SOLAR GRAVITY MODES FROM ACRIM/SMM IRRADIANCE DATA

Claus Fröhlich
Physikalisch-Meteorologisches Observatorium Davos
World Radiation Center
P.O.B. 173
CH-7260 Davos, Switzerland

ABSTRACT. Solar irradiance data from the ACRIM solar constant experiment on board the Solar Maximum Mission satellite (SMM) have been used to search for solar gravity modes. The power spectra of the time series of 270 days in 1980 and of 240 days in 1984 are analysed using a statistical method for the determination of the basic g-mode period separation T_0 and the rotational frequency ν_R. In the view of the proposal of weakly interacting massive particles (WIMP) in the solar core and their impact on T_0 the search has been extended down to 25 minutes. The results of the analysis of both time series in the frequency range from 10 to 40 μHz are best fitted by a T_0 of 29.85 minutes. This is close to the expected value for the WIMP model. The angular velocity in the center of the Sun inferred from the rotational splitting of the g-modes amounts to $6.6 \cdot 10^{-6}$ per sec, which is 2.3 times the photospheric rate.

1. SMM-ACRIM DATA SETS AND POWER SPECTRA

The visibility of internal gravity modes in total irradiance measurements is predicted for frequencies below about 60 μHz (Berthomieu, 1983). Thus, time series of orbital means of the ACRIM data taken on board the SMM spacecraft (Nyquist frequency: 86 μHz) are well suited for the search of g-modes. First attempts to detect internal g-modes in the SMM/ACRIM data of 1980 have been performed by Fröhlich and Delache (1984a and 1984b, in the following referred to as F&D). The present analysis includes also ACRIM data from 1984 and extends the range of g-mode determination to basic g-mode period spacing T_0 down to 25 minutes. The ACRIM solar irradiance measurements consist of individual readings at intervals of 132.071 seconds. For 1980 a complete set of data is available for day 49 through 325 when the pointing system of the SMM spacecraft failed. After the repair of SMM in spring 1984, good data are again available after day 125, 1984. In the present analysis 1980 (days 49-325) and 1984 (days 125-366) data are used. In order to minimize aliasing due to modulation by the orbital eclipses of 30 minutes every 95 minutes, orbital means are calculated in a similar way as described by F&D. Before calculating the periodograms the time series are detrended by fitting a 5th order polynomial.

J. Christensen-Dalsgaard and S. Frandsen (eds.), Advances in Helio- and Asteroseismology, 83–86.

The periodograms are calculated by squaring the amplitudes of standard FFT of the detrended time series. The natural resolution of the spectra is about 0.04 μHz. A typical feature of the spectra is the $1/\nu^2$ increase of power towards lower frequencies. At very low frequencies (<2 μHz) the power density of the 1980 spectrum is higher than the one of the 1984 spectrum due to the different level of solar activity. Moreover, the 1984 spectrum shows more power in the range from 2 to 30 μHz than the 1980 spectrum (up to one order of magnitude), which has still no obvious explanation.

2. METHOD TO DETERMINE T_0 AND ν_R AND RESULTS

At frequencies where the g-modes are expected to be seen (<60 μHz) their density is already high because of the equidistant spacing in period. The spectrum is further complicated by rotational splitting, which is a fixed amount in frequency. Therefore, it seems impossible to identify the peaks in the power spectrum individually and some statistical method has to be used as developed by F&D. It consists of comparing computed g-mode spectra with the real ones and searching for the g-mode spectrum which best fit the real one as a whole. The calculation of the frequencies of the g-modes could be based on e.g. assymptotic theory (Tassoul, 1980) with a given basic g-mode period spacing T_0 and a given rotational rate represented by the rotational frequency ν_R. Because of the internal rotation with a frequency which is only about a factor of ten smaller than the g-mode frequencies under consideration, coupling between the modes due to Coriolis forces has to be taken into account. Berthomieu et al (1978) have developed the necessary formalism to calculate the frequency shifts due to this effect. As in F&D this formalism is used to calculate the g-mode frequencies $\nu_{\ell,n,m}$ for a given T_0 and ν_R. The search for the real T_0 and ν_R is performed by the following steps:

(1) for a given T_0 and ν_R all $\nu_{\ell,n,m}$ of g-modes in the range 10-40 μHz are calculated for 5 ℓ,m combinations ($\ell=1$, $m=\pm1$; $\ell=2$, $m=\pm2$, 0) using the scheme described above,

(2) for each of the 5 modes the power of the analysed spectrum within the width of the natural resolution (0.04 μHz) and centered at $\nu_{\ell,n,m}$ is summed over the orders n and a mean power per mode calculated for the frequency range under consideration (10 to 40 μHz),

(3) step 1 and 2 is repeated for 250 T_0 between 25 and 40 minutes (step 0.06 minutes) and 40 ν_R between 0.4 and 2.0 μHz (step 0.04 μHz), yielding a 250*40 array of mean power for each mode $\ell=1$, $m=\pm1$ and $\ell=2$, $m=0$, ±2 and each spectrum analysed.

(4) search for the maximum power in all 5 arrays simultaneously, yielding the T_0 and ν_R of the Sun.

Because no a priori information about the relative amplitudes of the different modes is available, only one mode at the time is analysed, hence 5 arrays for each analysed spectrum. This means, however, that the information in the arrays is somewhat falsified by the power of the modes not considered and the power peaks in the arrays need not necessarily be found at the same place in the different arrays. Thus, only the comparison of the structure of the arrays with the structure of arrays calculated from synthetic spectra allows to find the real T_0 and

ν_R. The search is performed by calculating synthetic spectra with a T_0 and ν_R close to the one expected from a first visual inspection of the arrays and fine tune the parameters by moving the simulated arrays relative to the real ones until a good fit is achieved for all 5 arrays and for both SMM/ACRIM spectra simultaneously. Further iterations may be needed to determine the final values.

The best fit is found for T_0 = 29.85 minutes and ν_R = 1.05 μHz. It is interesting to note that the fit is better for ℓ=1 in the ACRIM 1980 data and for ℓ=2 in the ACRIM 84 data. It is difficult to judge the significance of the result. During the adjustment of the parameters the fit is sensitive to very small changes of T_0 and ν_R: changes of a few hundredths of a minute or μHz are easily distinguished. This does not mean that the result is accurate to this level due to the analysis adopted. An important qualitative statement is that for no other T_0-ν_R combination tested in the whole range of T_0 from 25 to 55 minutes a better visual fit was found.

3. COMPARISON WITH OTHER OBSERVATIONS

Other observations of g-modes have been published (excluding the 160-minute oscillation) by e.g. Delache and Scherrer (1983), Isaak et al (1984), Kotov et al (1984) and Pallé et al (1986). The published frequencies of Delache and Scherrer have been questioned by Scherrer (1986) as the location of peaks in the spectrum seem to depend on the method of detrending of the daily data; thus he no longer regards the published values as correct. Isaak et al do not publish tabulated values of their frequencies. A direct comparison of g-mode frequencies computed with T_0=29.85 minutes and ν_R=1.05 μHz with observed frequencies can only be done for the data of Kotov et al and of Pallé et al . This comparison together with the classification of the modes is presented in Table I.

TABLE I: Comparison of g-mode frequencies observed by Kotov et al (left) and Pallé et al (right) with computed ones for T_0=29.85 min. and ν_R=1.05 μHz as found from the ACRIM irradiance data. Only the ℓ=1 and 2 classified lines are listed.

Kotov et al (1984)

Frequency (μHz) obs.	calc.	Ident. n,ℓ,m
83.33	83.431	16,2,+2
84.90	84.808	9,1,-1
85.78	85.933	9,1,+1
90.83	90.949	14,2,-2
93.01	92.733	14,2, 0
94.70	94.505	14,2,+2
94.91	95.149	8,1,-1
97.58	97.690	13,2,-2
99.03	99.475	13,2, 0
108.72	108.344	7,1,-1
109.00	109.490	7,1,+1
116.39	116.405	11,2, 0
126.74	126.925	6,1,+1
128.90	129.017	10,2,+2
138.43	138.484	9,2,-2

Pallé et al (1986)

Frequency (μHz) obs.	year	calc.	Ident. n,ℓ,m
33.15	84	33.436	23,1,-1
33.45	85	33.436	23,1,-1
35.35	84	35.321	38,2, 0
34.25	85	34.516	23,1,+1
39.75	84	39.548	20,1,+1
58.90	85	59.051	13,1,-1
40.40	84	40.488	19,1,-1
76.60	85	76.484	10,1,-1
41.95	84	41.574	19,1,+1
77.30	85	77.064	17,2, 0
47.90	84	47.591	28,2, 0
79.70	85	79.881	16,2,-2
93.20	85	92.733	14,2, 0
55.20	84	55.276	24,2, 0
58.50	84	58.355	22,2,-2
66.30	84	65.926	20,2, 0
67.20	84	67.483	19,2,-2
70.55	84	70.752	11,1,+1
81.15	84	81.664	16,2, 0
92.00	84	92.733	14,2, 0
108.45	84	108.344	7,1,-1

The agreement with the data of Pallé et al is almost perfect: only 3 lines cannot be identified as modes with $\ell=1$ or 2. The correlation coefficient of the regression between the observed and calculated frequencies of the 21 lines is 0.99991 and the mean ratio ν_{obs}/ν_{calc} equals 0.9987. From the data set of Kotov et al only 15 lines out of 32 are classified as modes with $\ell=1$ and 2. The regression coefficient of 0.99994 for the 15 classified lines is also very high and the ratio $\nu_{obs}/\nu_{calc}=0.9990$ is very similar. The result of the ratio could indicate that T_0 is slighly higher (29.88 min.). The main reason for the unclassified lines is the sensitivity of the instruments to higher ℓ: the observations of Pallé et al are sensitive to modes with $\ell<4$, those of Kotov et al to modes with $\ell<7$. All the remaining lines can indeed be classified as modes with $\ell=3$ and $\ell=3$ to 6 respectively.

4. CONCLUSIONS

A basic g-mode period spacing of $T_0=29.85$ minutes determined from ACRIM irradiance data of 1980 and 1984 and supported by the observations of Pallé et al (1986) and of Kotov et al (1984), indicates, that the state of the solar core does not correspond to the one expected from a standard solar model with $T_0\cong 35$ minutes. The lower T_0 is also supported by the observed frequency separation of the odd or even low degree, high order p-modes. For the WIMP model Faulkner et al (1986) and Däppen et al (1986) predict 29 and 32 minutes respectively. Thus the result of the present analysis supports the WIMP hypothesis or an other mechanism yielding a reduced central temperature.
The splitting due to the rotation of the core close to the center where the g-modes are concentrated is determined as 1.05 μHz which is 2.3 times the surface rate. This value is in good agreement with the rotation rate at 0.15 solar radius of 0.9 μHz, inverted from p-mode observations of Duval and Harvey (1984).

REFERENCES

Berthomieu,G., G.Gonczi, Ph.Graff, J.Provost and A.Rocca: 1978, *Astron. Astrophys.* **70**, 579.
Berthomieu,G.: 1983, Observatoire de Nice, *private communication.*
Däppen,W., R.L.Gilliland & J.Christensen-Dalsgaard: 1986, *Nature,* **321**, p.229.
Delache,Ph. & P.Scherrer: 1983, *Nature,* **306**, p.651.
Duval T.L.Jr. & J.W.Harvey: 1984, *Nature,* **310**, p.22.
Faulkner,J., D.O.Gough & M.N.Vahia: 1986, *Nature,* **321**, p.226.
Fröhlich,C. and Ph.Delache: 1984a, *Mem.S.A.It.,* **55**, p.99.
Fröhlich,C. and Ph.Delache: 1984b, *JPL Publ. 84-84,* Dec.1984, p.183.
Isaak,G.R., H.B.van der Raay, P.L.Pallé, T.Roca Cortés and Ph.Delache: 1984, *Mem.S.A.It.,* **55**, p.91.
Kotov V.A., A.B.Severny and T.T.Tsap: 1984, *Mem.S.A.It.,* **55**, p.117.
Pallé, P.L. and T.Roca Cortés, *these proceedings.*
Scherrer,P.: 1986, *these proceedings.*
Tassoul,M.: 1980, *Astroph.J.,* **43**, p.469.