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Implications of Ground Based Photometric Images for Long Term Solar Irradiance Variations

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Data Description

- Cartesian Full Disk Telescope (CFDT) images from San Fernando Observatory (SFO), 1988–2004
  - $512 \times 512$ and $512 \times 512$ pixel images, 5″ square pixels
  - Ca II K filtergrams with 393.4 nm center, 1 nm bandpass; red filtergrams with 672.3 nm center, 10 nm bandpass
  - Analysis of these images previously reported in detail (see http://www.csun.edu/sfo/publications.html)
- Photometric Solar Patrol Telescope (PSPT) from 1998–2004
  - $2048 \times 2048$ pixel images, 1″ square pixels
  - Ca II K filtergrams with 607.095 nm center, 0.273 nm bandpass; red filtergrams with 607.095 nm center, 0.458 nm bandpass
Data Analysis 1

- San Fernando Observatory (SFO) algorithms applied to PSPT images to:
  - Fit an elliptical limb to the images
  - Divide each image by a mean quiet sun (QS) limb darkening (LD) curve
  - Pixel contrast defined as fractional change in brightness of pixel with respect to QS LD at that disk location

- Relative solar irradiance change in filter passband of all images computed by summing all image contrasts times the quiet sun limb darkening curve, suitably normalized:

\[
\Sigma = \sum_{\text{entire image}} C_i \phi(\mu_i)
\]

where \( C_i \) is the contrast of the \( i \)'th image pixel, \( \phi(\mu) \) is a suitably normalized limb darkening curve. We denote red and Ca II K \( \Sigma \) with a subscript \( r \) and \( K \), respectively. \( \Sigma \) computed from CFDT and PSPT are denoted with superscript \( C \) and \( P \), respectively.

- A fit to TSI $S$ of the form
  
  $$S(t) = S_0 + a \Sigma^C_r(t) + b \Sigma^C_K(t)$$

  ($S_0$, $a$, $b$ are the fit parameters) is a good model for $S$ during solar cycle 22 (1988 through 1996).

- The variation on solar cycle timescales is captured by $\Sigma^C_K$; $\Sigma^C_r$ is flat during the solar cycle.

- This implies that changes in the depths of spectral lines, not changes in the continuum, dominate solar cycle timescale changes in $S$. 
Data Analysis 2

Work from Paper I extended into cycle 23, and verified using PSPT data.

Fits to $S$ made using:

1. $\sum_r^C$ and $\sum_k^C$ from 1988 through 2004

2. $\sum_r^C$ and $\sum_k^C$ for solar cycle 22 alone (1988 through 1996-1-1)

3. $\sum_r^C$ and $\sum_k^C$ for solar cycle 23 alone (1996-1-1 through 2004-9-13)

4. $\sum_r^P$ and $\sum_k^P$ for 1998 through 2004-9-13

Dual purposes: to check consistency of models between cycles and compare results from CFDT and PSPT

The figures show these fits.
TSI Fit Using PSPT $\Sigma_r$ and $\Sigma_K$

Date

TSI (W/m$^2$)

TSI Fit Residual+1362
Simple Extrapolation to Zero Activity

Calendar year 1996 is taken as year of minimal solar activity for the purposes of computation. The mean TSI for this calendar year is

$$\bar{S}(1996) = 1365.403 \pm 0.008 \text{ W/m}^2$$

(all quoted errors on this page are standard deviations in the mean). The median $S_{med}(1996)$ is 1365.417 W/m$^2$.

If we simply take $\Sigma_r = \Sigma_K = 0$, the predicted value of $S$ in the absence of all solar activity is the $S_0$ term in the above fits. This value is only 0.1 to 0.2 W/m$^2$ below current solar minimum levels.
Biases in Evaluation of $S$ At No Activity I

There appears to be a slight bias in our computation of $\Sigma_r$, such that $\tilde{\Sigma}_r(1996)$ is $-69.6 \pm 4.8$. Assuming this value should be zero would raise all values of $\Sigma_r$ by this amount, and thus decrease $S_0$ by $a \tilde{\Sigma}_r(1996)$. Let this be $S_0^{\text{corr}}$ for “corrected” $S_0$.

For cycle 22:

\[
S_0^{\text{corr}} = S_0 - a \tilde{\Sigma}_r(1996) \\
= 1365.309 - 1196(69.6 \times 10^{-6}) \\
= 1365.23 \text{ W/m}^2
\]

Mean $\Sigma_K$ for 1996, $\tilde{\Sigma}_K(1996)$, is $1120 \pm 27$ ppm. Thus

\[
S_{\text{NA}} = S_0^{\text{corr}} - b \tilde{\Sigma}_K(1996) \\
= 1365.23 - 198.8(1120 \times 10^{-6}) \\
= 1365.016 \text{ W/m}^2
\]

where $S_{\text{NA}}$ is then an estimate of $S$ in the absence of all solar activity.
Biases in Evaluation of $S$ At No Activity II

For cycle 23, using the same values of $\bar{S}$ (1996):

$$S_{0}^{\text{corr}} = 1365.324 - 1457(69.6 \times 10^{-6})$$
$$= 1365.22 \text{ W/m}^2$$

$$S_{\text{NA}} = 1365.23 - 219.6(1120 \times 10^{-6})$$
$$= 1364.97 \text{ W/m}^2$$

Thus, our extrapolations give $S_{\text{NA}} \approx 1365.0 \text{ W/m}^2$, a level about 0.03% below present cycle minimum levels.
It has been suggested (Lean et al. 1995, GRL 22, 3195) that \( S \) at the Maunder Minimum was about 0.4% below current cycle minimum levels, or \( S_{NA} \approx 1360 \text{ W/m}^2 \). Most such estimates are based on extrapolations from photometry of “sun-like” stars (Baliunas and Jastrow 1990, Nature 348, 520) which have more recently been shown to not be very similar to the Sun.

Our work and others’ shows that current TSI variations on all timescales are well represented by measurements based on solar activity (sunspots and faculae)

This work suggests that values of TSI much lower than presently observed at solar minium would require an additional source of solar irradiance variation. No such mechanism is known.
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