Recent Helioseismological Results from Space:

Solar p-mode Oscillations from IPHIR on the PHOBOS Mission

C.Fröhlich[1], T.Toutain[2], R.M.Bonnet[3], A.V.Bruns[4],
J.P.Delaboudinière[2], V.Domingo[5], V.A.Kotov[4], Z.Kollath[6],
D.N.Rashkovsky[4], J.C.Vial[2], Ch.Wehrli[1]

[1] Physikalisch-Meteorologisches Observatorium Davos
World Radiation Center
CH-7260 Davos-Dorf
[2] Laboratoire de Physique Stellaire et Planetaire
F-91370 Verrières-le-Buisson
[3] Science Directorate of ESA
F-75738 Paris Cedex 15
[4] Crimean Astrophysical Observatory
Nauchny, Crimea 334413, USSR
[5] Space Science Department of ESA
NL-2200 AG Noordwijk
[6] Central Research Institute for Physics
H-1525 Budapest

ABSTRACT. IPHIR (InterPlanetary Helioseismology by IRradiance measurements) is a solar irradiance experiment on the USSR planetary mission PHOBOS to Mars and its satellite Phobos. The experiment was built by an international consortium including PMOD/WRC, LPSP, SSD/ESA, KrAO and CRIP. The sensor is a three channel sunphotometer (SPM) which measures the solar spectral irradiance at 335, 500 and 865 nm with a precision of better than 1 part-per-million (ppm). It is the first experiment dedicated to the investigation of solar oscillations from space. The results presented here are from a first evaluation of data gathered during 160 days of the cruise phase of PHOBOS II, launched on July, 12th 1988. The long uninterrupted observation produces a spectrum of the solar p-mode oscillations in the 5-minute range with a very high signal-to-noise ratio, which allows an accurate determination of frequencies and line shapes of these modes.

1. Introduction

Solar pressure mode oscillations can be observed by measuring either velocity variations or changes in the brightness temperature. By looking at the Sun as a star (no imaging) only low degree modes ($l \leq 4$) can be seen. The velocity signals have amplitudes of a few cm/s and the brightness signals of a few parts-per-million (ppm) of the irradiance. From the earth's surface p-mode oscillations can be observed with velocity measurements, whereas observations in brightness are marginal due to noise produced by transmittance changes of the earth' atmo-

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sphere. A major drawback of ground observations is the daily window function producing aliases at ±11.57 μHz (1 day period) and multiples thereof. This problem can be partly overcome with global multi-station networks as e.g. by the Birmingham group (Aindow et al.,1988), IRIS (Fossat, 1988) and GONG (e.g. F.Hill and Newkirk, 1985). Their operation requires quite important logistic efforts and the fitting of the data of two adjacent stations can still produce aliases. An other possibility are observations from the geographic south pole, where uninterrupted time series of up to 10 days can be gathered (e.g. Grec et al., 1983). Up to now observations from space have been limited to brightness measurements: by ACRIM on the Solar Maximum Mission (SMM) of NASA (Woodard and Hudson, 1983) and the IPHIR experiment on the USSR mission to Phobos (Fröhlich et al., 1988). Irradiance measurements are advantageous because they are not influenced by variable radial velocities of space-crafts relative to the Sun.

The best orbit for space observations over long periods of time is the Lagrange point L1 where SOHO, the Solar and Heliospheric Observatory of ESA/NASA, will be placed (1995 launch). SOHO will carry helioseismology experiments with brightness and velocity observations of the global and resolved Sun (experiments VIRGO, GOLF and SOI, see e.g. Bonnet, 1989). The next best orbits are the cruise phases of planetary missions and geostationary orbits, which allow uninterrupted observations of the Sun during at least a few months. The circular orbits around the Earth have durations of about 95 minutes, as e.g. SMM. This yields aliases at about ±180 μHz and multiples thereof, which deteriorate the signal-to-noise-ratio, but are still less disturbing the 5-minutes p-modes than the daily aliases of the ground observations.

The opportunity for a helioseismology experiment on a planetary mission came up in 1985 when the final payload of the USSR mission to the martian satellite Phobos was planned. The cruise phase of this mission offered the unique chance to gather for the first time uninterrupted time series of several months duration. The excellent results from ACRIM (Woodard and Hudson, 1983) suggested solar irradiance measurements for this experiment, and more specifically, the good experience with sunphotometers lead to a proposal of spectral measurements with a three channel instrument. This kind of sunphotometer (SPM) was already developed for other investigations (Brusa et al., 1983) and had proven its ability to observe solar oscillations with high resolution (Fröhlich and van der Raay, 1984) during stratospheric balloon experiments.

2. Instrument Description

The sensor part consists of a three channel SPM and a two axis sun sensor (TASS) with perpendicular linear arrays which monitor the pointing towards the Sun. The data processing unit with a microprocessor in a separate box controls the sensor, handles the data and ensures the interface with the spacecraft. A detailed description of IPHIR is given by Fröhlich et al.(1988). The SPM has three independent channels at 335, 500 and 865 nm (half-power-bandwidth of 5 nm) each consisting of a Silicon-diode interference-filter combination in a sealed housing. The channels have no image forming optics, but measure irradiance (W/m^2 within the bandpass of the filter) with a field-of-view of ±2.5° determined by two apertures, one (2 mm diam.) in front of the detector and the other (9 mm diam.) at a distance of 104 mm. The noise of the detector-amplifier circuit is less than 1 ppm of the full-scale signal for an integration time of the order of 10 s. The analog signals of the three channels are measured simultaneously by three dedicated voltage-to-frequency converters and counter circuits. The basic sampling period is 8.22 s, out of which 64 ms are used to perform electrical calibrations. Five such observation are summed before transmission to reduce the data rate; thus the sampling interval amounts to 41.1 s.

3. Data Handling and Evaluation

The data from the experiment are received every 4 days at the Space Research Institute (IKI) in Moscow, and are distributed to the team either directly by tape or through the Centre National d'Etudes Spatiales (CNES) in Toulouse (France) over a permanent telephone line. The data coverage is excellent with virtually no gaps due to transmission or operations. Two problems have been encountered with the sensors: degradation of the sensitivity and an unexpected influence of the offset pointing on the signal of all three channels. The degradation depends strongly on wavelength and is maximal for the blue channel with a 1/e time constant for the sensitivity decay of about 30 days. As we are interested in relative changes and as the degradation of the green and red channel (1/e: 300 and 600 days at the beginning of the mission) is moderate this smooth decrease in sensitivity is not really harming the results of the latter two channels. The effect of the pointing, however, is a more serious problem. The pointing of the S/C was specified to be within ± 1° and indeed the axis of the spacecraft oscillates slowly between ±0.6° in the ecliptic plane around the axis to the Sun with constant speed and fast turns. These movements have periods between 40 and 80 minutes and are further modulated by movements in the plane perpendicular to the ecliptic. During offset pointing the signal increases due to straylight, produced within the instrument by the light reflected at a small angle from the highly reflecting detector aperture into the baffle and back to the detector. The movement of the spacecraft translates into a roughly quadratic change between very pointed apexes. The amplitude of these peaks can reach several tenths of a percent of the signal. As the SPM have up to now always been used on well pointed platforms, this unexpected kind of behavior was detected only during the mission and was later examined in detail by ground tests with the spare instrument. It is obvious that the small amplitudes of the solar oscillations of only a few ppm are strongly masked by this effect.

An efficient method to reduce the influence of this adverse pointing effect for on the frequency spectrum of the p-mode oscillations in 5-minute range is to use a filter of the form $y_i - \Sigma f(y_{i+k})$ with $-6 \leq k \leq +6$ and f being e.g. a Hanning taper. At the pointed apexes, however, such a filter fails to smooth the data and a more sophisticated method has to be used: in the range of ±13 points around an apex both sides are fitted with a least square method to concave parabolas with their minima to the left and right of the apex reproducing the peak at the apex. The data are detrended with these two parabola and the center of the filter run over the range of ±6 points from the apex. By this method the time series can be smoothed to such a degree, that the noise in power spectrum from 1.5 to 6 mHz remains well below the ppm range and is mostly of solar origin.

4. Results

The power spectrum for the 5-minutes range is shown in Figure 1. The signal-to-noise ratio is 25:1 for the strongest p-mode, that is very high compared to the one of the ACRIM data of 7:1 (Woodard, 1984). It has to be noted that ACRIM was not designed to be used for such studies and the instrument operation is indeed not really suited for it. The signal-to-noise ratio improvement in IPHIR is due to the low instrumental noise (inherent and by proper sampling) and due to the continuity of the data (constant window function compared to the 35-40 minutes gaps every 90 minutes in ACRIM due to the orbit of SMM).

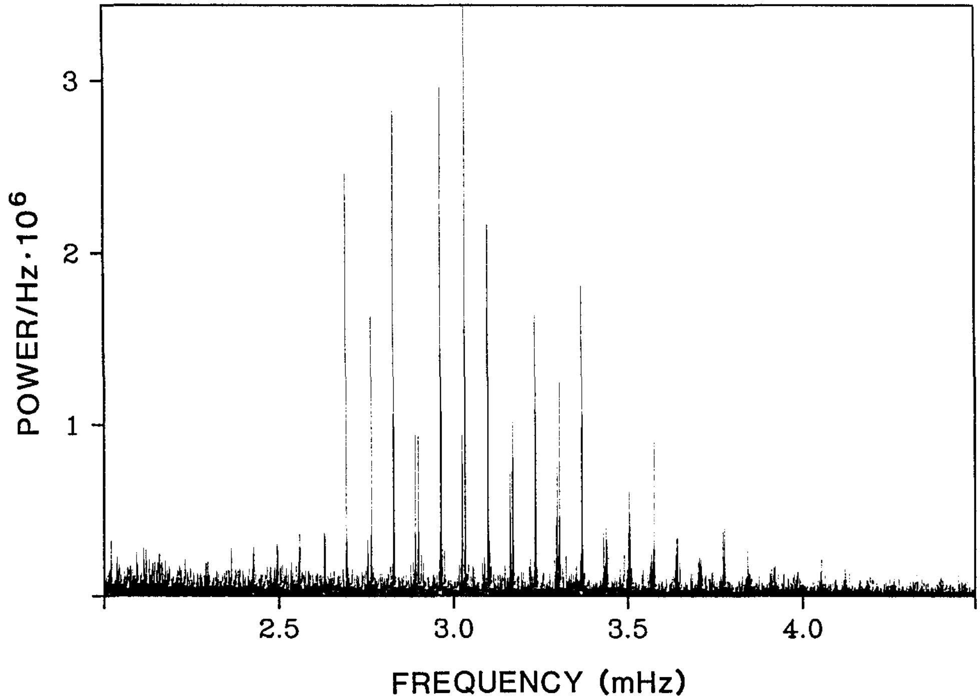

Figure 1: Power spectrum of the red channel in the 5-minutes range showing very accurately the solar p-mode oscillations with degrees *l*=0-2 and orders n=16-27. The time series spans 160 days from 15. July to 22. December 1988.

For low degree and high order modes (*l*<<n) the frequencies can be analyzed using the asymptotic approximation (e.g. Christensen-Dalsgaard, 1989):

$$\nu_{l,n} = \nu_0 \cdot (l/2 + n + \varepsilon) + \delta_{l,n}$$

ν_0, the spacing between different orders of the same degree, corresponds to the travel time of sound wave from surface to surface through the center and is a mainly determined by the sound speed near the surface. ε is usually taken as 1/2. The correction term $\delta_{l,n}$ manifested by the small frequency difference between the modes with degrees 0 and 2 and n different by one, depends on the properties in the core. Thus it can be used to distinguish between different solar models, e.g. standard, mixed and WIMP (Däppen et al., 1986, Faulkner et al., 1986). Although the formula is only an approximation and parameters may depend on frequency this is a very useful way to characterize the p-modes. By comparing the observed frequencies with the asymptotic formula the modes can be identified and some evaluation of the structure of the Sun (helioseismology) performed.

The frequency centroids of the strongest lines have been determined by either fitting Lorentz-lines or by searching the bary-center of the line within a range of ±2.5 μHz using the spectrum of the whole period (Figure 1). The differences between the two methods are normally smaller than 0.1 μHz but can reach 0.5 μHz (l=1, n=18). This difference indicates an asymmetry of the lines which could be due to the statistics of the excitation giving rise to a biased sample although the observation time is thirty to fifty times the 1/e lifetime of the modes. More likely, the asymmetry arises from a combination of frequency shift during the observation and a changes in the amplitudes. The rapid increase of solar activity should increase the frequency by about 0.1 μHz from July to the end of 1988. This value is estimated from the frequency data of the declining cycle from 1980 towards the minimum (Woodard and Noyes, 1985, Gelly et al., 1988; Pallé et al., 1988) using the solar irradiance data for scaling the values to the 1988 period (Kuhn et al., 1988, Kuhn, 1989; Fröhlich et al., 1990). As to the amplitude variation, Figure 3 shows indeed a quite unequal amplitude repartition during the period of observation. Until a more detailed analysis is available, best estimates for the frequency centroids are the means of the two values as presented in Table 1. The uncertainty is probably of the order of 0.1 μHz.

Table 1: Frequency centroids for l=0-2 and n=17-23

n	l=0	l=1	l=2
17		2559.40	2620.39
18	2629.84	2693.43	2754.02
19	2764.30	2828.45	2889.86
20	2898.07	2963.51	3024.82
21	3034.17	3098.65	3159.60
22	3169.16	3233.63	3295.19
23	3304.18		

For the determination of the asymptotic parameters and their frequency dependence, quadratic fits of the form

$$\nu_{l,n} = a\cdot(n + l/2 - 21.5)^2 + b\cdot(n + l/2 - 21.5) + c$$

are performed. For l=0,1 and 2 the following constants and the 1σ standard deviation of the fit in μHz are listed in Table 2.

Table 2: Coefficients of quadratic fits of mode frequencies

	a	b	c	σ
l=0:	0.0665	135.029	3101.55	0.09
l=1:	0.0947	135.194	3098.48	0.20
l=2:	0.0815	135.269	3092.43	0.47

The constant b corresponds to ν_0 and depends in a systematic way on the degree, what had already been observed in the ACRIM data of 1980 (Woodard, 1984). The ACRIM values, however, are lower by about 0.05 μHz. On the other hand, the constants c of IPHIR are lower than the ACRIM ones by ≤0.05 μHz. Differences between the a values are probably not significant.

The $\delta_{1,n}$ is calculated from the l=0 and l=2 values of Table 1 by fitting a straight line as function of frequency. The standard deviation of the fit is substantially decreased if the first value is dropped. This may indicate that the straight line is not an appropriate approximation. From the five remaining values the $\delta_{1,n}$ amounts to 9.35 μHz at 3.0 mHz and shows a slope of -2.4 μHz/mHz. This compares well with the results from ACRIM (9.30; Woodard, 1984) and is somewhat higher than the one calculated from the observations 1977-1985 at Tenerife (9.04; Jimenes et al., 1988).

In order to obtain more detailed information about the line-shapes, a superimposed analysis has been made for the modes listed in Table 1. For the superposition the centers of the l=0 and 1 lines are assumed to be at the frequencies calculated from the quadratic fit. The result is shown in Figure 2. The mean line width of the l=0 lines (n=18-23) equals 1.45 μHz; the real value is probably lower as the lines are superimposed at mean frequencies which adds the deviations from the fit to the line width. The value is lower than the one of Woodard (1984) for l=0 and n=20-23 but within his error bars. It is higher than the one (0.98 μHz) reported by the Birmingham group for the same l=0 and n=18-23 modes (Elsworth et al., 1988). The width of l=1 is 2.3 μHz; the difference to the l=0 width yields an estimate of the unresolved splitting of the l=1 mode of 0.85 μHz for a difference in m=2; the deduced rotational speed would amount to 0.42 μHz or 27.4 days. The superposition of the l=2 on the plot l=0/2 is not very accurate and depends on the difference $\delta_{1,n}$ which is a function of frequency. An interesting feature of is the broad pedestal of the lines. This is probably due to modulation of the intensity with periods longer than about 5 days from e.g. active regions.

The evolution in time of the amplitudes of p-modes can give information about the excitation and damping of these modes. Figure 3 shows this variation for the modes l=0-2 and n=17-27. The analysis is done for 5-day periods and it shows large variations as already known from ground observations (e.g. Jefferies et al, 1986). The continuity of the data of IPHIR, however, renders the results more reliable. They show a more or less random distribution with a suggestion of an more or less steady increase with time for l=0 and two maxima for l=1 in first and last third and no obvious correlation between the different degress seems to be present. It is obvious that the temporal behavior of p-modes contains a great deal of information and a detailed study on this subject is under way.

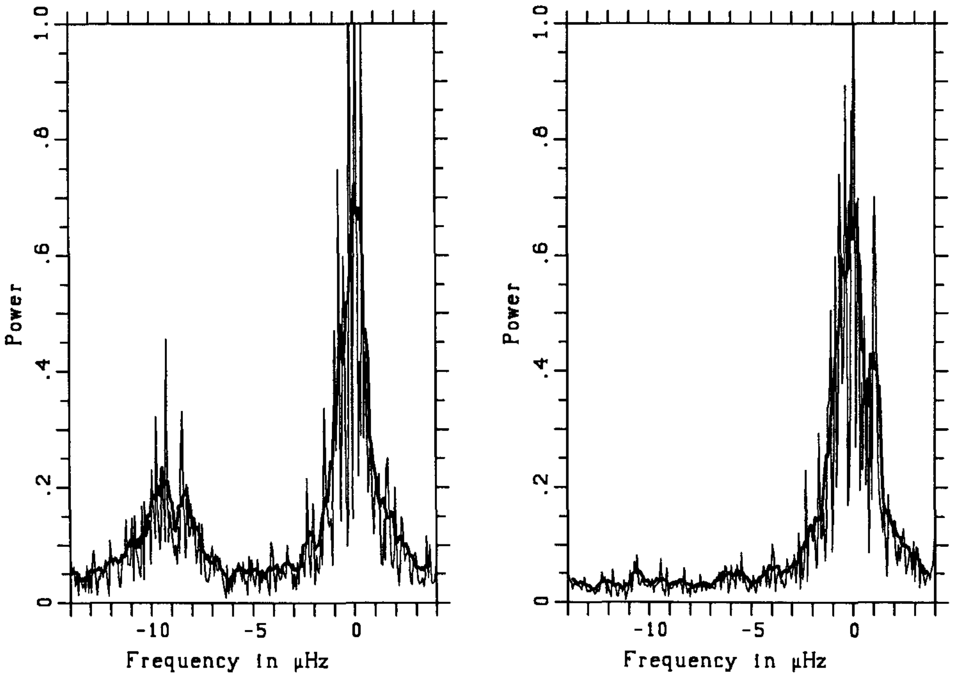

Figure 2: Epoch analysis of l=0 and l=2 (left) and l=1 (right) for orders 17 to 23. The difference in line-width of the l=0 and l=1 is due to unresolved rotational splitting. All lines show a broad pedestal due to modulation by low frequency irradiance variation.

5. Conclusions

The results presented here are the first outcome of the evaluation of the vast information contained in these data. The continuity of the observations with IPHIR are the major advantage of this experiment compared to ground based and Earth orbiting space observations. The results indicate that the achievable accuracy for the determination of absolute frequencies is limited, possibly due to the stability of the mode themselves and their changes during a solar cycle. On the other hand, these data allow an un-biased study of p-mode amplitudes and their evolution in time.

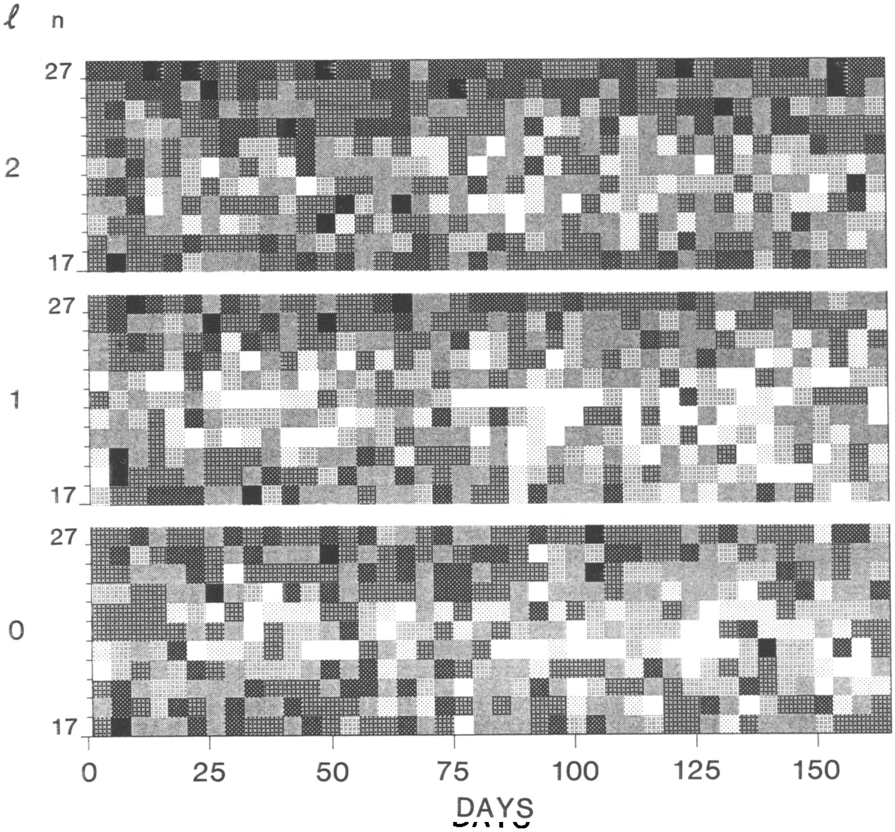

Figure 3: Time variation of the amplitudes of l=0..2 and n=17..27 modes from 31 time series of 5 days length each. The 7 levels of gray scale span relative amplitudes from 0.3 (black) to 1.3 (white). The highly variable amplitudes demonstrate the importance of long uninterrupted time series for the determination of unbiased mean characteristics of the p-modes.

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