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ScienceDirect
Advances in Space Research 40 (2007) 986–989
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
www.elsevier.com/locate/asr

Reconstruction of solar irradiance using the Group sunspot number

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Received 27 November 2006; received in revised form 2 February 2007; accepted 5 February 2007

Abstract

We present a reconstruction of total solar irradiance since 1610 to the present based on variations of the surface distribution of the solar magnetic field. The latter is calculated from the historical record of the Group sunspot number using a simple but consistent physical model. Our model successfully reproduces three independent data sets: total solar irradiance measurements available since 1978, total photospheric magnetic flux from 1974 and the open magnetic flux since 1868 (as empirically reconstructed from the geomagnetic aa-index). The model predicts an increase in the total solar irradiance since the Maunder Minimum of about 1.3 Wm^{-2}.
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Keywords: Solar activity; Solar irradiance; Solar magnetic fields

1. Introduction

Total solar irradiance changes by about 0.1% between solar activity maximum and minimum. Accurate measurements of this quantity are only available since 1978 (Fröhlich, 2006) and do not provide information on longer-term secular trends. In order to reliably evaluate the Sun's role in recent global climate change, longer time series are, however, needed. They can only be assessed with the help of suitable models. The most successful models are those attributing irradiance variations on timescales longer than a day to the evolution of the Sun's surface magnetic field (Solanki et al., 2005; Krivova and Solanki, 2005). Such models explain more than 90% of all observed changes in the total and spectral irradiance at these timescales (Krivova et al., 2003; Wenzler et al., 2004, 2005, 2006; Krivova et al., 2006). The continuously evolving distribution of the solar magnetic field on the surface is described in these models by recourse to magnetograms, which are only available since 1974. For a longer term reconstruction, another proxy of solar magnetic activity has to be employed. The available historical proxies of solar activity, such as the Group and Zurich sunspot numbers, sunspot, facular or Ca II plage areas mainly describe the evolution of the larger magnetic features, such as sunspots or faculae, but do not provide any direct information about the weaker features. Therefore, whereas the reconstruction of the cyclic component of the irradiance variation is typically not a problem, evaluation of the amount of the secular change is not straightforward (see Solanki and Krivova, 2004, and references therein). Solanki et al. (2000, 2002) proposed a simple physical mechanism which can lead to such a secular trend in the magnetic flux based on the overlap of consecutive activity cycles. Here, we use their model to reconstruct the magnetic flux of the Sun back to 1610 from the Group sunspot number (Hoyt and Schatten, 1998) which is employed to reconstruct total solar irradiance for the same period.

2. Approach

2.1. Photospheric magnetic flux

The basic assumption of our model is that the irradiance variations are caused entirely by the evolution of the magnetic features on the solar surface. As in the model of Solanki et al. (2002), magnetic features on the Sun's surface

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doi:10.1016/j.asr.2007.02.077

are divided into active regions (AR) and ephemeral regions (ER). The flux emergence rate in AR, ϕ_{act}, can be estimated from the Group sunspot number since it serves as a good proxy for the fresh flux threading the solar surface. The time evolution of the flux emerging in ephemeral regions, ϕ_{eph}, is more uncertain, however. Observations suggest that the emergence rate in ER is related to that of AR, but the exact shape of this relationship is not yet well established. They show that ER associated with the new cycle start emerging at the solar surface before the corresponding AR cycle begins and while magnetic features from the previous cycle are still appearing (Harvey, 1992, 1993). Thus, the ER cycle length is extended with respect to that of AR. Therefore we prescribe a sine approximation for the shape of the ER cycle, with its length being somewhat stretched in time with respect to that of the corresponding AR cycle and with its amplitude being proportional to the amplitude of the AR cycle (see Krivova et al., 2007, for details).

Both active and ephemeral regions contribute to the open flux (ϕ_{open}), which is dragged by the coronal gas and reaches far into the heliosphere. Since this flux is mainly unipolar, it decays slowly and lives much longer on the solar surface (up to several years) than the AR and ER flux.

The extended length of the ER cycles and the long lifetime of the open flux lead to an overlap between consecutive cycles such that some background magnetic flux is present on the solar surface even at activity minima. The amount of this flux changes with time due to variations in the length and the amplitude of the magnetic activity cycle. This mechanism thus provides a physical explanation for a secular change in the total photospheric magnetic flux.

2.2. Variations of the total solar irradiance

Following Krivova et al. (2003), Wenzler et al. (2005), the solar photosphere is divided into 5 atmospheric components: the quiet Sun, sunspot umbrae and penumbrae, faculae and the network, denoted with subindices q, u, p, f and n, respectively. The model consists of two main ingredients: one which is temporally invariant and another that introduces a variation with time.

The time-independent brightness of each component $F_{q,u,p,f,n}(\lambda)$, with λ being the wavelength, is calculated using the ATLAS9 code of Kurucz from plane-parallel model atmospheres (see Unruh et al., 1999, for a description of the models). Faculae and the network are described by the same model atmosphere. All fluxes obtained in this way depend only on the wavelength.

On the other hand, variability in time is due to the changing surface distribution of the magnetic components. To describe this, we need to determine which part of the solar surface is covered by each component at a given time, i.e. the corresponding filling factors, α. In case of sunspots they are directly extracted from the sunspot area time series available since 1874 (see Balmaceda et al., 2005). Before that time, sunspot areas are extrapolated by comparing them with the sunspot number. To estimate the filling factors for umbrae and penumbrae separately, we use the umbral to penumbral area ratio $\alpha_u/(\alpha_u + \alpha_p) = 0.2$ as found by Wenzler et al. (2006). The filling factors of the other components are obtained from the reconstructed solar magnetic flux. The magnetic flux in faculae, ϕ_f, can be obtained from $\phi_f = \phi_{act} - \phi_u - \phi_p$, where ϕ_{act} is the flux in AR and ϕ_u, ϕ_p represent the flux in sunspot umbrae and penumbrae, respectively. Finally, the evolution of the network magnetic flux, ϕ_n, which is responsible for the secular change, is given by the sum of the flux from ER, ϕ_{eph}, and the open flux, ϕ_{open}: $\phi_n = \phi_{eph} + \phi_{open}$.

The final step is the conversion of the magnetic flux in faculae and the network into the corresponding filling factors. For this, we follow the conversion scheme described by Fligge et al. (2000) and Krivova et al. (2003). The facular and network filling factors increase linearly from 0 at $\phi = 0$ to 1 at ϕ_{sat}. For magnetic flux larger than ϕ_{sat}, the filling factor remains unity. Following Krivova et al. (2003),Wenzler et al. (2004, 2005, 2006) we use the value $\phi_{sat,f} = 300$ G for faculae while for the network we employ $\phi_{sat,n} = 500$ G. This somewhat enhanced saturation level for the network takes into account the fact that a significant amount of weak magnetic flux in the network is lost due to the insufficient spatial resolution and relatively high noise level of the magnetograms employed.

Finally, the solar radiative flux at a given wavelength, λ, can be obtained by combining the fluxes from the 5 components:

$$F(\lambda, t) = \alpha_q(t)F_q(\lambda) + \alpha_u(t)F_u(\lambda) + \alpha_p(t)F_p(\lambda) + (\alpha_f(t) + \alpha_n(t)) \cdot F_f(\lambda).$$

Here, $\alpha_q(t) = 1 - \alpha_u(t) - \alpha_p(t) - \alpha_n(t) - \alpha_f(t)$. The total solar irradiance is then obtained by integrating $F(\lambda,t)$ over all wavelengths.

3. Results

The reconstructed total magnetic flux for individual Carrington rotations is compared to data obtained at different observatories, WSO, NSO KP and MWO, in Fig. 1a. The model reproduces both the amplitude and the length of the solar cycle in the observed magnetic flux. The evolution of the magnetic flux in active and ephemeral regions, as well as of the open and total magnetic flux is shown in Fig. 1b. The effect of the spatial resolution on the detection of small ER noted by Krivova and Solanki (2004) is taken into account by considering the quantity $\phi_{tot} = \phi_{act} + 0.4 \cdot \phi_{eph} + \phi_{open}$. Since ER cycles overlap, the flux in these regions varies only by a factor of 2 over a cycle, which is much smaller than the variation in the AR cycles. The ER flux is comparable to that of AR during activity maxima while it clearly dominates during minima, in agreement with Harvey (1993) and Krivova and Solanki (2004).

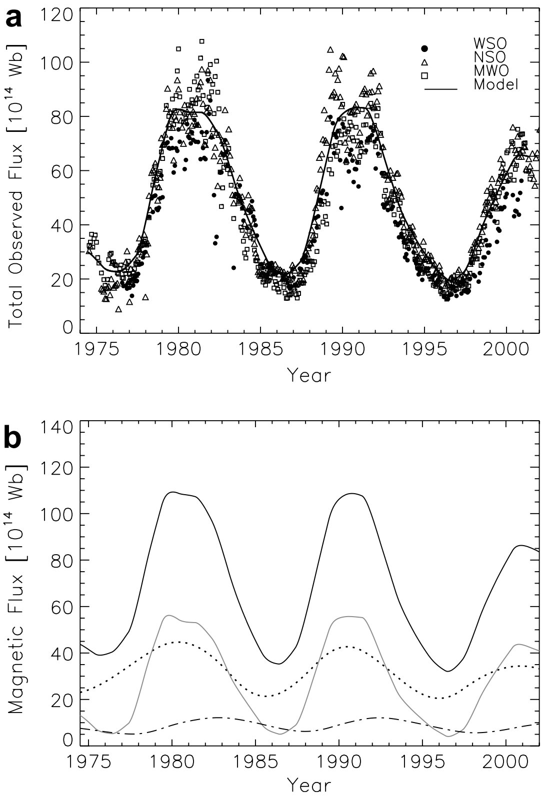

Fig. 1. (a) Total magnetic flux for individual Carrington rotations between 1974 and 2002. Different symbols represent data from synoptic charts obtained by different observatories (Arge et al., 2002). The solid line shows the magnetic flux calculated from the Group sunspot number. (b) Reconstructed magnetic flux in active regions (grey line), ephemeral regions (dotted), as well as the open (dot-dashed) and total flux (black line).

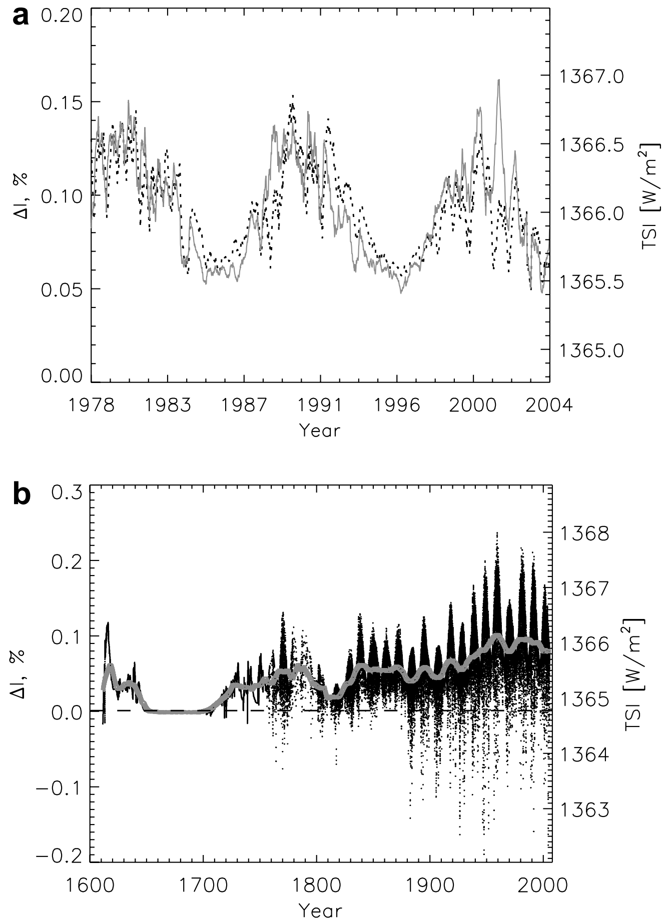

Fig. 3. (a) Three-month running mean of the daily sampled TSI for recent cycles: modelled (dots) and measured (solid line; PMOD composite). (b) Variation of the total solar irradiance since 1610. The grey solid line represents the 11-yr running mean of this variation.

Our model also reproduces the secular increase in the open flux during the last century found by Lockwood et al. (1999). This is illustrated in Fig. 2, where the modelled open flux is compared to the reconstruction based on the aa-index by these authors.

Fig. 3a shows the comparison between the PMOD composite of TSI (Fröhlich, 2006, grey solid line) and the solar irradiance reconstructed from the Group sunspot number (dotted line). In order to facilitate comparison, we plot 3-month running means. Note, however, that individual dips due to sunspots are also reproduced if daily time series is considered. Both the amplitude and the phase of the variations are reasonably reconstructed. Of course, the coarse magnetic flux model we use is rather simple to reproduce all details of the irradiance variations. For example, the sine approximation of the cycle shape does not produce the double-peak structure of cycle 23, as was observed.

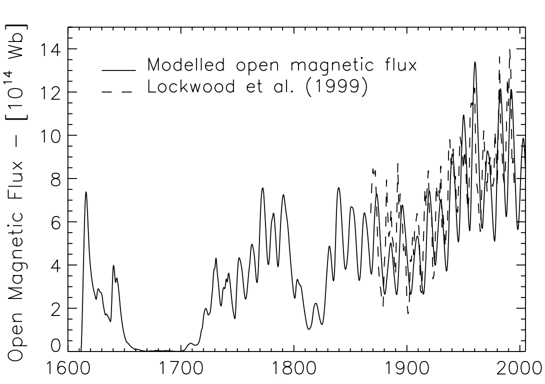

Fig. 2. The calculated open flux (solid line) and the reconstruction based on the geomagnetic aa-index by Lockwood et al., 1999.

The daily values of the reconstructed solar irradiance since 1610 are shown in Fig. 3b. The 11-yr running mean is indicated by the grey solid line. As mentioned before, for the period prior to 1874 when no sunspot area measurements are available, they are obtained by extrapolating sunspot number back to 1610. For the period prior to 1753 only monthly values of the Group sunspot number can be used. After 1753 daily values are available although prior to approximately 1850 there are many gaps in the data. Sampling becomes more regular after 1818. Our model predicts an increase in the solar irradiance since the end of the Maunder Minimum (i.e., 1700) till the present (average over about 30 years) of about 0.095% or 1.3 Wm^{-2}.

4. Conclusion

We have reconstructed total solar irradiance back to 1610. The cyclic variation of ER was assumed to be related to the properties of the corresponding AR cycle, whose variation can be estimated from the Group sunspot number (Solanki et al., 2002). The secular change in the total magnetic flux of the Sun and, therefore, in the irradiance is caused by the overlap of the consecutive ER cycles. The predicted secular change since 1700 is about 1.3 Wm^{-2}. This value lies within the range suggested by other recent reconstructions of solar irradiance (Foster, 2004; Wang et al., 2005), but is significantly lower than the ones obtained in earlier investigations based on stellar data ranging from 2 to 16 Wm^{-2} (e.g., Mendoza, 1997; Lean, 2000). However, the stellar evidence for such a change has been recently critized (Hall and Lockwood, 2004; Wright et al., 2004; Giampapa, 2005) and the magnitude of the increase in TSI obtained using these results might have been overestimated.

Acknowledgment

This work was supported by the *Deutsche Forschungsgemeinschaft*, *DFG* project number SO 711/1-1.

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