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Invited Review

SOLAR IRRADIANCE VARIATIONS: FROM CURRENT MEASUREMENTS TO LONG-TERM ESTIMATES

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Abstract. Variations of solar total and spectral irradiance are prime solar quantities purported to have an influence on the Earth's climate. Quantitative estimates of irradiance over as long a time as possible are needed to judge their effectiveness in forcing the climate. In order to do this reliably, first the measured record must be reproduced and a feeling for the physics underlying the irradiance variations must be developed. With the help of this knowledge combined with the available proxy data, reconstructions of irradiance in the past, generally since the Maunder minimum, are attempted. Here a brief introduction to some of the irradiance reconstruction work aiming at irradiance on time scales of days to the solar cycle is given, followed by a brief and incomplete overview of the longer-term reconstructions.

1. Introduction

The solar irradiance is one of the more recently discovered variables of the Sun, generally being referred to as the solar constant in the older literature. Measurements of total solar irradiance (TSI) having sufficient precision to show its variability are available since 1978. In this period of time the Sun has gone through three maxima and two minima of magnetic activity. The level of the Sun's total irradiance has also been varying along with the activity, although not entirely on a one-to-one basis. The irradiance measurements were not carried out by a single instrument over the whole length of time, but rather a composite of the data obtained by different instruments has to be created. The construction of such a composite is not entirely without problems and it is therefore not surprising that three significantly different composites now exist (Fröhlich, 2003; Willson and Mordvinov, 2003; Dewitte *et al.*, 2004).

As valuable as this precious record is, it has a very significant shortcoming in that its length is considerably shorter than required to work out the precise connection between solar irradiance variability and climate change on Earth. In addition, the nearly three solar cycles that it covers were rather similar.

It is therefore necessary to somehow extend the irradiance time series back in time. Suitable models can provide estimates (with all the uncertainties the modelling entails) of the evolution of the irradiance also at earlier times. Before carrying out such a longer-term reconstruction it is necessary to understand the possible causes of the directly observed variation. In a second step we can then try to extend the reconstruction of the irradiance to earlier times.

A thorough introduction to this whole subject is given by Lockwood (2004).

2. Irradiance Variations in the Last Decades

Many models have been constructed that aim to reproduce the measured total irradiance or related quantities. These models consist of different types. The oldest and most common are those that are based on linear or non-linear or multivariate regressions of some set of proxies. These models in general have multiple free parameters, often 2–3, to describe the irradiance variations (the absolute value of the irradiance at a particular time is generally not considered since it is measured with far lower accuracy). Generally employed proxies are sunspot statistics and the radiative output at some wavelength band, with Mg II core-to-wing ratio being a particularly often used one. Examples of such regression models are: Foukal and Lean (1988), Chapman *et al.* (1996), Fröhlich and Lean (1998), Fligge *et al.* (1998), Preminger, Walton, and Chapman (2002), Jain and Hasan (2004). In these models often a two-step approach is taken, with the effect of sunspots first being removed before the influence of faculae is taken into account via a regression.

The other type of models follows a more physics-based approach. In general, maps of a given proxy (e.g. Ca II K brightness or magnetogram signal) are analyzed and in a more or less intricate procedure converted into irradiance (or radiance), again involving multiple steps. Usually, model atmospheres are involved in the procedure. Examples of such models are those of Fontenla *et al.* (1999, 2004), Ermolli, Berrilli, and Florio (2003), Penza *et al.* (2003).

Here we discuss in greater detail one set of models belonging to the second type, described by Unruh, Solanki, and Fligge (1999), Fligge, Solanki, and Unruh (2000), Krivova *et al.* (2003). Here we refer to these models as SATIRE, for Spectral And Total Irradiance REconstruction. The basic assumption underlying SATIRE is that the TSI variations are caused entirely by the magnetic field at the solar surface. By comparing the TSI record constructed with the help of this assumption with irradiance data we can test whether this underlying assumption is valid. Note that SATIRE implicitly assumes that the theory presented by Spruit (1982a, b) is roughly correct, i.e. that magnetic features at the solar surface disrupt or enhance the flow of energy from the solar interior, causing a darkening in the case of sunspots and a brightening in the case of faculae. This energy is not emitted or held back elsewhere (e.g., no bright rings around sunspots) and the emission rate returns to normal once the magnetic feature dissolves at the solar surface.

The importance of surface magnetism, via its proxies, the sunpots and the faculae and network, in controlling irradiance variations is suggested already by the first impression of the irradiance time series. The data exhibit not only the gentle rise and fall with the solar activity cycle, but also sharp dips mainly concentrated around solar activity maximum. These dips are seen to coincide with the presence of sunspots on the solar disc. The measurements made by the VIRGO instrument near the time of solar activity minimum allow individual active regions to be singled out and their evolution to be followed, directly revealing the brightening due to faculae.

The reconstructions considered here are based on using a four-component model: sunspot umbrae, sunspot penumbrae, quiet Sun and bright magnetic features. This last component includes the effect of active region faculae and the network. The basic idea is that each component is described on the one hand by a time-independent spectrum obtained from an immutable model atmosphere ascribed to that component and on the other hand by a parameter describing the fraction of the solar disc that the particular component is covering. This fraction is time dependent and is often referred to by a filling factor (borrowing from the magnetic filling factor introduced decades ago to deal with the fact that the magnetic fine structure on the Sun was not spatially resolved by the observations). The model atmospheres give spectra $I(\mu, \lambda)$, where I is the intensity, $\mu = \cos\theta$ is the cosine of the heliocentric angle and λ is the wavelength, while the area coverage fraction α is a function of μ and time t. A more detailed description is given by Fligge, Solanki, and Unruh (2000) and Krivova *et al.* (2003).

For sunspots, α is deduced directly from continuum images: $\alpha_{u,p} = 1$ within a sunspot umbra or penumbra, respectively, and $\alpha_{u,p} = 0$ outside. For faculae, the situation is more complex and α_f is proportional to the magnetogram signal until it reaches unity and is constant beyond that. The magnetic flux $\Phi_{\rm sat}$ at which α_f saturates is the main free parameter of these reconstructions. Finally, the quiet Sun is assumed to fill all the space not covered by faculae and sunspots: $\alpha_q = 1 - \alpha_f - \alpha_u - \alpha_p$.

This model was first combined with MDI magnetograms and continuum intensity images in order to reconstruct the irradiance since 1996. The comparison with TSI measurements carried out by VIRGO on SOHO is shown in Figure 1. The excellent agreement can be quantified in a squared correlation coefficient of 0.92 between the two quantities, with the data points lying very closely around the expectation value curve when plotting reconstructed irradiance versus measured TSI. The same model also reproduces the spectral irradiance as measured by the detrended three VIRGO colour channels (Krivova *et al.*, 2003) and the UV irradiance difference between solar activity maximum and minimum longward of 200 nm as measured by the SOLSTICE instrument (Solanki and Unruh, 1998; Unruh, Solanki, and Fligge, 1999). The good agreement between the data and the model suggests that at least 90% of the total solar irradiance is produced by surface magnetism.

This model has two major shortcomings. The first is the fact that it still has a free parameter. This can in principle be removed and a parameter-free reconstruction is possible, although it requires a modification of the current approach. It is an aim for the future.

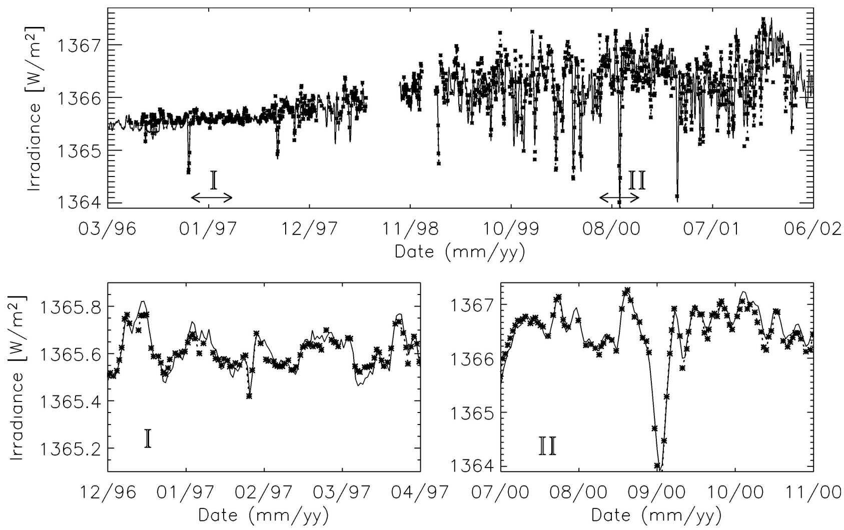


Figure 1. Top: reconstructed TSI variations (*asterisks*, connected by *dotted curve* when there are no data gaps) and VIRGO measurements (*solid line*) between 1996 and 2002. *Bottom*: enlargements of two shorter intervals at different activity levels. The periods corresponding to these enlargements are marked in the top panel by arrows and roman numerals (from Krivova and Solanki, 2003).

A second shortcoming is that the reconstruction based on MDI is limited to the period of time that SOHO is flying, i.e., to solar cycle 23. It would, however, be very interesting to have irradiance reconstructions of similar accuracy also for earlier cycles, ideally from 1978 onwards, when space-based total solar irradiance measurements started. The regularly obtained ground-based magnetograms with the highest resolution are those recorded at the vacuum tower on Kitt Peak, with regular observations starting in 1974. However, compared to MDI these ground-based data are not quite as homogeneous due to variable seeing. Another problem is that the instrument changed more than once in this period of time, with a complete refurbishment in 1992.

To accommodate these shortcomings a multi-step approach is being followed. In a first step the irradiance derived from the Kitt Peak magnetograms is compared over the SOHO time interval with the reconstruction obtained from the MDI magnetograms (Wenzler *et al.*, 2004). This gives the encouraging result that the irradiance reconstructed from these independent datasets correlates at the 0.95 level (squared correlation coefficient 0.90). In a second step Wenzler, Solanki, and Krivova (2004) have reconstructed the irradiance since 1992, i.e. since data from the improved KPNO spectropolarimeter are available. The basic finding is that the reconstruction compares with the measured irradiance (represented by the composite of Fröhlich, 2003) with a correlation coefficient of better than 0.92 (squared correlation coefficient 0.85). Also, no bias is found at all between cycles 22 and 23. This

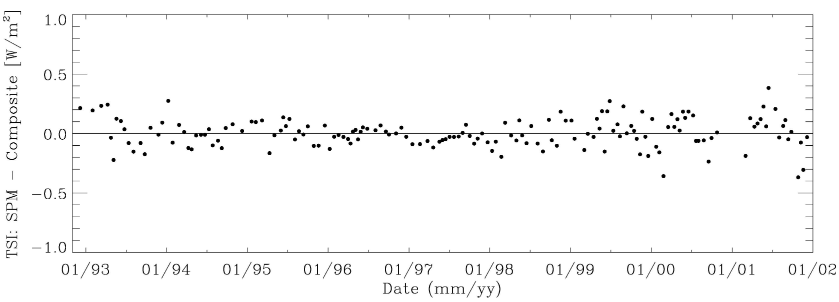


Figure 2. Difference between the reconstructed TSI based on KPNO data and the composite measurements. Every symbol represents a 10-day average value. The *solid line* indicates a perfect match (following Wenzler, Solanki, and Krivova, 2004).

is shown in Figure 2, where the 10-day averaged difference between reconstructed and measured irradiance is plotted. Therefore, we find no difference in behaviour of cycles 22 and 23. This implies that the conclusion that the dominant fraction of the solar irradiance variations is produced by solar surface magnetism is valid not just for cycle 23, but applies, in the somewhat weakened form that at least 85% of the variation is due to surface fields, also to cycle 22 and by implication also to earlier cycles. We believe that the lower fraction is mainly due to the lower data quality prior to 1996. These results therefore contradict those of de Toma *et al.* (2001), who found that solar irradiance behaves quite differently from other proxies when comparing solar cycle 22 with 23, but agree with those of de Toma *et al.* (2004).

The third step of these reconstructions, the extension to times before 1992, is currently underway (Wenzler *et al.*, in preparation).

3. Long-Term Irradiance Variations

Longer term reconstructions of irradiance are often broken up into a cyclic component and the secular variation of a background. The general ingredients are sunspots and faculae (including enhanced network to a certain extent), which describe the cyclic component and some other process that leads to secular variations, i.e. to changes in the level of the irradiance from one activity minimum to another. In the following we discuss these two parts of the longer term reconstructions separately.

Time series for over half a century of data useful for such reconstructions are the Group Sunspot Number, R_G (available since 1610), the Sunspot Relative Number, R_Z (often also called the Zürich number; available since 1700), sunspot areas, A_s (1874 ff), white-light facular areas, A_f (1874–1976), positions of sunspot groups (1874 ff) and Ca II plage areas, A_p (1915 ff). Various models use one or more of these proxies in order to reconstruct the irradiance.

Reconstructions have been published by, among others, Foukal and Lean (1990), Hoyt and Schatten (1993), Zhang *et al.* (1994), Lean, Beer, and Bradley (1995), Solanki and Fligge (1998, 1999), Lockwood and Stamper (1999), Fligge and Solanki (2000), Lean (2000), Foster and Lockwood (2004). Whereas Foukal and Lean (1990) only consider the cyclic component of the irradiance variations, the other authors have considered both the cyclic and the secular components.

3.1. Cyclic component

For the cyclic component often only very simple reconstructions have been attempted. Thus, for example, Lean, Beer, and Bradley (1995) postulated that the yearly averaged irradiance variation over the cycle is simply proportional to the sunspot number. The most thorough reconstructions of the cyclic component have been made for 1874 to the present by Foster (2004) and Foster and Lockwood (2004) and since 1700 by Solanki and Fligge (1999). In Figure 3 we plot the cyclic variations reconstructed by Solanki and Fligge (1999). In the more recent past better reconstructions are possible than at earlier times due to the availability of improved data. At the top of the figure the types of data used to reconstruct the cyclic variations are indicated. Since 1874 good data of the sunspot areas are available from the Royal Greenwich Observatory from which the Photometric Sunspot Index (PSI, Hudson *et al.*, 1982) is constructed. Combined with sunspot number and

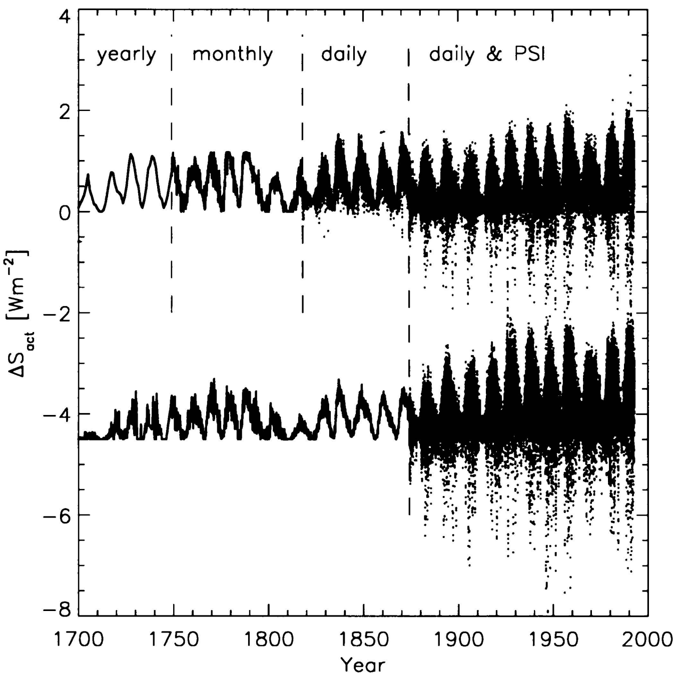


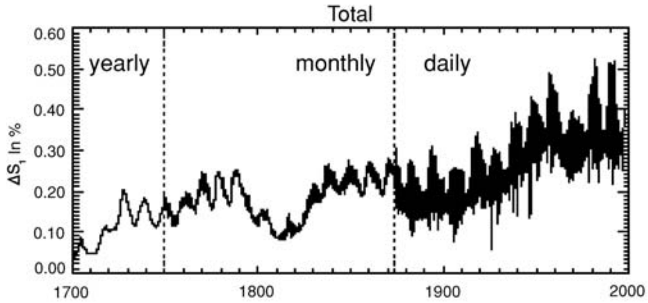
Figure 3. Cyclic component of the reconstructed total irradiance based on the R_Z (*top*) and R_G (*bottom*) records (from Solanki and Fligge, 1999).

with other proxies both the sunspot darkening and the facular brightening can be reconstructed. Before that only daily sunspot number data are available, still earlier on monthly value, etc. The two curves result from the use of two different datasets, the Zürich (or international) sunspot numbers (upper curve) and the Group sunspot number (lower curve). According to this diagram the amplitude of the cyclic irradiance variations varies by around a factor of 2–3 from cycle to cycle. The total change in the irradiance since the Maunder minimum due to this cyclic component is thus roughly 0.5 $\mathrm{W\,m^{-2}}$. Of course, cyclic changes produced by effects other than the magnetic field at the solar surface are possible, but since there is no need to invoke such effects in order to reproduce the irradiance observations over the last cycle, it would be artificial to postulate them for earlier cycles.

3.2. Secular component

A larger irradiance effect may be produced by a secular change of the magnetic field at the solar surface, but also by other processes. Evidence for such a secular change was initially provided by stellar data, although in an indirect manner. For example, measurements of a sample of field stars showed that the distribution of Ca II H and K emission has two peaks (Baliunas and Jastrow, 1990). The peak at higher activity levels was interpreted to represent stars exhibiting activity cycles, like the Sun, while the lower activity peak was interpreted to represent stars in a Maunder minimum state. Since the Sun, even at activity minimum, lies in the upper third of the activity range of that sample, this was interpreted to mean that the Sun is, even at minimum solar activity, much more active than it was during the Maunder minimum. Such a difference could be caused by the disappearance of the solar network during the Maunder minimum (White *et al.*, 1992), although even that appears not to be sufficient to account for the lowest levels of Ca II H and K flux observed in field stars. The uncertainty introduced when converting from the Ca II H and K index measured in stars to total irradiance is significant. For example, extrapolating from the relation between Ca II flux (or index) and irradiance measured over recent cycles to lower levels of activity than recent activity minima is not as straightforward as previously thought. For example, the Ca II intensity changes very differently with magnetic flux than the intensity at wavelengths arising in photospheric layers (Frazier, 1971), which has to do with the different properties of flux tubes in network and active region plage (Solanki and Stenflo, 1984) or between different levels of magnetic flux (Topka, Tarbell, and Title, 1997; Ortiz *et al.*, 2002). Published estimates on the difference in solar brightness between the Maunder minimum and now span a factor of roughly 4 (Lean *et al.*, 2001; Zhang *et al.*, 1994).

Using this result as the basis for modelling, a number of reconstructions of past solar total (and partly also spectral) irradiance have been carried out. The secular trend is generally, but not always, combined with a reconstruction of the cyclic variation to produce a record spanning one or more centuries, the longest



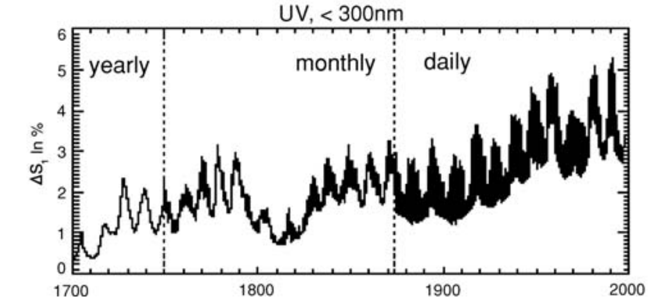


Figure 4. Reconstruction of the total (*top*) and UV (<300 nm, *bottom*) irradiance since the end of the Maunder minimum (from Fligge and Solanki, 2000).

ones going back to 1610, i.e., to before the Maunder minimum. An example each of a reconstructed total and UV time series (from Fligge and Solanki, 2000) is shown in Figure 4. During the period when direct observations are available, both reconstructions reproduce these with reasonable accuracy (which, however, is lower than that of the more sophisticated reconstructions presented in Section 2). The magnitude of the secular trend is the most uncertain parameter in this reconstruction.

The original stellar evidence of Baliunas and Jastrow was not conclusive and it has been called into question by recent studies. The debate on this issue is ongoing, so that at present stellar data are not a reliable guide for the magnitude of the secular variation. Foukal and Milano (2001) argued that the Mt. Wilson Ca II K images show as much network in the early part of the 20th century as at recent solar activity minima. Unfortunately, the Mt. Wilson images are uncalibrated, so that other interpretations are also possible.

It might be worthwhile to consider which mechanism might be responsible for removing the network during the Maunder minimum and making it vary over the solar cycle. The network, which decays within hours if not replenished (Hagenaar, 2001), is produced by flux emerging in ephemeral active regions (Harvey, 1993). These ephemeral regions emerge not just when the Sun is more active, but rather over an extended solar cycle, so that consecutive cycles overlap significantly as far as ephemeral regions are concerned. Based on these results, a model proposed by

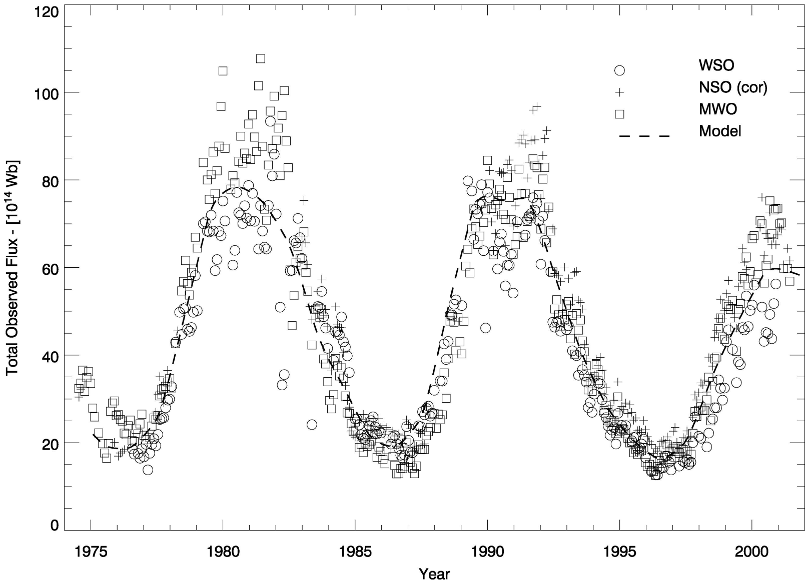


Figure 5. Measured and modelled (*dashed line*) total magnetic flux since 1975. Different symbols are used for different data sets (L. Balmaceda, private communication).

Solanki, Schüssler, and Fligge (2002) produces a secular change in the total magnetic flux, depending on the length and strength of the activity cycles (as represented by, e.g. the number of sunspots). The model reproduces the total flux regularly measured since 1974 (taking into account the finding of Krivova and Solanki, 2004a that at the most half of the Sun's magnetic field is seen in the employed synoptic charts; see Figure 5). Such a model can also explain the doubling in the Sun's open magnetic flux over the last century (cf. Lockwood, Stamper, and Wild, 1999; Solanki, Schüssler, and Fligge, 2000; Schrijver, DeRosa, and Title, 2002), whereby the slow decay of the open flux is made use of. Finally, the magnetic field predicted by such models also well reproduces the ^{10}Be data taken from the Greenland Dye-3 core (Beer *et al.*, 1990). A reconstruction of solar total irradiance based on the Solanki, Schüssler, and Fligge (2002) model is currently underway. Lean, Wang, and Sheeley (2002) have pointed out that if there is no overlap between the time span of emergence of bipolar regions belonging to different cycles, no secular trend in total flux will be present, while a secular trend in open flux will still be visible. Hence they argued that a trend in open flux does not automatically imply a corresponding trend in total magnetic flux and irradiance. Unfortunately, the basic assumption underlying the study of Lean, Wang, and Sheeley (2002) is contradicted by the observation of Harvey (1992, 1994a) that there is an overlap of 2–3 years between the times of emergence of ephemeral regions in consecutive activity cycles. Consequently it is no surprise that the model of Lean, Wang, and Sheeley (2002) fails to reproduce the background of network field which is present also at solar activity minimum (Harvey, 1994b), see also Figure 5. Note that the true level of this background is approximately a factor of 2 higher than suggested by this figure (Krivova and Solanki, 2004a).

Probably the most sophisticated reconstruction including a secular trend is due to Foster (2004) and to Foster and Lockwood (2004), who employed the dependence of facular contrast at a given wavelength on the magnetograph signal B and heliocentric angle μ (Ortiz *et al.*, 2002), as well as the Photometric Sunspot Index based on Greenwich sunspot areas and locations. By making the reasonable assumption that faculae are located near the sunspots they could construct butterfly diagrams also for the faculae. In this way they were able to make use of the information contained in the centre-to-limb variation of the contrast of faculae and network features. Then they converted, in a simple manner, the contrast measured at a single wavelength into the appropriate contrast of the wavelength-integrated radiation (which may introduce some uncertainty into the result). Finally, using the measured distribution function of the magnetic field at recent epochs and assuming that there were no faculae or network features on the Sun during the Maunder minimum they obtained an upper limit of the increase in brightness of the network since the Maunder minimum of 1.7 W m^{-2}. This is lower than most previous estimates of the secular trend (which, however, were based on a possibly flawed interpretation of stellar data). This is a promising avenue for further research. Obvious improvements to this method are the use of more realistic facular models, which include the temperature gradient that also reproduces the large change in irradiance in the UV (e.g. Woods, 2002; Krivova and Solanki, 2004b). This could influence estimates of the brightening since the Maunder minimum.

Estimates of the irradiance on an even longer time scale depend on the use of proxies, such as the cosmogenic isotopes ^{10}Be and ^{14}C. Although it is possible to convert from cosmogenic isotopes to irradiance using simple empirical relationships, an alternative approach is to introduce more physics. This has been done in a first step, from the isotope concentration in terrestrial archives to the sunspot number, by Usoskin *et al.* (2003). The crucial second step from sunspot number to irradiance still needs to be carried out.

4. Conclusions

Measurements of solar irradiance are now available for around 2.5 solar cycles. The ever improving accuracy of the measurements and the increasing length of the time series constantly raise the value of these measurements. Nonetheless, the debate about the presence or absence of a secular trend introduces an uncertainty. Each composite gives slightly different results, based on the weight and credence given to different measurements by the composers (Fröhlich, 2003; Willson and Mordvinov, 2003; Dewitte *et al.*, 2004). Also, for judging the effect on climate, it is important to have longer time series of irradiance. These can be obtained only from model estimates. Such estimates are best made with some understanding of the physical processes responsible for irradiance variations. In order to obtain these the measured solar irradiance must first be reproduced, so that the basic processes acting on the Sun can be identified. The reconstruction of solar irradiance has now progressed to a high level of accuracy on time scales up to the solar cycle. Further progress is still possible, and is indeed needed. This includes the removal of the remaining free parameter(s) in such models.

On a longer (and for climate studies more important) time scale things are less certain. The cyclic component of irradiance variations can be reconstructed back up to 1610, although with decreasing reliability and accuracy at earlier times. The magnitude of any secular trend remains a matter of intense debate. A recent, careful estimate by Foster and Lockwood (2004) gives a value of only 1.7 W m^{-2}. Further work on establishing this value with higher accuracy is of great importance.

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