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Models of Solar Irradiance Variations: Current Status

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Abstract. Regular monitoring of solar irradiance has been carried out since 1978 to show that solar total and spectral irradiance varies at different time scales. Whereas variations on time scales of minutes to hours are due to solar oscillations and granulation, variations on longer time scales are driven by the evolution of the solar surface magnetic field. Here the most recent advances in modelling of solar irradiance variations on time scales longer than a day are briefly reviewed.

Key words. Sun: activity, faculae, plages, magnetic fields—solar irradiance—solar-terrestrial relations—sunspots.

1. Introduction

Solar irradiance is the total amount of solar energy at a given wavelength received at the top of the earth's atmosphere per unit time. When integrated over all wavelengths, this quantity is called the total solar irradiance, previously known as the solar constant. Since 1978 we know, however, that the Sun is a variable star and solar irradiance varies on all time scales at which it has been measured, i.e., minutes to decades (Willson & Hudson 1988, 1991; Fröhlich 2005), and most probably, on longer time scales as well (cf. Lockwood *et al.* 1999; Solanki *et al.* 2000).

This has important implications for our understanding of global changes in the earth's climate system. As weak as they are ($\approx 0.1\%$ over the solar cycle), irradiance variations affect the terrestrial environment (e.g., Eddy 1976; Reid 1987; Haigh 1996, 2001; Bond *et al.* 2001; Rind 2002; Langematz *et al.* 2005). Thus in order to assess quantitatively contributions of different sources of climate fluctuations, first the solar signal has to be reliably isolated. However, global climate changes typically occur on time scales longer than the length of the available irradiance record. This calls for a reconstruction of irradiance variations back to the pre-satellite period over as long a period as possible, which is only possible with the help of suitable models. Such models should include as much of our understanding of the physical mechanisms responsible for irradiance variations as possible and, to be successful, they must reproduce all available observations. Therefore, in the first part of this review (section 2) we concentrate on irradiance models aimed at recreating the measured variations in total (TSI) and spectral (SSI) solar irradiance. Then, in section 3, reconstructions of solar irradiance for earlier times are discussed.

2. Solar irradiance in cycles 21–23

2.1 *Total solar irradiance*

Solar irradiance variations on time scales of minutes to hours are caused by solar oscillations and granulation (Solanki *et al.* 2003). Significant changes in the Sun's luminosity and radius on time scales of 10^6–10^{10} years are predicted by the theory of stellar evolution. Variations on other time scales are predominantly due to the evolution of the solar surface magnetic field.

The two most striking features of the observed record of solar irradiance are the variations by about 0.1% in phase with the solar cycle and sharp dips with a comparable or even greater amplitude typically lasting 7 to 10 days. These dips are caused by the passage of sunspot groups across the visible solar disc as the Sun rotates. Towards activity maxima, when the number of sunspots grows dramatically, the frequency and depth of the dips increase. On average, however, the Sun brightens. This is due to the increased amounts of bright features, faculae and network elements, on the solar surface. The total area of the solar surface covered by such features rises much more strongly as the cycle progresses than the area of dark sunspots.

The most direct way to replicate the observed irradiance variations is thus to combine proxies (two or more) describing sunspot darkening (e.g., sunspot number or areas) and facular brightening (such as facular areas, Ca II or Mg II indices), e.g., using regressions (e.g., Chapman *et al.* 1996; Fröhlich & Lean 1998; Preminger *et al.* 2002; Jain & Hasan 2004). More physics-based models have also been developed (e.g., Fontenla *et al.* 1999, 2004; Fligge *et al.* 2000; Krivova *et al.* 2003; Wenzler *et al.* 2004, 2005, 2006; Giorgi *et al.* 2007).

In these models, maps of a given proxy, e.g., Ca II K brightness (PSPT models: Ermolli *et al.* 2003; Fontenla *et al.* 2004; Harder *et al.* 2005; Giorgi *et al.* 2007) or magnetogram signal (SATIRE models: see Krivova & Solanki 2005a; Solanki *et al.* 2005, and references therein) are analysed in order to extract information about the distribution of the magnetic features (sunspot umbrae, penumbrae, faculae, plages, the network, etc.) on the Sun's surface and its evolution with time. They are then converted into irradiance using semi-empirical model atmospheres such as those by Fontenla *et al.* (1999, 2006) and Unruh *et al.* (1999).

Figure 1 compares the total solar irradiance in cycles 21–23 calculated by Wenzler *et al.* (2006) using the SATIRE model and the Kitt Peak NSO magnetograms and continuum images with direct TSI measurements (Fröhlich 2006). The correlation coefficient between the data and the model is 0.91 for the whole period 1978–2003 and 0.94 for the period since 1992, when the new magnetograph came into operation at Kitt Peak and the quality of the data improved significantly. Moreover, if space-based magnetograms and continuum images from the MDI instrument on SoHO are used (which are only available since 1996), the correlation coefficient improves further reaching 0.96 (Krivova *et al.* 2003). Note that the reconstruction by Wenzler *et al.* (2006) extends the available TSI record by about 4 years going back to 1974, although with significant gaps.

2.2 *Spectral solar irradiance*

The advantage of the irradiance models involving model atmospheres is that both TSI and SSI can be calculated (Fontenla *et al.* 2004; Fontenla & Harder 2005;

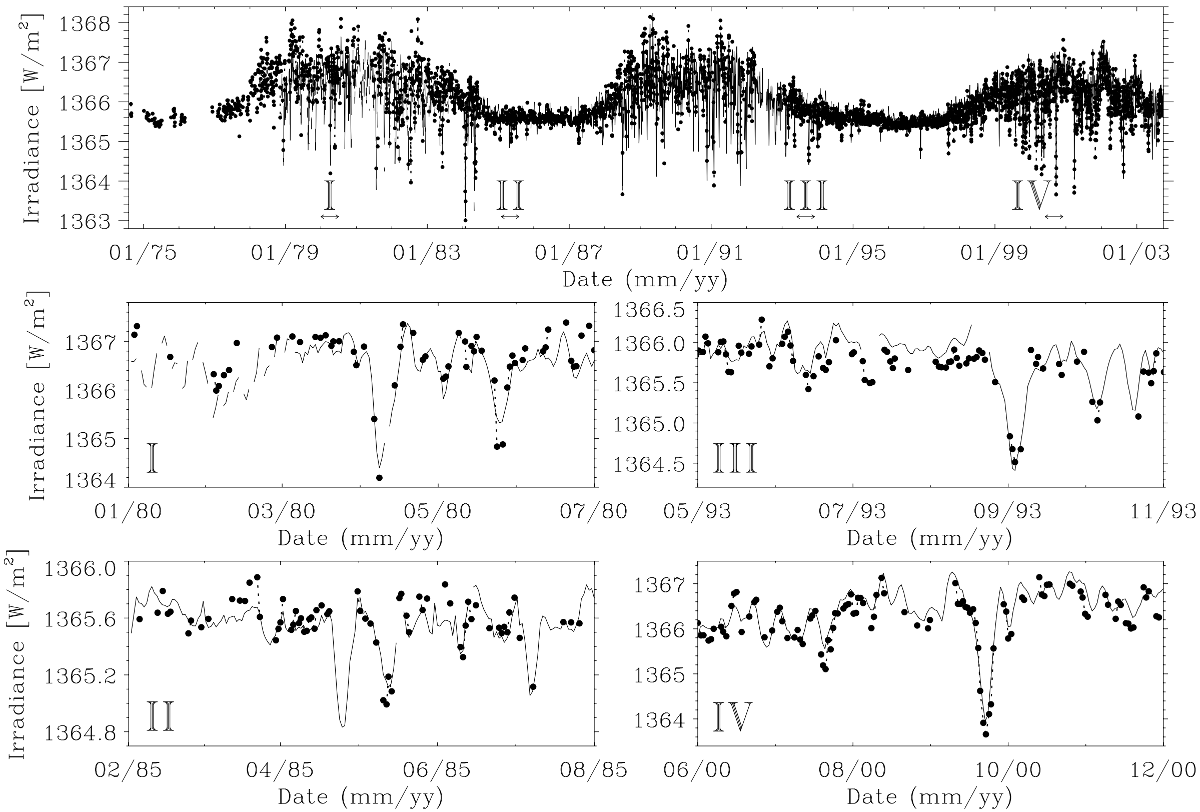

Figure 1. **Top panel:** The reconstructed TSI (filled circles, connected by dotted curve when there are no data gaps) based on NSO/KP data between 1974 and 2003. The solid line represents the measured total solar irradiance (PMOD composite, Fröhlich 2006) between 1978 and 2003. The **bottom panels** are enlargements of four shorter intervals at different activity levels from different cycles (from Wenzler *et al.* 2006).

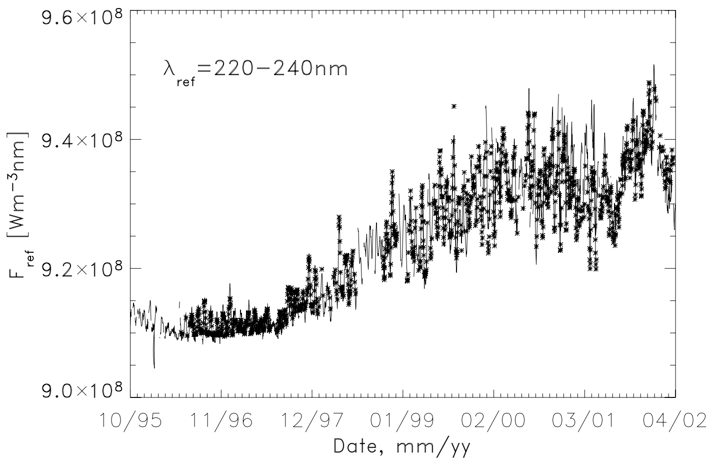

Figure 2. The solar irradiance integrated over the wavelength range 220–240 nm as a function of time. The solid line represents the SUSIM measurements (Floyd *et al.* 2003) and asterisks the SATIRE model. The correlation coefficient between the calculated and observed records is 0.97. (From Krivova *et al.* 2006).

Krivova & Solanki 2005b; Krivova *et al.* 2006; Danilovic *et al.* 2007). The models reproduce reasonably the observed SSI variations in the near-UV (above approximately 200 nm), visible and near-IR (Unruh *et al.* 1999; Krivova *et al.* 2003; Harder *et al.* 2005; Krivova & Solanki 2005b; Danilovic *et al.* 2007). One example is shown in Fig. 2, where the irradiance integrated over the wavelength range 220–240 nm obtained with SATIRE (asterisks) is compared to UARS SUSIM measurements. The correlation coefficient between the two time series is 0.97.

These models, however, fail at shorter wavelengths due to the LTE approximation which is often taken to compute model atmospheres but is no longer good in this spectral region. Employment of a non-LTE approximation is one possible line of attack on the problem (e.g., Fontenla *et al.* 1999, 2006). But since such calculations are much more arduous, non-LTE models remain as yet imperfectly developed and further efforts are needed in this direction (e.g., Haberreiter *et al.* 2005).

An alternative approach has recently been developed by Krivova & Solanki (2005b) and Krivova *et al.* (2006) that allows an empirical extrapolation of the SATIRE models down to 115 nm using available SUSIM measurements. Since the SATIRE model has been found to work well in the spectral range 220–240 nm (see Fig. 2), they used empirical relationships between the irradiance in this range and irradiance at other wavelengths covered by the SUSIM detectors (115–410 nm), to also calculate SSI at all these wavelengths. As an example, the calculated solar Ly-α irradiance is compared in Fig. 3 to SUSIM measurements and to the composite of UARS SOLSTICE measurements and related proxy models by Woods *et al.* (2000). Note that the latter record is adjusted to the UARS SOLSTICE absolute values, so that the difference between the two models is only due to the difference of about 5% in the magnitude of the Ly-α cycle shown by SUSIM and SOLSTICE. Other than that, the model agrees well with the completely independent

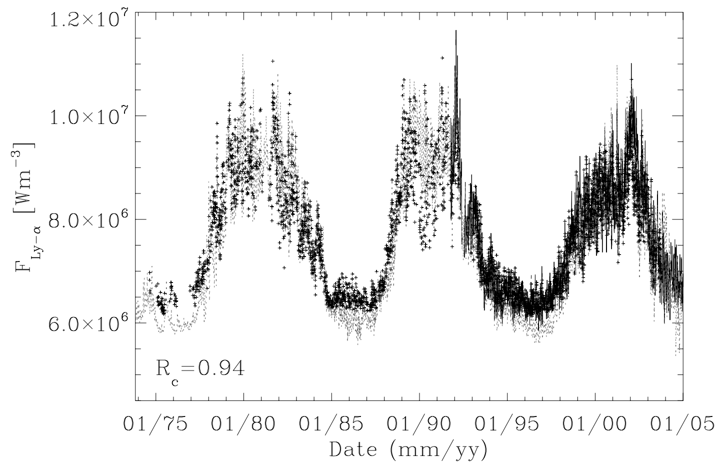

Figure 3. Solar Ly-α irradiance since 1974: reconstructed (plusses), measured by SUSIM (solid line) and compiled by Woods *et al.* (2000, dotted line). The correlation coefficient between the model and the composite is 0.94.

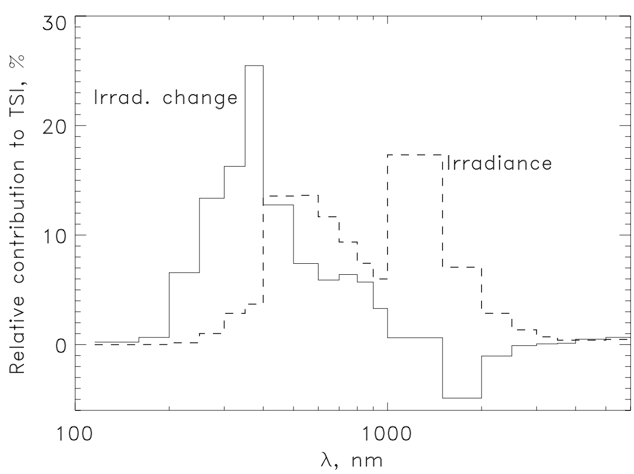

Figure 4. The relative contribution of different wavelength ranges to the TSI (dashed histogram) and its solar cycle variations (solid histogram). Note different sizes of bins: about 40 nm below 200 nm, 50 nm between 200 nm and 400 nm, 100 nm between 400 and 1000 nm and 500 nm at yet longer wavelengths. From Krivova *et al.* (2006).

composite time series, with a correlation coefficient of 0.94 (Krivova *et al.* in prep.).

Figure 4 shows the contribution of different spectral ranges to solar irradiance (dashed) and its solar cycle variation (solid) calculated by Krivova *et al.* (2006). The contribution of the UV irradiance variations to the total irradiance change is very high: about 60% of all TSI variations originate below 400 nm.

3. Going back in time

3.1 *Solar irradiance since 1610*

The remarkable agreement of the modelled variations of TSI and SSI with their measurements implies that it is the solar surface magnetic field which is responsible for their modulation. Thus the reconstruction of solar irradiance on longer time scales requires the computation of the Sun's magnetic field for the same time scale. When doing this, it is necessary to distinguish between cyclic variations, which can often be well described by proxies (e.g., the sunspot number), and secular variations, which are more tricky to estimate. A simple physical model has been developed by Solanki *et al.* (2000, 2002) that allows a reconstruction of the solar total and open magnetic flux from the sunspot number and provides an explanation for the origin of the secular variation. In this model, the sunspot number is used as a proxy for the freshly emerging magnetic flux in active regions. Emergence of magnetic flux in smaller ephemeral regions is considered separately. In doing so, it is taken into account that, firstly, the ephemeral regions start to emerge earlier than the active regions of the same activity cycle (e.g., Harvey 1992), and secondly, that the open flux lives much longer on the Sun's surface than the corresponding closed flux, e.g., in active regions. This leads to an overlap between activity cycles of the ephemeral regions and, thus to a build-up of the background magnetic flux, whose level varies with time.

This model has recently been used by Krivova *et al.* (2007) to reconstruct solar total irradiance back to 1700 using the Zurich sunspot number and to 1610 using the Group sunspot number. The reconstructed TSI is presented in Fig. 5. The model predicts an increase in the cycle-averaged TSI since the Maunder minimum of $1.3^{+0.2}_{-0.4}\,\mathrm{Wm}^{-2}$, which is in agreement with other recent estimates. Wang *et al.* (2005) obtained a value of $1\,\mathrm{Wm}^{-2}$, but since they neglected the extended length of the ephemeral region cycle, this should be considered as a lower limit. On the other hand, Foster (2004), cf. Lockwood (2005), obtained an upper limit of $1.7\,\mathrm{Wm}^{-2}$ by assuming that the network disappeared during the Maunder minimum.

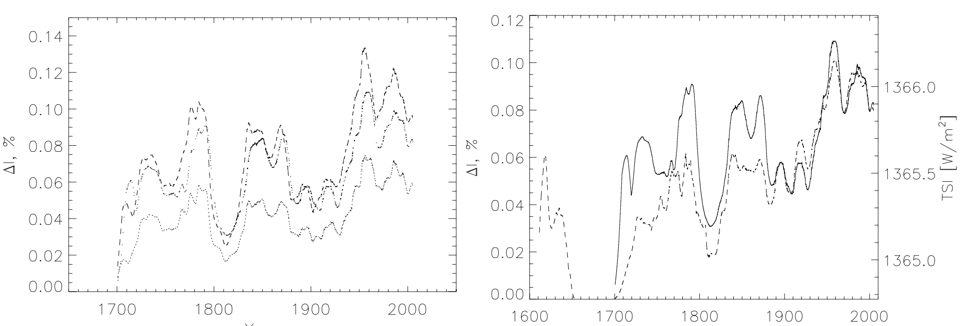

Figure 5. **Left:** 11-yr running mean of the reconstructed TSI based on the Zurich sunspot number since 1700 (solid line). The dashed and dotted lines show the models obtained under extreme assumptions and represent the upper and lower limits on the magnitude of the secular increase in the TSI, respectively. **Right:** Same but now for the TSI reconstructed using Zurich (solid line) and Group number (dashed line). (From Krivova *et al.* 2007).

3.2 *Solar irradiance before 1610*

On even longer time scales no direct measurements of solar variability are available. Therefore, indirect proxies must be used, such as the cosmogenic isotopes ^{10}Be and ^{14}C, which are produced when high-energy cosmic rays enter the earth's atmosphere and react with nitrogen and other atoms. Since the cosmic ray flux at the earth is modulated by the Sun's magnetic activity, it is possible to reconstruct the strength of the solar open magnetic flux using the production rates of cosmogenic isotopes stored in natural terrestrial archives. This allows a reconstruction of the sunspot number (Solanki *et al.* 2004; Usoskin *et al.* 2006) over the last 7 millennia (or even 11, although somewhat less reliably). This reconstruction has shown that the Sun is currently in a state of unusually high magnetic activity.

Since only a cycle-averaged sunspot number can be obtained, the model described in section 3.1 cannot be applied in a straightforward manner to calculate the variations of the TSI. Nevertheless, analysing the behaviour of the cycle-averaged sunspot number, solar magnetic flux and the TSI during the last 4 centuries and applying these relationships to the complete reconstructed time series of the sunspot number, it is possible to assess the evolution of the solar irradiance over the last few millennia. Such a reconstruction is currently on the way (Vieira *et al.* in prep.).

4. Summary and outlook

Models of solar irradiance have progressed significantly in the past years. Observed variations of solar total and spectral irradiance are reproduced with high accuracy. Advances have also been made in reconstructing the past behaviour of the solar irradiance, on time scales of centuries to millennia. It has been shown that solar total irradiance has increased by approximately 0.1% since the end of the Maunder minimum, which is comparable to the 11-yr modulation during the 3 recent activity cycles but is significantly less than was previously assumed. On even longer time scales, the Sun appears to be in an unusually active state: over a period of 11,400 years, a similar level of activity as in the last 60 years was only reached during about 3% of the time.

Despite this progress, there is still considerable work to be done. The following developments are needed, some of which can be expected in the near future:

- removal of the remaining free parameter(s) from the models;
- reconstruction of the solar spectral irradiance back to the Maunder minimum;
- reconstruction of the TSI and SSI over the last 7000 years;
- improvement of the employed semiempirical model atmospheres using new sunspot and facular observations (e.g., Ortiz *et al.* 2002; Ermolli *et al.* 2007; Mathew *et al.* 2006) and measurements of SSI from SORCE and SCHIAMACHY;
- non-LTE model atmospheres.

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