Solar Variability 101

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What we knew about TSI variation before SMM/ACRIM

**Fig. 1.**—Autocorrelation function of APO daily solar flux measurements (residuals) for 1923–1952. The abscissa is time shift in days, the ordinate is the relative value of the autocorrelation function normalized to a value of 10. The first and second significant recurrence peaks are indicated at 30 days and 54 days.

**Fig. 2.**—Cross-correlation function of APO daily solar flux measurements (residuals) and facular projected areas (residuals) for 1923–1952. The abscissa is time shift in days, the ordinate is the relative cross-correlation value normalized to unity. The approximate recurrence period of faculae at intermediate latitudes is marked as ± 28, ± 56 days.

**Fig. 3.**—Cross-correlation function of APO daily solar flux measurements (residuals) and sunspot projected areas (residuals) for 1923–1952. The abscissa is time shift in days, the ordinate is the relative cross-correlation value normalized to unity.
Two Faces of the Sun: Activity and Also...Inertia
“Climate - Effective” Solar Variability

- Total Solar Irradiance (TSI)- i.e. solar luminosity
- Ultraviolet Irradiance (ozone – effective wavelength range: ~ 130- 240 nm)
- Fluxes of Plasmas and Magnetic Fields
Total Solar Irradiance (TSI) Variation ….. and What Causes It

- Sun brightens < 0.1% at spot maxima
- 27- day variation (solar rotation) < 0.3%
- Dark sunspots decrease TSI
- Bright faculae increase TSI
- Other influences on TSI?
Broad Band Imaging of Spot, Facular Contributions to TSI Variation

Solar Bolometric Imager (SBI) *images* the solar photosphere with the same spectrally flat (~ 200 – 3000 nm) response, as *non-imaging* radiometers, like ACRIM or TIM.
Why do spots cause TSI variation?

**Observations:** radiometry and photometry of spot-induced TSI dips match, so blocked heat is *not re-radiated*, must be stored over time > spot lifetime.

**Calculation:** The blocked heat is stored as a tiny increase of the Sun’s internal and potential energy.
Why is a sunspot dark?

Because its strong vertical magnetic field obstructs convection of heat to the photosphere - it is a "thermal plug."

The blocked heat is redistributed and stored efficiently in the solar interior.
Why are Faculae Bright?

Because the vertical magnetic field reduces density, making a cavity that facilitates radiation from its brighter walls into space – it is a thermal “short circuit”.
Measured and Reconstructed TSI Variation 1980-present

PMOD radiometry (red) and TSI(F10.7)
Reconstructing the 20th century facular irradiance contribution

• ~ 20,000 archival daily Ca K spectroheliograms 1915-1984 (Mt Wilson; also 1907-present at Kodaikanal, Sacramento Peak, Arcetri...)

• Digitized, reduced by CRI, Pulkovo, UCLA, Rome...
Two independent reductions of Mt Wilson facular areas: CRI(solid) and UCLA (dashed)
TSI and Fuv to beginning of regular spot record

**TSI annual means 1700-2009**

**F_{uv} annual means 1700 - 2009**
150 yrs of TSI, Fuv, and Global Temperature
GCR modulation by heliospheric fields supplied by the solar wind and coronal mass ejections
Solar activity from radio-isotopes over the past millennium (N.B.: high activity decreases radio-isotope production)

\[ ^{10}\text{Be in ice cores from Antarctica and } ^{14}\text{C in tree-rings (all converted in } ^{14}\text{C units)} \]

\[ \Delta ^{14}\text{C atmosphère [permil]} \]

High \(^{10}\text{Be production by GCR (quiet Sun)}\)

Low \(^{10}\text{Be production by GCR (active Sun)}\)

Year A.D.

Could Extended Solar “Hyperactivity” have Occurred During the Holocene?

• Unlikely (Solanki et al., 2004)
• But that study does not consider $C14$ production by solar energetic particles (SEP’s)
• Total $C14 = \text{production by (GCR’s + SEP’s)}$. SEP’s are oppositely correlated with activity level.

![Graph showing sunspot number over years BP](image)
How Did the Solar Cycle Behave When The Sun Was 650 million yrs (15%) Younger?

Elatina varves: sedimentary deposits laid down 650 million yrs ago? (Williams, 1983).

Tracings across 11- 14 year varve cycles: 30,000 (!) yr time span.
CalTech Team Drilling Varve Cores
(photo by courtesy of T. Raub and J. Kirschvink)
Conclusions

• Jack’s two basic points - that the Maunder Minimum was real, and that it coincided with the Little Ice Age, have remained robust

• These two findings continue to drive Sun – climate studies 35 years later; to many they are still the most persuasive evidence of a causal relationship between solar activity and climate

• Sun – climate studies remain, after > two centuries, a high-risk, high-stakes field of astronomy and climate physics. Onward and upward!