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An estimate of the solar background irradiance power spectrum

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Abstract. Knowledge of the solar irradiance background is of great importance to solar and stellar physics. In particular, its contribution to the solar oscillations power spectrum is highly relevant as it represents the ultimate limit to the sensitivity of solar oscillations' observations. An analysis of the power spectra of the solar photometric data coming from four different instruments - two space-borne (ACRIM and IPHIR) and two earth-based instruments (SLOT and LOI-T) - has been performed to obtain the upper limit to the solar irradiance background's spectrum. These observations have been compared to a numerical model computed for the non-coherent solar surface phenomena, namely granulation, mesogranulation and supergranulation. There is an overall good agreement between the general trend of the model and the observed data.

Key words: Sun: oscillations – Sun: general – Sun: granulation

1. Introduction

The solar irradiance background signal is defined as the contribution from the time and spatial variation of small scale solar surface structures integrated over the solar disk. From low to high frequencies, surface inhomogeneities such as faculae, sunspots, etc. coupled with the sun's rotation, convective structures (super, meso and granulation) and their evolution produce the "noise" signal that we call the irradiance background signal. Knowledge of this signal, and of the relative contribution at different frequencies from each of these structures, is of great importance to understand these processes and look for other weak signals which have disappeared in the background. In particular, this information is highly relevant for Asteroseismology, where photometric data is easier to obtain than velocity data and, in most cases, is the only data available. It is also useful when searching for earth-like planets in other stars by measuring the occultation of the starlight by the planet.

For Helioseismology in particular, it is of paramount importance for detecting long period solar oscillations, the so-called g-modes, to gain information on the solar core. Global solar oscillations are concentrated on a frequency band below about 6000 μHz. Particularly, the frequency band below 200 μHz is extremely interesting since it contains the majority of g-modes. All searches for g-modes have yielded negative results, either in velocity or in irradiance measurements (Pallé 1991; Hill et al. 1991). These results are the consequence of a combination of several factors: the low surface amplitude of g-modes, instrumental noise, bad window functions, the terrestrial atmospheric noise and the solar background signal. Both in order to increase the duty cycle and to avoid the noise introduced by the earth's atmosphere g-mode detection requires the use of space missions. But even in the case of measurements taken under ideal observing conditions, the observations would ultimately be contaminated by the unavoidable solar background "noise" produced by these non-periodic, surface phenomena.

The VIRGO experiment proposal to ESA (Fröhlich et al. 1987) contains an estimate of the solar irradiance background variations spectrum. Further, a direct numerical model simulation of the convective structures (Andersen 1991a,b) was made which has been compared to observational data (Andersen et al. 1994) in limited frequency ranges.

Unfortunately, intensity or irradiance measurements are less abundant than velocity measurements which allowed a good estimation of the background velocity solar spectrum (Pallé et al. 1995). However, sufficient data exist to estimate the upper limit of the solar background spectrum in a wide frequency range. In this work the best available Earth-based and space data sets have been used to generate a power spectrum which has been compared with the one obtained from a theoretical numerical simulation of the involved phenomena.

2. Observational data

From the available intensity observations, we have chosen data from four instruments, SLOT and LOI-T, both ground based, and from the space experiments IPHIR and ACRIM.

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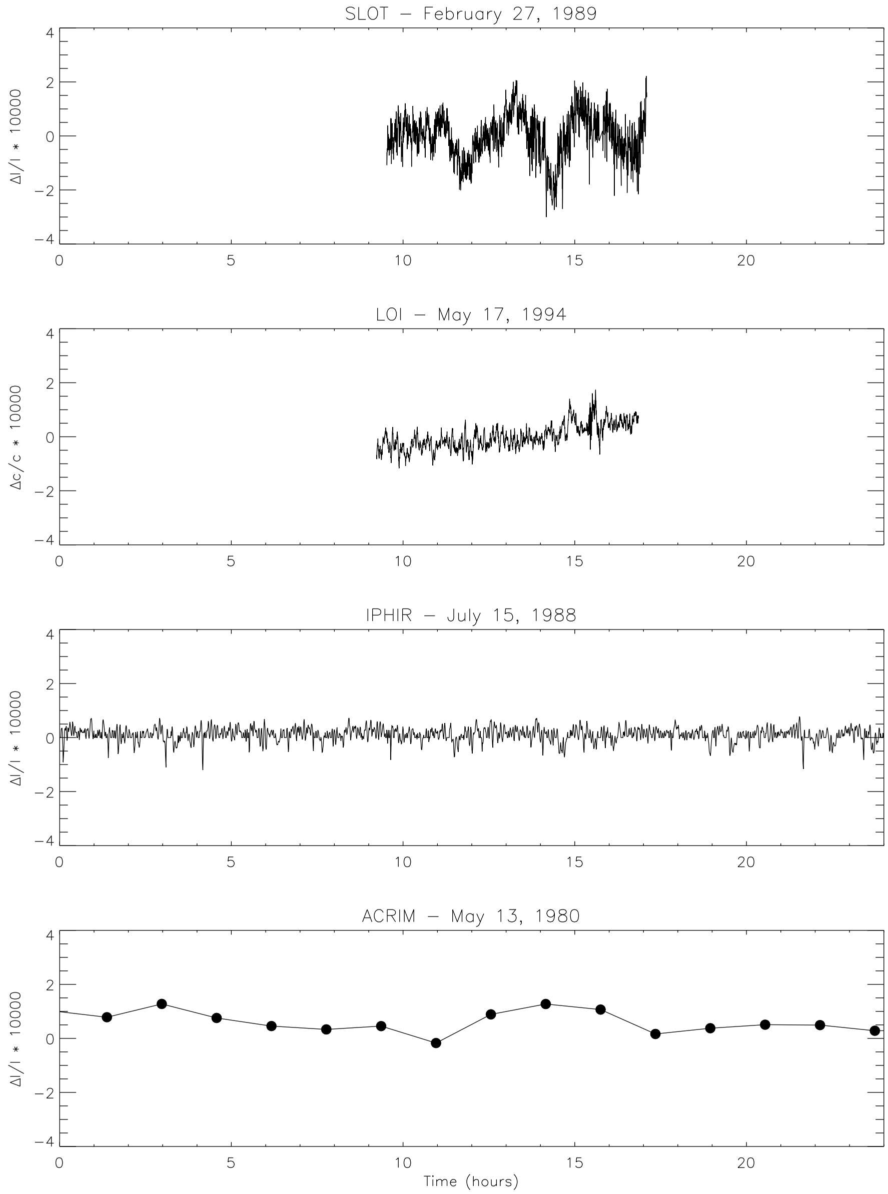

Fig. 1. Residuals obtained for typical observing runs with the 4 instruments SLOT, LOI-T, IPHIR and ACRIM analysed here. Note that in the case of LOI-T the measurements are a radiance ratio

2.1. SLOT

The Solar Luminosity Oscillation Telescope (SLOT) is a four channel photometer built to measure disk integrated sunlight (Andersen et al. 1988a). Solar irradiance has been measured simultaneously at four different wavelengths using interference filters, at the Observatorio del Teide (Tenerife) from August 1984 to May 1989 (Jiménez et al. 1987, 1988, 1990). The best 37 days (7.4 hours around noon), with the smallest variance during the observational period, from the 500 nm channel (10 nm full width) have been selected for the current study. For an extensive discussion on the calculation of residuals see Jiménez et al. (1988) and Rabello Soares et al. (1994). Fig. 1 shows the irradiance residual data for a typical day. The daily power spectra ($\Delta\nu$ = 37.56 μHz) are computed and the average of 37 such spectra shown in Fig. 2.

2.2. LOI-T

The LOI (Luminosity Oscillation Imager) photometric telescope is built following an Andersen et al.'s (1988b) original idea. It is one of the instruments included in the VIRGO experiment on-board the SOHO spacecraft. The Qualification Model (LOI-T) was installed at the Observatorio del Teide (Tenerife) in May 1994, and has been in operation continuously since then (Appourchaux et al. 1995a,b). It consists of a Ritchey-Chrétien Telescope (f = 130.7 cm) imaging the Sun through a 5 nm passband interference filter at 500 nm. The image is projected on a photodiode array detector made up of 12 scientific pixels and 4 guiding pixels (see Appourchaux et al. 1995c).

As the LOI-T instrument has some spatial resolution, it is possible to reduce the effects of the atmospheric extinction. The ratio of the sum of the 4 central pixels (30% of solar disk) to the sum of all 12 pixels (c = I_c/I_t) is used, instead of the solar irradiance obtained by the other experiments. This ratio reduces the effects of the earth's atmosphere (see Rabello Soares et al. 1995). Due to the lack of spatial and time correlation of the surface structures causing the solar background signal, this rationing increases the solar signal relative to the noise produced by the Earth's atmosphere. Fig. 1 shows the typical daily variation of the signal; its power spectrum is calculated using 7.6 hours for each day around noon. Finally, the average of the power density spectra of the best 27 days, selected as before, is obtained and plotted in Fig. 2. Note, in both figures, the substantial reduction of the (atmospheric) noise level as compared to SLOT data.

2.3. IPHIR

The InterPlanetary Helioseismology by IRradiance (IPHIR) measurements, flown on the PHOBOS mission to Mars, gathered long and uninterrupted solar irradiance time series. The IPHIR instrument, built at PMOD/WRC in Davos, was a three channel sunphotometer which measured the solar irradiance at 335, 500 and 865 nm (Fröhlich et al. 1988).

The data analysed in this study were obtained in the period from July to December 1988 of the 500 nm channel (5 nm full width). All the observations were divided into series of 23.4 hours obtaining a total amount of 160 consecutive series of 2048 points each. Fig. 1 shows the typical residuals for one of the series calculated as described by Schrijver et al. (1991). Unfortunately, the data exhibited a strong influence of the pointing errors of the spacecraft, and high-pass filters had to be applied before any further meaningful analysis could be done. Therefore, spectral data below 1500 μHz have not been used in this analysis. The filtered power spectra of each series was computed and the average value of the 160 spectra is shown in Fig. 2.

2.4. ACRIM

The ACRIM-I (Active Cavity Radiometer Monitor) data on board the SMM (Solar Maximum Mission) satellite (e.g. Fröhlich et al. 1991) were also used in this work, providing some information at the lower frequency range (below $\sim$ 90 μHz) obtained from orbital averaged data (Fröhlich & Delache 1984), and at higher frequencies (higher than 480 μHz) time series of the so-called "no-shutter" mode ($\sim$ 3 months of data in late 1989) of the ACRIM were used (Hudson 1993). In Fig. 1 the orbital averaged data for May 13, 1980 series are shown, while Fig. 2 presents the power spectra (smoothed over 9 points) for years 1980 and 1985. These years correspond to maximum and minimum solar activity cycle, respectively (Fröhlich et al. 1991). The smoothed power spectrum at higher frequencies by Hudson (1993) is also shown in Fig. 2.

3. A numerical model simulation

It is interesting to compare these observations with the results of numerical model simulations of the solar background spectrum. The comparison has been made on the basis of results inferred from a direct and simple numerical simulation of the three scales of convective cells observed: granulation, mesogranulation and supergranulation. The model (see Andersen et al. 1994; Andersen 1991a,b) calculates the time evolution of the visible solar hemisphere with a pixel size of 8*8 $arcsec$. The effect of rotation is only taken into account for the supergranular signal and active regions are not included. Since the solar intensity structures are smaller than the pixel size, the high resolution observations are binned into the pixel dimension. This produces some uncertainty in the model, especially for granulation, where the accurate size distribution at its lower limit is difficult to determine. The input parameters have been chosen from high resolution observations of granulation, meso- and supergranulation: lifetimes of 500, 8000 and 72000 seconds and the r.m.s. contrast at full resolution is 11%, 3% and 2%, respectively. The power spectra of the output of such realizations by the numerical simulation is also plotted in Fig. 2.

4. Results and interpretation

The power spectra of each of the observational time series described already, and shown in Fig. 2, clearly show the five minute oscillations (only marginally for SLOT) at roughly the same level of power, plus some "noise". Such "noise" is the sum of instrumental noise, earth-atmospheric noise plus the solar atmospheric non-coherent signal which we have named "solar background" power. It is obvious that the two space instruments are free from earth-atmospheric noise and will hence yield a better estimate of the solar background. This is particularly true at high frequencies where the five-minute oscillation signal appears. IPHIR and LOI-T data are almost at the same level, while in the earth-bound SLOT this signal is barely visible. Between $\sim$ 3500 and 6000 μHz, LOI-T observations of the solar background show even slightly less power than IPHIR. This maybe due to the method used (the radiance ratio) in the residual calculations and/or due to the extra noise in the IPHIR data due pointing effects.

For the frequency band from 200 to 2000 μHz, the spectrum seems to behave as a power law therefore allowing a linear fit in the log-log plot. The results of the fit give a slope of -1.46 $\pm$ 0.05 - for the LOI-T power spectrum. The SLOT power spectrum has a somewhat similar slope: -1.72 $\pm$ 0.05. In addition, the latter is always placed above the former by nearly an order of magnitude. As both are affected by the same earth-atmospheric noise this difference must be found in the method used to analyse the sets of data. Evidently the use of more information, in the case of LOI-T, allows to define a signal in which atmospheric noise has been effectively removed. In fact, the ACRIM power spectra, which are not contaminated by the earth-atmospheric noise, has a very similar slope to the LOI-T, -1.41 $\pm$ 0.03 (see also Fisher et al. 1990). The fact that the ACRIM power spectra lie above LOI-T by about a factor 2 could be due to the difference in the spectral range (LOI-T at 500 nm and ACRIM total irradiance with 50% cut at 700 nm) and/or instrumental noise (see Fröhlich et al.

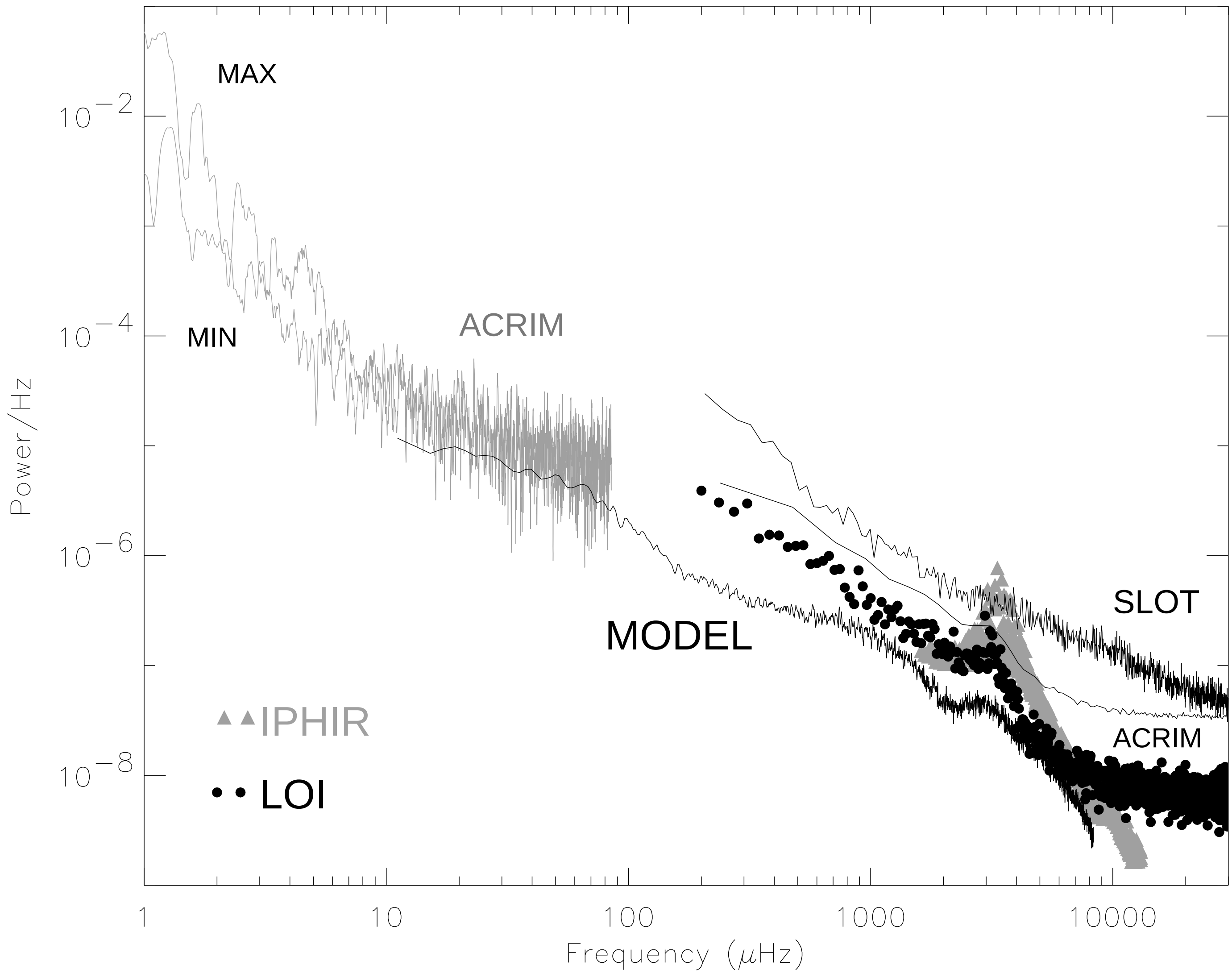

Fig. 2. Average power spectra of the several data sets yielded by the instruments mentioned (see Fig. 1) and a numerical realization of the solar background signal

1991). At intermediate frequencies, data from IPHIR cannot be used as explained above.

Below 10 μHz, the time variable components coming from active regions and the solar rotation dominate the spectra, but between 20 - 100 μHz approximately stationary components are dominant. At these frequencies, only ACRIM data can be used. Indeed, for the frequency band from 10 to 85 μHz, the ACRIM power spectra slope is -0.68 $\pm$ 0.03 and -0.77 $\pm$ 0.03 over periods of low and high solar activity phases, respectively; while for even lower frequencies (0.1 to 10 μHz), the slope is -1.99 $\pm$ 0.06 and -2.69 $\pm$ 0.06 over periods of low and high solar activity. These variations in the slope are attributed to active-region effects (Fröhlich et al. 1991).

When comparing with the solar velocity background spectrum, a similar behaviour is apparent. Pallé et al. (1995) found a slope of -1.53 $\pm$ 0.01 in the frequency range from 100 to 1000 μHz, which resembles the one found here. However, for lower frequencies (0.1 to 10 μHz) the same authors infer a slope of -0.89 $\pm$ 0.06 for both maximum and minimum solar activity which is different from the ACRIM results. Evidently, the contribution of active regions to both signals is of a fairly different nature.

The power level of the numerical simulation in the five-minute region is only a factor of two smaller than that observed by IPHIR and LOI-T. The kinks in the observed background power spectra shown around 3000 μHz are most probably due to a contamination from the p-modes caused by the limited spectral resolution of the averaged data. The kink in the model realization is caused by the choice of lifetime/intensity parameters of the granulation and mesogranulation. A further fine tuning of the input parameters of model maybe required to achieve a better fit for the observations. At higher frequencies, the differences diminish, in remarkable agreement around the acoustical cut-off frequency. At lower frequencies, from 200 to 1000 μHz, the spectrum slope of the model agrees with observations while its power level is a factor two lower than LOI-T. At even lower frequencies - from 10 to 100 μHz - the model output can only be compared to ACRIM results; again the model changes its slope at $\sim$ 100 μHz and virtually reaches the power observed by ACRIM.

The reasonably good agreement in the overall shape of the power spectra of the model realization and the observations suggests that the former is reliable and that the input data chosen are adequate. The fact that the model output lies slightly lower than is observed can be interpreted as due to the presence of some instrumental noise in the observed spectra and/or to uncertainties in the input data of the model.

At the moment, the power spectra shown here are the best representation of the irradiance background continuum spectra, mainly at high frequencies. At intermediate frequencies, from 40 to 1200 μHz, where the g-mode and low order p-mode oscillations are predicted, the lack of good space data compel us to rely on earth-based data which can only constitute an upper limit to it. The slopes from the two different instruments (LOI-T, ACRIM), the model and even the velocity data agree reasonably well. It should be noted that the LOI-T data reductions presented here have removed a significant part of the earth-atmospheric noise. From these considerations, we believe that the solar background spectrum contributes significantly to the signal observed. At even lower frequencies, comparison of the model with ACRIM data turns out to be good enough to conclude that the model presented can be considered as a reasonable estimate of the solar non-oscillatory background signal. Obviously, reliable space data are needed at these frequencies and we look forward to the results from the VIRGO experiment on-board SOHO. Preliminary reductions of data from commisioning phase of VIRGO show a clear flattening of the power spectra at frequencies below 200 μHz. In addition no kink in the background spectra in the p-mode range is observed. These results are in accordance with our interpretation of the observations presented here.

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