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Properties of Flux Tubes and the Relation with Solar Irradiance Variability

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Abstract. At the solar surface the magnetic field is bundled into discrete elements of concentrated flux, often referred to as magnetic flux tubes, which cover only a small fraction of the solar surface. Flux tubes span a whole spectrum of sizes, ranging from sunspots to features well below the best currently obtainable spatial resolution.

Whereas sunspots have been well studied, our knowledge of the true brightness of small-scale magnetic features is hampered by the insufficient spatial resolution of the observations. A better understanding of the thermal and magnetic properties of these small-scale features, however, is crucial for an understanding of (climate-relevant) long-term solar irradiance variations.

Key words. Irradiance—flux tube—sunspot—plage.

1. Solar irradiance variations

Space-borne measurements of solar irradiance reveal a remarkably inconstant Sun with variations on time-scales of minutes up to the length of the solar cycle. Most prominent is a 0.1% increase of total irradiance in phase with the solar activity cycle. While sunspots and active region faculae dominate solar irradiance variations on time-scales of days to months (Fig. 1), the active network is also an important contributor to the long-term variations on the solar cycle time-scale.

Sunspots have been studied relatively well. Their large-scale magnetic field structure is rather simple and the temperature is close to that expected from radiative equilibrium (Severino *et al.* 1994; Del Toro Iniesta *et al.* 1994). Based on these simplifications, the influence of sunspots on solar irradiance can be modelled relatively accurately (Foukal 1981; Hudson *et al.* 1982; Fligge *et al.* 1998, 2000). In contrast, our knowledge of the true brightness of small-scale magnetic features composing the faculae and active network is still very incomplete. Observations of these features are challenging and hard to perform due to their complex morphology (Fig. 2) and the low contrast relative to the quiet Sun. Their brightness signature depends on many factors such as limb distance, averaged field strength, wavelength or spatial resolution of the observations (see Solanki 1993, for an overview). The contribution of small-scale magnetic features to solar irradiance changes is one of the largest unknowns in present irradiance reconstructions — especially on time-scales of the solar cycle.

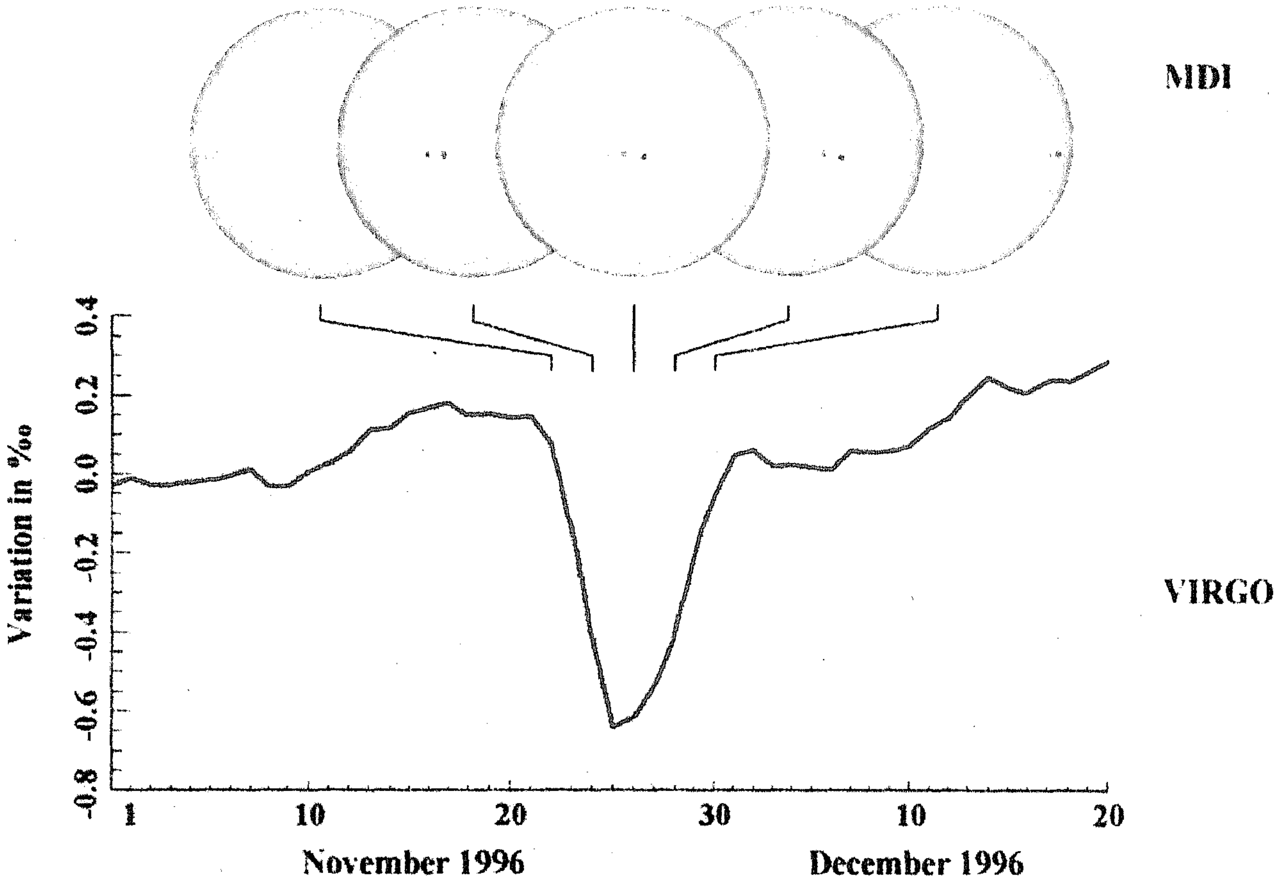

Figure 1. **Top:** A series of MDI continuum intensity images illustrating the passage of a spot-dominated active region across the solar disc at the end of 1996. **Bottom:** Simultaneously recorded values of total irradiance variations measured by VIRGO. The dark spots show up as a distinct dip in the solar irradiance record.

2. Basic properties of flux tubes

At the solar surface the magnetic field is bundled into discrete elements with field strength of the order of 1 kG. The physical properties of these magnetic elements are generally interpreted using the framework of magnetic flux tubes (Spruit 1981; Solanki 1993).

At photospheric heights, the kinetic energy of the gas inside the flux tube is comparable to the energy of the flux tube's magnetic field. The magnetic field, therefore, inhibits the convective energy transport within the flux tube and attenuates the heat flux from below; the flux tube is cooled. In addition, the internal gas pressure is reduced to preserve the pressure equilibrium between the inside of the flux tube and its surrounding, leading to a lowering of the $\tau = 1$ level within the flux tube (Wilson depression, Fig. 3). As a result deeper layers become visible. The walls of the flux tube below the external τ=1 level are hot due to the rapid rise in temperature with depth.

For small (optically thin) flux tubes the radiative inflow through the hot walls is able to significantly heat up the middle and upper parts of the flux tube's photosphere making these layers hotter than in the quiet Sun (.Grossmann-Doerth *et al.* 1989). This leads to an increased contrast within spectral lines compared to the continuum (Frazier 1971) — something which is also seen in MHD models of the solar photosphere (Fig. 4, Gadun *et al.* 2000). As the diameter and, thus, the optical thickness of

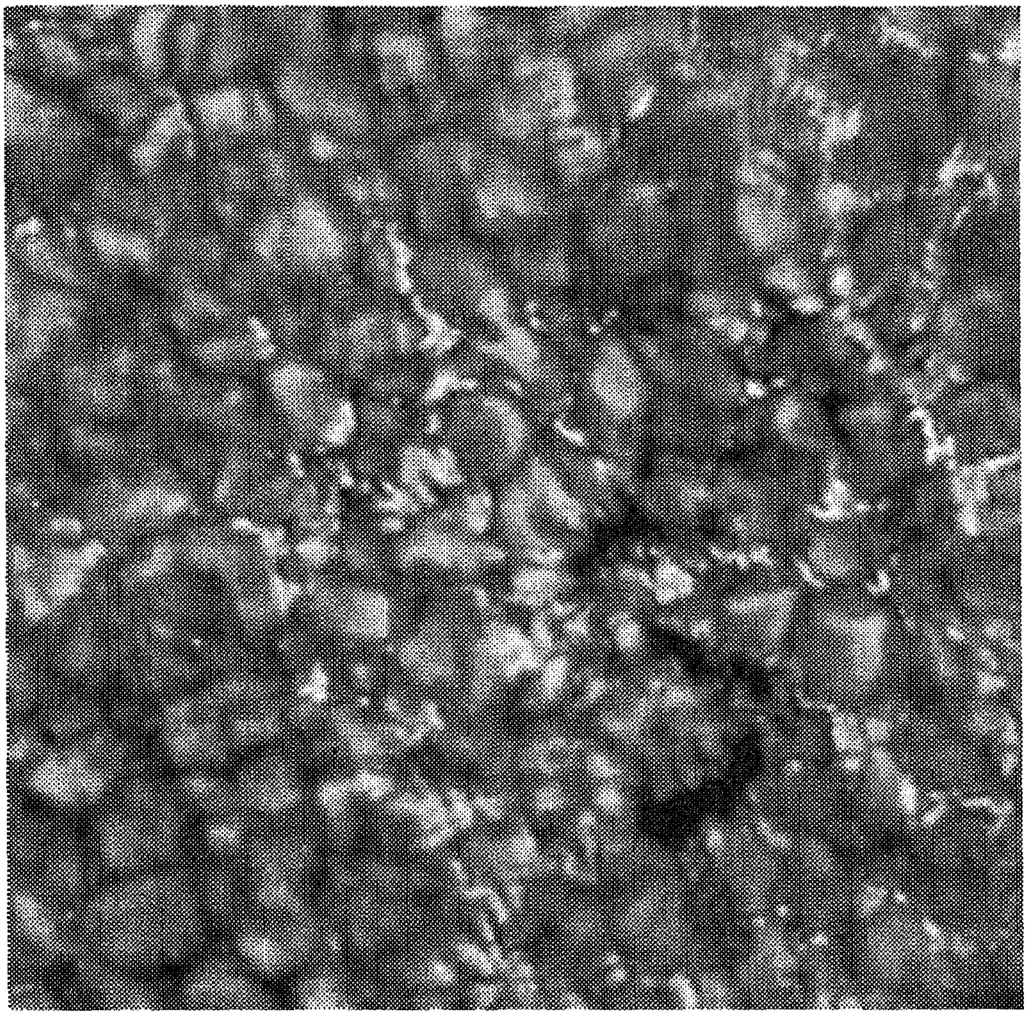

Figure 2. High resolution g-band (430.5 nm) image of an active network region. The bright points along the intergranular lanes mark the presence of small-scale magnetic features. (Courtesy of NSO/KP).

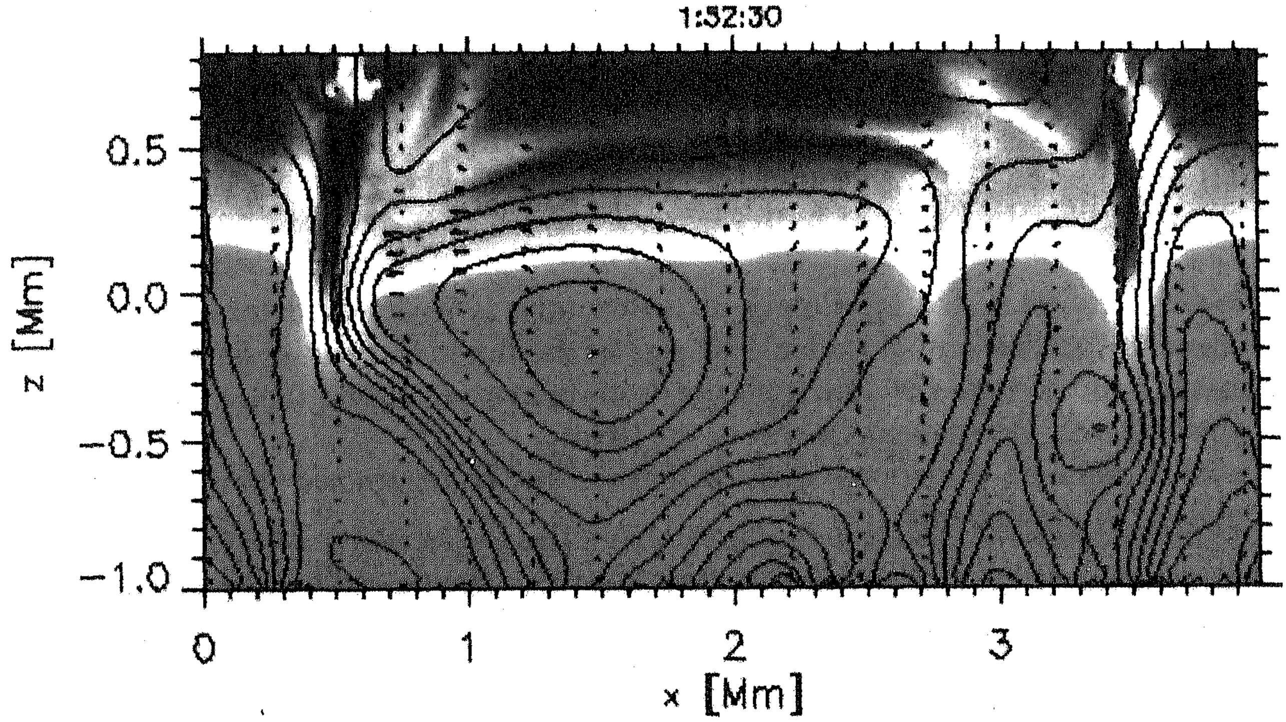

Figure 3. Vertical cut through the solar surface from a 2D-MHD simulation of the solar granulation. It illustrates the concentration of the magnetic field lines and the formation of flux tubes. Two such concentrations are seen: near $x = 0.5$ Mm and 3.5 Mm. (Figure provided by S.R.O. Ploner based on the simulations of Gadun *et al.* 2000).

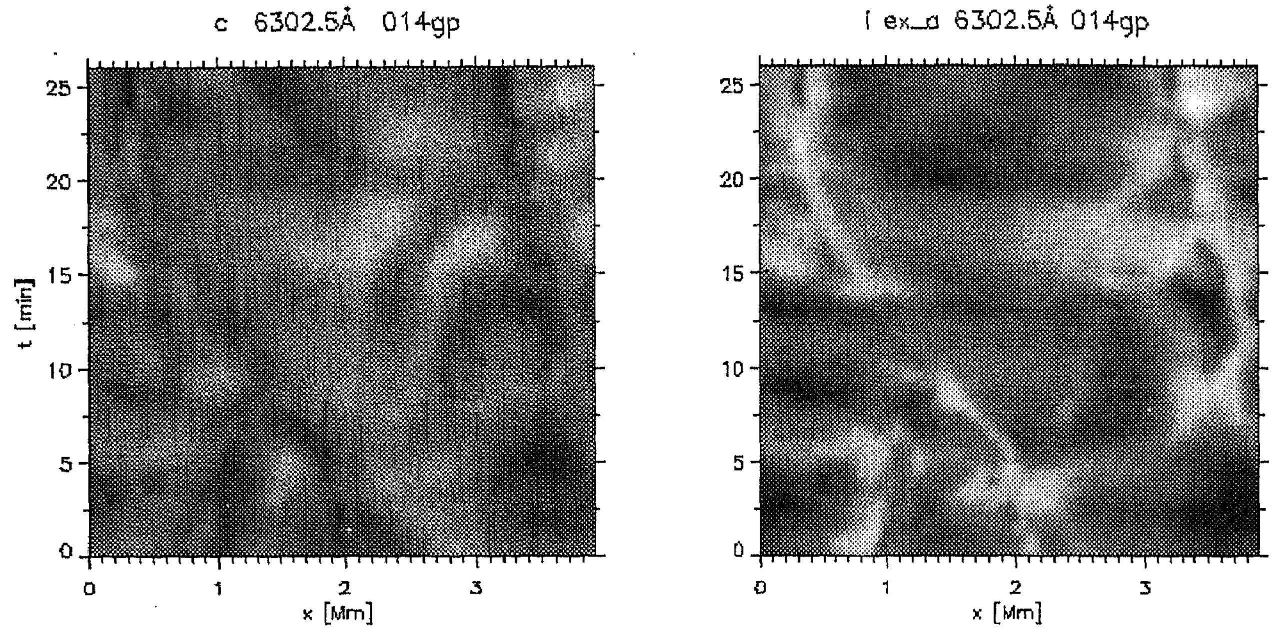

Figure 4. Temporal evolution of the emergent radiation of a vertical cut through the solar atmosphere using a 2D MHD model of the solar granulation (Gadun *et al.* 2000). The x-axis covers roughly 4 Mm. As expected, these simulations show an increased contrast in the core of a spectral line (right panel) compared to the continuum (left panel) for regions of concentrated flux.

the flux tube increases, the effectiveness of the heating by the inflowing radiation from the hot walls decreases. The brightness of a flux tube therefore, is to a large extent determined by its diameter. However, the brightness of flux tubes also shows a very pronounced center-to-limb variation (CLV) since the visibility of the hot walls increases towards the limb (Spruit 1976).

In summary, large flux tubes (pores and sunspots) are dark while small flux tubes (composing the faculae and active network features) usually are bright. This is plotted schematically in Fig. 5 (from Solanki 1999). Flux tubes of intermediate size are bright at the limb and dark at disc centre in the continuum, although they may be bright in some spectral lines.

3. Irradiance models

Following section 2, the brightness of a flux tube is basically determined by two parameters: size and limb distance. The size of the flux tubes within an active region increases with average field strength, i.e. with increasing filling factor (Solanki and Brigljevic 1992; Grossmann-Doerth *et al.* 1994).

Solar irradiance variations can, therefore, be reconstructed based upon the following two ingredients:

(1) A detailed description of the distribution of the solar surface magnetic field and its evolution in time.
(2) The brightness of individual magnetic features as a function of limb distance μ and filling factor α.

The first can, to a large extent, be obtained by examining full-disc magnetograms. The latter, however, requires detailed magneto-hydrodynamic and radiative transfer modelling of flux tubes and their surroundings (e.g. Steiner *et al.* 1996; Gadun *et al.*

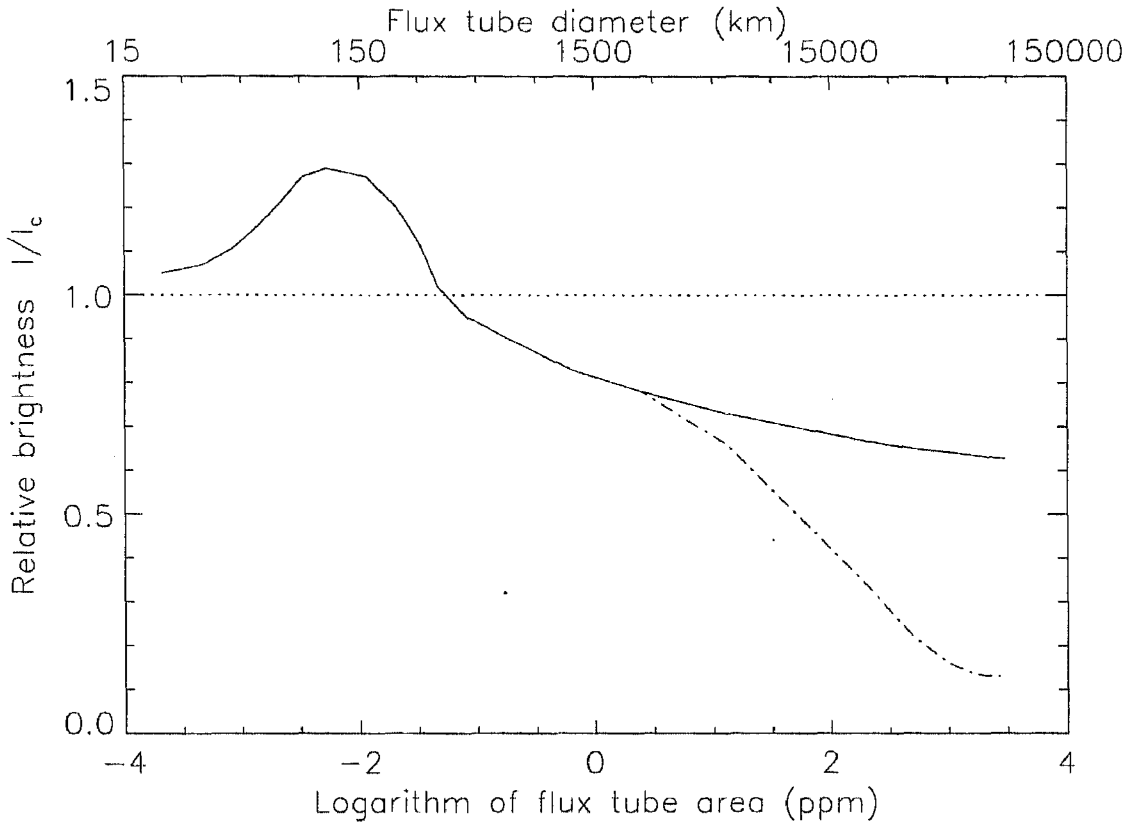

Figure 5. White-light contrast of flux tubes relative to the quiet Sun as a function of flux tube diameter, i.e. logarithmic flux tube area (in ppm). The solid line represents the relative brightness averaged over the whole spot while the dashed-dotted line is for the umbra only.

2000), or the empirical determination of their properties based upon, e.g., sophisticated inversion techniques (Ruiz Cobo & Del Toro Iniesta 1992, 1994; Frutiger *et al.* 1999).

To bypass the difficulties arising from such multi-dimensional or multi-component approaches, we present a method to reconstruct solar irradiance variations based on the representation of sunspots and faculae (and the quiet Sun) by simple 1-component models whose brightness can be derived using ATLAS, a spectral synthesis code developed by Kuracz (1992).

In this model the intensity $I_{i,j}(\lambda; t)$ of an element (i,j) on the solar surface at time t and wavelength λ is given by

$$\begin{aligned} I_{i,j}(\lambda;t) = & (1 - \alpha^s_{i,j}(\Phi;t) - \alpha^f_{i,j}(\Phi;t)) \cdot I^q(\mu(i,j),\lambda) \\ & + \alpha^s_{i,j}(\Phi;t) \cdot I^s(\mu(i,j),\lambda) \\ & + \alpha^f_{i,j}(\Phi;t) \cdot I^f(\mu(i,j),\lambda), \end{aligned} \quad (1)$$

where $I^q(\mu(i,j),\lambda)$, $I^s(\mu(i,j),\lambda)$ and $I^f(\mu(i,j),\lambda)$ are the calculated intensity spectra of the quiet Sun, the sunspot and the facular model, respectively. The fractional coverage of the solar surface element (ij) by the three components is described by the filling factors $\alpha^s_{i,j}(\Phi;t)$ (sunspots) and $\alpha^f_{i,j}(\Phi;t)$ (faculae). The filling factors are deduced from full-disc magnetograms by converting the measured magnetic flux within the element (i,j) into a corresponding filling factor.

The model has been used by Fligge *et al.* (2000) to reconstruct short-term solar total and spectral irradiance variations measured by VIRGO . The high correlation (roughly

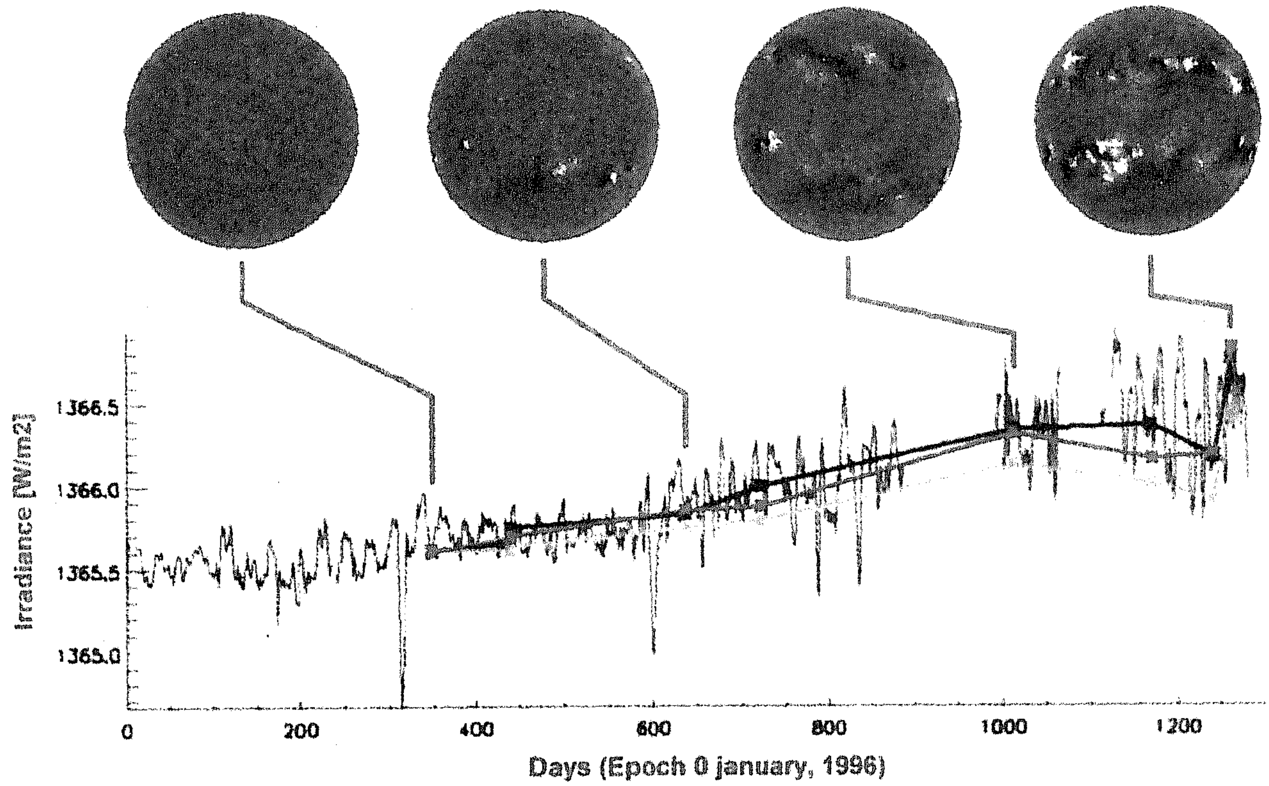

Figure 6. **Upper part:** Full-disc magnetograms of MDI indicating the increase of solar activity from the minimum of cycle 22/23 towards the maximum of cycle 23, **Lower part:** Total solar irradiance as measured by VIRGO (thin line). The black squares represent VIRGO measurements on 10 selected days. The reconstruction of irradiance on these days using 20-minutes averaged magnetograms is given by the dark gray squares, the reconstruction using standard 1-minute magnetograms by light gray ones.

0.95) between the measured and reconstructed time-series confirms the dominant influence of simspots and active region faculae to irradiance changes on time-scales of a few weeks.

It is still under debate as to what extent long-term changes of solar irradiance, i.e. the increase of the solar brightness between activity minimum and maximum can be explained by models based on solar surface magnetic fields only. Addressing these time-scales, the slowly varying contribution of the active network must be carefully taken into account.

In a preliminary analysis, we applied the method described above to reconstruct solar irradiance changes during the onset of cycle 23. To this end, we picked out 10 days between 1996 and 1999 when complete sequences of at least 20 successive MDI full-disc magnetograms taken at a cadence of 1 per minute were available. Finally, we reconstructed relative solar irradiance values for each day using either a single 1-minute (recA) or an average over 20 1-minute (recB) magnetograms, thereby, increasing the signal-to-noise ratio by a factor of ≈ 4.5.

This is illustrated in Fig. 6. The four magnetograms on the top denote the increase of solar magnetic activity during the time period considered. The VIRGO time-series of daily total solar irradiance measurements is shown by the thin line, while the measured irradiance values for the 10 selected days are marked with squares and connected with a thick, black line.

The predicted increase of total solar irradiance due to recA (light gray) is too small. Due to the higher noise level within the 1-minute magnetograms (20 G) most network points elude detection. The network contribution, therefore, is heavily underestimated.

However, recB, represented by the gray line, closely follows the VIRGO measurements. This indicates that even on these time-scales, it is the solar surface magnetic field that produces most of the observed solar irradiance changes.

4. Conclusions and outlook

In recent years there has been increasing evidence that the solar surface magnetic field is by far the most important driver of solar irradiance variations on time-scales of days up to the solar activity cycle length (and probably even longer). Models based purely on the evolution of solar surface magnetic features have been highly successful in reproducing not only total and spectral irradiance variations but also a number of other solar phenomena related to solar activity like, e.g., the variation of the ratio of facular to sunspot areas (Fligge *et al.* 1998) or variations of the amount of line-blanketing over the solar cycle (Unruh *et al.* 1999).

Although solar irradiance modelling has made substantial progress many details have still to be worked out. One major simplification implicit in current models is that they completely neglect the physical nature of faculae, namely that they are composed of small-scale flux tubes. A way to improve the irradiance models and to deepen our understanding about the brightness variations produced by solar surface magnetic features is to derive the atmospheric parameters from spectro-polarimetric measurements using inversion techniques (Ruiz Cobo & Del Toro Iniesta 1992; Frutiger *et al.* 1999). By simultaneous inversion of multiple spectral lines different layers of the solar atmosphere can be probed and thermal stratification can be derived. New techniques, such as the use of *response functions* (Ruiz Cobo & Del Toro Iniesta 1994) are able to dramatically speed up the inversion of depth-dependent quantities making such investigations feasible. To validate future models, however, new experiments providing irradiance records of high temporal *and* spectral resolution are needed. Such measurements are expected to become available within the next few years.

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