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Evolution of the Sun's Spectral Irradiance Since the Maunder Minimum

Judith Lean

E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, DC

Abstract. Because of the dependence of the Sun's irradiance on solar activity, reductions from contemporary levels are expected during the seventeenth century Maunder Minimum. New reconstructions of spectral irradiance are developed since 1600 with absolute scales traceable to space-based observations. The long-term variations track the envelope of group sunspot numbers and have amplitudes consistent with the range of Ca II brightness in Sun-like stars. Estimated increases since 1675 are 0.7%, 0.2% and 0.07% in broad ultraviolet, visible/near infrared and infrared spectral bands, with a total irradiance increase of 0.2%.

Introduction

Variations in the irradiance of the Sun during past centuries may influence Earth's climate in ways that amplify or mitigate anthropogenic impacts. Direct measurements provide unambiguous evidence for wavelength-dependent variability of the Sun's spectrum [*Lean et al.*, 1997, *Fröhlich and Lean*, 1998]. Solar activity modulates irradiance because it produces dark sunspots and bright faculae that respectively deplete and enhance solar radiation locally. Spectral irradiance variability, like that of total irradiance, is the net of competing influences from all such features present on the solar disk [*Lean et al.*, 1998] and is an order of magnitude larger at shorter ultraviolet (UV) wavelengths than in the visible (VIS) and near infrared (IR) spectral regions.

Levels of total and spectral irradiance track solar activity during the 11-year cycle, but variability amplitudes and mechanisms on longer time scales are uncertain. Geomagnetic activity [*Lockwood and Stamper*, 1999] and δ^{10}Be cosmogenic isotopes in ice-cores [*Bard et al.*, 1997] exhibit long-term increases in past centuries that exceed the amplitudes of their decadal cycles. Since the Sun is a source of variability in these terrestrial indices, their trends suggest that long-term irradiance fluctuations may likewise exceed those of recent cycles. Consistent with this, the range of Ca II flux (a proxy for facular brightening) in Sun-like stars exceeds that of the contemporary Sun, with non-cycling stars exhibiting lower overall fluxes [*Baliunas and Jastrow*, 1990].

Historical reconstructions of total solar irradiance predict increases of 0.05% to 0.5% since the Maunder Minimum, depending on assumptions about the background irradiance changes on which 11-year cycles are superimposed [*Hoyt and Schatten*, 1993; *Lean et al.*, 1995]. In response to a 0.25% irradiance increase, Earth's surface temperate is estimated to increase ~0.45°C [*Rind et al.*, 1999]. However, this estimate does not account for the spectrum of the solar forcing, which may affect tropospheric feedback processes of water vapor, cloud cover and sea-ice, and stratospheric processes involving ozone in different ways. To facilitate more realistic simulations of solar-forced climate change on multi-decadal and centennial time scales, historical reconstructions of the solar spectral irradiance are developed at wavelengths from 0.1 to 100 μm, at 0.001 μm intervals, annually since 1600 and daily since 1882, and described here. The reconstructions use contemporary observations to relate solar irradiance and solar activity, and proxies of solar activity to extend these relationships historically.

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Contemporary Irradiance Variability

In a composite record constructed from multiple, cross-calibrated measurements corrected for instrumental drifts, total irradiance increased from 1365.6 Wm^{-2} at solar minimum (Sept. 1986) to 1366.8 Wm^{-2} at solar maximum (Nov. 1989). A model that combines the influences of sunspot darkening and facular brightening replicates the observed changes, explaining more than 80% of the variance [*Fröhlich and Lean*, 1998].

Wavelength dependent solar spectrum changes accompany total irradiance variability. Whereas the irradiance itself, shown in Figure 1, reaches peak levels at visible wavelengths, its variability is larger at shorter wavelengths. Direct measurements made by the Solar Steller Irradiance Comparison Experiment (SOLSTICE) on the Upper Atmosphere Research Satellite (UARS), and models derived from the data, provide relatively firm estimates of solar cycle UV spectral irradiance variability [*Lean et al.*, 1997]. Since requisite long-term observations are lacking at longer wavelengths, estimates of solar cycle visible and IR variations rely on solar models that predict spectral characteristics of sunspots and faculae such as the contrasts in Figure 1 [*Solanki and Unruh*, 1998]. At 0.2 μm, sunspots are a factor of two darker than they are at 0.5 μm while faculae are two orders of magnitude brighter. As a result, faculae dominate spectral irradiance variations at UV wavelengths, compete with sunspots at visible and near/IR wavelengths, and have least impact near 1.6 μm, where their contrasts are lowest.

Solar cycle spectrum changes derived from measurements and models, and shown in Figure 2, are 14% near 0.15 μm, 8.3% near 0.2 μm, 0.85% near 0.3 μm, 0.12% near 0.5 μm, -0.02% at 1.6 μm and 0.4% near 100 μm. Broad spectral bands from 0.12-0.4 μm, 0.4-1 μm and 1-100 μm are estimated to increase 0.425 Wm^{-2} (0.39%), 0.663 Wm^{-2} (0.08%) and 0.102 Wm^{-2} (0.03%) during the solar cycle, contributing respectively 36%, 56% and 8% to a total irradiance change of 1.2 Wm^{-2}.

Historical Irradiance Reconstructions

The approach for reconstructing long-term solar spectral irradiance is to use historical estimates of facular brightening, $P_F^{prox}(t)$, and sunspot darkening, $P_S(t)$, shown in Figure

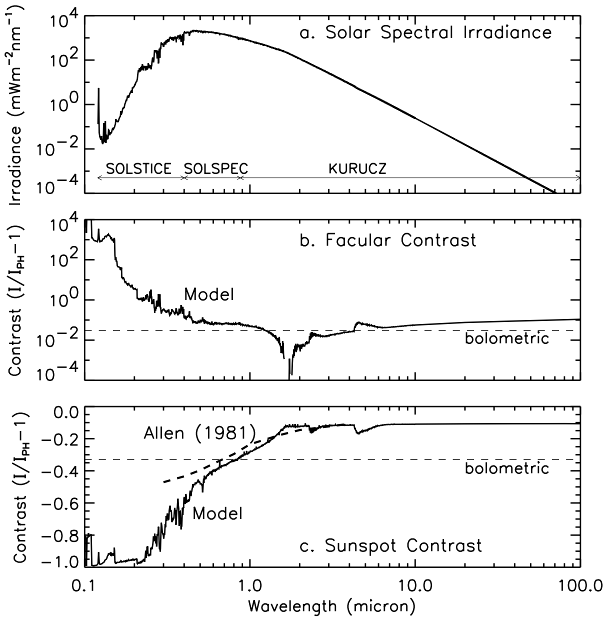

Figure 1. Shown in a) is the Sun's spectrum and in b) and c) are ratios of emission, I, in bright faculae and dark sunspots to the background 'quiet' solar photosphere, I_{ph}, expressed as residual contrasts. The dashed lines are bolometric residual contrasts.

3, to extend in time wavelength-dependent parameterizations of spectral irradiance variability derived from contemporary measurements and models.

Bolometric $P_S(t)$ are calculated from direct observations of sunspot areas and heliocentric locations [*Lean et al.*, 1998], with areas prior to 1976 reduced by 20% to account for systematic differences between Greenwhich and Air Force SOON measurements [*Fligge and Solanki*, 1997]. The facular proxy, $P_F^{prox}(t)$ is constructed by superimposing 11-year activity cycles on a longer-term component. Cycles since 1976 are based on ratios of core-to-wing emissions in the Mg II and Ca II Fraunhofer lines, cross-calibrated and compiled in a composite time series. Cycles from 1950 to 1976 are estimated from linear combinations of daily Ca plage indices and 100-day mean 10.7 cm radio fluxes, and prior to that from daily and mean sunspot group numbers [*Hoyt et al.*, 1994]. The long-term component is a 15-year running mean of annual sunspot group numbers in which the reduction from the quiet Sun to the Maunder Minimum is 92% of the increase from the quiet Sun to cycle maximum. These changes mimic the reduced Ca II fluxes in non-cycling Sun-like stars (for which the mean S index is 0.146) compared with the range of fluxes in cycling Sun-like stars (for which the present Sun is estimated to vary from a quiet value of 0.168 to a cycle maximum value of 0.192) [*Radick et al.*, 1998; *Lean et al.*, 2000].

The spectral irradiance $F(\lambda, t)$ at wavelength λ and time t is determined for $\lambda<0.4$ μm by associating irradiance changes observed by SOLSTICE relative to a reference spectrum, $F(\lambda)^{ref}$, with corresponding changes in facular brightening and sunspot darkening. Thus,

$$\frac{F(\lambda,t)}{F(\lambda)^{ref}}-1=a(\lambda)+b(\lambda)(\frac{P_F(t)}{P_F^{ref}}-1)+c(\lambda)(\frac{P_S(t)}{P_S^{ref}}-1) \quad (1)$$

where $a(\lambda)$, $b(\lambda)$ and $c(\lambda)$ are coefficients determined from multiple regression. To avoid possible instrumental effects, the relative changes are confined to rotational modulation [*Lean et al.*, 1997] and are thus lower limits of solar cycle variability.

The spectral irradiance at $\lambda\geq 0.4$ μm is

$$F(\lambda,t)=F(\lambda)_{quiet}+\Delta F_F(\lambda,t)+\Delta F_S(\lambda,t) \quad (2)$$

where $F(\lambda)_{quiet}$ refers to the contemporary 'quiet' Sun, defined by the absence of sunspots and faculae, and $\Delta F_F(\lambda,t)$ and $\Delta F_S(\lambda,t)$ are irradiance increments caused by their presence. Adopted for $F(\lambda)_{quiet}$ is the composite spectrum in Figure 1, compiled from space-based observations made by SOLSTICE (0.12-0.401 μm) and SOLSPEC (0.401-0.874 μm) [*Thuillier et al.*, 1998], and a theoretical spectrum at longer wavelengths [*Kurucz*, 1991]. The agreement among these three spectra in their regions of overlap is better than 2%, well within their absolute measurements uncertainties [*Thuillier et al.*, 1998]. The initially compiled spectrum was multiplied by 0.99 to make its integral equal the measured total irradiance of the quiet Sun (1365.5 Wm^{-2}).

Sunspots cause spectral irradiance to change by

$$\Delta F_S(\lambda,t)=\alpha_S F(\lambda)_{quiet}\frac{C_S(\lambda)-1}{C_S^{bol}-1}P_S(t) \quad (3)$$

where $C_S(\lambda)-1$ are the contrasts in Figure 1, $C_S^{bol}=0.68$, and $P_S(t)$ are 10^{-6} of the values in Figure 3. The constant $\alpha_S=0.99$ ensures that $\int(\Delta F_S(\lambda,t_{cmax})-\Delta F_S(\lambda,t_{cmin}))d\lambda = -1.1\ Wm^{-2}$, which is the bolometric solar cycle change determined independently from modeling total solar irradiance [*Fröhlich and Lean*, 1998].

For lack of reliable data on facular areas, center-to-limb functions and contrasts, the spectral irradiance change due to faculae is derived linearly from the facular proxy $P_F^{prox}(t)$ in Figure 3 as

$$\Delta F_F(\lambda,t)=\alpha_F B(\lambda)(P_F^{prox}(t)-P_F^{prox}(t_{quiet})) \quad (4)$$

The function $B(\lambda)$, whose shape approximates that of $(C_F(\lambda)-1)F(\lambda)_{quiet}$, is determined as the change in spectral irradiance adjusted for sunspot darkening, $F^{adj}(\lambda,t)=F(\lambda,t)-$

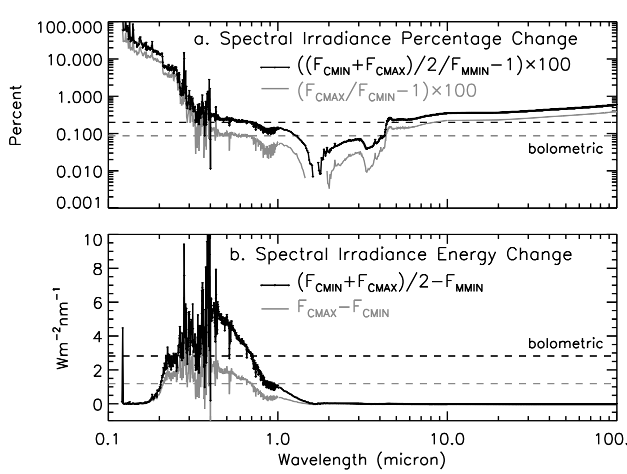

Figure 2. Shown are estimated changes in spectral irradiance from solar cycle minimum (CMIN) to maximum (CMAX), and from the Maunder Minimum (MMIN) to the mean of the solar cycle, expressed as percentage changes in a) and as energy changes in b).

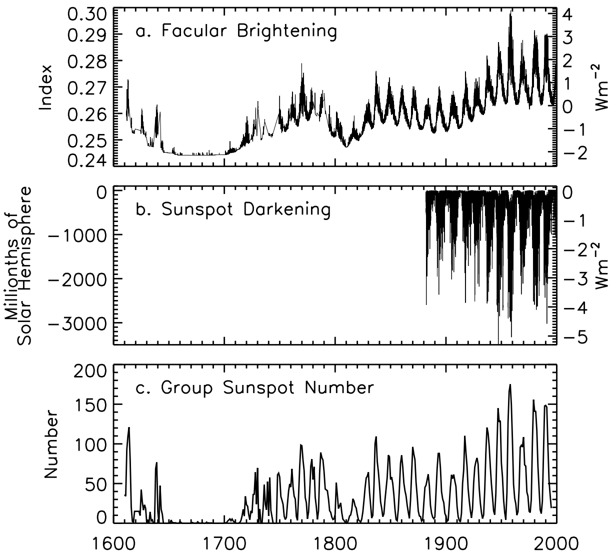

Figure 3. Variations since 1600 are shown for a) an index of facular brightening in units of the Mg II core-to-wing ratio and b) sunspot darkening functions. The right hand axes indicate their contributions to total solar irradiance variability, derived from modeling contemporary data. Shown in c) are annual means of the group sunspot number.

$\Delta F_S(\lambda, t)$, per unit change in facular proxy. Thus,

$$B(\lambda) = \frac{F^{adj}(\lambda, t_{cmax}) - F^{adj}(\lambda, t_{cmin})}{P_F^{prox}(t_{cmax}) - P_F^{prox}(t_{cmin})} \quad (5)$$

where $F(\lambda, t_{cmax}) = F(\lambda)_{quiet}(V(\lambda)+1)$ for solar cycle variability $V(\lambda)$ in Figure 2, and $F(\lambda, t_{cmin}) \sim F(\lambda)_{quiet} \times 1.0001$. The constant α_F=0.99 ensures that $\int(\Delta F_F(\lambda, t_{cmax}) - \Delta F_F(\lambda, t_{cmin}))d\lambda$=2.27 Wm^{-2}, which is the bolometric facular increase during the solar cycle determined directly from modeling total solar irradiance.

The increases in spectral irradiance shown in Figure 2 from the Maunder Minimum to the present are calculated using Equations 1 and 2 and the P_F^{prox} and P_S values in Figure 3. Estimated changes are 24% at 0.15 μm, 13.5% at 0.2 μm, 1.4% at 0.3 μm, 0.3% at 0.5 μm, 0.005% at 1.6 μm and 0.6% near 100 μm. Broad spectral bands at 0.12-0.4 μm, 0.4-1 μm and 1-100 μm, whose annual values since 1600 are shown in Figure 4, are estimated to increase 0.8 Wm^{-2} (0.7%), 1.7 Wm^{-2} (0.2%) and 0.3 Wm^{-2} (0.07%), contributing an increase of 2.8 Wm^{-2} (0.2%) in total solar irradiance. Prior to the availability of daily $P_S(t)$ since 1882, the activity cycles are reconstructed from annual mean group sunspot numbers by using linear relationships between group sunspot numbers and annual mean irradiances calculated in subsequent cycles.

Discussion

Since direct irradiance observations exist for only two decades and in limited spectral regions, estimating historical solar spectral irradiance involves speculations and assumptions. Most secure are the assumptions, based on analyses of contemporary solar activity cycles, that faculae and sunspots are dominant causes of spectral irradiance changes and that solar atmosphere models provide realistic representations of their wavelength dependent characteristics. Least secure are assumptions about the nature of long-term irradiance variability, if it exists, and the applicability of Sun-like stars for estimating its amplitude. Thus, the reconstructions of the 11-year spectral irradiance cycles are relatively robust whereas the multi-decadal to centennial changes on which the cycles are superimposed are far more speculative. Significant effects not yet detected in the extant observations and absent from the modeled variations may substantially affect the reconstructions. An example is the potential influence on irradiance of speculated changes in solar diameter.

The spectral irradiance reconstructions utilize a proxy of facular brightening in which long-term variations exceed recent activity cycles. This assumption is consistent with the range of Ca II emission (which is enhanced in solar regions associated with faculae) in Sun-like stars. Further assumed is that lower flux levels in those stars which lack activity cycles typify the Maunder Minimum Sun, whereas the higher flux levels in cycling stars typify the contemporary Sun. Were the present-day Sun to represent a larger portion of the Ca II flux distribution of Sun-like stars, the flux decrease from cycle minimum to the Maunder Minimum would be reduced compared with that used for these reconstructions, and the simulated spectral irradiance variations would be smaller. Placing the Sun in the context of Sun-like stars is a challenging task [*Radick et al.*, 1998]. Whereas solar observations are constrained to view the heliographic equator, other stars may be sampled in arbitrary orientations that alter the modulation of their flux levels by

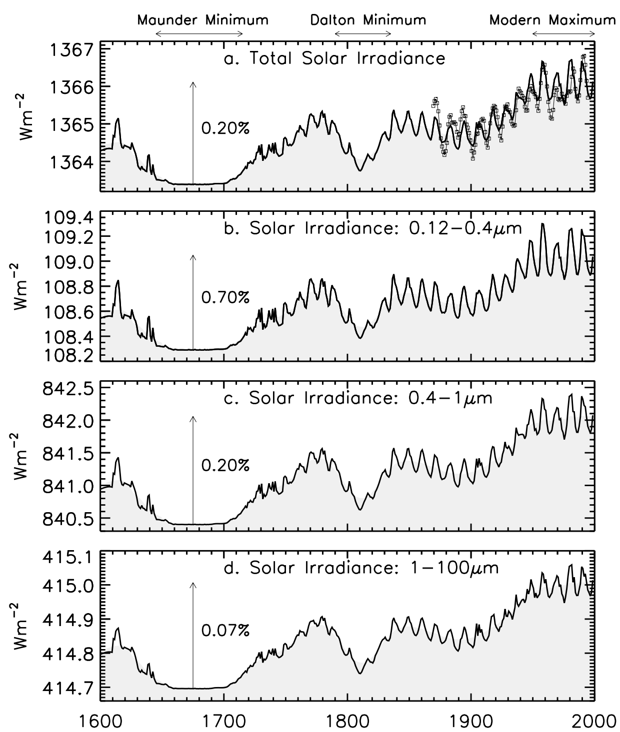

Figure 4. Compared are reconstructions of annual total irradiance in a) with spectral irradiance in broad bands from b) 0.12-0.4 μm, c) 0.4-1 μm and d) 1-100 μm. The summed bands in b), c) and d) equal the total irradiance variations in a). The shading identifies 11-year running means and the arrows show percentage increases from 1675 to the mean of cycle 22 (1986-1996). The symbols in a) are estimates of total irradiance (scaled by 0.999) determined independently by *Lockwood and Stamper* [1999].

sunspots and faculae (whose occurrences and radiances are latitudinally dependent) [*Schatten*, 1993].

The amplitude of the total irradiance increase since the Maunder Minimum derived from the spectral irradiance reconstructions (and independently from modeling direct observations) is at the low end of previous estimates, which range from 0.2% to 0.5%, but exceeds the variability due to the amplitude evolution of the 11-year cycle alone (0.05%). The total irradiance increase of 2.8 $\mathrm{Wm^{-2}}$ differs slightly from a previous estimate of 3.3 $\mathrm{Wm^{-2}}$ (0.24%) [*Lean et al.*, 1995] because of revision of the relationship between solar and stellar Ca II fluxes using a larger database of lunar S observations. Subsequent lunar data may cause further revision of the adopted solar-stellar relationship, and alter the adopted long-term P_F^{prox} amplitudes.

Despite these significant caveats, the reconstructed total irradiance during the present century (11-year means from 1900 to 1995, shown by the shading in Figure 4) agrees well with an alternative, independent estimate based on extrapolated interplanetary magnetic field observations (and the aa proxy for these) to the solar sources of its variability [*Lockwood and Stamper*, 1999]. Since 1950, solar cycle minima in the spectral irradiance reconstructions do not have a significant upward trend, which is consistent with the record of solar radio fluxes at 10.7 cm. Since the 10.7 cm radio flux varies in response to the presence of both faculae and sunspots on the solar disk it may be expected to reflect, at some level, a long-term facular component. This suggests that overall solar activity has leveled off during the Modern Maximum, following its increase during the first half of the twentieth century. Contrary to the behavior in both these reconstructions and the 10.7 cm flux, solar irradiance reconstructions that are based on the length, rather than amplitude, of the solar cycle [*Hoyt and Schatten*, 1993] do predict a significant upward trend (in excess of 1 $\mathrm{Wm^{-2}}$) in their background component in recent decades. This raises questions about the suitability of solar cycle length parameterizations for climate attribution studies, a number of which have inferred that surface warming in the first part of the 20th century is attributable to the Sun because of the shape of the solar cycle length index over this period. The reconstructions in Figure 4 do show increases in the first part of the twentieth century, but they lag cycle length reconstructions by about 20 years.

Ultimate validation of the calculated spectral irradiance changes, both historically and during the solar cycle, awaits a new generation of observations. These are planned to be made by the University of Colorado's Solar Radiation and Climate Experiment (SORCE) commencing in 2002, as part of the EOS program, and subsequently by the National Polar-orbiting Operational Environmental Satellite System (NPOESS). Uninterrupted, long-term monitoring of solar spectral irradiance with high precision and stability is crucial for advancing investigations of climate and ozone response to solar forcing.

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J. Lean, Code 7673L, Naval Research Laboratory, Washington, DC 20375 (e-mail: lean@demeter.nrl.navy.mil)

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