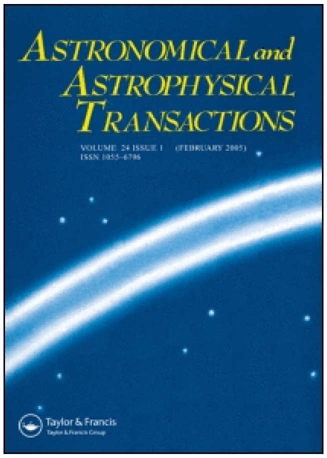

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

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Online Publication Date: 01 October 2001
To cite this Article: Fligge, M. and Solanki, S. K. (2001) 'The sun's variable spectrum and its terrestrial effects', Astronomical & Astrophysical Transactions, 20:3, 467 - 474
To link to this article: DOI: 10.1080/10556790108213585
URL: http://dx.doi.org/10.1080/10556790108213585

Astronomical and Astrophysical Transactions, 2001,
Vol. 20, pp. 467–474
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THE SUN'S VARIABLE SPECTRUM AND ITS TERRESTRIAL EFFECTS

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(Received October 11, 2000)

The solar radiation exhibits strong temporal variations not only in intensity but also in its spectrum which are linked to the evolution of the Sun through its magnetic activity cycle. The irradiance variability increases from longer to shorter wavelengths, with variations in the UV being orders of magnitude larger than those in the visible. While 99% of the total solar radiative output occurs at wavelengths longer than 300 nm, solar UV radiation accounts for up to 30% of the total variation.

The continuous rise of the Earth's surface temperature over the last decades urgently raises a question about the physical origin of so-called global warming. A reliable estimate of the influence of human activity on the Earth's climate requires detailed knowledge about the natural sources of variability. One of the unknown boundary conditions for models of the evolution of the Earth's climate is the variation of the solar irradiance.

KEY WORDS Solar irradiance, global warming, solar cycle, solar variability

1 INTRODUCTION

4th April 2000, 15:41 UT. A coronal mass ejection produces a shock front which heads towards Earth at a speed of up to 2000 km s^{-1}. Two days later, on April 6th, the Earth's magnetic shield gets pounded by a stream of charged particles, some of which reach the Earth's outer atmosphere around the polar cusps and produce a spectacular aurora which is visible down to unusually low latitudes. This and other similar events typical of the current period of very high solar activity are a stark reminder of our close neighborhood to the Sun. The delicate interactions between the Sun and the Earth are manifold and take place on various time-scales. E.g., the temperature of the Earth's surface has increased by roughly 0.6° C over the last century. A part of this is attributable to the increased emission of man-made greenhouse gases since the pre-industrial area. However, the Sun is also expected to have contributed to so-called global warming.

In the following review we focus on one particular aspect of the solar-terrestrial relationship, namely the changing radiation of the Sun and its impact on the Earth's atmosphere and climate. Sect. 2 gives a brief insight into our current knowledge

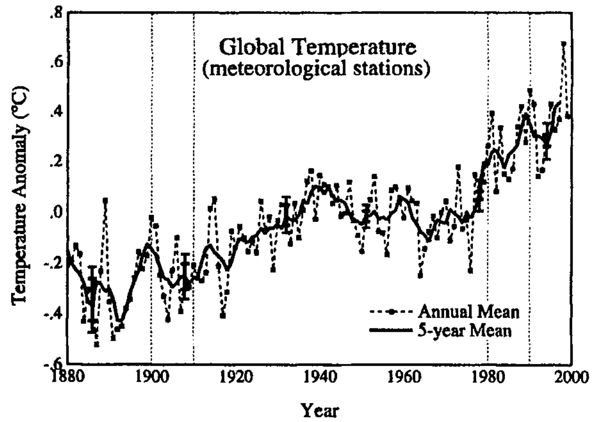

Figure 1 Global annual-mean surface air temperature deviations relative to the mean between 1950 and 1981. The error bars (95% confidence levels) only account for the incomplete spatial sampling of the meteorological data (Provided by NASA/GISS).

about solar irradiance variations gained from space-borne measurements over the last 22 years. The influence of the increased UV radiation during activity maximum is briefly discussed in Sect. 3, while we focus on the longer and more climate relevant time-scales of solar irradiance variations from decades to centuries in Sect. 4. Finally, we present our conclusions in Sect. 5.

2 THE ORIGIN OF SOLAR IRRADIANCE VARIATIONS

Over the last 22 years the integrated solar spectrum, i.e. the 'solar constant' or total solar irradiance, has been monitored almost continuously by space-borne instruments (Willson *et al.*, 1981; Willson and Hudson, 1991; Frohlich and Lean, 1998). These measurements demonstrate impressively that the term 'solar constant' is not appropriate at all since variations have been found on a wide range of time-scales ranging from minutes up to the solar cycle and probably even longer (Baliunas and Jastrow, 1990; White *et al.*, 1992; Beer *et al.*, 1994; Beer, 2000).

Figure 2 shows a composite of several irradiance datasets recorded by various instruments between 1978 and 1999 (Frohlich and Lean, 1998). Most prominent is a 0.1% increase of the total solar irradiance in phase with the solar magnetic activity cycle. Superimposed upon this long-term and periodic change of roughly 11-years are short-term variations on time-scales of the solar rotation which are caused by the appearance and evolution of solar surface magnetic features (Willson and Hudson, 1988; Foukal and Lean, 1986; Foukal and Lean, 1988; Fligge *et al.*, 1998; Fligge *et al.*, 2000). Note that almost all of the variations in Figure 2 are real, i.e. of solar origin, since the noise in the relative irradiance measurements is generally much smaller (i.e., $< 0.01\%$ on short time-scales).

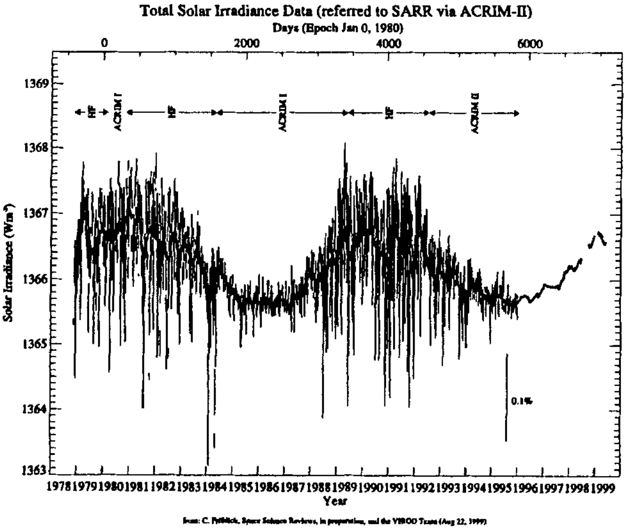

Figure 2 The total solar irradiance between 1978 and 1999 vs. time. Plotted is a composite of the measurements from various instruments (see (Frohlich and Lean, 1998) for details). Figure kindly provided by C. Fröhlich.

Phenomenologically, the magnetic features on the solar disc can be divided into two classes: The large-scale features, i.e. sunspots, are dark because their strong magnetic field is able to significantly reduce the convective energy transport from below (Spruit, 1976). The small-scale elements, composing the faculae and enhanced network, usually are bright. They form the second class of main solar surface magnetic features (see Solanki, 1993) for a detailed discussion of the properties of small-scale magnetic features).

Sunspots are able to reduce the solar irradiance temporarily by up to 0.4%. Due to their short life-time they dominate solar irradiance changes on time-scales of a few days to weeks. The smaller scale magnetic elements, in contrast, exhibit a completely different brightness signature having a very low contrast at disc center (in white light) which increases towards the limb. Due to the fact that the decay products of both sunspots and active region faculae is the (enhanced) network, which survives considerably longer than the sunspots, these features do more than compensate the darkening influence of the spots on the solar cycle time-scale, making the Sun brighter during activity maximum than during the minimum.

Yet, it is still under debate whether the contribution of small-scale magnetic features can account for all of the observed increase of total solar irradiance between activity minimum and maximum. Contributions of non-magnetic or only indirectly magnetic origin have been proposed to contribute substantially to the observed increase based on photometric observations of the solar limb at different latitudes (Kuhn and Libbrecht, 1991). However, models based purely on solar surface magnetic features have not only been able to successfully reproduce short-term

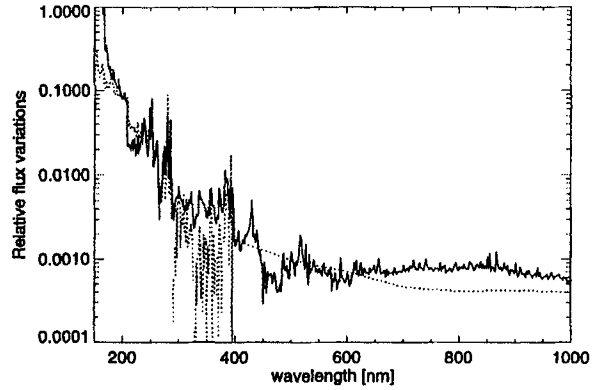

Figure 3 Variations of the solar spectral irradiance between activity minimum and maximum for the spectral range of 200 to 1000 nm. The dashed line represents a compilation from different datasets by Lean (1997) (for $\lambda < 400$ nm) while the solid line is from the model of Unruh et al. (1999).

irradiance changes on time-scales of the solar rotation (Lean and Foukal, 1988; Lean *et al.*, 1998; Fligge *et al.*, 2000) but may also be able to reproduce the long-term trend in solar irradiance between activity minimum and maximum as is suggested by Fligge and Solanki (2001) based on preliminary models.

A brief look at the Sun's face at different wavelengths reveals that the solar irradiance also exhibits a strong wavelength dependence. A closer inspection shows that the amount of variability increases rapidly towards shorter wavelengths (Figure 3). The spectral regions shorter than ~300 nm exhibit variations that are orders of magnitude larger than the ones seen in visible and IR wavelength ranges. A detailed examination of the spectral dependencies of solar irradiance variations is crucial since it provides tighter constraints on the physical basis of current irradiance models.

3 THE INFLUENCE OF THE SHORT-WAVELENGTH RADIATION ON THE EARTH'S ATMOSPHERE

Most of the solar radiation is emitted at visible and near IR wavelengths. This part of the solar spectrum is only moderately variable but provides the main energy input to maintain the average surface temperature of the Earth of roughly 15°C, since it penetrates the Earth's atmosphere almost unhampered.

The more variable part of the solar spectrum below approximately 300 nm is absorbed higher up in the Earth's atmosphere (Figure 4) where it significantly alters the chemical composition (Haigh, 1994; 1996) and the dynamics (Labitzke and Loon, 1997) of these layers. In particular, solar UV radiation controls the stratospheric ozone concentration by photo-dissociation of molecular oxygen. The resulting changes of the stratospheric ozone concentration have been proposed to

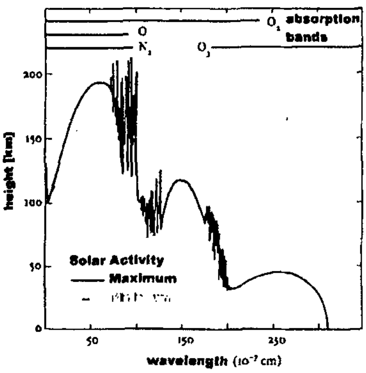

Figure 4 Height in the Earth's atmosphere at which $1/e$ of the incoming solar radiation between 1 and 350 nm is absorbed. Adapted from (Meier, 1991).

be a possible — although indirect – driver of Sun-induced changes of the Earth's climate (Larkin *et al.*, 2000).

Radiation at even shorter wavelengths, i.e. below 170 nm, is deposited in the very upper parts of the Earth's atmosphere, i.e. the ionosphere, which is then heated in response from a temperature of roughly 750° C at solar activity minimum up to 1250° C during maximum activity. The resulting expansion of the outermost layers of the Earth's atmosphere has important implications for space-flight as was learned by the untimely end of the SkyLab mission in 1979.

4 LONG-TERM SOLAR VARIABILITY AND CLIMATE

There is evidence that in the past solar irradiance underwent secular changes on time-scales of decades to centuries which may have influenced the Earth's climate. From historical records we know, e.g., that the prolonged period of reduced temperatures in Europe during the 17th and the beginning of the 18th century (i.e., the little ice age) coincides with a period of extraordinarily low solar surface activity, when hardly any sunspots were observed for decades. This hyphenation of solar activity is known as the Maunder Minimum. From present-day observations we know that the total solar irradiance changes by 0.1% between activity minimum and maximum which seems unlikely to have such an incisive impact on the Earth's climate. Therefore, the Sun must have been significantly dimmer during that time period than it is during today's minima (if the main influence of the Sun on climate is due to irradiance changes).

There is indirect evidence for long-term changes of the solar brightness. Measurements of the concentration of cosmogenic isotopes in terrestrial archives like trees (^{14}C) or Greenland ice cores (^{10}Be) paint a picture of a highly variable interplanetary magnetic field (Beer et al., 1994; Eddy, 1977) which, in turn, is fed by

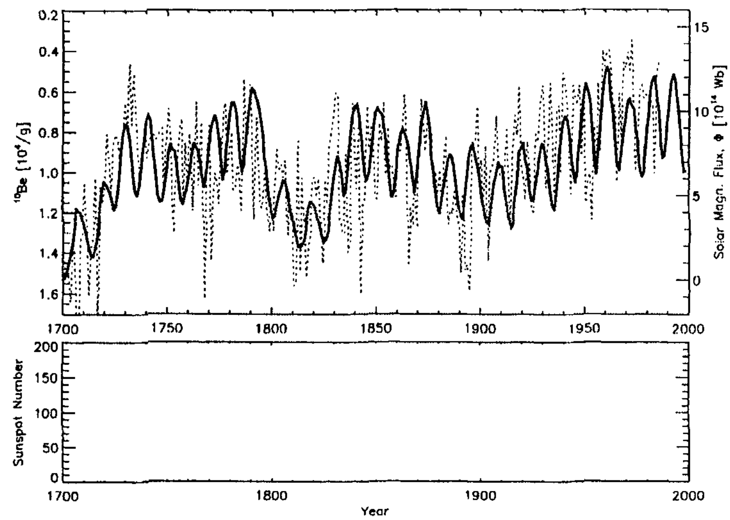

Figure 5 Evolution of the open network magnetic flux at the solar surface since the end of the Maunder Minimum in 1700 as predicted by a simple model (upper panel, dark solid curve). For comparison, the flux of the interplanetary magnetic field (Lockwood et al., 1999) reconstructed from the geomagnetic aa-index (light solid curve) and the ^{10}Be concentration in ice cores (Beer *et al.*, 1990) (dotted curve and left-hand, inverted scale) are also plotted. The interplanetary flux values have been multiplied by a factor of 2 in order to obtain the total unsigned flux. The ^{10}Be record has been plotted without any smoothing or filtering. For comparison, the lower panel shows the corresponding time sequence of the sunspot number, R (from Solanki *et al.*, 2000).

the emission of magnetic flux on the solar surface (Figure 5). Taking into account the close relation between the changes of the solar surface magnetic field and the solar brightness, substantial variations of the solar irradiance on those time-scales appear at least plausible (Lockwood *et al.*, 1999), although they do not necessarily follow.

Other evidence comes from the study of Sun-like stars. Many of these exhibit considerably lower activity levels than the Sun (Baliunas and Jastrow, 1990). If one assumes that these stars are in a Maunder-minimum-like state, one can extrapolate the brightness of the Sun down to such activity levels (White *et al.*, 1992; Lean *et al.*, 1992; Zhang *et al.*, 1994), obtaining a Maunder minimum irradiance 0.2–0.6 W m^{-2} lower than present-day values.

Finally, observations of sun-like stars reveal that the Sun's brightness variations over a cycle are unusually small compared to its level of magnetic activity as inferred from Ca II K measurements (Lockwood *et al.*, 1992), suggesting that the Sun's possible range of brightness variation is much larger than what we have observed during the past 22 years. Recent new observations (Henry et al., 2000) and re-evaluations of the older observations of sun-like stars (Radick *et al.*, 1998), however, lead to the conclusion that the difference between the Sun and these stars may have been heavily overestimated.

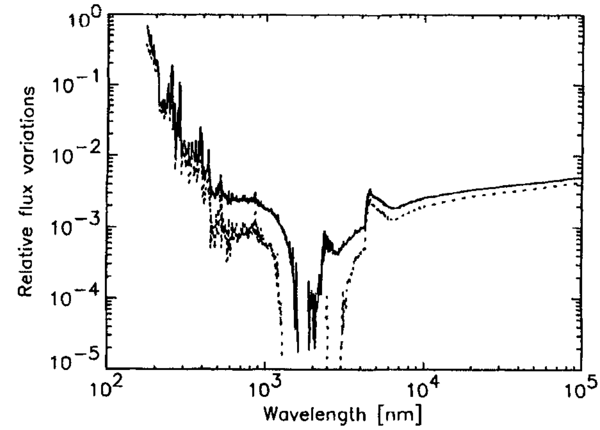

Figure 6 Relative solar irradiance changes between (present-day) activity maximum and minimum (dotted line) as well as between (present-day) activity minimum and the Sun in a Maunder minimum state (solid line). From a model by Fligge and Solanki (2000).

A better understanding of the long-term solar total and spectral irradiance variations, however, is crucial if one wants to uncover a possible link between solar and climate variability. This is mainly for the following reasons: Firstly, the large heat capacity of the oceans smears out any short-term changes in the energy input to the Earth's atmosphere. Secondly, we are looking for solar induced temperature changes of a few tenths of a degree while seasonal changes easily reach 20° C and more. Hence, reliable reconstructions of both the past solar irradiance as well as the past climate evolution are needed on as long a time period as possible.

Reconstructions of solar total (Hoyt and Schatten, 1993; Lean *et al.*, 1995a; Solanki and Fligge, 1998; 1999) and spectral (Fligge and Solanki, 2000; Lean, 2000b) irradiance variations over the last 300 years give an increase of roughly 0.3% of the total solar irradiance since the Maunder Minimum (depending on the model applied) while, e.g, the solar UV radiation has increased by approximately 3.0% since then (Fligge and Solanki, 2000). Figure 6 shows the relative flux variations of the Sun between a present-day activity maximum and minimum as well as between a present-day minimum and the Maunder minimum based on the model by Fligge and Solanki (2000).

5 CONCLUSIONS

The continuous increase of the terrestrial surface temperature urgently raises the question about the origin of this climate change. To estimate the influence of man-made greenhouse gases, the potentially most important driver, however, the natural variability must be known. Hence, it is becoming increasingly important to understand the physical nature of the solar-terrestrial relationships – not only for solar physicists but for humanity as a whole since only on the basis of this knowledge will it be possible to come to the right political and social decisions that ought to guide our future actions.

References

Baliunas, S. and Jastrow, R. (1990) *Nature* **348**, 520.

Beer, J. (2000) In: E. Friis-Christensen, C. Fröhlich, J. Haigh, M. Schüssler and R. von Steiger (eds.) *Solar Variability and Climate*, Kluwer Academic Publishers, Dordrecht.

Beer, J., Blinov, A., Bonani, G., Hofmann, H. J., and Finkel, R. C., (1990) *Nature* **347**, 164.

Beer, J., Baumgartner, S. T., Dittrich-Hannen, B., Hauenstein, J., Kubik, P., Lukasczyk, C., Mende, W., Stellmacher, B., and Suter, M. (1994) In: J. Pap, C. Fröhlich, H. Hudson and S. Solanki (eds.) *IAU Colloquium 143. The Sun as a Variable Star: Solar and Stellar Irradiance Variations.* Cambridge Univ. Press, Cambridge, p. 291.

Eddy, J. A. (1977) *Climatic Change* **1**, 173.

Fligge, M. and Solanki, S. K. (2000) *Geophys. Res. Lett.* **27**, 2157.

Fligge, M. and Solanki, S. K. (2001) *Astron. Astrophys.* to be submitted.

Fligge, M., Solanki, S. K., Unruh, Y. C., Fröhlich, C. and Wehrli, C. (1998) *Astron. Astrophys.* **335**, 709.

Fligge, M., Solanki, S. K., and Unruh, Y. C. (2000) *Astron. Astrophys.* **353**, 380.

Fröhlich, C. and Lean, J. (1998) *Geophys. Res. Lett.* **25** 4377.

Foukal, P. and Lean, J. (1986) *Astrophys. J.* **302**, 826.

Foukal, P. and Lean, J. (1988) *Astrophys. J.* **328**, 347.

Haigh, J. D. (1994) *Nature* **370**, 544.

Haigh, J. D. (1996) *Science* **272**, 981.

Henry, G. W., Baliunas, S. L., Donahue, R. A., Fekel, F. C., and Soon, W. (2000) *Astrophys. J.* **531**, 415.

Hoyt, D. V. and Schatten, K. H. (1993) *J. Geophys. Res.* **98**, 18895.

Kuhn, J. R. and Libbrecht, K. G. (1991) *Astrophys. J.* **381**, L35.

Labitzke, K. and Van Loon, H. (1997) *Space Science Reviews* **80**, 393.

Larkin, A., Haigh, J., and Djavidnia, S. (2000) *Space Science Reviews*, in press.

Lean, J. (1997) *Ann. Rev. Astron. Astrophys.* **35**, 33.

Lean, J. (2000) *Geophys. Res. Lett.* **27**, 2425.

Lean, J. and Foukal, P. (1988) *Science* **240**, 906.

Lean, J., Skumanich, A., and White, O. (1992) *Geophys. Res. Lett.* **19**, 1595.

Lean, J., Beer, J., and Bradley, R. (1995) *Geophys. Res. Lett.* **22**, 3195.

Lean, J. L., Cook, J., Marquette, W., and Johannesson, A. (1998) *Astrophys. J.* **492**, 390.

Lockwood, G. W., Skiff, B. A., Baliunas, S. L., and Radick, R. R. (1992) *Nature* **360**, 653.

Lockwood, M., Stamper, R., and Wild, M. N. (1999) *Nature* **399**, 437.

Meier, R. R. (1991) *Space Science Reviews* **58**, 1.

Radick, R. R., Lockwood, G. W., Skiff, B. A., and Baliunas, S. L. (1998) **118**, 239.

Solanki, S. K. (1993) *Space Science Reviews* **63**, 1.

Solanki, S. K. and Fligge, M. (1998) *Geophys. Res. Lett.* **25**, 341.

Solanki, S. K. and Fligge, M. (1999) *Geophys. Res. Lett.* **26**, 2465.

Solanki, S. K., Schüssler, M., and Fligge, M. (2000) *Nature*, submitted.

Spruit, H. C. (1976) *Sol. Phys.* **50**, 269.

Unruh, Y. C., Solanki, S. K., and Fligge, M. (1999) *Astron. Astrophys.* **345**, 635.

White, O. R., Skumanich, A., Lean, J., Livingston, W. C., and Keil, S. L. (1992) *Publ. Astron. Soc. Pac.* **104**, 1139.

Willson, R. C., Gulkis, S., Janssen, M., Hudson, H. S., and Chapman, G. A. (1981) *Science* **211**, 700.

Willson, R. C. and Hudson, H. S. (1988) *Nature* **332**, 810.

Willson, R. C. and Hudson, H. S. (1991) *Nature* **351**, 42.

Zhang, Q., Soon, W. H., Baliunas, S. L., Lockwood, G. W., Skiff, B. A., and Radick, R. R. (1994) *Astrophys. J.* **427**, L111.