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Understanding Solar Variability as Groundwork for Planet Transit Detection

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Abstract. Detection of planetary transits holds the greatest promise for the search of extrasolar terrestrial planets. However, intrinsic stellar variability can mask real transits or lead to 'false' planet transit detections. Understanding the origin of stellar variability can help to estimate the minimum sizes of planets detectable with this technique around different types of stars and to identify the best wavelength range for such measurements. The only star for which data with sufficient photometric accuracy and temporal sampling exist is the Sun. We analyze and model solar variability on timescales relevant for planetary transits (hours to several days) using a variety of components, such as granulation, network (supergranulation), faculae and sunspots. This study extends our successful modeling of solar irradiance variations on days to years timescales to these shorter timescales.

1. Introduction

The most successful method for detecting extrasolar planets to date is based on radial velocity measurements. However, it is essentially limited to giant planets. In order to search for extrasolar terrestrial planets a different technique must be applied. Best suited is the detection of planetary transits. A 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 and is less than 0.01% for Earth-type planets.

However, the majority of stars are variable. Intrinsic variability of the parent star is the dominant source of noise during the planetary transit observations 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 the accuracy of such measurements.

In this paper we take the Sun as the closest and best studied star and analyze its variability. Observations of the Sun provide currently the only relevant data set which is long, well sampled and accurate enough for our analysis. We consider solar total and spectral irradiance measurements made by the VIRGO instrument on board the SOHO spacecraft (Fröhlich et al. 1997). Spectral data include measurements in 3 channels: red, green and blue centered at 862nm, 500nm and 402nm respectively. We first analyze variability on time scales of a day and longer and then on shorter time scales. In particular, we distinguish between the influence of magnetism and convection and construct models describing the influence of each of the two mechanisms.

2. Irradiance Changes on Timescales Longer than a Day

Let us first consider irradiance variations on timescales longer than a day. Long timescales attract considerable interest in connection with Sun-climate studies (see e.g., Solanki 2002; Krivova & Solanki 2003 and references therein). Therefore we will only briefly run through the main idea and refer the reader to papers by Fligge et al. (2000) and Krivova et al. (2003) for more details.

Our model is based on the assumption that all irradiance changes on timescales of days to years are entirely due to the evolution of the solar magnetic flux on the surface and includes four components of the solar photosphere: quiet Sun (solar surface free of magnetic fields), umbra and penumbra of sunspots as well as faculae and the network (described as a single component). Calculation of solar irradiance requires two input sets. The first one is the intensities of each atmospheric component as a function of the wavelength and the heliospheric angle. They are calculated from the corresponding model atmospheres using the ATLAS9 code of Kurucz (1992; see Unruh et al. 1999 for details). The second, empirical set is the maps describing the solar surface magnetic field at a given time. They are produced from daily magnetograms and continuum images recorded by MDI on board SOHO.

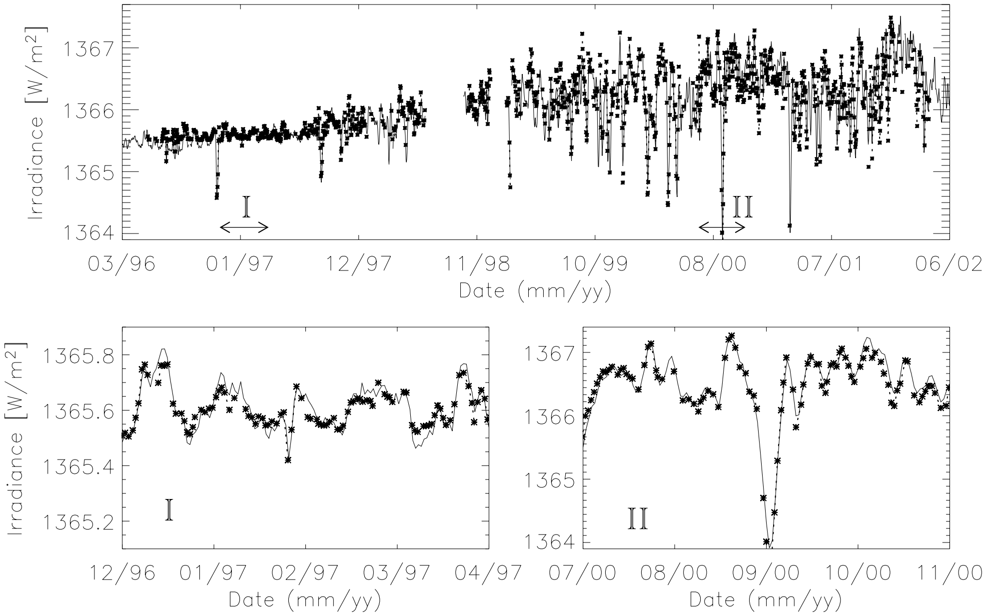

Figure 1. Reconstruction (asterisks) of TSI for about half a solar cycle between 1996 and 2002. The irradiance measurements by VIRGO are presented by the solid line. The bottom panels show zoom-ins to 2 shorter intervals (marked by roman numerals in the top panel).

The reconstructed irradiance and the corresponding VIRGO measurements for the period between 1996 and 2002 are shown in Fig. **??**. The excellent agreement between the model and data leads to the conclusion that the main driver of the solar irradiance variability at time scales of a day up to, at least, a solar cycle is the magnetic field at the solar surface.

3. Short-term Solar Variability

3.1. Mechanism

The origin of irradiance variations at shorter timescales remains, however, unclear. If they are also related to the Sun's magnetic activity, then they should follow the 11-year cycle. Therefore we have analyzed VIRGO records for the quiet (1996–1997) and active (1999–2000) Sun periods individually. We have applied Fourier and wavelet techniques to the data. Both gave basically the same results, except that the global wavelet power spectrum shows smaller fluctuations due to the smoothing introduced by Morlet wavelets (see Seleznyov et al. 2003 and Solanki et al. 2003 for more details).

The ratio of the wavelet power spectrum for the active Sun period to that for the quiet Sun is shown in Fig. **??**. As expected, the ratio is considerably higher than 1 at periods longer than 1–2 days, where magnetic fields dominate the variability. At shorter periods, the ratio is essentially 1 (values below 1 in the 3 colour channels may be an instrumental artifact). This seems to be indicative of a non-magnetic origin of the irradiance variations, with convection being a possible main contributor. At timescales between approximately an hour and a day (which is of particular interest for planetary transits) both mechanisms may play a part.

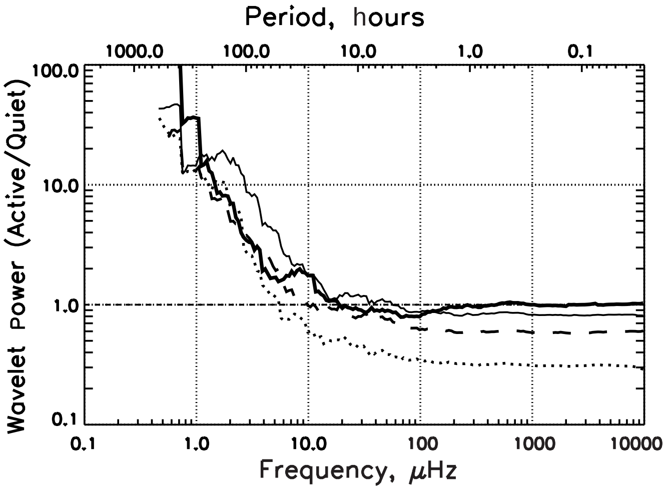

Figure 2. Ratio of wavelet global power spectra of activity maximum to those at activity minimum for the TSI (thick line) and three VIRGO channels: red (thin solid line), green (dashed) and blue (dotted).

3.2. Granulation Model

In order 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) show any intrinsic brightness contrast after contribution of magnetic fields is eliminated (see Solanki et al. 2003 and references therein). We therefore concentrate on modeling the granulation.

The key features of our model are: 1) The main birth and death mechanisms of convective cells (granules) are fragmentation (birth and death) and emergence from (birth) or dissolution into (death) the background. 2) The brightness of each granule is assigned randomly within a fixed range with uniform distribution. 3) The lifetime distribution of all granules follows an exponential law (Fig. **??**a)

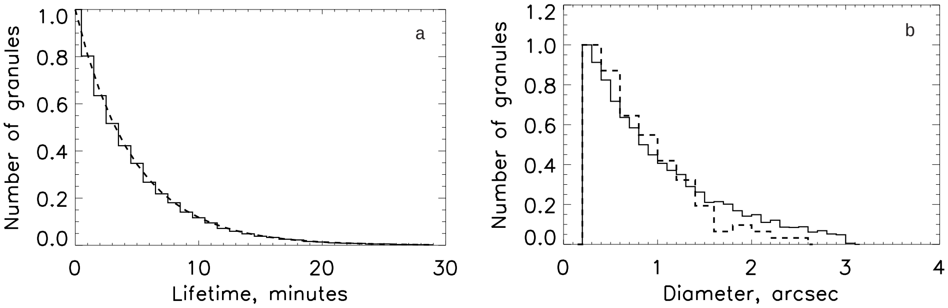

Figure 3. Normalized distributions: a) granule lifetimes; b) granule sizes. Dashed lines give observed distributions, solid — distribution used in the ‘standard’ model.

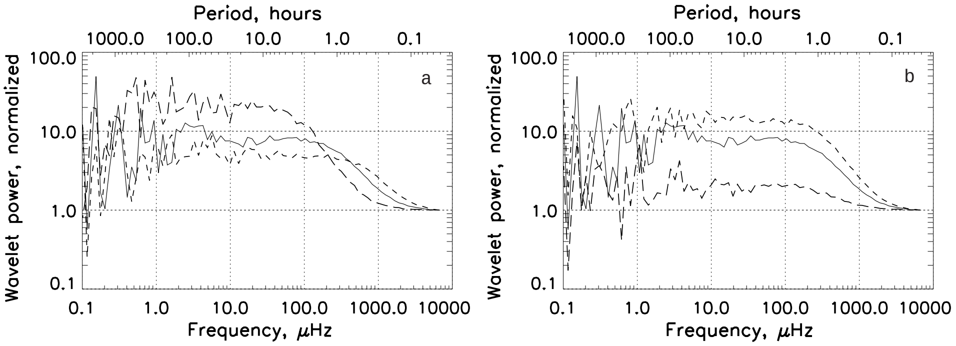

Figure 4. Wavelet power spectra for: a) different granule lifetimes (the solid line shows the observed distribution with the mean lifetime of ∼5.2 min., the long dashed line is for longer lifetimes with a mean of ∼23.7 min. and the short dashed line for shorter lifetimes with the mean of ∼2.9 min.); b) different intergranular lane thicknesses (solid line — width of the intergranular lane is 0.1 arcsec, long dashed — 0.5 arcsec, short dashed — 0.01 arcsec).

that has been derived empirically (Hirzberger et al. 1999). 4) The granular size distribution (Fig. **??**b) is also taken in accordance with the observations (Roudier & Muller, 1987). In order to check the importance of these parameters, we have alternately varied each of them. Two other parameters, the total number of granules, N_{tot}, and the brightness contrast between granule and intergranular lanes will only move the irradiance power spectrum up or down, but not influence its slope or shape.

Some results of our modeling are shown in Fig. **??**. Lifetime of granules and thickness of the intergranular lanes were varied in Figs. **??** a and b, respectively. Longer lifetimes and/or thinner intergranular lanes lead to a steeper slope of the power below several hours. An increase in granular sizes also moves the turning point of the power towards longer periods.

4. Conclusions

We have analyzed solar irradiance variations on timescales between minutes and a solar cycle. Whereas on timescales of a few days and longer, the main mechanism of variations is solar magnetic activity, on shorter timescales convection becomes more and more important. Our simple model implies that granule lifetime and diameters, relative fractions of splitting and dissolving granules as well as thickness of intergranular lanes are important factors determining the shape of the power spectrum at periods shorter than several hours. The crossover between magnetic and convective signatures coincides with the frequency band of most interest for planetary transit observations. Further improvement of the granulation model and combining it with the model due to magnetic field evolution is therefore needed, followed by a generalization to other stars.

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