ON THE ORIGIN OF SOLAR VARIABILITY, WITH AN APPLICATION TO THE SEARCH FOR EXTRASOLAR PLANETS

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ABSTRACT

Detection of planetary transits holds great promise for the search of terrestrial planets. However, most stars are variable at the level of the signal produced by the transit of an Earth-like planet. Hence, intrinsic stellar variability can lead to "false" planet transit detections. An understanding of the origin of the stellar variability is needed to ensure reliable transit detections. We consider the Sun as the closest and best studied star and analyze its variability on timescales relevant to the transit effect, namely from an hour to several days. Total and spectral solar irradiance measurements obtained by the VIRGO instrument on board the SOHO spacecraft have been analyzed by applying Fourier and wavelet techniques. Preliminary results suggest that at the time scales of interest solar variability is driven partly by solar magnetic activity, which dominates at longer time scales, and convection, in particular solar granulation, which dominates at shorter time scales. As part of a more quantitative analysis a simple numerical model of the irradiance variations due to granulation has been constructed. Irradiance variability of stars with different surface gravity was calculated in the frequency band of relevance to transits.

1. INTRODUCTION

The most successful method of extrasolar planets detection to date is based on radial velocity measurements. However, it is essentially limited to detecting giant planets. In order to detect extrasolar terrestrial planets a different technique must be applied. One of the best suited methods for detection of extrasolar terrestrial planets is to look for transits. It is based on measurements of variations of the stellar brightness: a planet passing in front of its parent star blocks a part of the starlight. The planetary transit is manifested by a dip in the stellar light curve. The depth of the dip is proportional to the ratio of the surface area of the planet to that of the parent star.

A Jupiter-sized planet will cause a ~1% decrease of the parent star's brightness for a main sequence star, an Earth-sized planet causes a decrease of less than 0.01% (Fig. 1).

However, the majority of stars are variable. This is true for the Sun (see Fig. 1 and Fig. 2 for the behaviour of the "solar constant"). Intrinsic variability of the parent star is the dominant source of noise during the planetary transit detections which can lead to spurious detections or mask real ones. An understanding of the origin of stellar variability is therefore important in order to improve planetary transit detections. In this paper we take the Sun as the closest and best studied star with the best data available and analyze its variability on the time scales relevant to planetary transits, ranging from an hour to several days. In particular we distinguish between the influence of magnetism and convection, make a model describing the influence of the latter and finally extrapolate to other stars.

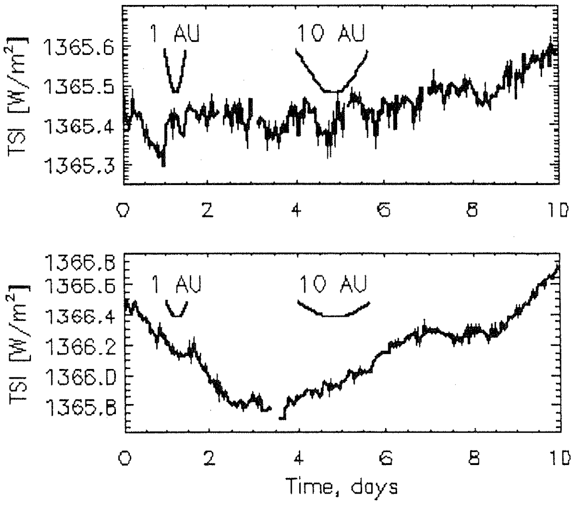

Figure 1: Variation of the total solar irradiance (TSI) measured by the VIRGO instrument (see Sect. 2) at activity minimum (1996, top panel) and maximum (2001, bottom). Curves marked by 1AU and 10AU show an amplitude and duration of the Earth's equatorial transit in front of the Sun.

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2. SOLAR IRRADIANCE DATA

We use solar total (Fig. 2) and spectral irradiance measurements recorded every minute by the VIRGO instrument on board the SOHO spacecraft [1]. Spectral data include measurements in three channels: red, green and blue at 862nm, 500nm and 402nm, respectively. Due to the long exposure to the solar radiation there is a degradation in the VIRGO radiometers, which leads to a heavy trend present in the colour channels. Detrending techniques must be applied prior to any data analysis. Another problem contaminating the data set is the presence of gaps, most of which are caused by VIRGO's calibration procedures. The biggest are several months long (at the time of loss of contact with SOHO), gaps about 20 minutes long are present each day at random times. The gaps have been treated using linear interpolation, as it introduced the least noise compared to other methods.

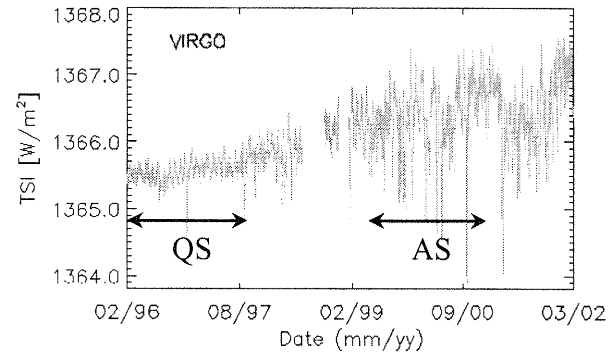

Figure 2: Total solar irradiance measured by VIRGO. The period in 1996- 1997 marked as QS is a quiet Sun period, while 1999- 2000 is a period when the Sun was very active (AS).

Since variations in the solar output related to its magnetic activity follow the solar 11-year cycle it is of interest to compare solar variability during a period of low solar activity with that at high activity. Therefore quiet Sun and active Sun periods are considered separately and then compared. The quiet period we have chosen for analysis corresponds to the years 1996- 1997, the active period to 1999- 2000 (Fig. 2).

3. FOURIER ANALYSIS

We initially analysed solar irradiance data using the Fourier transform. The obtained power spectra are relatively noisy (Fig. 3). At a period of 5 minutes one can clearly see the enhanced power in the p-modes, eigen oscillations of the Sun. To analyze changes of irradiance variability with the solar cycle we have compared the mean power at different frequencies for the active and quiet periods.

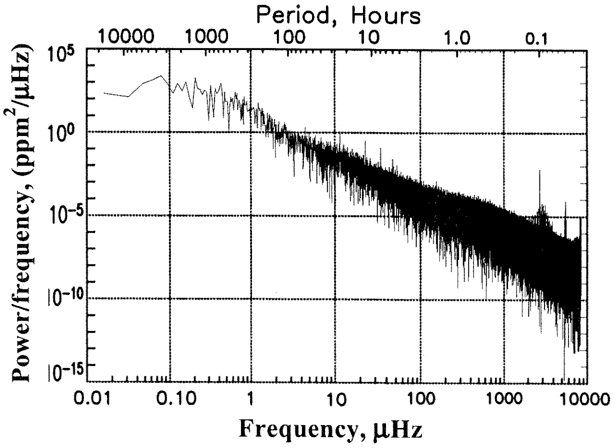

Figure 3: Power spectrum of the total solar irradiance data from 1996 to 1997 sampled at minute cadence.

Comparison of the quiet and active period power spectra suggests that at frequencies lower than 10 µHz (~1 day), where solar variability is governed by surface magnetic field of the Sun [2], more power is present during the active period than during the quiet period. At higher frequencies, above 100 µHz (~3 hours), however, the power at quiet periods is comparable to or a little bit higher than at times of high activity. This suggests that at these frequencies solar irradiance variations do not follow the solar magnetic activity cycle and thus are not dominated by solar magnetism. In the frequency band of 10- 100 µHz, which is especially interesting for us due to the fact that transits of planets in and near habitable zones happen exactly at these frequencies, magnetic and non-magnetic solar variability effects are of similar importance.

4. WAVELET ANALYSIS

Since Fourier spectra are relatively noisy, we have repeated the analysis of total and spectral solar irradiance time series by applying the wavelet transform to the same data series (Morlet wavelets). The wavelet transform gives much smoother spectra, mainly due to the choice of parameters such that a relatively low spectral resolution is chosen, and, in addition, decomposes a time series into time-frequency space, giving thus the frequency spectrum as a function of time.

To see how solar irradiance changes with time over 11-year solar cycle, the ratio of the solar irradiance power spectrum for the active Sun to that for the quiet Sun period has been plotted (Fig. 4).

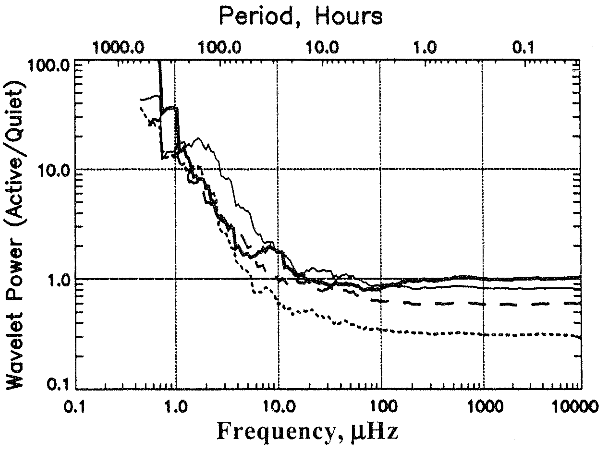

Figure 4: Ratio of the wavelet power during the active Sun period to that of the quiet Sun period for the TSI (thick line) and three VIRGO channels: red (thin solid line), green (dashed) and blue (dotted).

This plot clearly supports the result obtained with Fourier analysis. At periods longer than ~1 day (10 μHz) active Sun irradiance has more power than the quiet Sun irradiance. At periods shorter than ~3 hours (100 μHz), however, power in the quiet Sun is higher than that of the active Sun. The fact that in the spectral channels quiet Sun power exceeds active Sun power can possibly be explained by the heavy degradation of the VIRGO radiometers with time caused by solar UV radiation (C. Fröhlich, private communication). This suggests that correction and post calibration did not remove all the consequences of the degradation. This interpretation is supported by the fact that the total solar irradiance at frequencies between 1000 and 10000 μHz exhibits a ratio very close to unity.

The conclusion suggested by the wavelet analysis is the same as obtained using the Fourier transform: at frequencies lower than ~10 μHz solar irradiance variability is governed by surface magnetic field of the Sun. At the frequencies higher than 10-100 μHz, variability is caused by non-magnetic effects. At periods of interest both effects are important.

5. GRANULATION MODEL

In order to be able to extrapolate from the Sun to other stars it is not sufficient to just identify the sources of solar irradiance variations at timescales of an hour to several days. It is also necessary to construct models that are easily scalable to other stars. Here we concentrate on convection. Of the main scales of solar convection, there is no evidence that the larger scales (meso- and supergranulation) produce any brightness contrast. In the case of supergranulation Rast [3] has actually set rather high upper limit on any such contrasts (that are not related to magnetic field). We therefore concentrate on modelling the granulation.

The main features of the simple model of irradiance variability due to granulation are:

1) The main birth and death mechanisms of convective cells (granules) are fragmentation (at the same time birth and death) and emergence from (birth) or dissolution into (death) the background.

2) The brightness of each granule is assigned randomly within fixed limits with uniform distribution. Thus the contrast between a given granule and the network of intergranular lanes is also randomly distributed within a given range.

3) The lifetime distribution of all granules follows an exponential law (Fig. 5) that has been derived empirically [4, 5].

4) The granular size distribution (Fig. 6) also correlates with the observations [5, 6].

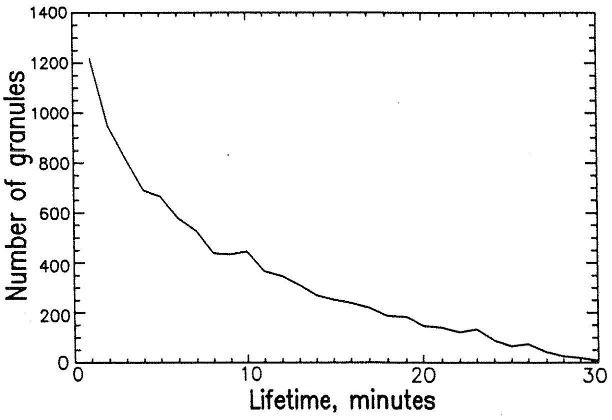

Figure 5: Distribution of lifetime of granules in the model.

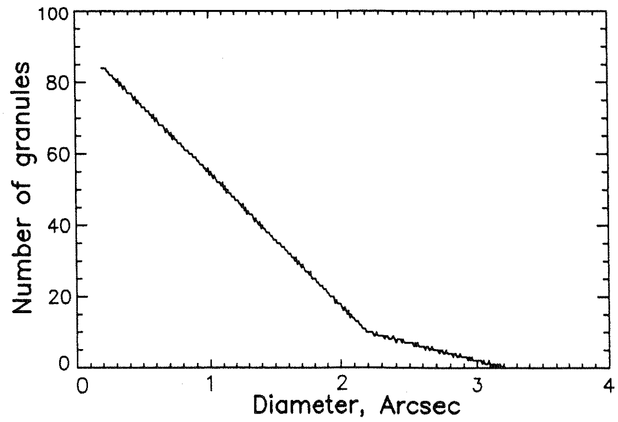

Figure 6: Distribution of granular diameters (arcsec) in the model (cf. [5]).

Results of the modelling give us simulated irradiance sets with variations caused exclusively by the granulation convection. The power spectrum of such variations (Fig. 7) looks quite similar to the high frequency part of the observed one (Fig. 3). Absolute value of power scales with the number of granules in the model.

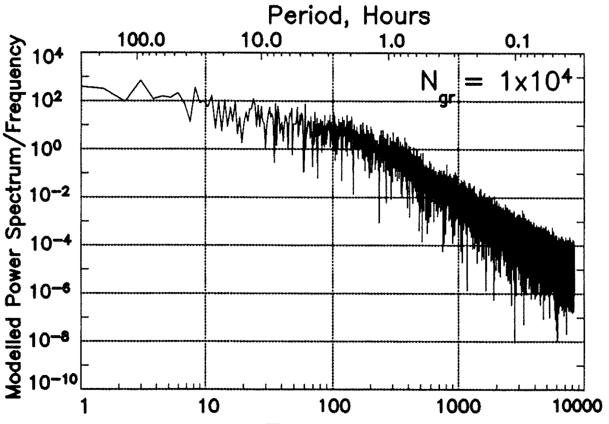

Figure 7: Power spectrum of the modelled stellar irradiance for the case of star with 10^4 *granules.*

The number of granules present on the disc of a given star and the granular contrast are expected to depend on surface gravity, g, and effective temperature, T_{eff}, of a star, since the mean granule size is essentially determined by the photospheric pressure scale height [7, 8]. Thus M. Schwarzschild [7] showed that convective cells on the giant stars are large and their number is very limited: N_{gr} ~ 10- 100, compared with roughly 10^6 for the Sun.

This model can thus be scaled for application to stars with a variety of effective temperatures and surface gravities. The variation of granule lifetime with stellar properties is harder to predict, so for the moment the model treats the granule lifetime as being invariant along the main sequence. Contrast between a granule and the network of intergranular lanes is treated as invariant as well.

In order to look at the cases of stars other than our Sun, we have run the model with different numbers of granules as an input parameter, namely from 10^4 to 10^6 (Fig. 8).

Since giant stars have a relatively small number of convective cells, they produce a lot of noise in the frequency band interesting to us. Magnitude of transit effect of an Earth-sized planet becomes significant relative to the granular noise in the case of stars with about half a million and more granules on the disc. Note that the model does not include the magnetic variability, which will lead to a higher amplitude of variations.

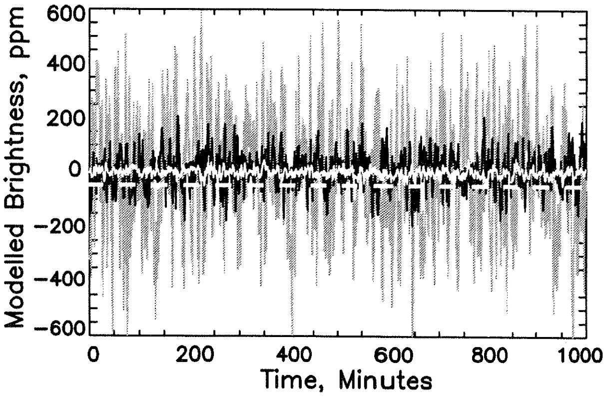

Figure 8: Modelled brightness in the band 10- 100 μHz for stars with different numbers of granules: $5x10^3$ *(grey line),* $5x10^4$ *(black),* 10^6 *(white), (Sun: ~* 10^6 *granules). Also plotted is the magnitude of the effect of the Earth's transit (dashed white horizontal bar).*

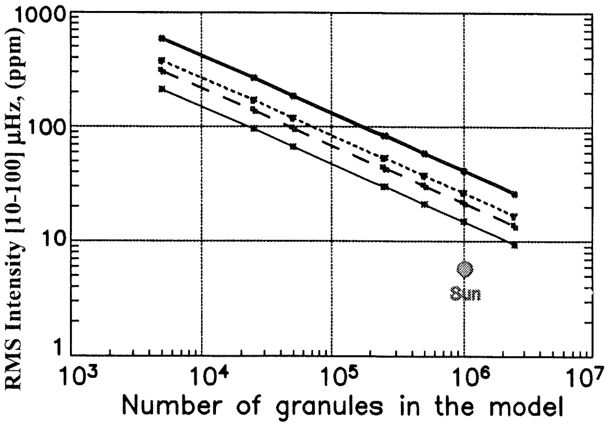

Figure 9: RMS intensity in the band 10- 100 μHz modelled for stars with different number of granules. Shown are: the total irradiance (thick line) and three channels: red (thin solid line), green (dashed) and blue (dotted).

RMS stellar irradiance intensity in the band 10- 100 μHz modelled for different stars has been calculated as a function of number of granules, N_{gr} (Fig. 9). Not surprisingly this model shows that RMS irradiance is proportional to $N_{gr}^{-1/2}$.

Freytag [9] has derived using sophisticated 2-D simulations the mean diameter of a granule relative to that of the star as a function of gravitational acceleration, g, and the effective temperature, T_{eff}.

Using his results we have recalculated RMS stellar irradiance intensity in the band 10- 100 μHz as a function of stellar surface gravity, *g*, for the cases of different stars (Fig. 10).

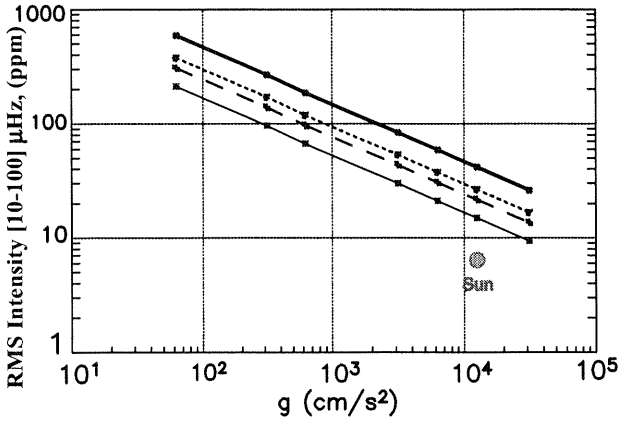

Figure 10: RMS intensity in the band 10- 100 μHz modelled for stars with different surface gravity. Shown are: the total irradiance (thick line) and three channels: red (thin solid line), green (dashed) and blue (dotted).

Results give us following dependence for the RMS irradiance intensity as a function of g:

$$\mathrm{RMS} \sim g^p, \text{ where } p = -1/2.$$

As we can see, in the frequency band related to detection of extrasolar terrestrial planetary transits, 10- 100 μHz, the bigger the star (the smaller its surface gravity), the higher is the power of its intrinsic "noise" caused by the surface granular convection.

6. CONCLUSIONS

Solar irradiance power at low frequencies (periods longer than a day) is clearly higher during the active Sun periods, the cause is high magnetic activity at the solar surface. Power at the periods of interest (less than a few days) is comparable during the quiet and active Sun periods. This suggests that the variability at these time scales is not entirely or even dominantly driven by solar magnetic activity, with solar surface granular convection being the main alternative.

The crossover between magnetic and convective signatures coincides with the frequency band of most interest for extrasolar terrestrial planet transit-search experiments looking for signals with durations of the order of 12 hours.

Granulation convection model shows dependence of the RMS stellar irradiance intensity (in the band related to transits) on the surface gravity of the star:

$$\mathrm{RMS} \sim g^p, \text{ where } p = -1/2.$$

The results show that it is more difficult to detect planet transiting in front of a star, with low surface gravity, e.g. red giants. For such stars the size ratio of planet to star is also particularly unfavourable. The best stellar candidates for the extrasolar terrestrial planets transit-search observations, due to their low noise at related time scales, are small stars with high surface gravity and low surface temperature, e.g. cool dwarves.

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