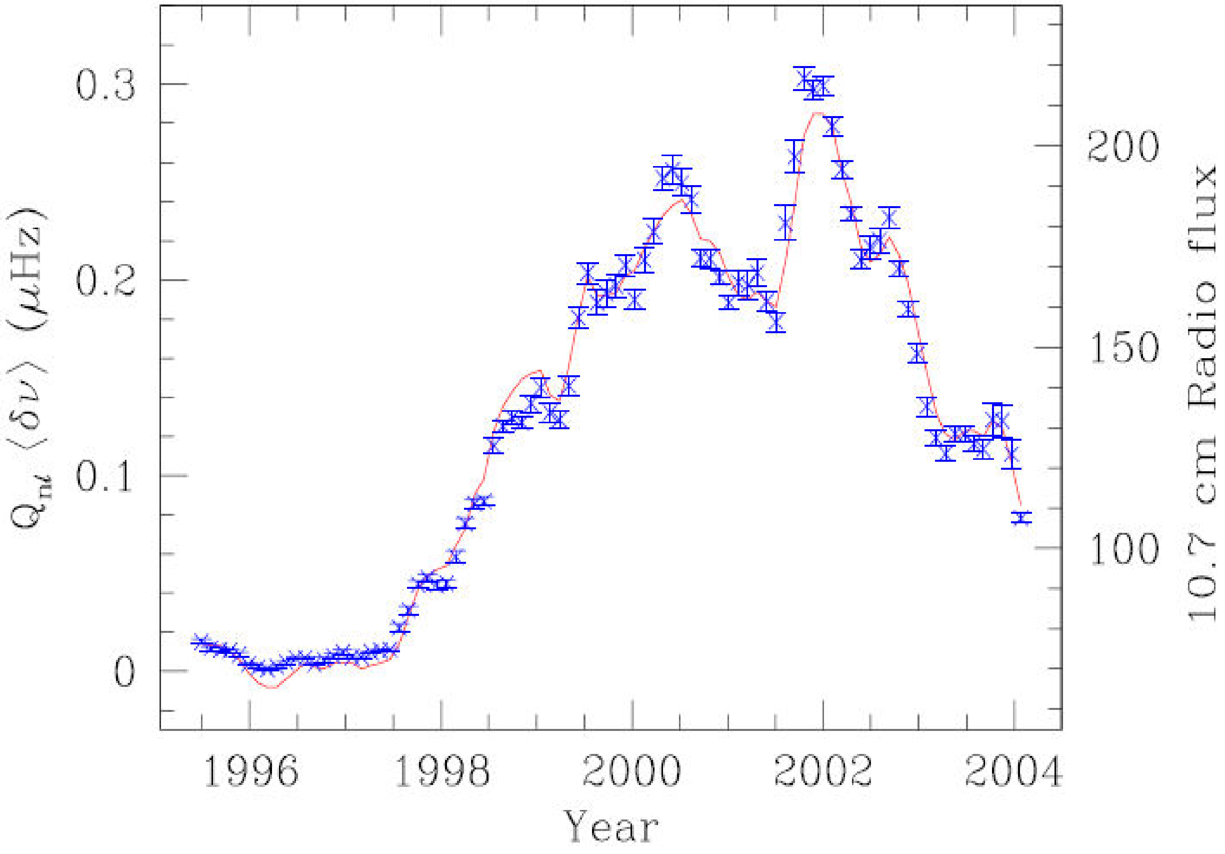
ϵ, A, δ, c depends on the physics of the whole solar sphere and can be calculated from a solar model, involving the evolution and the chemical composition.

That is the first step of the successful analysis,

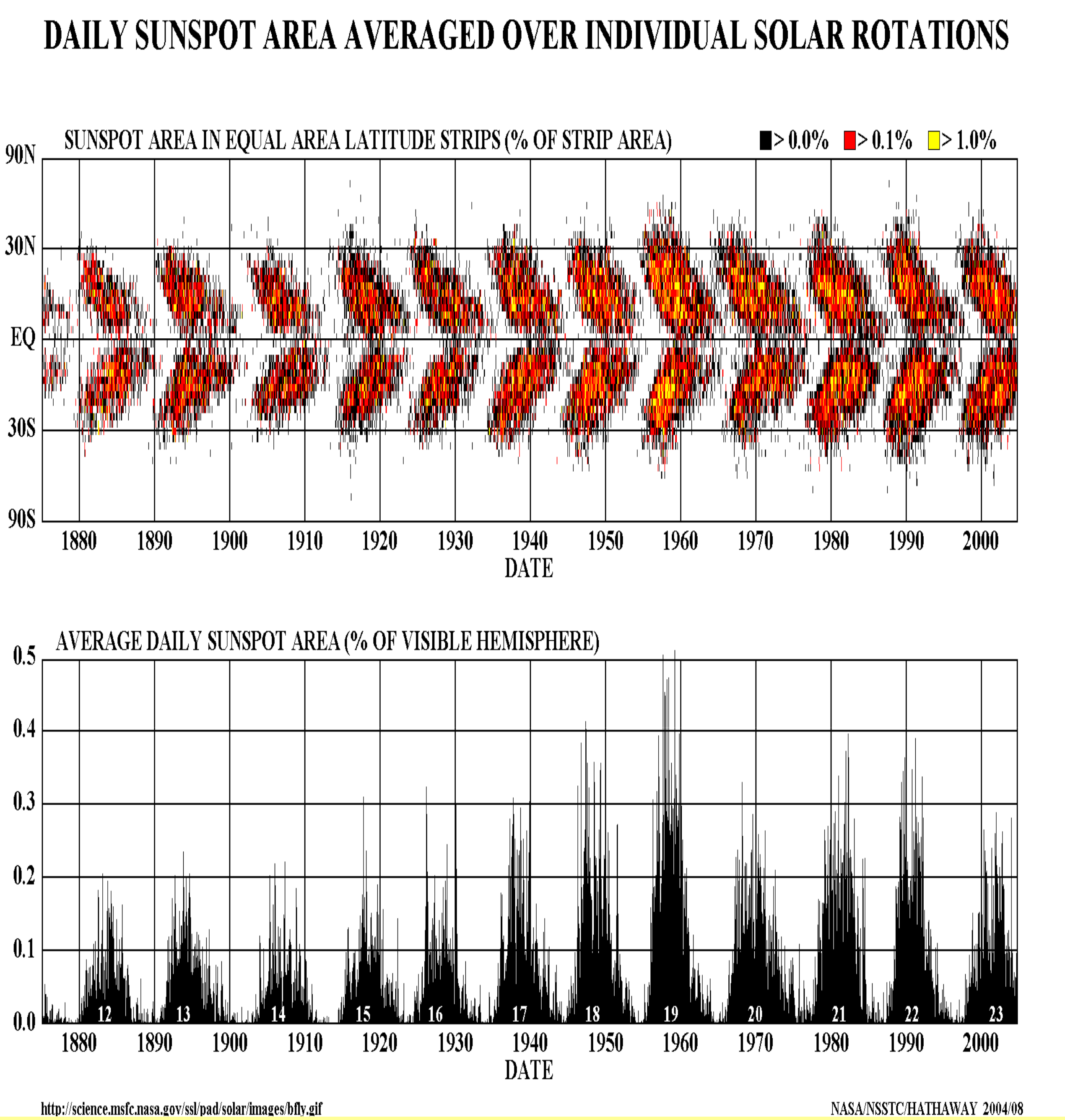
but...

The “numerical Sun” is not the real Sun.

The Sun is a variable star,
the Sun is a magnetic star...



10.7 cm radio flux for the current solar cycle


DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS
SUNSPOT AREA IN EQUAL AREA LATITUDE STRIPS (% OF STRIP AREA)
■> 0.0% 🟥> 0.1% 🟨> 1.0%
90N
30N
EQ
30S
90S
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
DATE
AVERAGE DAILY SUNSPOT AREA (% OF VISIBLE HEMISPHERE)
0.5
0.4
0.3
0.2
0.1
0.0
12
13
14
15
16
17
18
19
20
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23
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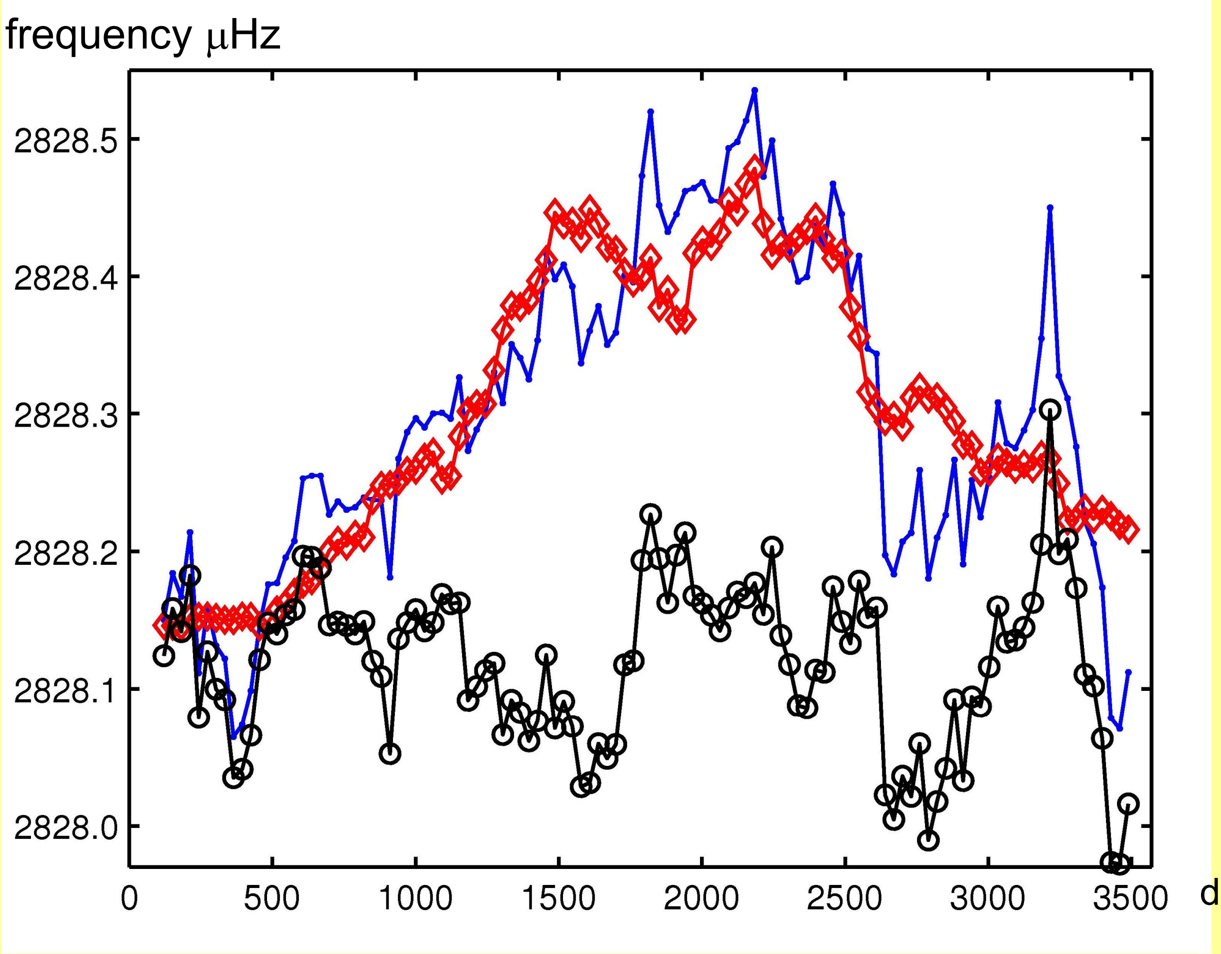
2000
DATE
http://science.msfc.nasa.gov/ssl/pad/solar/images/bfly.gif
NASA/NSSTC/HATHAWAY 2004/08

All analytic calculations made from the data coming from p-mode observations are not able to include the magnetic activity.

Next question for observers:

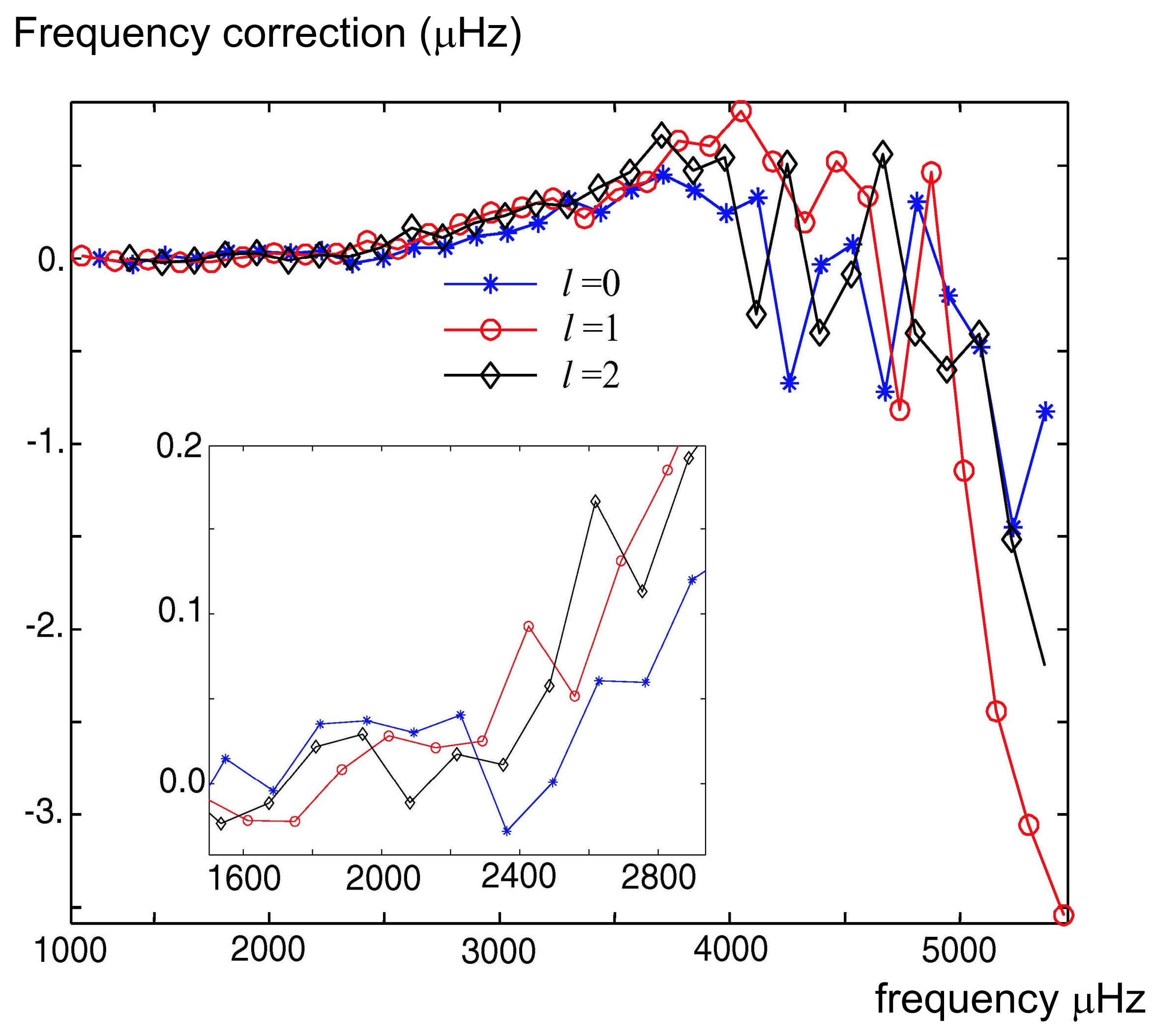
Do the p-mode frequencies change with the solar activity ?

from a preprint on GOLF data analysis :
M. Lazrek, G. Grec, E. Fossat, C.Renaud

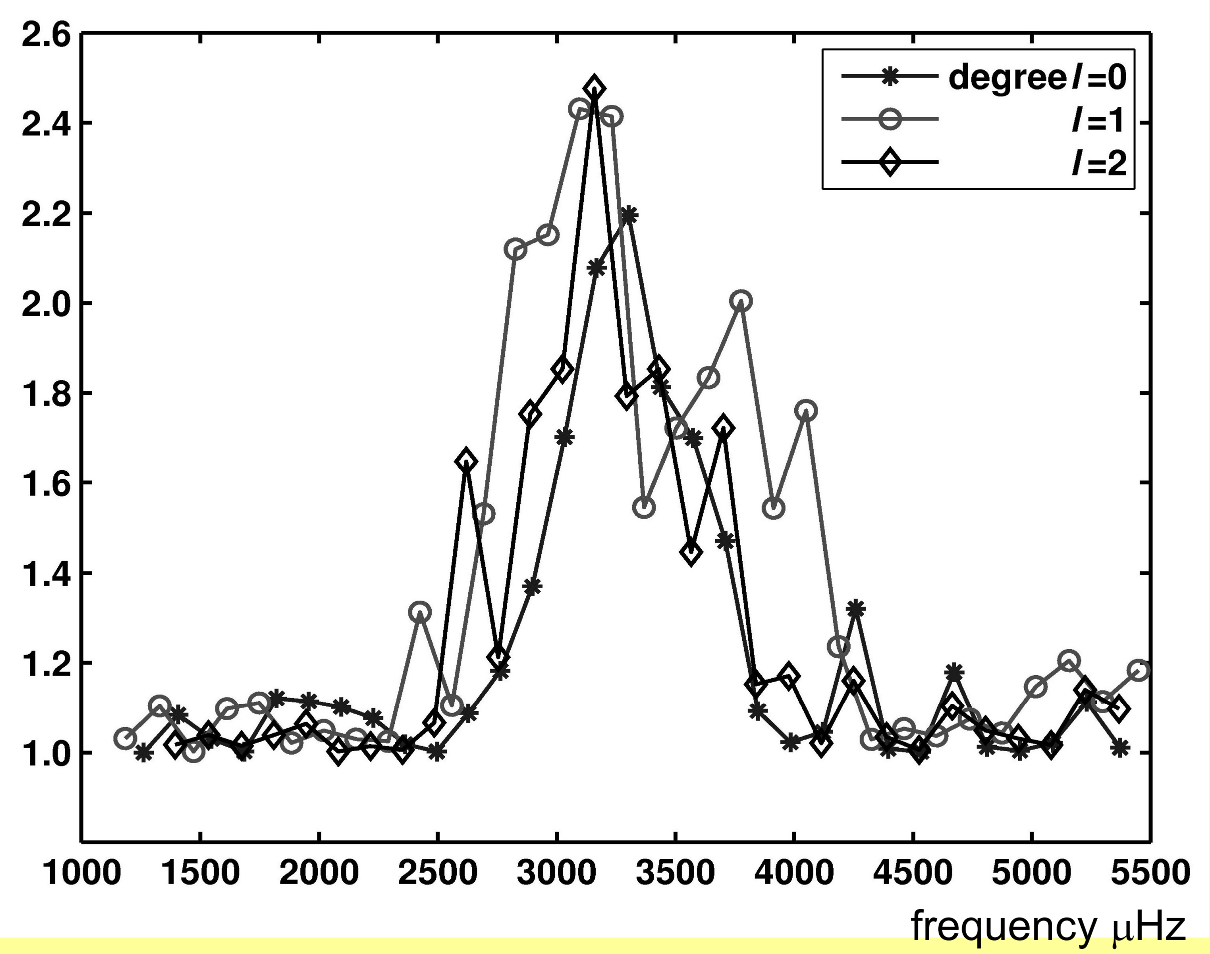


04 1996 02 2006

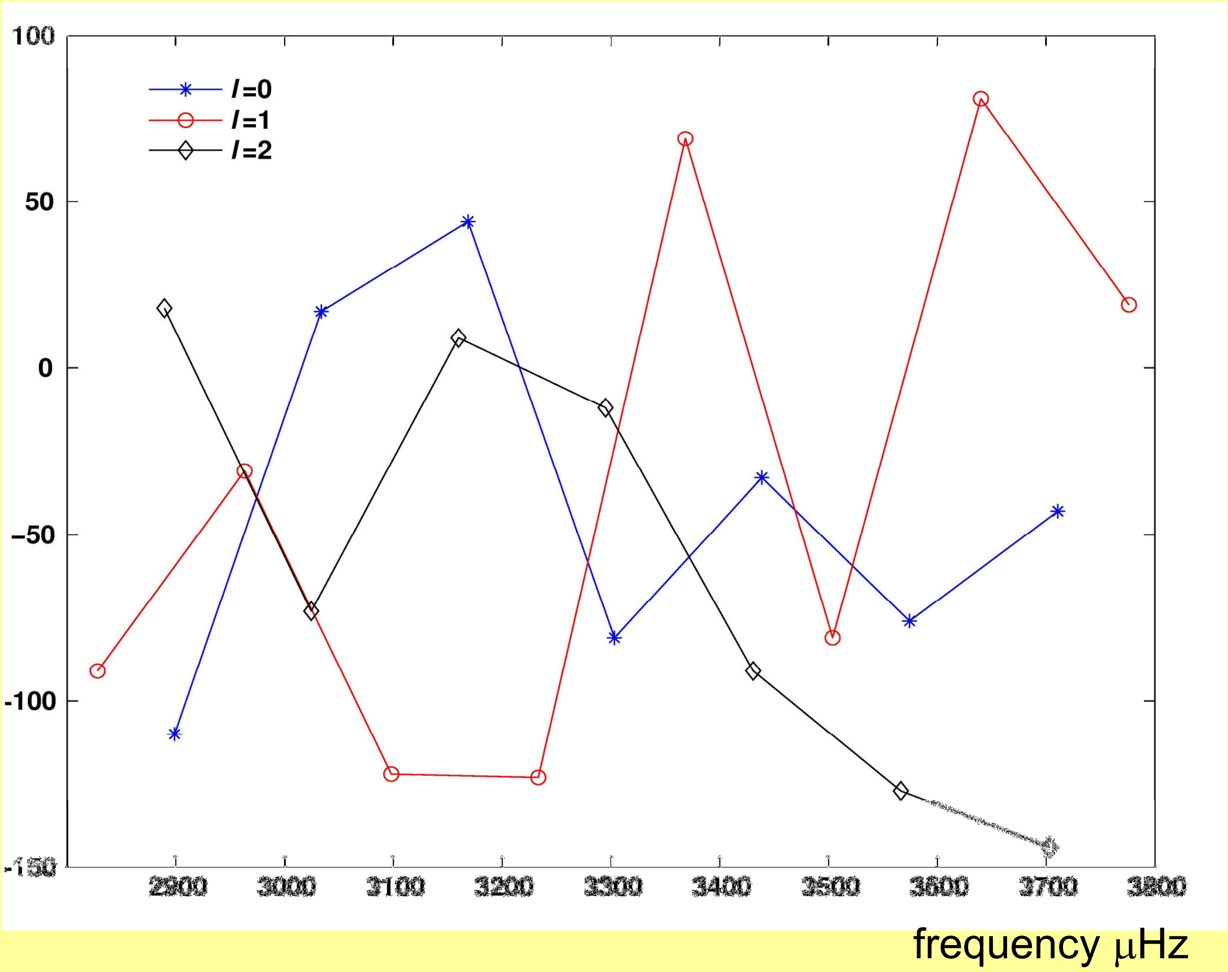
Frequency changes of a single acoustic mode (solid line)
Solar activity : Mount Wilson MPSI (squares)
Corrected frequency (circles)



Amplitude of the corrections for the magnetic activity induced shift, computed for each mode of degree *l*=0, *l*=1 and *l*=2



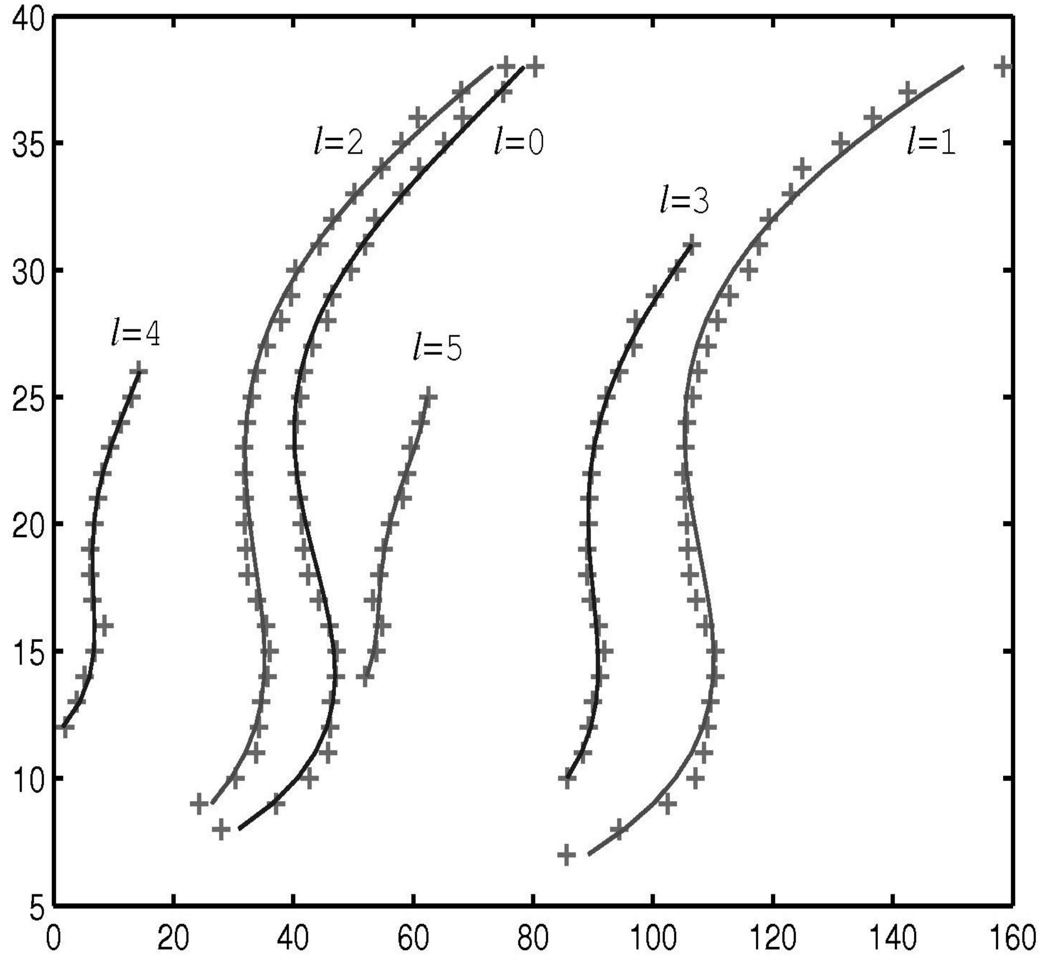
Ratio of σ measured without correction for the solar activity to σ measured after correction



Delay (in d) for the best fit of solar activity index to p mode frequencies. Most p modes vary earlier

Table 1: Frequency f and his uncertainty σ of p modes of degree l and radial order n, the unit is μHz. (M. Lazrek, G. Grec, E. Fossat, C. Renaud, submitted to A & A)

	l=0		l=1		l=2		l=3		l=4		l=5	
n	f	σ	f	σ	f	σ	f	σ	f	σ	f	σ
7			1185.577	0.012								
8	1263.220	0.008	1329.637	0.007	1394.676	0.022						
9	1407.489	0.016	1472.846	0.014	1535.862	0.017	1591.31	0.04				
10	1548.310	0.013	1612.730	0.010	1674.541	0.017	1729.09	0.05	1778.01	0.07		
11	1686.584	0.017	1749.314	0.010	1810.302	0.017	1865.30	0.04	1915.06	0.06		
12	1822.161	0.013	1885.080	0.014	1945.772	0.019	2001.18	0.04	2051.62	0.11	2098.33	0.09
13	1957.416	0.014	2020.788	0.017	2082.131	0.022	2137.56	0.06	2188.42	0.05	2235.45	0.09
14	2093.492	0.014	2156.794	0.021	2217.647	0.027	2273.43	0.05	2325.02	0.26	2371.65	0.46
15	2228.760	0.020	2291.993	0.026	2352.282	0.032	2407.69	0.05	2458.42	0.29	2505.51	0.49
16	2362.846	0.019	2425.523	0.019	2485.869	0.026	2541.62	0.04	2593.30	0.18	2641.60	0.52
17	2496.233	0.019	2559.217	0.019	2619.630	0.021	2676.18	0.05	2728.50	0.16	2777.43	0.59
18	2629.685	0.023	2693.331	0.019	2754.493	0.027	2811.44	0.03	2864.41	0.10	2913.70	0.34
19	2764.17	0.02	2828.12	0.02	2889.55	0.02	2946.89	0.03	3000.24	0.06	3051.00	0.28
20	2899.03	0.02	2963.23	0.02	3024.68	0.02	3082.17	0.03	3136.11	0.05	3186.59	0.24
21	3033.75	0.02	3098.08	0.02	3159.75	0.02	3217.71	0.04	3272.62	0.24	3322.84	0.25
22	3168.62	0.02	3233.05	0.02	3295.01	0.03	3353.47	0.04	3409.59	0.27	3459.69	0.38
23	3303.39	0.03	3368.59	0.03	3430.63	0.04	3489.45	0.05	3546.60	0.31	3596.12	0.27
24	3438.95	0.03	3504.10	0.04	3566.67	0.08	3625.88	0.11	3682.96	0.38		
25	3574.70	0.04	3640.24	0.05	3702.74	0.08	3763.20	0.17				
26	3710.59	0.07	3776.40	0.06	3839.57	0.13	3900.71	0.29				
27	3847.16	0.12	3913.57	0.08	3977.11	0.15	4036.35	0.61				
28	3984.89	0.14	4049.98	0.10	4113.98	0.21	4174.76	0.49				
29	4120.86	0.16	4187.19	0.11	4249.87	0.18	4313.60	0.50				
30	4259.19	0.18	4325.58	0.15	4389.12	0.18	4451.28	0.61				
31	4396.72	0.25	4462.90	0.20	4526.55	0.15						
32	4533.46	0.18	4599.32	0.18	4665.33	0.22						
33	4673.26	0.23	4738.23	0.32	4805.17	0.21						
34	4811.39	0.26	4875.29	0.32	4943.67	0.37						
35	4950.7	0.3	5016.9	0.4	5081.6	0.4						
36	5089.0	0.4	5157.4	0.7	5223.9	0.5						
37	5231.0	0.4	5298.5	0.9	5366.8	0.9						
38	5371.6	0.6	5449.6	1.2								



echelle diagram of the GOLF solar spectrum
The horizontal scale is in μHz,
the vertical scale is the radial order *n* for
degrees *l*=0 and *l*=1

Table 1: Rotationnal splitting s and his uncertainty σ of p modes of degree l and radial order n, the unit is nHz.

	l=1		l=2		l=3	
n	s	σ	s	σ	s	σ
7	429	6				
8	437	4	429	7		
9	432	6	429	5	432	7
10	445	7	435	6	440	8
11	428	8	435	6	431	9
12	434	11	432	8	433	9
13	454	13	422	8	431	11
14	431	17	422	14	433	11
15	448	18	417	14	434	14
16	434	25	437	15	446	11
17	439	24	459	12	450	13
18	426	25	441	14	438	12
19	439	25	440	6	444	10
20	477	33	435	13	445	14
21	464	27	438	26	461	15
22			393	23	429	23
23					472	32

Application to the solar modeling :

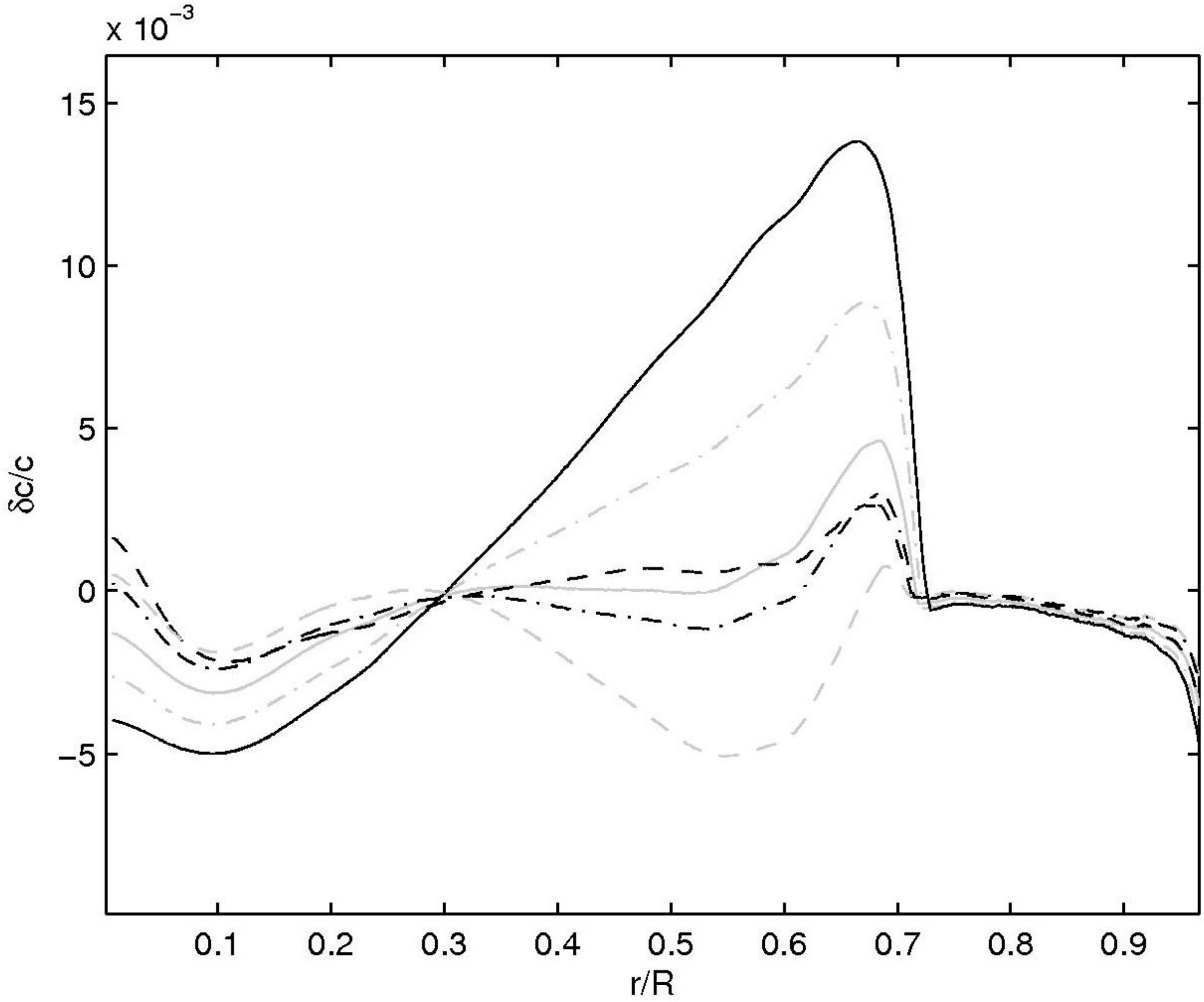
How does the change of solar abundances affect the low degree p-mode frequency spectrum?

From a poster for the meeting SoHO 18

J. Provost, A. Zaatri, G. Berthomieu, P. Morel, T. Corbard

Sound speed profile

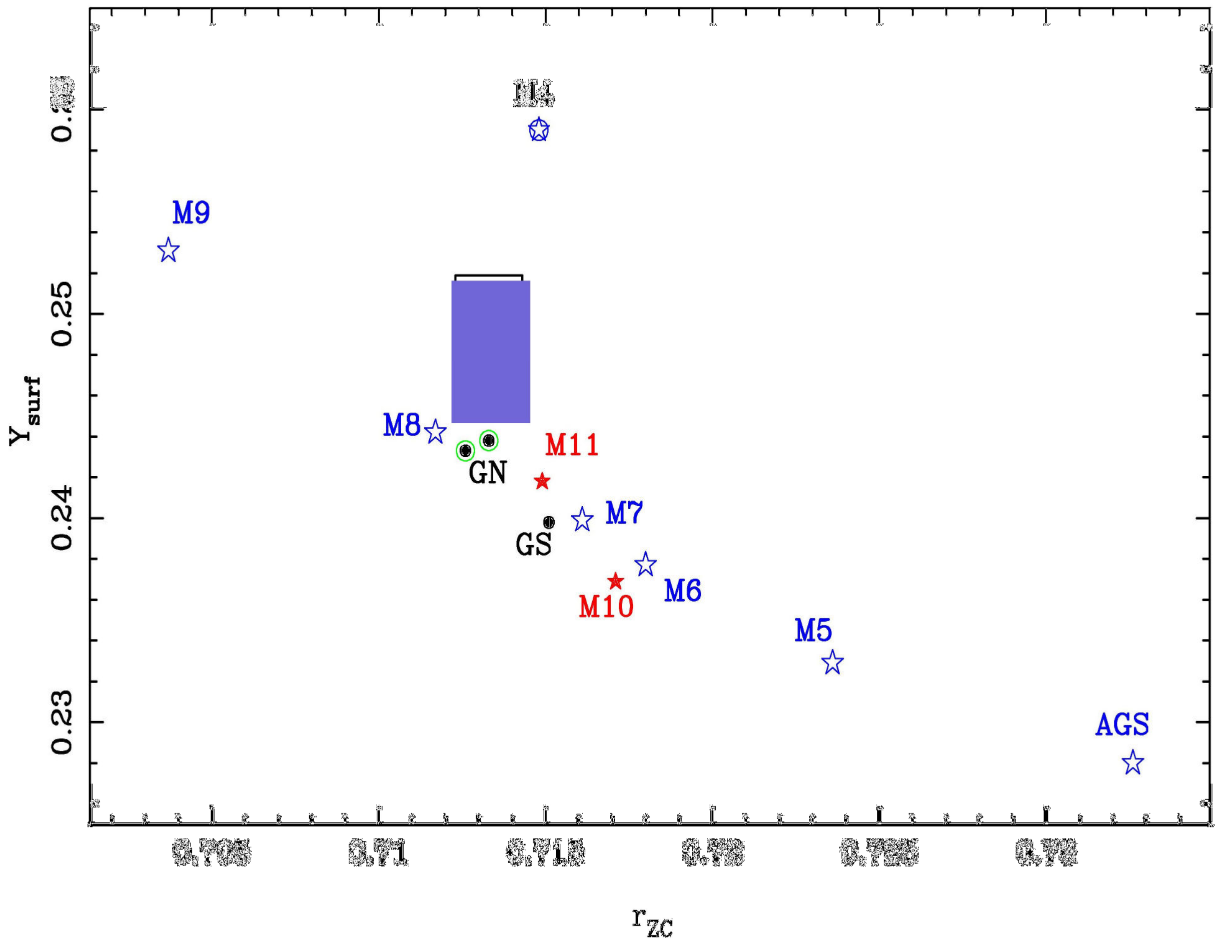
We compare seismic sound speed profile with those of the computed models. The worse concordance between the model using Asplund et. al abundances (AGS) and the seismic model is shown by about 15% under the base of the convection zone. Models M3, M4, M5 bring an idea of how big the neon abundance increase have to be in order to minimize the discrepancy. We have estimated this increase to 0.4-0.5Dex, which is in accordance with Bahcall et al 2005.



Relative sound speed differences between the Sun and the models. GN dark dashed, AGS dark full, M3 light dashed-dotted, M4 light full, M5 light dashed, M6dark dashed-dotted

Solar envelope characteristics

Y_s and r_{ZC} increases and decreases, respectively, as the neon abundance increases. Nevertheless, none of these values is in accordance with the seismic value, even for the 0.4-0.5 augmentation of the neon abundance. In the aim to bring closer the values of to those of the seismic determination, we constructed the model M6 in which the neon abun-dance is increased by 0.4dex and the other revised elements (C,N,O) and meteoritic determined elements (Si, Mg) are increased until the limit of their error bar estimation. We notice that seismic sound speed, Ys and r_{ZC} of the M6 model is the closest one to the seismic values.



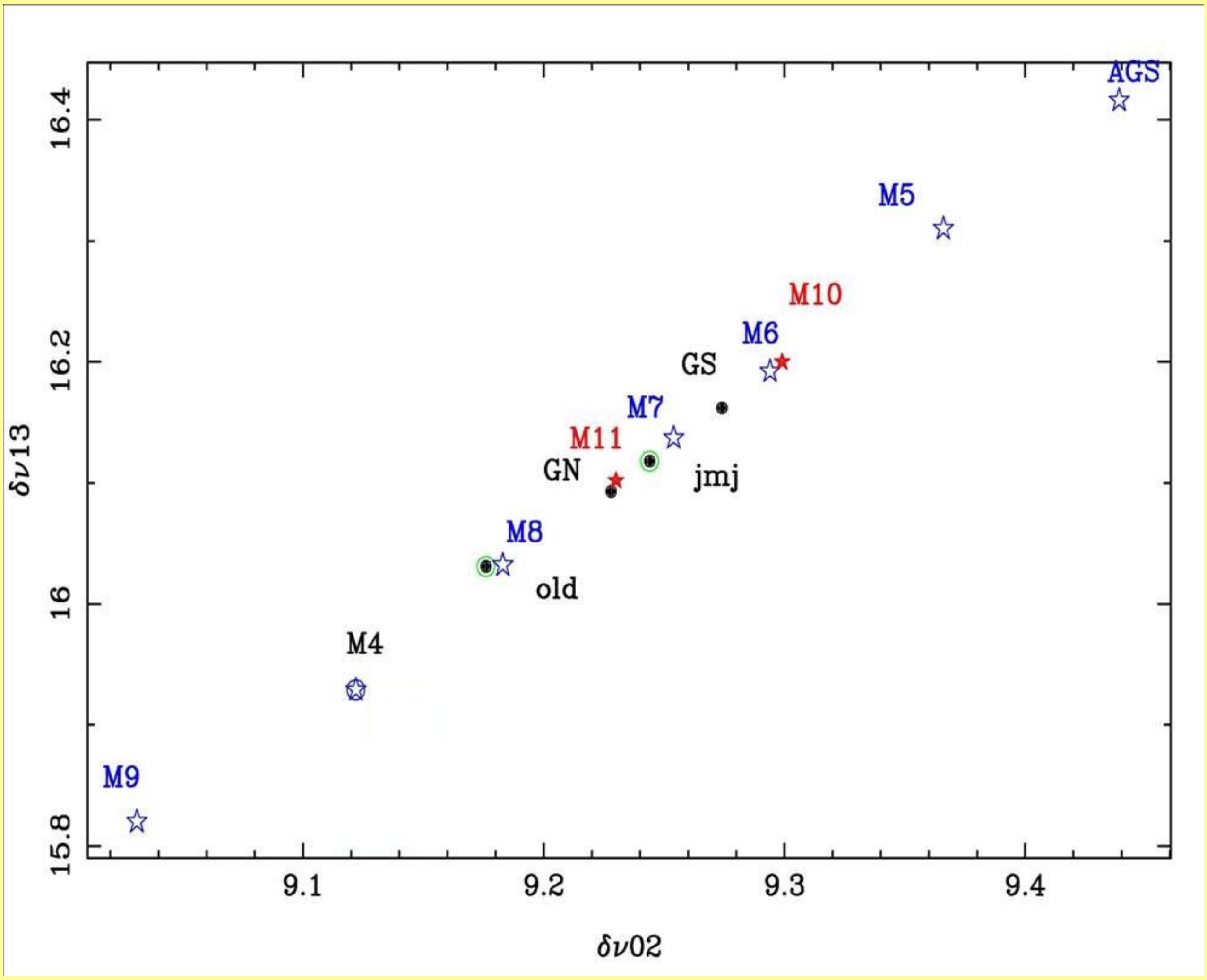
Characteristics of the solar envelope, Ys and rzc for models. GN: filled circle; models with GN,for the sequence of models computed with AGS abundance, but varying the one of neon. AGS and M3 to M5: empty stars; M6 filled stars. The box represents the seismic values with their errors (Basu and Antia, 2005)

p-mode characteristics of the core

$$\Delta\nu_{n,l} = \nu_{n,l} - \nu_{n-1,l}$$
$$\delta\nu_{02} = \nu_{n+1,l=0} - \nu_{n,l=2} \,,$$
$$\delta\nu_{13} = \nu_{n+1,l=1} - \nu_{n,l=3} \,,$$
$$\delta\nu_{01} = 2\,\nu_{n,l=0} - (\nu_{n,l=1} + \nu_{n-1,l=1})$$

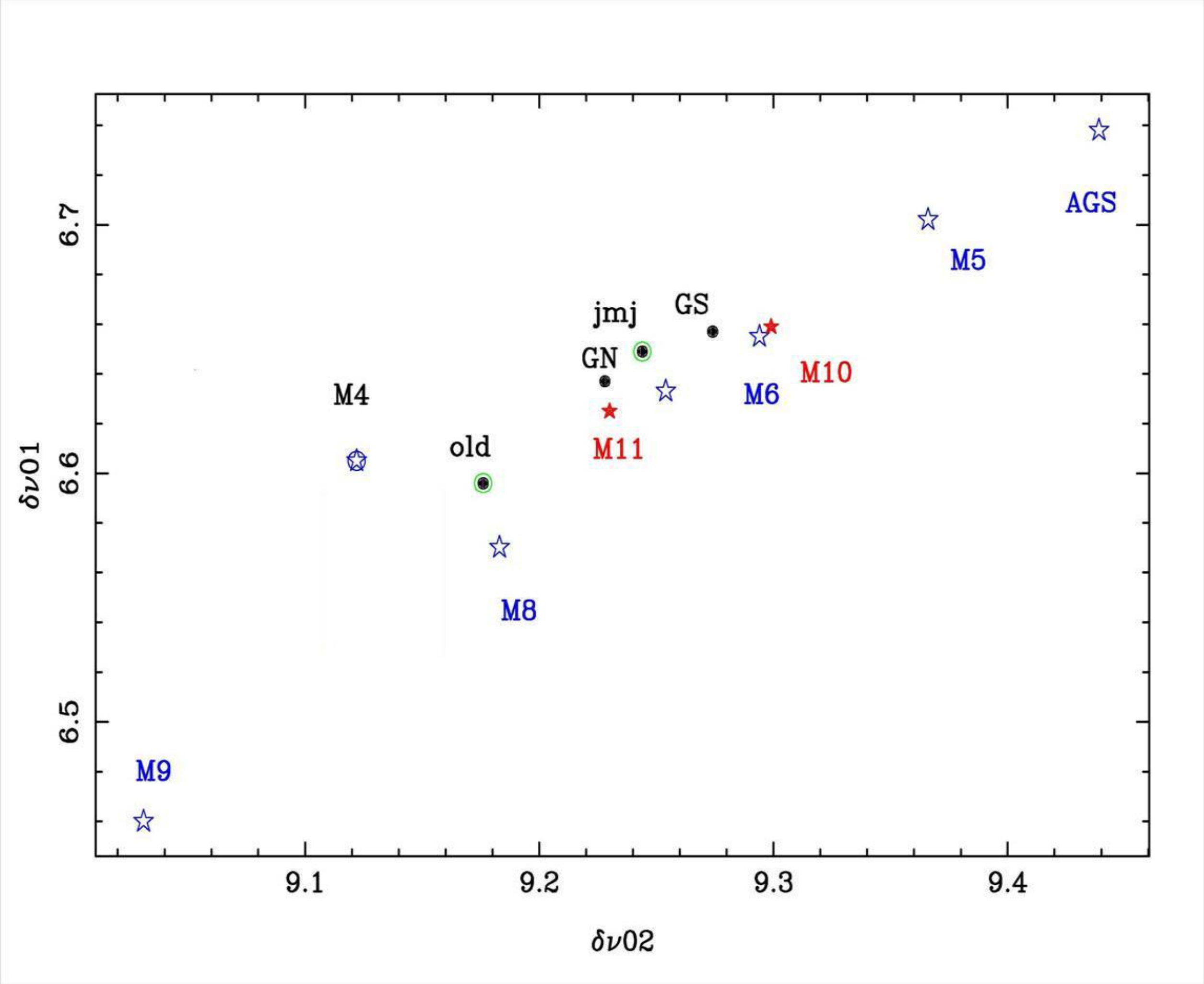
$\Delta\nu_{n,l} = \nu_{n,l} -, \nu_{n-1,l}$ is almost constant at high frequency and close to ν_0.

Small frequency spacings $\delta\nu_{02}$, $\delta\nu_{13}$ and $\delta\nu_{01}$ are combinations of acoustic modes penetrating Differently towards the center and thus very sensitive to the central part of the solar interior. In order to compare the models to the observations, we compute the mean of the frequency small spacings δν02, δν13 and δν01 for radial orders from 16 to 24, which corresponds to a frequency range about 2500−3600 \muHz. The low limit of this range insures that the behavior of the frequency is almost asymptotic, the high limit corresponds to observed modes with very high accuracy.



Enclosed circles: Gelly et al., 2002
Filled stars: Lazrek et al., 2006

comparison of models and observations:
mean difference of frequency of *l*=0 and *l*=2 vs. *l*=1 and *l*=3
deduced from the GOLF data



Enclosed circles: Gelly et al., 2002
Filled stars: Lazrek et al., 2006

comparison of models and observations:
mean difference of frequency of *l*=0 and *l*=1 vs. *l*=0 and *l*=2 deduced from the GOLF data

Can we detect g modes in the photospheric velocity power spectrum?

Several difficulties or questions occur:

- the mechanism of excitation.

- g modes are vanishing in the convective zone, due to the lack of restoring force.

- the predicted frequencies are in the low part of the spectrum, where the solar noise increases (this noise being related to convection, solar activity, or other sources).

The frequency of solar modes is shifted due to the rotation, following their geometrical structure (the degree *l* and the tesseral order *m*). Then multiplets should be observed. That gives a way to detect a g mode by collapsing the power spectrum in order to add all possible components of a mode.

Those so-called "collapsogram" are used in the paper from Appourcheaux *et al.* for the analysis of GONG and MDI observations.

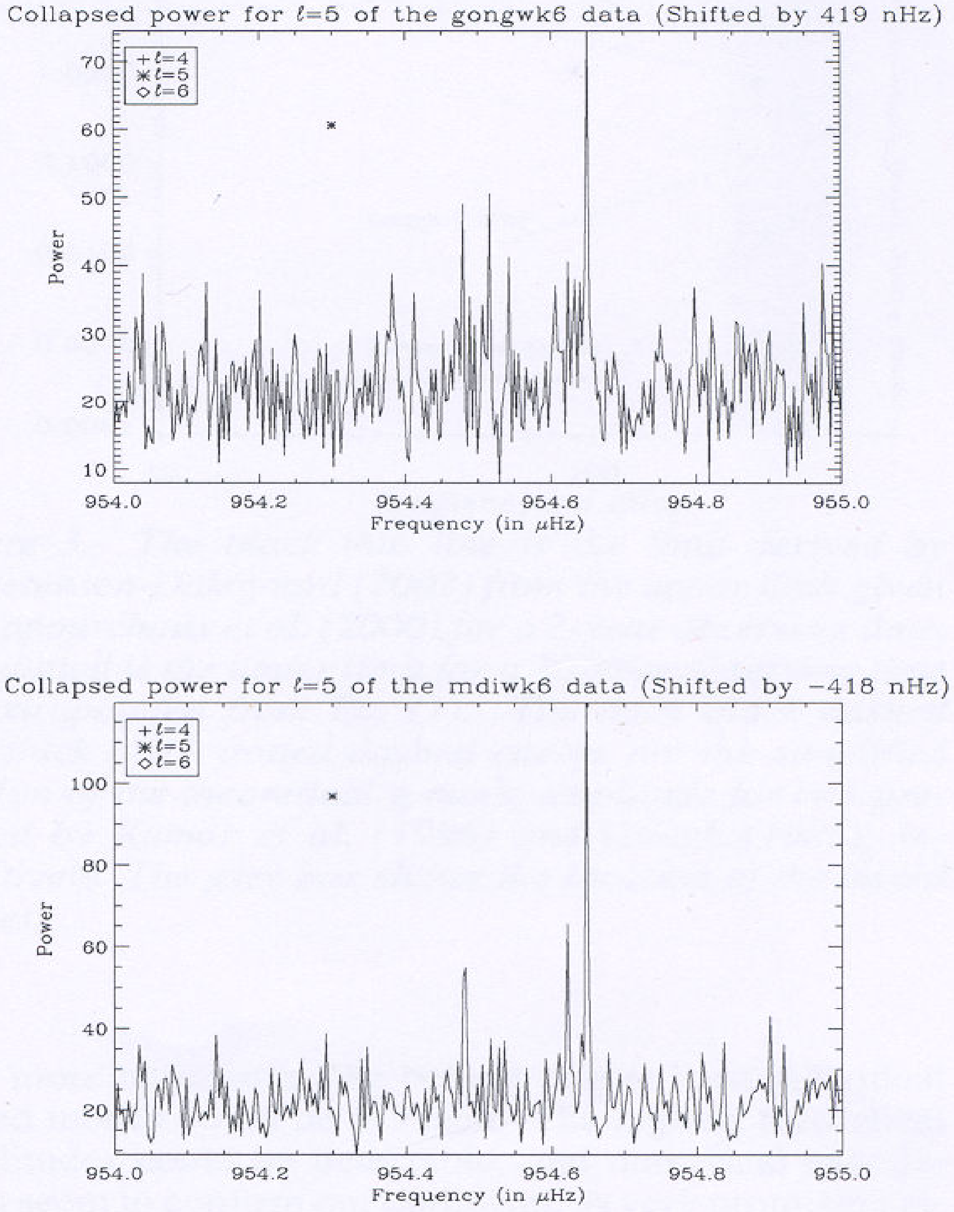


Figure 1. Collapsogramme obtained for the GONG data (top) and MDI data (bottom). Both are almost 10 years of data for l=5 mode. The star indicates the theoretical location of the $l = 5, n = 4$ *mode.*

The asymptotic distribution of g modes (practically for radial order *n* > 30) should be equally spaced in period, (p modes are equally spaced in frequency).

A French-Spanish group claims to detect such a signature of a periodic pattern in the periodogram deduced from the PS of the GOLF data. After comparison with a numerical model, they suggest the result obtained from GOLF observations is related to *l* =1 g modes.

“Detection of the periodic signature of *l* =1 g modes with 10 years of OLF/SoHO data”.

García *et al.* SoHO 17 meeting

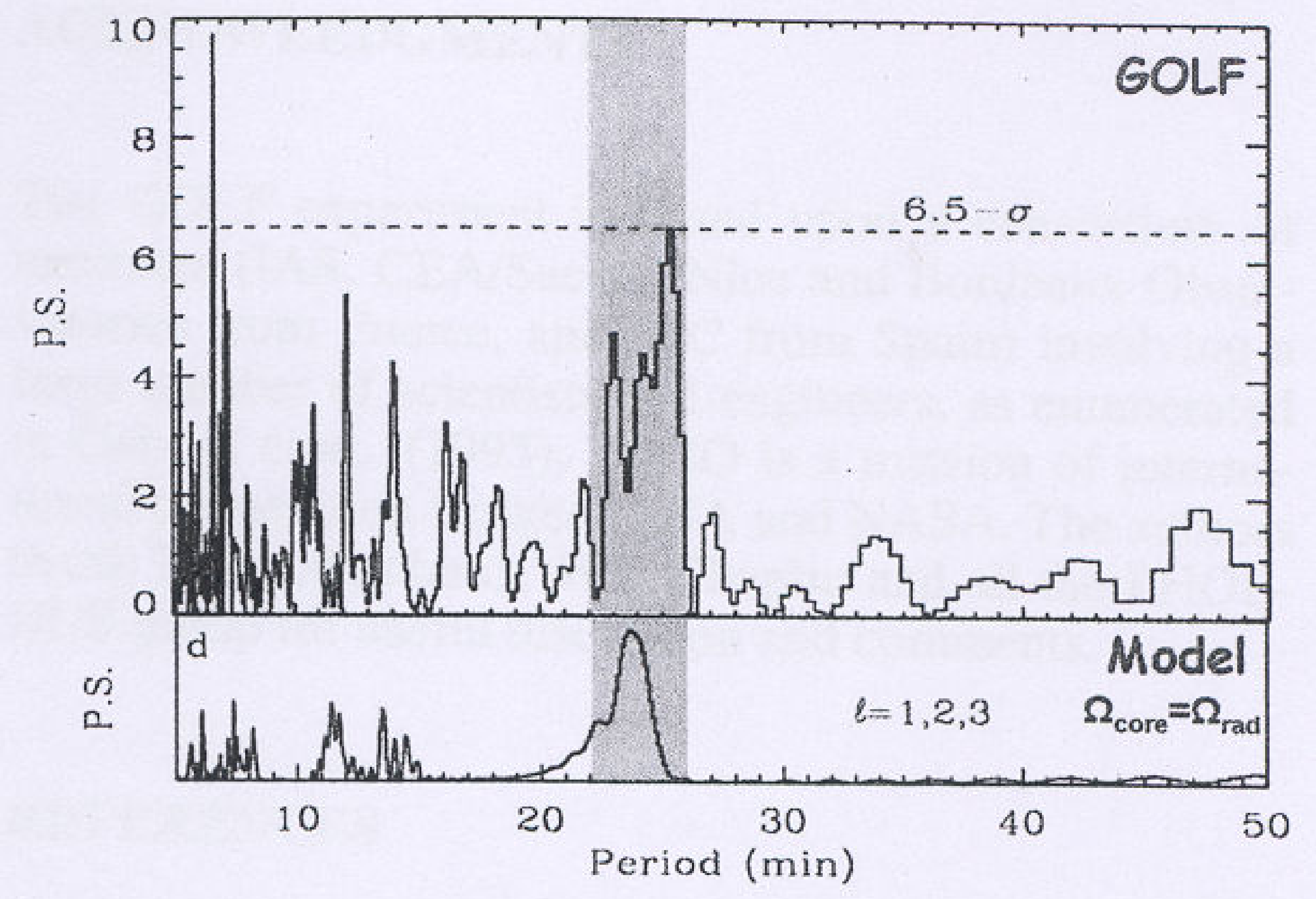


Figure 4. Top: PS of the PSD expressed in period computed from 3481 days of GOLF velocity time series. Bottom: PS of the $PSD(P)$ from theoretical g-modes computed from the seismic model and using a rigid core rotation.

The temporal analysis of the p-mode frequency variations, averaged over short periods.
Can we detect a cross-talk with g-modes?

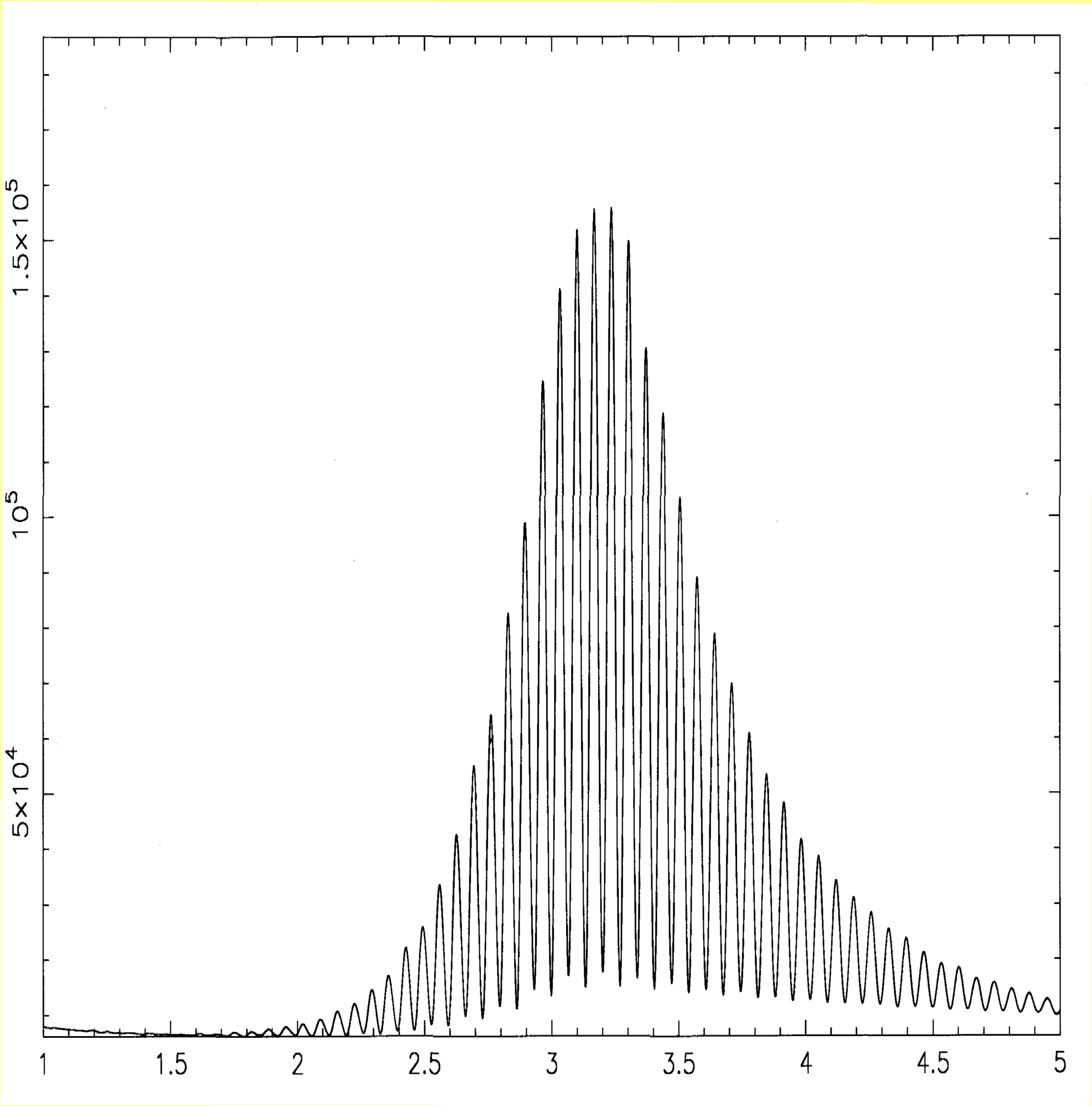
preprint on GOLF data analysis :
G. Grec, C.Renaud, E. Fossat

The analysis is made using 10 y of GOLF data, with a low frequency resolution.
We estimate the variable frequency of the p-modes as a time function and we calculate his Fourier transform.
Are those frequencies modulated by G-modes?

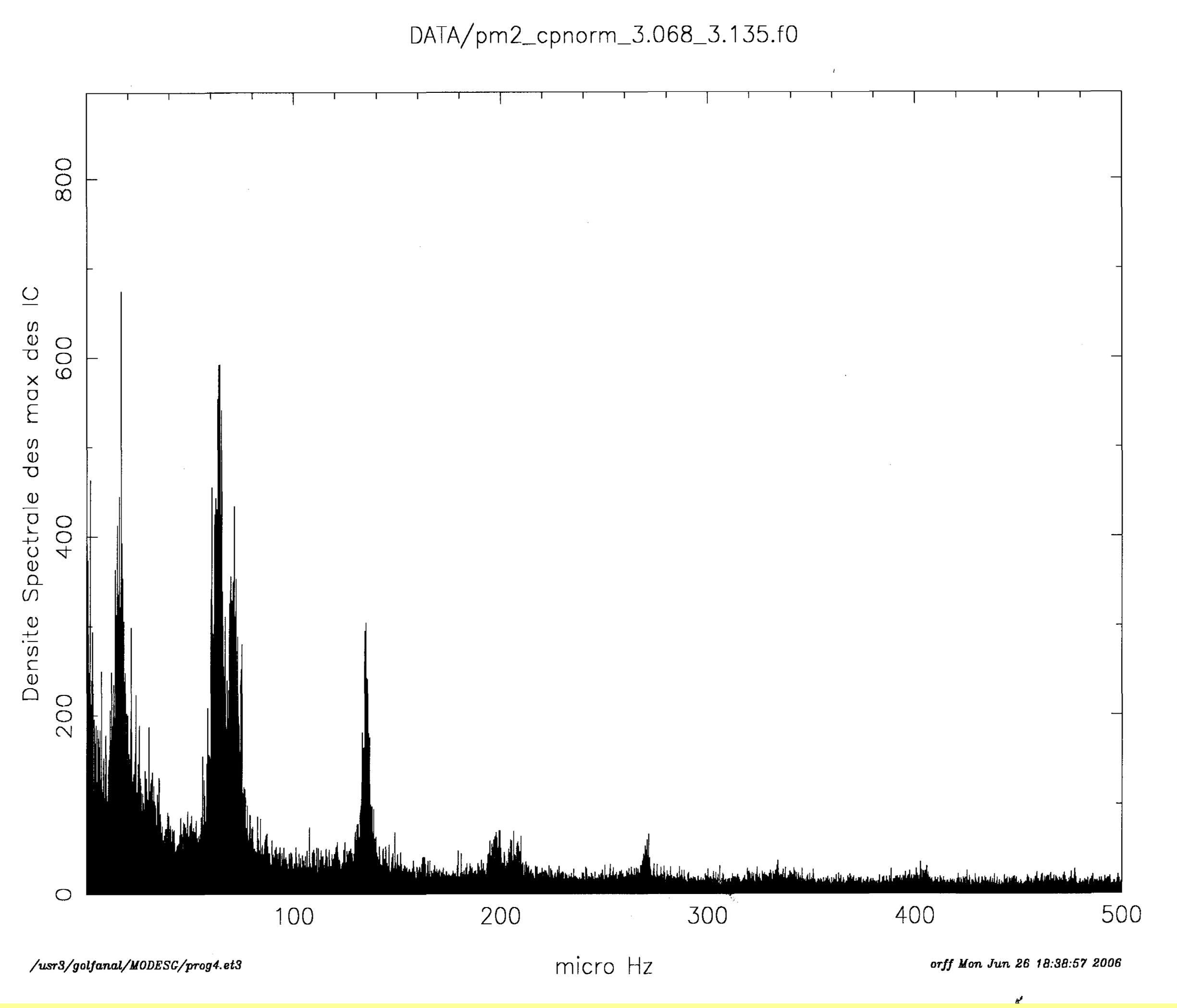
Search for an evidence of a cross-talk with g-modes :

- to translate the PS from a frequency scale to a time scale;
- to make a FT, in order to detect a regular pattern in period.

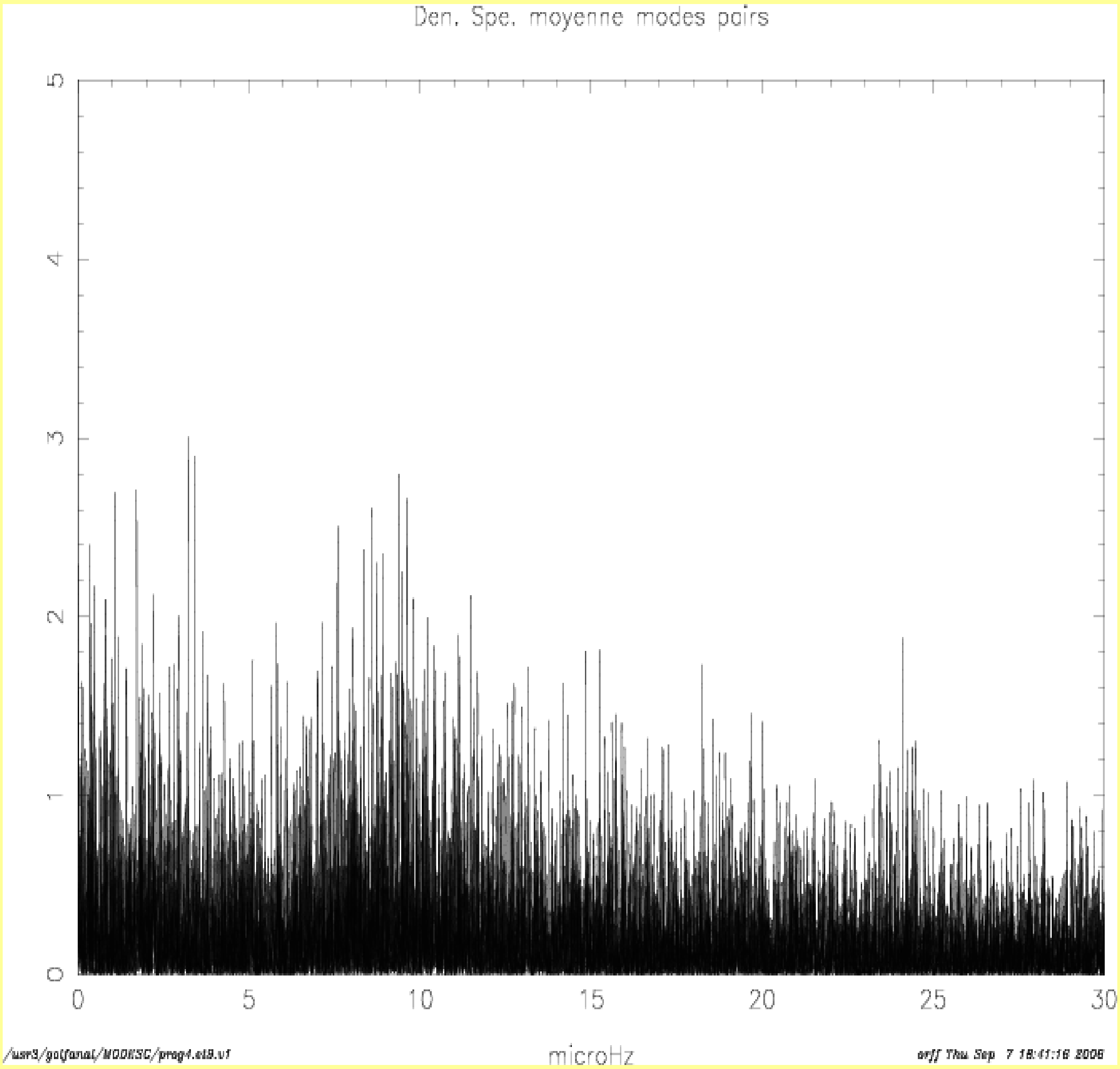
For g-modes of degree *l* >1, we should be in asymptotic frequency range.
For degree *l* =1 the spacing should be about 23 min, or 700μHz, decreasing with the radial order *n* we have from a model for modes close to 80 μHz
$l=2$ ΔT=796s, 1255μHz
$l=3$ ΔT=578s, 1728μHz (J. Provost)



low resolution p-mode spectrum averaged over 10 y

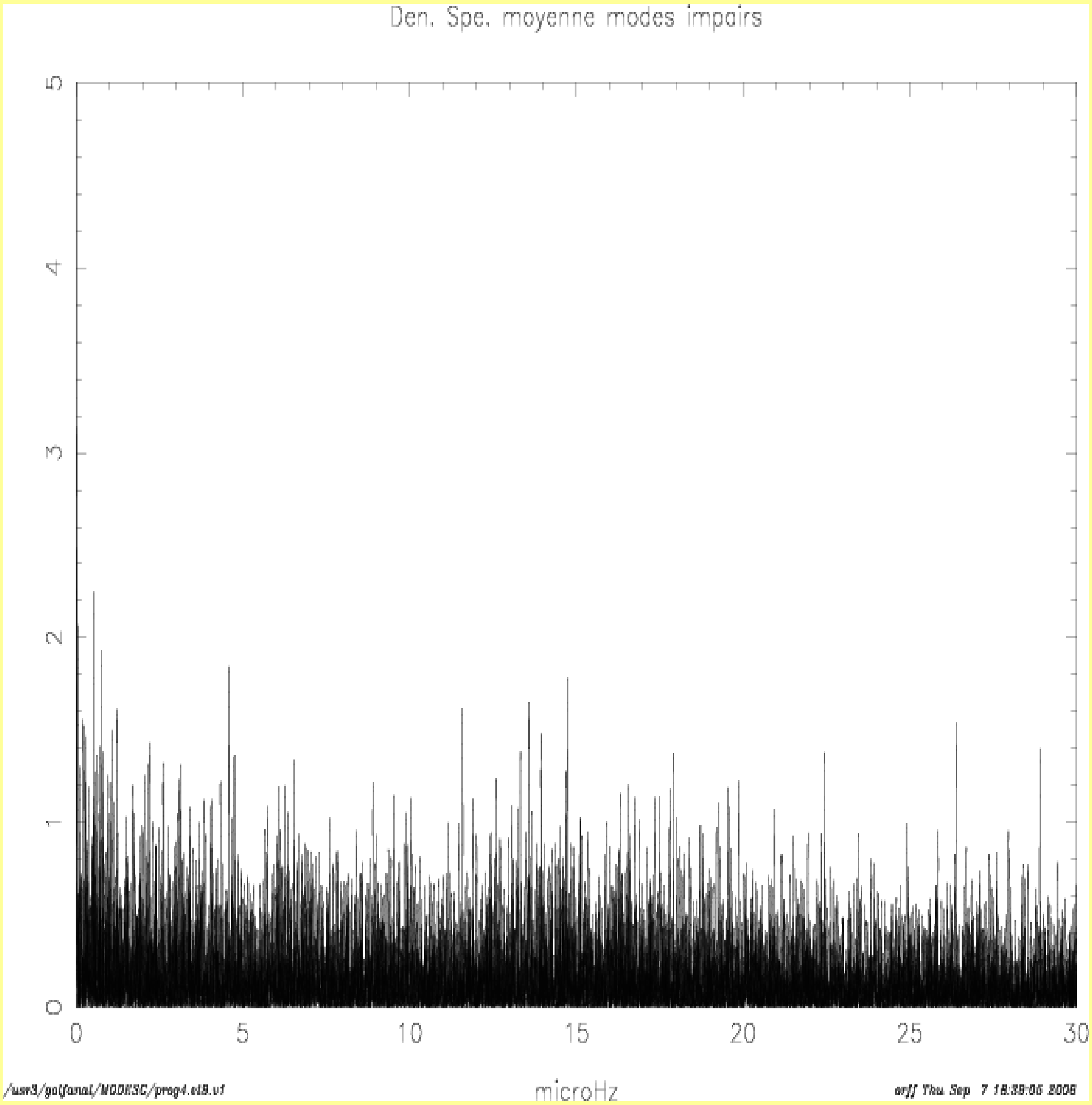


Power spectrum of the fast variations of the frequency of a p-mode: test of the method, detection of the artifacts due to the use of non-apodized windows.
The beating are related to the regular frequency spacing of modes



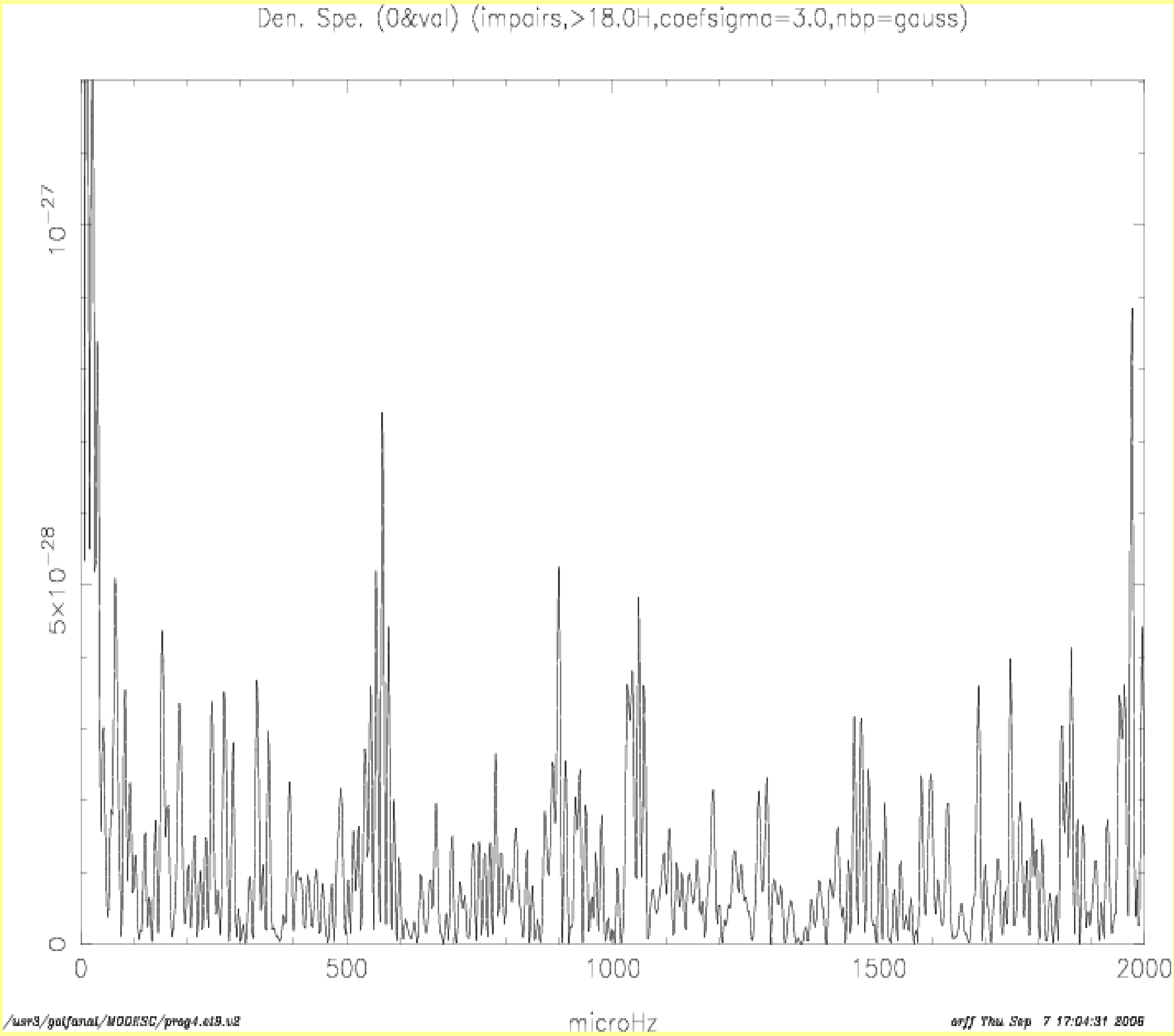
Frequency scale 0-30μHz

The power spectrum of the even p-mode frequency variations, *l* =0 and *l* =2 beating around 10μHz



Frequency scale 0-30μHz

The power spectrum of the odd p-mode frequency variations



The power spectrum of the periodogram deduced from the power spectrum of p-mode frequency variations.
A signal is clearly detected in the 600 μHz range

conclusion, for today :

real result on g-mode detection...

...or computer jokes?