SOLAR MAGNETIC ACTIVITY AND TOTAL IRRADIANCE SINCE THE MAUNDER MINIMUM

K.F. Tapping[1], D. Boteler[2], A. Crouch[3], P. Charbonneau[3], A. Manson[4], H. Paquette[3]
[1] *Herzberg Institute of Astrophysics, National Research Council, P.O. Box 248, Penticton, British Columbia, V2A 6J9, Canada.* (ken.tapping@nrc-cnrc.gc.ca)
[2] *Geomagnetics Laboratory, Natural Resources Canada, 2617 Anderson Road, Ottawa, Ontario, K2A 0Y3 Canada.* (david.boteler@nrcan-rnrcan.gc.ca)
[3] *Université of Montréal, Montréal, Québec, H3T 1J4 Canada* (ash@astro.umontreal.ca, paulchar@astro.umontreal.ca, paquette@umontreal.ca)
[4] *Institute for Space and Atmospheric Studies, University of Saskatchewan, Saskatoon, Saskatchewan, S7N 5E2 Canada* (alan.manson@usask.ca)

Received ; accepted

Abstract.
We develop a model for solar total irradiance based upon the 10.7 cm solar radio flux ($F_{10.7}$). Using this we estimate total irradiance back to tbe beginning of the 10.7 cm solar radio flux in 1947. Then, using the sunspot number record to estimate values of $F_{10.7}$ back to the Maunder Minimum, we estimate total solar irradiance since that date.

Keywords: Maunder Minimum, solar variability, irradiance

1. Introduction

Understanding the variability in solar irradiance and its role in global climate change requires as long as possible record of historical irradiance variations. In the absence of observations currently extending back in the past beyond about three solar solar activity cycles, this can only be obtained through proxy quantities and modelling. The modelling process is extremely complicated, entailing physics that is poorly understood in many cases, the use of proxies with connections with the values being represented weak to doubtful. Then, the required precision is not available through calculations, so fitting the model to irradiance data is usually needed. Finally, deriving the required historical record requires extrapolation of the model well outside the parameter space used to derive it.

Over the last 2000 years there have been instances where solar activity fell to a low level for some decades. These have become known as the Wolf (1280-1350AD), Spörer (1420-1540AD), Maunder (1645-1715) and Dalton (1795-1825) minima. Connections between these minima and periods of anomalous global cooling were first pointed out by Eddy (1976 *a*, *b*, 1977, 1979, 1980). The period between 1700 and the present is important in that there is a continuous record of sunspot number, which is a directly measured index of solar activity, of known pedigree with established relationships with other activity indices, and which antedates the rapid increase in anthropogenic greenhouse gases that began with the industrial revolution.That there is a connection between solar variability and terrestrial environmental change is well-documented, and evident in both recent, mediaeval and geological records (see for example, Anderson, 1991).

Although the long-term solar variability connected with evolutionary processes is now well understood, this is not the case for the shorter-term variations. There are currently two main schools of thought on short-term solar variability. One proposes that the observed irradiance variations come from the changing relative distributions over the photosphere of different activity phenomena with different emissivities, such as sunspots, faculae and elements of the active network. It is well established that the shorter-term irradiance variations follow changes in solar magnetic activity (Willson and Hudson, 1991; Fröhlich, 1994; Kuhn, 1996), and that changes in solar irradiance correlate with bright faculae and magnetic network (Foukal and Lean, 1988). Upon this basis, using recent measurements and older proxies, Lean (2000) has estimated irradiance variations back to the Maunder Minimum. The other school of thought proposes that to adequately model irradiance variations, some additional phenomena associated with magnetic activity need to be included. Suggestions include variations in the solar radius (Delache *et al.*, 1986; Ulrich and Bertello, 1995; Antia, 2003), large convective cells (Ribes *et al.*, 1985; Fox and Sofia, 1994; Sofia, 2004; Sofia and Li, 2004). In all cases solar magnetic activity, both above, at and below the photosphere need to be considered. A discussion of the magnetic interpretation of solar activity is given by Parker (1994).The visible manifestations of solar activity take place primarily in *complexes of activity*, that may contain several active regions at various stages in their evolution, together with their decay products. These complexes persist for up to a dozen solar rotations. A detailed study of these complexes and their evolution is given by Gaizauskas *et al.* (1983).

Photospheric magnetic activity comprises three main processes: the emergence of new magnetic flux at the the photosphere and its subsequent submergence; the fragmentation of concentration of magnetic flux in areas of high magnetic field strength into flux fragments of lower magnetic field strength, and their diffusion away across the photosphere (mainly poleward). Some signs of magnetic activity are always present, even at solar activity minima. There are ephemeral regions (short-lived magnetic bipoles) forming and dissipating, and large areas of weaker magnetic flux remaining from the decay of old active regions (see the discussion in Zwaan and Harvey, 1994). Sunspots might be a good indicator of magnetic activity when present, but they are not useful when activity is low. When examining solar activity during a sustained change in the solar activity cycle, or even a temporary cessation, one needs to examine two issues: firstly, does the nature of the process by which magnetic flux is processed change, and secondly, what is the solar activity machine below the photosphere doing? There have been previous attempts at modelling the history of solar magnetic activity. The use of solar magnetic fields as a basis for irradiance modelling was examined by Harvey (1994), and more recently by Fox (2004). In work conducted since, particularly noteworthy are models by Solanki *et al.* (2000, 2002), which model the processing of magnetic flux over the solar cycle. In the case of this investigation, the input to the model has to be sunspot number, which is the only direct index of solar activity available. In this paper we develop a model for the processing of solar magnetic flux and use it to model the historical record of total irradiance. In the discussions here we use sunspot number and the 10.7 cm solar radio flux as starting points.In this paper we use $F_{10.7}$ to estimate the total amount of magnetic flux in active regions, use this as input to a magnetic flux processing model, and thence estimate irradiance contributions. Using $F_{10.7}$ we estimate solar total irradiance back to 1947, when $F_{10.7}$ record begins, and then, using sunspot number to estimate the 10.7 cm solar radio flux, we extend the estimates back to 1700 and the Maunder Minimum.

2. Input Data

2.1. Sunspot Number

Sunspot number is the oldest directly-measured index of solar activity, and now forms a consistent, continuous record covering more than 300 years. The main database of sunspot numbers is maintained by the Solar Influences Data Centre (SIDC) in Belgium, but available through a number of sources worldwide. The sunspot number data used in this paper, covering the period 1700 to the present, were obtained from the National Geophysical Data Center, Boulder, Colorado.The sunspot number index (more correctly referred to as the Zürich Sunspot Number) has proved itself to be a very useful indicator of the level of solar activity. Its disadvantage is that it is empirical and cannot be theoretically related to solar and active region parameters, and the slope of plots of sunspot number against other indices changes at the low-activity end, making extrapolation uncertain. However, for reasons explained later, operating the model requires sunspot data antedating the Maunder Minimum. Thomson (private communication), using research by Hoyt *et. al.* (1995*a* and *b*, 1996 and 1998*a* and *b*) made estimates of sunspot number from 1610 onwards.

2.2. 10.7 cm Solar Radio Flux

The 10.7 cm solar radio flux values are measurements of the intensity, at 10.7 cm wavelength, of the slowly-varying component (S-component) of solar radio emission. The S-component can be observed at wavelengths from about 50 to 1 cm, but is brightest at wavelengths close to 10 cm, hence the value of measurements at 10.7 cm wavelength. It is thermal in origin, and comes from coronal plasma trapped in the magnetic fields overlying active regions.

In active regions where the ambient magnetic fields supporting the plasma are low enough for the electron gyrofrequency (roughly $f_B = 2.8 \times 10^6 B$ Hz, where B is in Gauss) is less than about a third of the observing frequency, the main contributor to the total absorption coefficient is free-free interactions between thermal electrons and ions. In places where the magnetic fields are stronger, for example over sunspots, thermal gyroresonance can produce much brighter emission due to the higher absorption coefficient. A more detailed discussion of the S-component and its origins are given in monographs by Kundu (1965) and Krüger (1979), and in Tapping and Harvey (1994). The intensity of the S-component at 10.7 cm wavelength, which is known as the 10.7 cm solar radio flux, or $F_{10.7}$, is a well-established index of solar activity. A specific discussion of the 10.7 cm solar radio flux is given in Tapping (1987). The S-component is a composite of contributions from all the active regions on the solar disc plus emissions originating outside active regions. Studies of active region radio sources as contributors to the S-component have been made by Tapping and Zwaan (2002) and Tapping *et al.* (2003). The 10.7 cm solar radio flux is given in solar flux units (1 solar flux unit (sfu) $\equiv 10^{-22}\mathrm{Wm^{-2}Hz^{-1}}$). In this discussion it is the enhancement of the emission over the Quiet Sun base level that is important, so we define the *10.7 cm S-component flux*, $S_{10.7}$, which is the strength of the slowly-varying component at 10.7 cm wavelength, which is $F_{10.7}$ with the Quiet Sun flux density (assumed here to be 68 solar flux units) subtracted.

2.3. Magnetic Flux Measurements

For more than two decades, the magnetograph at the National Solar Observatory at Kitt Peak has been used to measure the distribution of magnetic flux at the photosphere with near-arc-second resolution. The instrument is essentially a high-angular resolution spectrometer that can be used to measure the Zeeman splitting of selected photospheric spectral lines). Harvey (1992) analyzed magnetograms over more than a solar activity cycle to estimate the contributions to the total magnetic flux coming from the various types of magnetic structure, including sunspots, faculae, the active network, the intra-network fields and possibly a background component. She found that to a very large degree, the magnetic elements measured by the magnetograph fall into two distinct classes (see also Zwaan and Harvey, 1994): *strong-field elements* having average magnetic field strengths higher than a certain threshold value, and *weak-field elements*, located outside active regions, with average magnetic field strengths smaller than this value. Moreover, she demonstrated that this threshold magnetic field strength could be varied over the range 25-40 Gauss without significantly affecting the relative budget, so clearly different populations are identified. Elements having intermediate values for magnetic field strength exist only transiently during region fragmentation. Following the practice used by Harvey, all the magnetic flux values used here, unless it is stated otherwise, are given in *magnetic flux units* (1 magnetic flux unit (mfu) $\equiv 10^{22}$ Maxwells).

The strong-field elements lie in active regions and in elements of the active network. Their intrinsic field strengths range from about 1,000 Gauss (in network elements) to 3,000 Gauss (in sunspots). Since these elements often lie below the resolution of the magnetograms, the field strengths measured are averages over the element and consequently smaller. Ephemeral regions are considered to be simply the small-scale end of the size distribution of active regions. Setting them aside as a separate category of active structures may well be an artifact of previous lines of research (Zwaan and Harvey, 1994). The weak-field elements include the *intra-network field* (INF), which are probably a product of collapse of field lines in network elements, that due to their weakness, are trapped between the canopy of strong field lines connecting the network elements, and which repeatedly emerge and submerge above and below the photosphere between their end-points. The INF occurs all over the photosphere.

The strong-field elements lie in active regions. The weak-field elements are scattered over the rest of the solar disc. The calibration of the Φ_S values are taken as correct, but it has been pointed out there is a question about the weaker-field components. Fortunately, for more than three decades, the National Solar Observatory has provided values of the average photospheric magnetic field strength (B_{av}), from which we can calculate the total photospheric magnetic flux ($\Phi_T = 4\pi R_{\odot}^2$), where $R_{\odot}$ is the photospheric radius, from which the weaker-field magnetic flux (Φ_W) may be obtained by difference: $\Phi_W = \Phi_T - \Phi_S$).

2.4. Irradiance

Through a succession of instruments, irradiance measurements have been made over almost three solar activity cycles so far, from 1978 to the present. The instruments and observation record intervals are presented in Table I.

A review of the measurements, measurement methods and instrumentation is given by Fröhlich *et al.* (1991). Integration of these separate data sets into a single, consistent and calibrated record is described by Pap and Fröhlich (1999) and Fröhlich (2004), and references therein (see also

Table I. Summary of the instruments used to observe the total solar irradiance.

Radiometer	Satellite	Extent of Data Record
H-F	Nimbus 7	1978 - 1992
ACRIM I	SMM	1980 - 1989
ERBE	ERBS	1984 - Present
ACRIM II	UARS	1991 - 2001
VIRGO	SOHO	1996 - Present
ACRIM III	ACRIM-Sat	2000 - Present

Fröhlich and Lean 1998*a* and b). The uncertainties and problems in this integration process are matters of continuing discussion. This integrated irradiance database was obtained from PMOD/WRC, Davos, Switzerland. The irradiance values used in this paper are annual averages.

3. Models

The strong-field (active region) magnetic flux is estimated using the $S_{10.7}$ index. This is input into a simple cascade model to estimate the weak-field magnetic flux and the background leve. The irradiance model invokes two components: modulation of irradiance by the changing distribution over the photosphere of magnetic structures of differing emissivity, and a general change in photospheric brightness due to energy transfer from a heat reservoir below that has a thermal time constant long enough to smooth out the modulation by the activity cycle. but allows slower variations in the background irradiance, which causes the observed slope in the irradiance plots.

3.1. $F_{10.7}$ AND $S_{10.7}$ FROM N_s

The 10.7 cm solar radio flux $F_{10.7}$ and the 10.7 cm S-component flux $S_{10.7}$ ($S_{10.7}$ is simply $F_{10.7}$ with the quiet sun level subtracted) are measures of the total amount of strong-field magnetic flux. The fluxes are highly correlated, but the relationship between them is non-linear. Figure 1 shows annually-averaged $F_{10.7}$ values plotted against sunspot number (N_s).

An empirical relationship that relates the two quantities is:

$$F_{10.7} = \frac{N_s}{2}\left(2 - \exp(-0.01 N_s)\right) + 68 \qquad (1)$$

and $S_{10.7} = F_{10.7} - 68$.

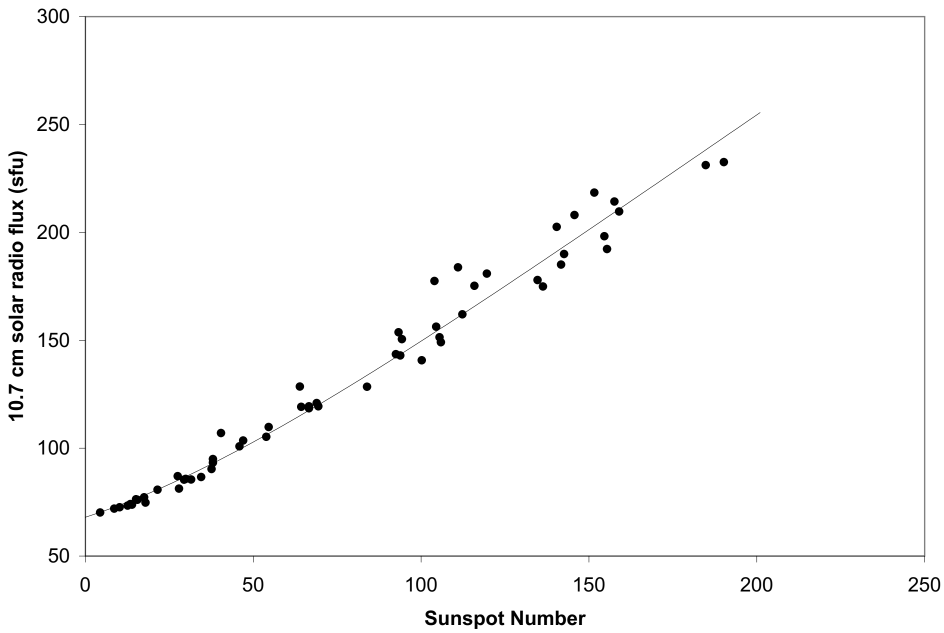

Figure 1. Annually-averaged values of the 10.7 cm solar radio flux ($F_{10.7}$) since 1947 plotted against sunspot number.

3.2. Magnetic Flux

Figure 2 shows the strong-field magnetic flux over a solar activity cycle plotted against the S-component flux.The correlation is high ($R^2 = 0.99$) and linear $\Phi_S = 0.4392 S_1 07$. The zero intercept underlines the well-established connection between $S_{10.7}$ and active regions. The empirical relationship is used to estimate Φ_S.

$$\frac{\partial \Phi_W}{\partial t} = E_W - S_W + I_W - L_W \tag{2}$$

where E_W and S_W are rates of emergence and submergence of magnetic flux into that structure class, I_W is the input from the decay of strong-field elements, and L_W is the loss by dissipation. If active regions fragment mainly around the periphery, the rate of fragmentation will be related to

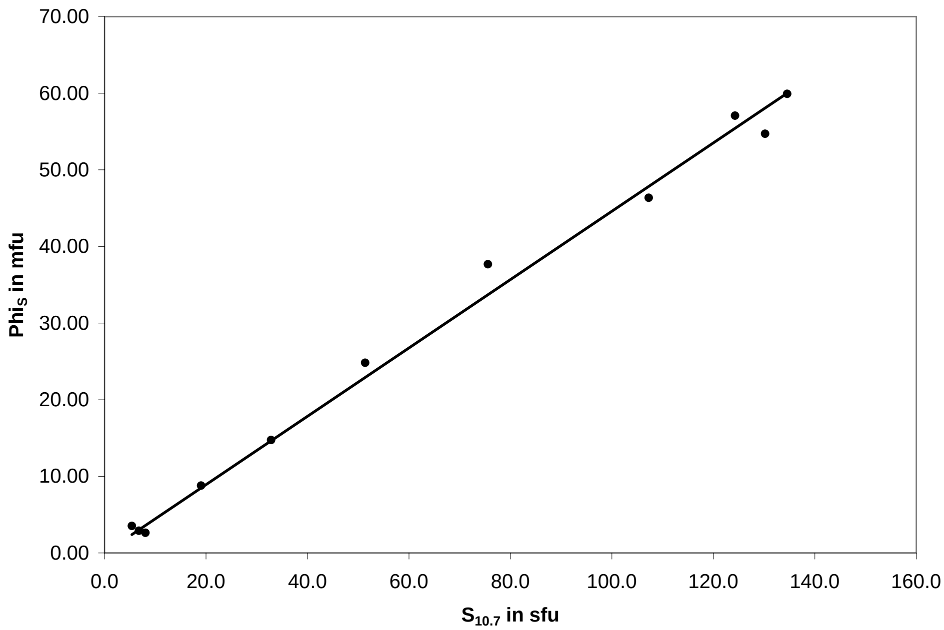

Figure 2. Annually-averaged values of the strong-field magnetic flux plotted against similarly-averaged values of the 10.7-cm S-component flux, together with a fitted line

the perimeter distance, which would in turn be related to $A^{1/2}$, where A is the total active region area, and $\Phi_S \propto A$. If the dissipation is exponential:

$$\frac{\partial \Phi_W}{\partial t} = E_W - S_W + a\Phi_S^{1/2} - \beta\Phi_W \tag{3}$$

Figure 3 shows a plot of annually-averaged strong and weak-field magnetic fluxes over a solar activity cycle. Two things stand out: the weak-field comprises a variation that is in phase with that of the strong-field magnetic flux, and a background level of roughly 45 mfu.This would suggest that either the strong and weak magnetic fluxes are modulated by the same thing - the solar activity cycle - or that the transfer between them is over a timescale short compared with the one-year averaging time. The average age of an active region is one or two solar rotations, so no phase delay might be detected in either case.

Figure 3. Annually-averaged values of total strong (solid circles/solid lines) and weak-field (open squares/dashed lines) magnetic fluxes over a solar activity cycle.

The figure suggests that over year timescales, all the parameters are in equilibrim and the time-derivative of Φ_W averaged over a year is smaller than the other parameters, and we can write:

$$\Phi_W \approx \frac{1}{\beta}\left(E_W - S_W + a\Phi_S^{1/2}\right) \tag{4}$$

If roughly $E_W - S_W = b\Phi_S$, then:

$$\Phi_W \approx \frac{1}{\beta}\left(b\Phi_S + a\Phi_S^{1/2}\right) \tag{5}$$

A fit to the observed data yields $a/\beta = 2.81$ and $b/\beta = -0.14$ The fitted curve and rotationally-averaged weak and strong magnetic fluxes are shown in Figure 4.

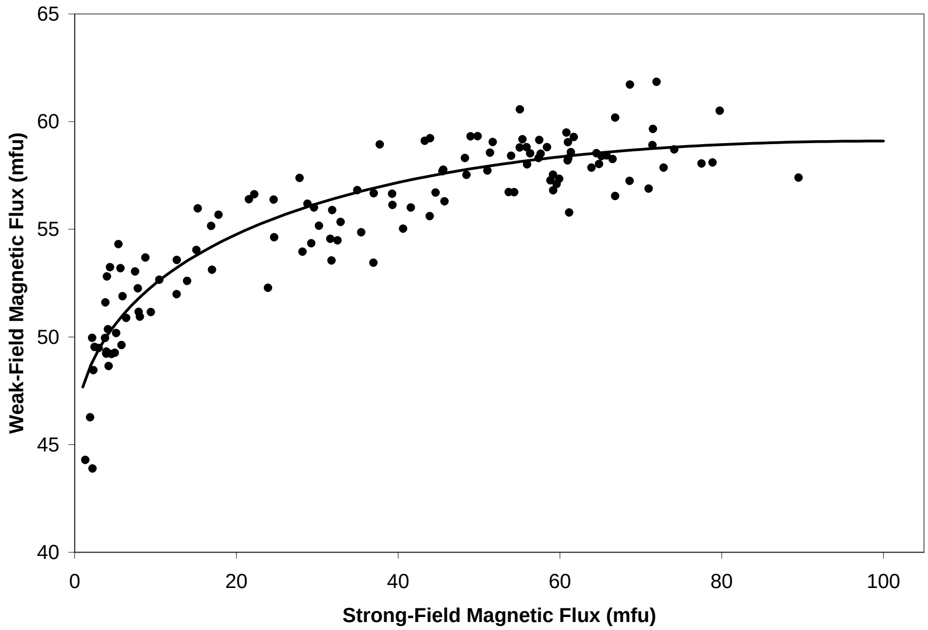

Figure 4. Rotationally-averaged values of the weak-field magnetic flux plotted against the strong-field magnetic flux, with the fitted model.A background of 45 mfu is included.

Figure 5 shows the estimated strong and weak-field magnetic fluxes since 1600 derived from the sunspot number record by means of this model. The constant background of about 45 mfu has not been included.

3.3. Irradiance

Figure 6 shows annually-averaged total irradiance and $F_{10.7}$ plotted against time. Two points stand out: firstly there is the variation in total irradiance over the solar activity cycle, as exemplified by $F_{10.7}$, and there is a downward trend in the line drawn through the irradiance minima of about 0.006 W.m^{-2}.year^{-1}.

This can be explained in terms of a two-component model: $I(t) = I_a(t) + I_{\odot}(t)$, where $I_a(t)$ the irradiance contributions from active region structures and $I_{\odot}(t)$ comes from a generally-varying brightness of the photosphere

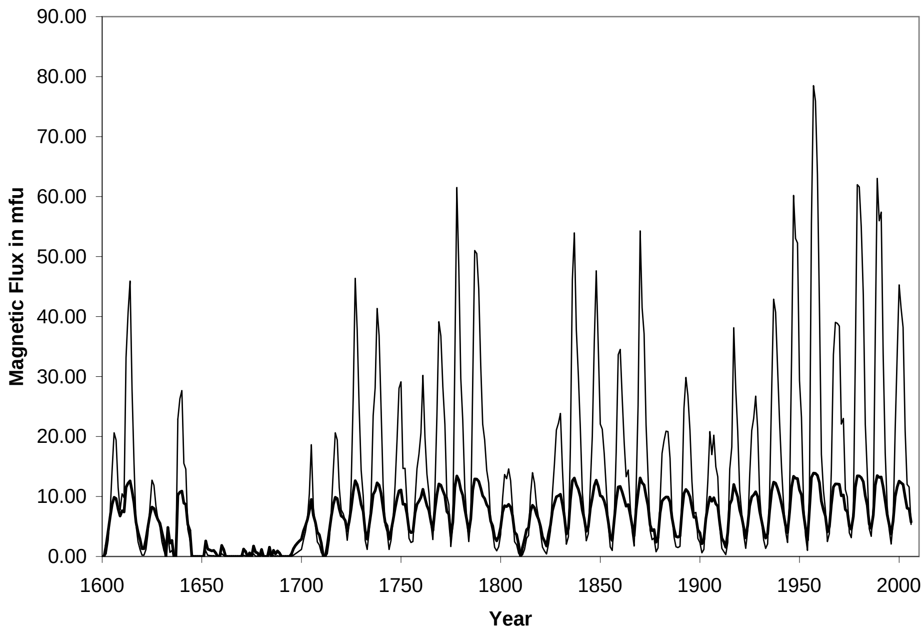

Figure 5. Estimated strong and weak-field magnetic fluxes since 1600, derived from the sunspot number record. The background of 45 mfu is not included.

outside the active regions. The variation of irradiance following the rhythm of the solar activity cycle is assuemd to be related to the formation and decay of active regions. Since the variations between the irradiance and the 10.7 cm solar radio flux are in-phase, the background cannot be due to decay of active regions, because the observed variation showed by a line through the irradiance minima in the plot would require a decay time constant big enough to generate an immediately-visible phase delay betweem irradiance and $F_{10.7}$.

With the high correlation between the activity index and irradiance, together with the absence of any phase delay between them comparable with or larger than the one-year averaging, the baseline slope is assumed to be another phenomenon, so that the irradiance model would be of the form:

$$I(t) = I_a(t) + I_{\odot}(t) \tag{6}$$

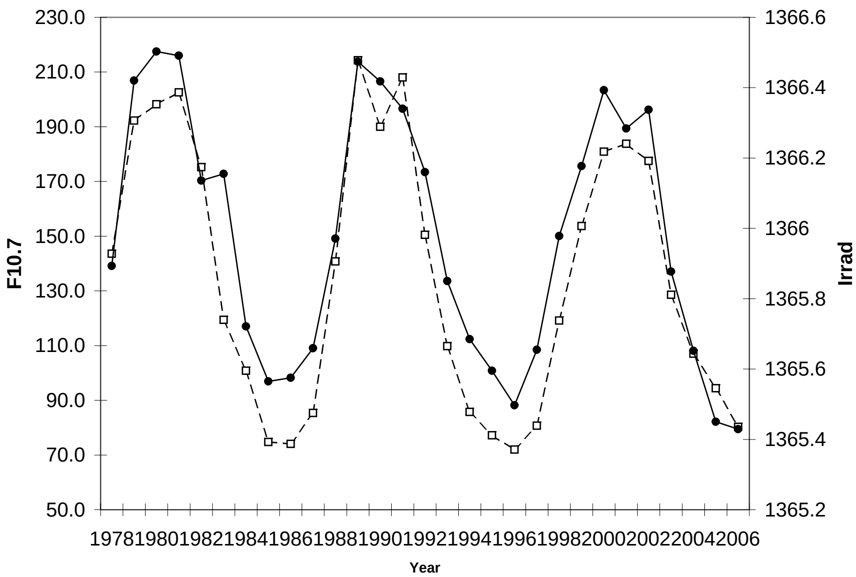

Figure 6. Annually-averaged values of the 10.7 cm solar radio flux (dahed line and open squares) and total irradiance (solid line and circles) plotted against time

In terms of the areas of active structure classes:

$$I(t) = \sum_i (\epsilon_i - \epsilon_\odot) A_i(t) + I_\odot(t) \tag{7}$$

where ϵ_i is the emissivity of the ith class of active structure and $\epsilon_\odot$ is the emissivity of the surrounding photosphere. If the area of each class of active structure is proportional to the total magnetic flux, the model becomes:

$$I(t) = \sum_i \eta_i \Phi_i(t) + I_\odot(t) \tag{8}$$

In the case of there being two classes of magnetic structure, strong-field and weak-field structure:

$$I(t) = \eta_S \Phi_S(t) + \eta_W \Phi_W(t) + I_\odot(t) \tag{9}$$

3.3.1. $I_\odot(t)$

A line through the minima in the figure suggests an average decay in $\mathbf{I}_\odot$ of about 0.006 W.m^{-2}.year^{-1}, which is not shared by active region indices such as $F_{10.7}$).

A possibility is that there is a magnetic flux reservoir below the photosphere from which that we see at the photosphere emerges, and which contains considerably more than we see at the photosphere, and which persists over timescales long compared with the solar activity cycle, and which modulates the flow of energy to the photosphere. One possible modulation mechanism could be the role this magnetic flux would have in the pressure balance below the photosphere, causing small changes in structure of the Sun and small changes in photospheric temperature.Spruit (2000) showed the thermal time constant increases with depth below the photosphere, so there could be considerable smoothing of the variations in the rate of radial heat outflow. If $I_\odot(t) = F(\mathcal{S}_{10.7}$, where $\mathcal{S}_{10.7}$ is the filtered time series of $S_{10.7}$ data, and the degree of modulation as a fraction of the mean value of $I_\odot$, the equation can be simplified to:

$$I_\odot(t) = \zeta + \xi \mathcal{S}_{10.7} \tag{10}$$

The amount of magnetic flux in this reservoir would be proportional to one of the standard activity indices with the actitivity cycle removed by filtering.Figure 7. The

Of course $\zeta \neq 0$ and we do not have the value. However inspection of the $\mathcal{S}_{10.7}$ shows that over the period 1980-2006, during which $I_\odot$ decreases at an average rate of -0.006 W.m^{-2}.year^{-1}, $\mathcal{S}_{10.7}$ decreases at an average rate of -0.75 sfy.year^{-1}. Therefore

$$\frac{\partial I_\odot(t)}{\partial \mathcal{S}_{10.7}} = 0.008 \tag{11}$$

In 1985, at a solar activity minimum, the value of I was 1365.57 W.m^{-2}. We assume this is a value of $I_\odot$, so at other times:

$$I_\odot(t) = I_\odot(1985) - 0.008\,(\mathcal{S}_{10.7}(t) - \mathcal{S}_{10.7}(1985)) \tag{12}$$

We can use this equation to remove the effect of the variation in $I_\odot$ from the $I(t)$, leaving $I_a(t)$, the variation due to active regions.

3.3.2. $I_a(t)$

From above, the active region contribution to the irradiance is:

$$I_a(t) = \eta_S \Phi_S(t) + \eta_W \Phi_W(t) \tag{13}$$

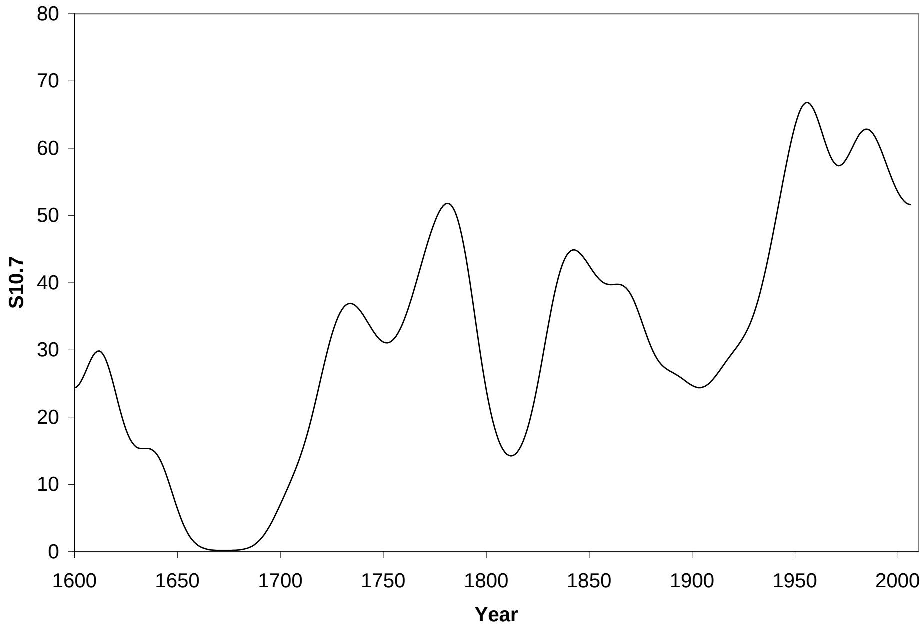

Figure 7. The variation in modelled $S_{10.7}$ since 1600 after filtering to remove the modulation by the solar activity cycle.

From a fit to the irradiance record $I(t)-I_{\odot}(t)$, we obtain $I_a(t) = 0.015\Phi_S(t)+0.003\Phi_W(t)$.The estimated values of $I_{\odot}$ and $I = I_a+I_{\odot}$ since 1600 are shown in Figure 8.

Gray and Livingstone (1997) used spectrum measurement techniques to estimate changes in average photospheric temperature over solar cycles. Typical variations were of the order of 0.5 K.If $I_a(t)$ is due to the active regions and $I_{\odot}(t)$ due to variations in the total photospheric emissivity, the estimated variation in $I_{\odot}$ since the Maunder Minimum, of 0.2 W.m^{m-2} is equivalent to an increase in average photospheric temperature of about

$$\Delta T \approx \frac{T_0}{4}\frac{\Delta I}{I_0} \tag{14}$$

If $I_0 = 1365.5$ W.m^{-2}, $T_0 = 6000$ K and $\Delta I = 0.2$ W.m^{-2}, $\Delta T \approx 0.2$ K.

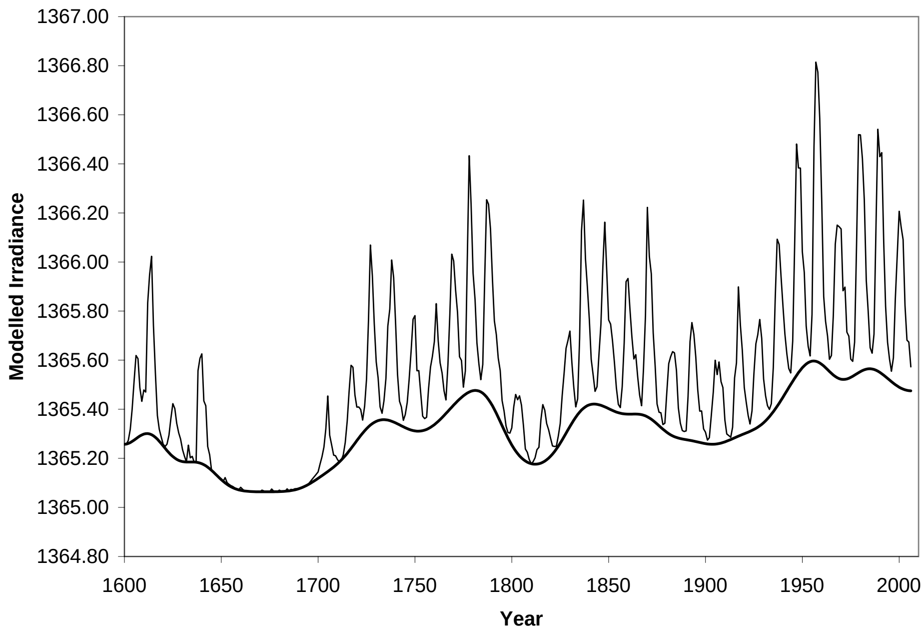

Figure 8. The thick line is a plot of estimated $\mathbf{I}_{\odot}$, and the thin line a plot of estimated $I(t) = I_a(t) + I_{\odot}$ since 1600.

4. Monte-Carlo Error Simulation

The table below lists the various errors included in the analysis. Some quantities, such as the quiet sun radio flux density have an 90% error band listed. Others, such as the estimated S-component radio flux, has an error related to its value, due to the increasingly complex mix of contributions as the general activity is higher.

Parameter	Symbol	Value	Error	Units
Quiet Sun radio flux density	F_0	67.5	± 0.5	sfu
Estimated S-component Flux	$S_{10.7}$	-	$\epsilon = 0.02 S_{10.7}$	sfu
Strong-Field Flux	Φ_S	-	$\epsilon = 0.05 \Phi_S$	mfu
Weak-Field Flux	Φ_W	-	± 3, random	mfu
Slow Activity	$\frac{\partial I}{\partial S^*_{10.7}}$	0.016	± 0.008, random	$W.m^{-2}.sfu^{-1}$
Irradiance	I	-	± 0.1, random	$W.m^{-2}$.

In all cases the quantities are assumed to have Gaussian distributions with the indicated bands or errors indicating the 90% probability bands. A large number of Monte-Carlo simulations were run. Figure 9 shows a central plot showing values where no error is assumed, and the lines above and below this plot define the space wherein 90% of the solutions including errors lie.

5. Discussion and Conclusions

Modelling historical variations is necessary but difficult. A purely physical approach is too complex, and proxies have to be used.It is therefore valuable to try as many different approaches as possible, and thus to at least define the boundaries of the solution space wherein the desired results lie. The historical record of sunspot number is a logical starting point, since it is the only intrinsic index of solar activity available that starts at a time antedating the industrial revolution.

The sunspot number record becomes a continuous time-series at about 1700AD. This is directly after the end of the Maunder Minimum, and it is possible that the record of systematic observations extends further back in time than that time, except that few sunspots were recorded. The Maunder Minimum itself is an interesting test interval for examining the behaviour of models, so sunspot data antedating the start of the Maunder Minimum is highly desirable. Fortunately, some estimates of sunspot number back to about 1600 AD were provided by Thomson (Private Communication).

Models usually address the issue of active-region related irradiance variability through estimates of facular brightness and sunspot blocking (see for instance Lean, 2000). This works well when suitable active region observations are available. When working back towards the Maunder Minimum, it is necessary to assume some relationship between sunspot number and the other active region properties.In the case of the model used here, which is based upon the active region magnetic flux (designated strong-field magnetic flux, Φ_S), it is implicitly assumed there is a monotonic relationship between sunspot number and the total magnetic flux in an active region, which is

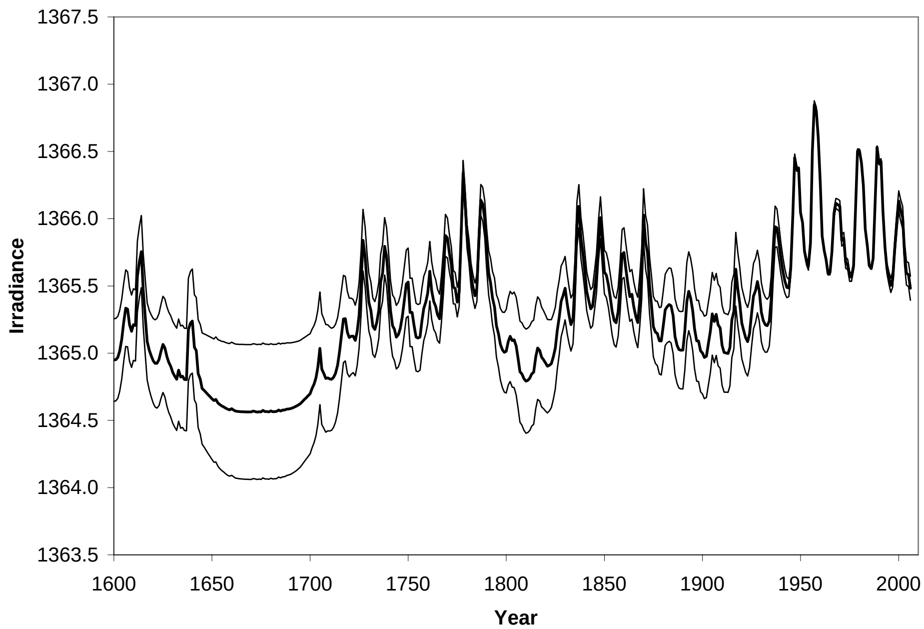

Figure 9. The central (thick) line shows the modelled irradiance values and the thin lines above and below bound the variable space containing 90% of the plots obtained in the Monte Carlo simulation.

distributed between sunspots and faculae in a fixed proportion. For a single active region such an assumption is out of the question, but when many active regions at all states of evolution over a year are averaged together, this assumption seems reasonable.

An important evaluation point for all models is the estimated irradiance during the Maunder Minimum, when activity was low, but it seems the solar activity cycle was still running. The centre-line of the error band shows an irradiance during the Maunder Minimum that is about 2 W.m^{-2} lower than present values compared with about 3.5 W.m^{-2} as estimated by Lean (2000). However, considering the uncertainty range of the model discussed here and the that inherent in the Lean (2000) estimates, there is some agreeement between them.

The model here is based ultimately on the use of sunspot number as a base for proxy development.This activity index is largely empirical, and irradiance variability involves more than just the sunspots.The 10.7 cm solar radio flux is an index more generally related to the active regions as a whole.In principle this would be a better index for irradiance issues except that the data base only extends back to 1947. Beyond that we use sunspot number as an estimate of the $F_{10.7}$. Although the correlation between these indices is very high, the relationship between them changes markedly as the level of solar activity decreases. Considering the extensive use of both these activity indices and their use as proxies for one another, this non-linearity in the relationship between them needs to be examined.

The model described here, like all others, involves assumptions that quantities maintain the same relationships over multiple solar cycles and that the time-series of sunspot number and other indices are statistically homogeneous with time.

Although the models invoking irradiance modulation by active region structures, and those invoking radius changes, small variations in average photospheric temperature due to more global structural changes, it is perhaps reasonable to investigate options involving both, since the fundamental rhythm of the solar activity cycle manifests itself over all scales, from small active region structures to the Sun as a whole. This paper describes a simple, initial look at this issue.

Acknowledgements

Firstly we would like to thank Karen Harvey for providing the magnetic flux budget data for a range of thresholds over a solar activity cycle.These were derived from magnetograms from the National Solar Observatory at Kitt Peak, which is operated cooperatively by the National Science Foundation/National Optical Astronomy Observatories, National Aeronautics and Space Administration/Goddard Space Flight Center, and National Oceanic and Atmospheric Administration/Space Environment Laboratory. We also thank David Thomson of Queen's University, Kingston, Ontario, for constructing a composite record of sunspot number prior to the Maunder Minimum. Hélène Paquette thanks the National Research Council Women in Engineering and Science Student Programme for supporting her participation in this project. The database of measurements of total irradiance was obtained from Physikalisch-Meteorologisches Observatoriu Davos, and a very special thanks is due to those who laboured to produce, from a number of different databases, a continuous record of observed irradiance covering almost three solar activity cycles. The sunspot data from 1700 onwards were downloaded from the National Geophysical Data Center at

Boulder, Colorado, magnetic flux data were obtained from the National Solar Observatory at Kitt Peak, and the 10.7 cm solar radio flux data are provided as a service by the National Research Council of Canada.

References

Anderson R.Y.: 1991. 'Solar variability captured in climatic and high-resolution palaeoclimatic records: a geologic perspective'. In: Sonett C.P., Giampapa M.S., Matthews M.S. (Eds), *The Sun in time*, University of Arizona Press, 543-561.

Antia H.M.: 2003. 'Does the Sun Shrink with Increasing Magnetic Activity?'. *Astrophys. J.*, **590**, 567.

Bhatnagar A., Jain K., Tripathy S.C.: 1999. 'Gong p-mode frequency changes with solar activity.' *Astrophys. J.*, **521**, 885-888.

Delache Ph, Lacrare F., Sadsaout H.: 1986. 'Long periods in diameter, irradiance and activity of the Sun'. In: Christensen-Dalsgaard J., Frandsen S. (Eds), *Advances in Asterioseismology*, IAU Press, 223-226.

Eddy J.A.: 1976 (a). 'The Maunder Minimum'. *Science*, **192**, 1189-1202.

Eddy J.A.: 1976 (b). 'The Sun since the Bronze Age', In: Willaims D.G. (Ed.), *Physics of solar planetary environments*, American Geophysical Union, Washington, DC, 958-972.

Eddy J.A.: 1977. 'Historical evidence for the existence of the solar cycle'. In: White O.R. (Ed.) *The solar output and its variation*, University of Colorado Associated University Press - Boulder, 51-71.

Eddy J.A.: 1979. 'The new Sun: the solar results form skylab', *NASA - SP402*.

Eddy J.A.: 1980. 'The historical record of solar activity'. In: Pepin R.O., Eddy J.A., Merril R.B. (Eds), *The ancient Sun: fossil record in the Sun, Moon and meteorites*, Pergamon Press, New York, 119-134.

Foukal P., Lean J.: 1988. 'Magnetic modulation of solar luminosity by photospheric activity', *Astrophys. J.*, **328**, 347-357.

Foukal P., Spruit H.: 2004. 'Comment on "Variations of Total Irradiance Produced by Structural Changes in the Solar Interior " '. *EOS*, **49**, 524.

Fox P., Sofia S. 1994. 'Convection and Irradiance Variations'. In: Pap J.M., Hudson H.S., Solanki S.K. (Eds), *The Sun as a Variable Star: Solar and Stellar Irradiance Variations*, Cambridge University Press, 280-290.

Fox P.: 2004 'Solar Activity and Irradiance Variations'. In. In: Pap J.M., Fox P. (Eds), *Solar Variability and its Effects on Climate*, Geophysical Monograph Series No. 141, American Geophysical Union, 141-170.

Fröhlich C., Foukal P.V., Hickey J.R., Hudson H.S., Willson R.C.: 1991. 'Solar irradiance variability from modern measurements'. In: Sonett C.P., Giampapa M.S., Matthews M.S. (Eds), *The Sun in time*, University of Arizona Press, 11-29.

Fröhlich C.: 1994. 'Irradiance Variations in the Sun'. In: Pap J.M., Hudson H.S., Solanki S.K. (Eds), *The Sun as a Variable Star: Solar and Stellar Irradiance Variations*, Cambridge University Press, 28-36.

Fröhlich C., Lean J.: 1998. 'Total Solar Irradiance Variations.', in *New Eyes to see inside the Sun and Stars*, F.L.Deubner et al., Eds., Proceedings IAU Symposium 185, Kyoto, August 1997, Kluwer Academic Publ., Dordrecht, The Netherlands, pp. 89-102.

Fröhlich C., Lean J.: 1998. 'The Sun's total irradiance: cycles, trends and related climate change uncertainties since 1978.', *Geophys.Res.Let.*, **25**, 4377-4380.

Fröhlich C.: 2004. 'Solar Irradiance Variability'. In: Pap J.M., Fox P. (Eds), *Solar Variability and its Effects on Climate*, Geophysical Monograph Series No. 141, American Geophysical Union, 97-110.

Gaizauskas V., Harvey K.L., Harvey J.W., Zwaan C.: 1983. 'Large-scale patterns formed by active regions during the ascending phase of Cycle 21'. *Astrophys, J.*, **265**, 1056-1065.

Gray D., Livingston W.: 1997.'Monitoring the solar temperatureL spectroscopic temperature variations of the Sun.' *Astrophys. J.*, **474**, 802-809.

Harvey K.L.: 1992. 'Measurement of Solar Magnetic Fields as an Indicator of Solar Activity Evolution.' In: Donnelly R.F. (Ed.), *Proceedings of the Workshop on the Solar Electromagnetic Radiation Study for Solar Cycle 22*, NOAA/ERL/SEL, Boulder, Colorado, 113-129.

Harvey K.L.: 1994. 'Irradiance models based upon solar magnetic fields.' In: Pap J.M., Hudson H.S., Solanki S.K. (Eds), *The Sun as a Variable Star: Solar and Stellar Irradiance Variations*, Cambridge University Press, 217-225.

Hoyt D.V., Schatten K.H.: 1995*a*, 'Overlooked sunspot observations by Helvelius in the early Maunder Minimum, 1653-1684', *Solar Physics*, **160**, 371-378.

Hoyt D.V., Schatten K.H.: 1995*b*, 'Observations of sunspots by Flamsteed during the Maunder Minimum', *Solar Physics*, **160**, 379-385.

Hoyt D.V., Schatten K.H.: 1996, 'How well was the Maunder Minimum observed?', *Solar Physics*, **165**, 181-192.

Hoyt D.V., Schatten K.H.: 1998*a*, 'Group sunspot numbers: a new solar activity reconstruction', *Solar Physics*, **179**, 189-219.

Hoyt D.V., Schatten K.H.: 1998*b*, 'Group sunspot numbers: a new solar activity reconstruction', *Solar Physics*, **181**, 491-512.

Krüger A.: 1979. 'Introduction to Solar Radio Astronomy and Radio Physics.' Dordrecht Reidel Publishing Company, Dordrecht, Holland.

Kuhn J.: 1996. 'Global Changes in the Sun'. In: Roca-Cortés T. (Ed.), *The Structure of the Sun: VI Winter School at the Instituto d'Astrophysica de Canarias*, Cambridge University Press, 231-278.

Kuhn J.: 2004. 'Irradiance and Solar Cycle Variability: Clues in Phase Properties.' *Advances in Space Research*, **34**, 302-307.

Kundu M.R.: 1965. 'Solar Radio Astronomy', John Wiley, Publishers.

Lean J.L., Cook J., Marquette W., Johanneson A.: 1998. 'Magnetic sources of the solar irradiance cycle.' *Astrophys. J.*, **492**, 390-401.

Lean J.: 2000. 'Evolution of the Sun's spectral irradiance since the Maunder Minimum.' *Geophysical Research Letters*, **27**, No. 16, 2425-2428.

Pap J.M., Fröhlich C.: 1999. 'Total solar irradiance variations.' *Journal of Atmospheric and Solar-Terrestrial Physics*, **61**, 15-24.

Parker E.N.: 1994. 'Theoretical interpretation of magnetic activity'. In: Pap J.M., Hudson H.S., Solanki S.K. (Eds), *The Sun as a Variable Star: Solar and Stellar Irradiance Variations*, Cambridge University Press, 264-269.

Ribes E., Mein P., Mangeney A.: 1985. 'A large-scale meridional circulation in the convective zone'. *Nature*, **318**, 170-171.

Sofia S.: 2004. 'Variations of Total Solar Irradiance Produced by Structural Changes in the Solar Interior'. *EOS. Trans. AGU.*, **22**, 217.

Sofia S., Li L.: 2004. 'Solar Variability Caused by Structural Changes in the Convection Zone.' In *Solar Variability and its Effects on Climate. Geophys. Monogr. Ser.***141**

Solanki S.K., Unruh Y.C.: 1998. 'A model for the wavelength dependence of solar irradiance variations. ' *Astron. Astrophys.* **329**, 747-753.

Solanki S.K., Schüssler M., Fligge M.: 2000, 'Evolution of the Sun's large-scale magnetic field since the Maunder Minimum.', *Nature*, **408**, 445-447.

Solanki S.K., Schüssler M., Fligge M.: 2002, 'Secular variation of the Sun's magnetic flux.', *Astron. Astrophys.*, **383**, 706-712.

Spruit H.: 2000. 'Theory of Solar Irradiance Variations', *Space Science Reviews*, **94**, 113-126.

Tapping K.F.: 1987. 'Recent solar radio astronomy at centimeter wavelengths: the temporal variability of the 10.7-cm flux.' *J. Geophys. Res.*, **92**, No. D1, 829-838.

Tapping K.F., Harvey K.L.: 1994. 'Slowly-varying microwave emissions from the solar corona'. In: Pap J.M., Hudson H.S., Solanki S.K. (Eds), *The Sun as a Variable Star: Solar and Stellar Irradiance Variations*, Cambridge University Press, 182-195.

Tapping K.F., Zwann C.: 2002. 'Sources of the slowly-varying component of solar microwave emission and their relationship with their host active regions.' *Solar Physics*, **199**, 317-344.

Tapping K.F., Cameron H.T., Willis A.G.: 2003. 'S-component sources at 21 cm wavelength in the rising phase of Cycle 23.', *Solar Physics*, **215**, 357-383.

Ulrich R., Bertello L.: 1995. 'Solar cycle dependence of the Sun's photospheric radius in the neutral iron spectral line of 525.5 nm', *Nature*, **377**, 214-215.

Willson R.C., Hudson H.S.: 1991. 'The Sun's luminosity over a complete solar cycle.', *Nature*, **351**, 42-44.

Woodard M.F.: 1987. 'Frequencies of low-degree solar acoustic oscillations and the phase of the solar cycle', *Solar Physics*, **114**, 114-128.

Zwaan C., Harvey K.L.: 1994. 'Patterns in the Solar Magnetic Field', In: Schüssler M., Schmidt W. (Eds), *Solar Magnetic Fields*, Cambridge University Press, 27-48.