RECONSTRUCTION OF PAST SOLAR IRRADIANCE

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Abstract. Accurate measurements of solar irradiance started in 1978, but a much longer time series is needed in order to uncover a possible influence on the Earth's climate. In order to reconstruct the irradiance prior to 1978 we require both an understanding of the underlying causes of solar irradiance variability as well as data describing the state of the Sun (in particular its magnetic field) at the relevant epochs.

Evidence is accumulating that on the time-scale of the solar cycle or less, variations in solar irradiance are produced mainly by changes in the amount and distribution of magnetic flux on the solar surface. The main solar features contributing to a darkening of the Sun are sunspots, while active-region faculae and the network lead to a brightening. There is also increasing evidence for secular changes of the solar magnetic field and the associated of solar brightness variability. In part the behavior of sun-like stars is used as a guide of such secular changes.

Under the assumption that solar irradiance variations are due to solar surface magnetism on all relevant time scales it is possible to reconstruct the irradiance with some reliability from today to around 1874, and with lower accuracy back to the Maunder minimum. One major problem is the decreasing amount and accuracy of the relevant data with age. In this review the various reconstructions of past solar irradiance are presented and the assumptions underlying them are scrutinized.

1. Introduction

Changes in the total or UV irradiance of the Sun have been proposed as a possible cause of climate change. Reliable and (almost) continuous measurements of the total solar irradiance started in 1978 (Willson et al., 1981; Willson and Hudson, 1988; Hoyt et al., 1992; Fröhlich and Lean, 1998). Likewise, UV irradiance has been regularly recorded since 1978 (Heath and Schlesinger, 1986; Labs et al., 1987; Rottman, 1988).

The total solar irradiance has now been collected over almost 2 solar cycles (see Fröhlich and Lean, 1998, for a composite of the measurements made by different instruments). These measurements revealed short-term changes of irradiance caused by the disc-passage and evolution of sunspots and faculae. However, the main discovery was the brightening of the Sun by approximately 1.3 W/m^2 at solar activity maximum relative to activity minimum (corresponding to roughly 0.1% of the total solar irradiance).

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In order to detect the influence of solar irradiance variations on climate a longer record is required since the signature of the 11-year cycle has not been reliably detected in tropospheric temperature.

Hence there is a need to reconstruct past solar irradiance over as long a period as possible. Solar irradiance observations provide only limited guidance on the presence or physical causes of changes in the irradiance on a time-scale longer than a solar cycle. Therefore past irradiance can be reconstructed only under certain assumptions regarding the underlying physical mechanisms. These assumptions are outlined in Sect. 2.

Due to our inability to compute the precise solar irradiance from first principles the modeling often restricts itself to finding a simple relationship between some readily available proxy or proxies of the irradiance and the measured value. Such proxy data therefore play a central role in the reconstruction of past solar irradiance and are briefly introduced in Sect. 3. A far more thorough discussion is given by Lean (2000).

In Sect. 4 various reconstructions are reviewed critically. Finally, in Sect. 5 some ideas on how these reconstructions may be improved are given.

2. Basic Assumption

Many processes can all lead to solar irradiance variations. These include changes in the amount and distribution of magnetic flux at the solar surface (Foukal and Lean, 1986, 1988; Lean et al., 1998), changes in convective efficiency and in the internal temperature gradient of the Sun (Kuhn et al., 1988; Kuhn and Libbrecht, 1991), long period r-modes of oscillation (Wolff and Hickey, 1987), release of energy stored in the toroidal magnetic field at the bottom of the solar convection zone and thermal shadowing by this field.

Of all these mechanisms the influence of magnetic fields at the solar surface (through their manifestations, such as sunspots, faculae, network elements) on the solar irradiance is established best. The passage of sunspots across the solar disc (driven by rotation) causes dips in brightness lasting 1–2 weeks (e.g., Willson et al., 1981; Chapman et al., 1994). Similarly, faculae cause a brightening, which however has a more complex temporal profile since they are brightest near the limb (e.g., Fröhlich et al., 1997). Since faculae are more extended, more common and longer lived than sunspots the total, disc-averaged brightening varies more gradually than the darkening (e.g., Chapman, 1987). The disk-integrated contribution of the network is even more stable, since the network is distributed comparatively evenly over the solar surface, so that rotational modulation is small. The magnetic flux in the network changes slowly with time, and is still quite prominent even at activity minimum when few, if any sunspots or faculae are present.

The importance of these surface magnetic features in reproducing observed solar irradiance variations on time-scales of the solar rotation was pointed out by

Willson et al. (1981), Hudson et al. (1982), Chapman et al. (1994), Fligge et al. (2000), and on time-scales up to the solar cycle by Foukal and Lean (1986, 1988), Chapman et al. (1994, 1996), Fligge et al. (1998), Lean et al. (1998). The physical basis for the irradiance variations introduced by surface magnetic features was worked out by Spruit (1982). Due to the high thermal conductivity and the immense heat capacity of the convection zone any perturbation of the heat loss at the surface (due to spots and faculae) influences the complete convection zone (a result of its high conductivity) and only immeasurably affects its properties (caused by its high heat capacity). Hence a local perturbation like a sunspot leads to an instantaneous change in irradiance (Spruit, 2000).

Models based on the assumption that the irradiance variations on solar cycle time-scales are entirely caused by changes in surface magnetism have been remarkably successful in reproducing not only the total irradiance time series (Foukal and Lean, 1990; Chapman et al., 1996; Lean et al., 1995; Fligge et al., 1998), but also a whole row of other observations. These include the change in the spectrum of the irradiance between activity maximum and minimum (Solanki and Unruh, 1998; Fligge et al., 1998; Unruh et al., 1999), the ratio of facular to sunspot areas (Fligge et al., 1998), the variation of the amount of line-blanketing over the solar cycle (Unruh et al., 1999) and the evolution of UV irradiance (Lean et al., 1998). The variations of the ratios between selected spectral lines over the solar cycle (Gray and Livingston, 1997) is at least roughly reproduced (Unruh et al., 2000), although there is still room for improvement.

The main observation which has not as yet been reproduced by current models are the brightness changes measured by limb photometers (Kuhn et al., 1988; Kuhn and Libbrecht, 1991). Efforts should be made to use these additional observations to better constrain the models and possibly the proportion of the irradiance changes produced by surface magnetism.

Kuhn et al. (1988) have argued that their limb photometer restricts surface magnetism, to 50 % of the contribution to the total irradiance. Due to the success of surface-magnetism based models in reproducing a large number and variety of other observations this now appears unlikely on time-scales of the solar cycle or less (although it cannot be completely ruled out, of course). The relative contribution of the various mechanisms to longer-term variations, however, is as yet unknown.

Hence, when reconstructing past solar irradiance the cyclic and (long-term) secular variations are modeled separately. Both partial reconstructions are then combined to give a final reconstruction. An example will be shown in Sect. 4. Here and in the following we count all variations on the time-scale of the solar cycle or less to the cyclic variations.

It should be noted that the reliability of reconstructions of the cyclic component of the variability is much higher than that of the secular trend. Even the existence of the latter is not certain beyond a doubt. Hence, claims by Willson (1997) that the irradiance at two consecutive activity minima is significantly different have subsequently not been confirmed (e.g., Fröhlich and Lean, 1998). The main evidence for such a component is indirect, coming from the reconstructions of the interplanetary magnetic field (Lockwood et al., 1999) and the comparison of the strength of chromospheric network and plage emission from the Sun with Sun-like stars. Plage are the chromospheric counterparts of faculae. It still needs to be established, however, how strongly the interplanetary magnetic field is connected to irradiance variations.

Baliunas and Jastrow (1990) revealed that the flux in the cores of the Ca II H&K lines in a sample of Sun-like stars exhibits a much wider scatter than the Sun does in the course of a typical activity cycle. Significant is the fact that many of these stars show much weaker Ca II emission than the Sun, even at its activity minimum. Moreover, the stars with the weakest such emission are in a non-cyclic state akin to the Maunder Minimum, a period in the 17th century when the Sun exhibited very few sunspots, a sign of low magnetic activity.

Now, Ca II core emission is sensitive to the temperature in the chromospheric layers of the solar, respectively, stellar atmosphere. It is thought that a minimum chromospheric temperature (i.e. Ca II flux) is maintained by the dissipation of acoustic waves (basal flux, Schrijver, 1987; Ulmschneider et al., 1999) while higher Ca II flux values signal the presence of surface magnetic fields. On the Sun Ca II brightness is well correlated with the network and with faculae, i.e. features that are also bright in white light. Since over the last few solar cycles the magnetic network has been present even at sunspot activity minimum the minimum Ca II flux has been distinctly higher than the basal value. Therefore, if the Ca II flux of the Sun had in the past decreased below the current minimum level the Sun would have been less bright at that time.

Using the stellar measurements it is possible to estimate how bright the Sun was during the Maunder Minimum and thus obtain an estimate of how large the longer-term variation of solar brightness is (White et al., 1992; Lean et al., 1992). Note that the longer-term variation obtained in this manner is still due mainly to the magnetic field, since only it significantly affects the strength of the Ca II emission. It is thought that the strength of the magnetic network changes on time-scales longer than the solar cycle. At present we cannot, however, rule out small changes in the convective energy flux, which should leave the Ca flux relatively unaffected. These could in principle produce even larger secular fluctuations in solar irradiance which would, however, have gone undetected by the proxies available to us.

Most reconstructions in recent years have made the assumption that all variations of solar irradiance in the past centuries have been driven by changes in the amount and distribution of magnetic flux on the solar surface. There are, however, exceptions. More details are given in Sect. 4.

3. Historical Records of Proxy Data

It is currently not possible to predict or reconstruct the precise amount or distribution of magnetic flux on the solar surface from first principles. Hence, all reconstructions of solar irradiance are based on measured time-series of the magnetic flux (magnetograms) or other proxies of either the magnetic field or the irradiance.

A variety of records exist which are in some way related to solar magnetism and thus to irradiance. In addition to the direct proxies of solar activity, indirect indicators, caused by the modulation of cosmic-ray flux by solar activity, are stored in terrestrial archives (e.g., ^{10}Be and ^{14}C records). These are discussed in detail elsewhere (Beer, 2000).

These proxy records are not without their problems. For one, fewer records are available at earlier times. Also, they are often of variable quality, with the older data often being less precise and having longer gaps. Efforts to uncover and incorporate further historical observations are ongoing (Foukal, 1993; Hoyt et al., 1994; Hoyt and Schatten, 1998). Often even recently acquired data need to be scrutinized closely, particularly when multiple observatories are involved. For example, when the daily recording of sunspot areas passed from Royal Greenwich Observatory to other stations there was a 20% jump in the average recorded areas, although this was not obviously visible from the time-series (Fligge and Solanki, 1997).

Another problem is how these proxy records relate qualitatively to the brightness fluctuations caused by sunspots, faculae and the network. In particular the network turns out to be elusive and none of the 4 direct proxy records lasting longer than a century is directly sensitive to it. It is therefore not straightforward to constrain the exact behavior of the secular trend exhibited by the irradiance, whose presence has been deduced, e.g., from the behavior of other stars (see Sect. 2).

Various secondary time-series can be constructed from the primary time-series. Examples are the length, the amplitude and the total strength of the solar cycle (the latter defined as the integral of the record over a cycle). The decay time of sunspots is another secondary proxy that has been employed for irradiance modelling (Hoyt and Schatten, 1993). These secondary proxies are often used to describe the slowly varying, secular component of the irradiance.

4. Reconstruction of the Past Total Solar Irradiance

Early reconstructions of solar irradiance only considered cyclic variations. Thus Foukal and Lean (1986, 1988, 1990), Lean and Foukal (1988) took into account sunspots and faculae (the network was counted to the faculae) to reconstruct solar irradiance to as far back as 1874. Sunspot areas, A_s, in combination with other parameters were used to calculate the darkening due to sunspots. Different proxies were used to reconstruct the brightening due to faculae because the best proxies have been available for only a relatively short time.

The construction of relations between the employed proxies and the irradiance form a central part of the model building exercise. Such relations are calibrated using the direct irradiance measurements of the past 20 years. For earlier times it is generally assumed that these calibrations are equally valid (but see Fligge and Solanki, 1998; Solanki and Fligge, 1998). Separate (although not always ideal) proxies of the sunspots and faculae are available since 1874. From this year on the active-region (cyclic) contribution to irradiance change can be reconstructed with a fair measure of reliability. The remaining uncertainty is largely introduced by inaccuracies in the historical proxy observations and the assumption that the conversion relation between the proxy and the irradiance is time independent.

The various reconstructions of the irradiance for this period differ, depending on how carefully the proxy data were chosen, on the level of sophistication of the calibration between proxy and irradiance, etc. For example, Lean et al. (1995) assumed a linear relation between the group sunspot number, R_{g}, of Hoyt and Schatten (1998) and the irradiance residuals. In contrast, Foukal and Lean (1990) as well as Solanki and Fligge (1998) treated spots and faculae separately. After removing the influence of spots using measurements of their total area, they calibrated the facular proxies against irradiance measurements using linear and quadratic relations, respectively. Further major improvements are expected from the use of images of proxies of facular brightening, e.g. Ca K images, from the time from which they are available.

Prior to 1874 the reliability of the reconstructions decreases. This is mainly due to the lack of independent proxies of sunspot and facular contributions. Recently, Solanki and Fligge (1999) found a way of achieving reasonable, if not perfect, reconstructions in spite of this handicap by making use of the fact that sunspots and faculae evolve on somewhat different time-scales.

A composite of reconstructed cyclic irradiance is plotted in Fig. 1. The quality of the reconstruction improves in steps: It is lowest in the 1700–1750 period, when only yearly values of R_{Z} and R_{g} were available and is highest since 1874, when separate proxies were used for spots and faculae.

Averaged over the solar cycle the rise in solar irradiance since 1880 due to the contribution of active regions and the cyclic variations of the network alone is only 0.5 W/m^2, much smaller than the 1.3 W/m^2 that the irradiance changes in the course of a cycle. However, as pointed out in Sect. 2, evidence has emerged from the study of the Earth's atmosphere and of Sun-like stars, that there is probably a secular component in solar variability. The magnitude of this component is assumed to be 2.5 W/m^2 by Lean et al. (1992) and White et al. (1992), 2–6 W/m^2 by Zhang et al. (1994), 3.5 W/m^2 by Hoyt and Schatten (1993) and 2.5 W/m^2 by Solanki and Fligge (1998). This component thus dominates the total irradiance changes.

Not only is there considerable disagreement between different researchers regarding the amplitude of the secular change in irradiance, there is equal disparity

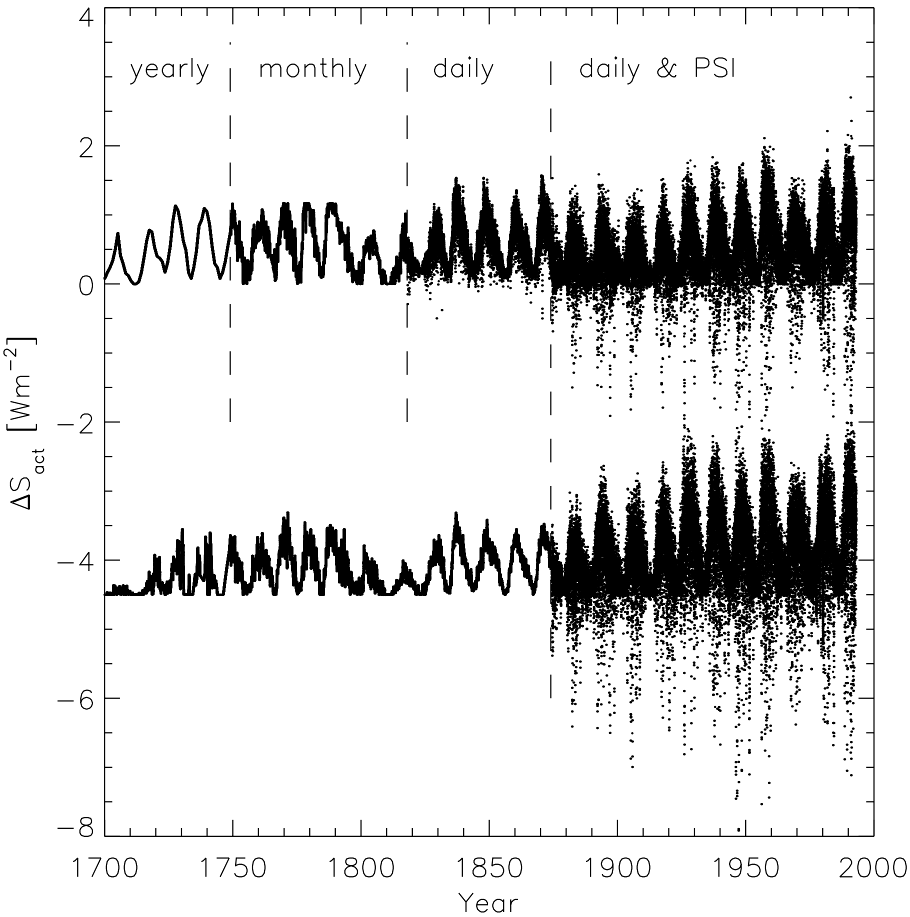

Figure 1. Reconstructed excess irradiance due to active regions between 1700 and 1999. The upper curve corresponds to the composite irradiance record based on Zurich sunspot relative number, R_Z, using different reconstruction methods while the lower curve (shifted by -4.5 W/m^2) is based on the group sunspot number, R_g. The type of data available for the reconstruction is indicated in the figure. PSI denotes 'Photometic Sunspot Index' (From Solanki and Fligge, 1999).

regarding its time variation. The stellar data themselves give conflicting indications. On the one hand they have been interpreted by Lean et al. (1992, 1995) and White et al. (1992) to suggest that the irradiance changes linearly with the strength of the activity indicator, respectively with the cycle amplitude. On the other hand, Baliunas and Soon (1995) present evidence that the irradiance may correlate with the length of the cycle. Which of these indicators is better, or indeed if either of them is adequate, is at present unknown. One reason why it is difficult to distinguish between them is that there is a correlation between the cycle amplitude and length (e.g., Hoyng, 1996).

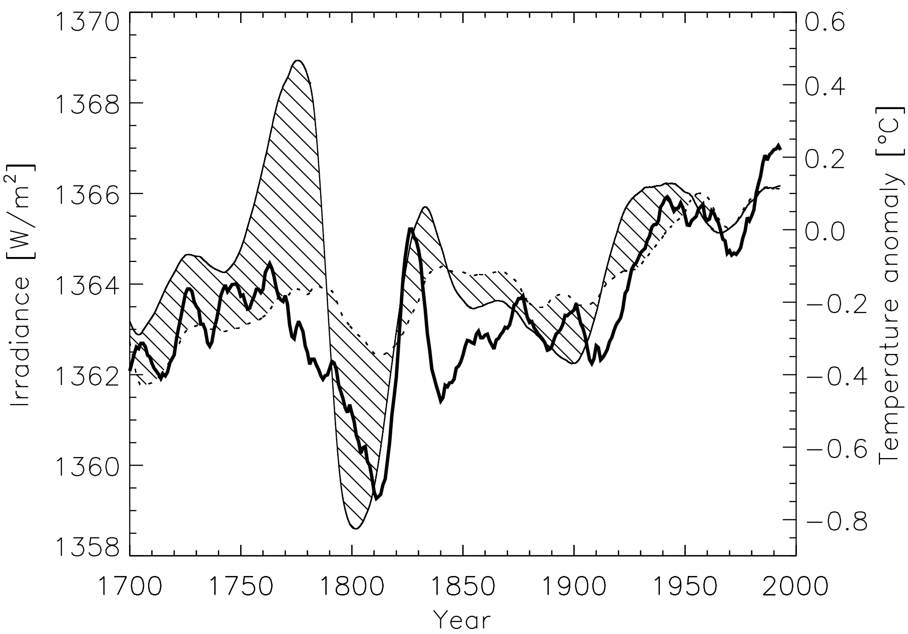

Figure 2. 11-year running mean of two reconstructions of total solar irradiance, including the contribution of both the cyclic and secular components. Thin solid curve: the secular trend is represented by the solar cycle length; thin dashed curve: The amplitude of R_g is used as a proxy of the secular trend. The hatched area between these curves thus gives a rough indication of the uncertainty in the reconstructions. Also plotted is the northern hemisphere land temperature (thick solid curve) according to Groveman and Landsberg (1700 – 1880) and the IPCC (1880 – 1990) (From Solanki and Fligge, 1999).

It is nevertheless important to distinguish between these two possibilities, since the correlation coefficient between cycle length and strength is increased considerably if a phase lag of approximately a solar cycle is introduced in the sense that the cycle length runs ahead of the cycle amplitude by approximately one solar cycle. This timing is crucial when comparing with climate measurements, since the cycle length runs ahead of global climate change (or correlates well with air temperatures above northern hemisphere land-masses) while the cycle amplitude appears to slightly lag behind some climate indicators.

Solanki and Fligge (1998, 1999) have employed both the cycle length and the amplitude, thus effectively creating two reconstructions of solar irradiance that can be directly compared to each other. The largest difference between the two proxies is seen at around 1750 – 1800 (see Fig. 2). The cycle amplitude shows a decreased value around this epoch, while the cycle length exhibits large excursions in both directions. This epoch is interesting because it coincides with an anomaly in the Earth’s temperature. One problem with the cycle length as a long-term proxy is that it is ill defined over prolonged periods of low activity such as the Maunder

Minimum. This is particular unfortunate since it is exactly the Maunder Minimum which is usually used to scale the amplitude of the longer-term irradiance changes.

In the only reconstruction that does *not* assume that surface magnetism is responsible for all irradiance variations Hoyt and Schatten (1993) use a host of indicators of solar activity as proxies of long-term irradiance changes. These include the solar equatorial rotation rate, the amplitude, length and decay rate of the solar cycle and the structure (umbral to penumbral area ratio) and decay rate of sunspots. By combining all these proxies in a suitably weighted manner they obtain a secular variation that looks rather similar to the cycle length. Their approach still awaits empirical validation whether most of their proxies are indeed related to irradiance variations.

In summary, the secular variability is obviously the most uncertain (but a very significant) part of the irradiance reconstruction. This is the part which in future deserves the most attention.

5. Outlook

Over the last 15 years our understanding of the underlying causes of irradiance variations as well as the quantitative reconstruction of solar irradiance have improved greatly, although the basic premise, namely that solar surface magnetism is the main agent, has remained unchanged.

Nevertheless, there are considerable further grounds for improvement. These include making use of larger, more sophisticated data sets for the reconstruction of the cyclic component of irradiance variations (such as magnetograms or Ca II spectroheliograms), as well as attempting to close the considerable and serious gaps in our knowledge concerning the secular variation.

The obvious next major step as far as the cyclic variations are concerned is to move from disc-integrated proxies to images of the solar disc, at least for the time that these are available. The case for using such data has been amply demonstrated by Lean et al. (1997) and Fligge et al. (2000), who employed Ca II K images and magnetograms, respectively. These investigations have been restricted to fractions of the solar cycle, however. Extending them to cover a number of solar cycles is a major and time-consuming exercise, but should provide significantly improved estimates of the irradiance variations.

In parallel, the quantitative relation between irradiance, on the one hand, and magnetogram signal, Ca II K brightness (or some other proxy), on the other, needs to be improved. The work of Lean et al. (1997), Unruh et al. (1999) and Fligge et al. (2000) represent steps in this direction. One interesting extension of this work is to incorporate the difference in brightness between magnetic elements in the network and in active regions found by Solanki and Stenflo (1984), Solanki and Brigljević (1992). This difference is probably to a large extent due to the different magnetic filling factors in the two regions - filling factor is the fraction of the solar surface covered by the magnetic field within a given area.

Also, the problems associated with Ca II K brightness (different underlying physical processes from those governing irradiance variations) and magnetograms (decreasing signal toward the limb, since only the line-of-sight component of the vertical magnetic field is measured) need to be dealt with.

We expect that the recent advances in modeling the solar spectral irradiance (Solanki and Unruh, 1998; Fligge et al., 1998; Unruh et al., 1999; Fontenla et al., 1999) and the success in reproducing the temporal evolution of UV irradiance observations (Lean et al., 1997) will in the near future lead to considerable improvements of reconstructions of past UV irradiance.

Particularly worrisome is the fact that most of the evidence for a secular change of the irradiance comes from indirect sources such as stellar observations, activity of the Earth's magnetosphere or cosmogenic isotopes such as ^{10}Be or ^{14}C. It is also troubling that there has been no physical explanation for such a variation. Additional evidence for a secular variation would be very helpful. A more precise estimate of the change in solar irradiance since the Maunder Minimum is particularly needed. Just as important is to uncover the physical causes of secular irradiance variations.

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