Jack Eddy’s Study of the Maunder Minimum Inspires a Long Series of Satellite-Based Solar Irradiance Measurements

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Outline

• Jack Eddy’s “The Maunder Minimum”
  – 1976 Science paper

• Satellite Measurements
  – “solar constant” and total solar irradiance (TSI) measurements and variability
  – HAO solar irradiance programs

• Sun-Climate Change
  – Climate change in MM and trending now
John A “Jack” Eddy

• March 25, 1931 – June 10, 2009
• Graduated from the US Naval Academy in 1953
  – Served during Korean War
• 1957-1961: CU Astro-Geophysics department first graduate student
  – PhD thesis on solar corona was titled “The Stratospheric Solar Aureole”
• 1961-1973: his HAO years
Jack Eddy’s “The Maunder Minimum”

- Gustav Spörer’s 1887 and 1889 papers
- E. W. Maunder’s 1894 and 1922 papers: “A Prolonged Sunspot Minimum”
- Eddy’s Evidence: sunspot record, $^{14}$C tree ring data, auroral sightings, solar eclipse corona images
Jack Eddy’s “The Maunder Minimum”

- Eddy’s Evidence: sunspot record, $^{14}$C tree ring data, **auroral sightings**, solar eclipse corona images
Jack Eddy’s “The Maunder Minimum”

- Eddy’s Evidence: solar eclipse corona images were inconclusive

http://mlso.hao.ucar.edu/hao-eclipse-archive.php
Jack Eddy’s “The Maunder Minimum”

- He dismisses the concepts that the 17th century technology was inferior and that there were not many observations.

The reality of the Maunder Minimum and its implications of basic solar change may be but one more defeat in our long and losing battle to keep the sun perfect, or, if not perfect, constant, and if inconstant, regular. Why we think the sun should be any of these when other stars are not is more a question for social than for physical science.
Monthly Average Sunspot Number

https://www2.hao.ucar.edu/Education/SolarPhysicsHistoricalTimeline
Jack’s Paper Inspires New Studies of the Maunder Minimum

- Maunder Minimum interest peaks after each cycle minimum.


Solar Cycle Minima

Jack Eddy’s Paper
“The Maunder Minimum”
Jack’s Paper Inspires New Studies of the Maunder Minimum

- 1970s also mark the rise of “solar irradiance” and the fall of “solar constant”.

“solar constant” measurements from the ground

Photographs of the Sun began in the 1840s

[Yearly Averaged Sunspot Numbers 1610-2000 graph]

- Pouillet: 700 W/m²
- Langley: 2900 W/m²
- Abbot: 1320-1470 W/m²

https://www2.hao.ucar.edu/Education/SolarPhysicsHistoricalTimeline
Satellite Measurements of the TSI at 1-AU

TSI = Total Solar Irradiance (all wavelengths)

11-year solar cycle variation is about 0.1%

TSI and visible radiation have two primary components:
1) Bright faculae
2) Dark sunspots

Figure adapted from Kopp & Lean, GRL, 2011
Spectral Regions of the Solar Spectrum

\[ TSI = \int_0^\infty I(\lambda) \, d\lambda \]

Total Solar Irradiance (TSI)

Sun is G2V star
\[ T \approx 5700 \text{ K} \]

- Visible
- Near UV
- Middle UV
- Extreme UV
- Far UV
- Near IR
- Far IR

Irradiance (W m\(^{-2}\) nm\(^{-1}\))

Wavelength (nm)
Solar Variability at Different Wavelengths

- Various images of the sun from SOHO showing solar activity

- Full-disk images:
  - B/W: visible light from MDI showing sunspots
  - Red & Green: EUV images from EIT showing active regions and flares

- Off-disk images:
  - LASCO coronagraph showing streamers of particles and coronal mass ejections (CMEs)

movie from SOHO web site
figures from J. Lean
Rottman and Woods Solar Irradiance Projects

1992-1997

HAO Years

Dick White
Gary Rottman
Tom Woods
Stan Solomon
Juan Fontenla
John Worden
Giuliana de Toma
Marty Snow

Solar EUV Irradiance and FUV Airglow Rockets
2002, 2003, 2004

Solar UV Irradiance: 119-420 nm

HAO 75th Anniversary
METEOR Solar EUV Experiment (SEE)

- HAO builds satellite instrument in 3 months!
METEOR SEE Launched in 1995

• Greg Card, Greg Ucker, and Tom Woods waiting for Conestoga launch in October 1995…
Rottman and Woods Solar Irradiance Projects

Dick White  Gary Rottman  Tom Woods  Stan Solomon  Juan Fontenla  John Worden  Giuliana de Toma  Marty Snow

1992-1997 HAO Years

Solar UV Irradiance: 119-420 nm

TIMED SEE (1993) 2001-now
Solar EUV Irradiance: 0.1-190 nm

Solar Radiation and Climate Experiment (SORCE) (1989) 2003-now
Solar Irradiance: TSI, 0.1-27 nm, 115-2700 nm

HAO 75th Anniversary
Composite H I Lyman-α (121.6 nm) Record was started as HAO research project

TIMED SEE Measures Solar VUV Irradiance

TIMED spacecraft was launched on 7 December 2001, and its mission has been extended through 2017.

EGS = EUV Grating Spectrograph
Rowland-circle grating spectrograph with 64x1024 CODACON (MCP-based) detector

XPS = XUV Photometer System
Set of 12 Si photodiodes - 8 for XUV, 1 for Ly-α, and 3 for window calibrations

<table>
<thead>
<tr>
<th>XUV</th>
<th>EUV</th>
<th>FUV</th>
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</thead>
<tbody>
<tr>
<td>EGS 27-194 nm with Δλ=0.4 nm</td>
<td>XPS 0.1-34 nm with Δλ=7-10 nm and Ly-α (121.6 nm) with Δλ=2 nm</td>
<td></td>
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</tbody>
</table>
Earth Responds to X17 Flare on 28 Oct 2003

- Thermospheric temperature, neutral density, and total electron content (TEC) increase in the thermosphere due to flares

Neutral Temperature at ~450 km

TIME-GCM using TIMED SEE data

From Gang Lu (2005)
**SORCE Measures TSI and SSI**

<table>
<thead>
<tr>
<th>Instrument</th>
<th>λ Range (nm)</th>
<th>Δλ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIM: Total Irradiance Monitor</td>
<td>TSI (all)</td>
<td>-</td>
</tr>
<tr>
<td>SIM: Spectral Irradiance Monitor</td>
<td>200-2700</td>
<td>1-30</td>
</tr>
<tr>
<td>SOLSTICE: Solar Stellar Irradiance Comparison Experiment</td>
<td>115-320</td>
<td>0.1</td>
</tr>
<tr>
<td>XPS: XUV Photometer System</td>
<td>0.1-27, 121.6</td>
<td>7-10</td>
</tr>
</tbody>
</table>

SORCE spacecraft was launched on 25 January 2003, and its mission is extended through 2017.

Next Sun-Climate workshop is Nov. 10-13, 2015 in Savannah, GA

http://lasp.colorado.edu/home/sorce/
SORCE TIM Detects X17 Flare in TSI Time Series

First detection of flare in TSI record (G. Kopp, 2003)

Figures from G. Kopp
Flare Total Energy is Larger than Expected

Flare total energy is 10 times more than previous estimates (e.g. Emslie et al., JGR, 2004).

XPS 0-27 nm flare contribution to total energy is 25% - 85% (Woods et al., JGR, 2006).

Flare total energy, as observed at Earth, is highly dependent on the flare location.

Figures from Woods et al., JGR, 2006.
Modeling of the Solar Irradiance Variability

HAO models solar irradiance variability with solar images. e.g. Ca II K model by Skumanich et al., ApJ, 1984

\[ K = K_{\text{quiet}} + \Delta K_{\text{net}} + K_{\text{plage}} \]
\[ = K_{\text{quiet}} + K_{\text{cell}} \Delta f_N(C_K^N - 1) + \frac{K_{\text{cell}}(\mu = 1)}{\int_0^1 R_C(\mu)\mu d\mu} \]
\[ \times \sum_i A_i^{\text{WDC}} \mu_i R_K(\mu_i)(C_K^P w_i - 1), \]

Tom Bogdan, Dick White, Andy Skumanich
Gary Rottman, John Worden, Juan Fontenla, Mark Rast, Phil Judge, Judith Lean
Sun-Climate Studies Inspired by Jack Eddy

  - Maunder Minimum (MM): 1645-1715 with very few sunspots
  - Spörer & Maunder studies in 1890s

  - More analysis confirms MM

Figure is from Scafetta and West, *GRL*, 2006.

-0.6 K

-3.0 W/m² based on sun-like stars

-2.5 W/m² based on sun-like stars

-1.2 W/m² based on mag. fields

Global is about -0.4 K

NH is -0.6 K
Many Components for Climate Change

- Solar Variations
  +0.1 K over 11-year cycle
  Higher “I” irradiance
- Greenhouse Gas
  +0.1 K per decade (trend)
  Smaller “ε” emissivity
- El Nino (ENSO)
  ±0.3 K variations
  Modulates “ε” emissivity
- Volcanoes
  -0.4 K occasionally
  Higher “a” albedo

\[
\frac{I}{4} \cdot (1 - a) = \varepsilon \sigma T^4
\]
Regional Temperature Changes

- Global temperature change from solar variability is about 0.1 K (0.2 F)
- But **regional temperature changes** from modeling the solar input **are much larger** - *some hotter, some cooler*

Figure is from Woods and Lean, *EOS*, 2007.
Less Solar Activity Can Affect Earth’s Global Temperature

- Maunder Minimum (MM) period in late 1600s has lower solar activity
  - Did the solar irradiance floor (solar cycle minimum) change during MM?
- Estimates range from none to -4 W/m²
Lower Solar EUV Irradiance

- SOHO SEM 26-34 nm is about 10% less in 2008 than in 1996
  - Uncertainty is ~6%
  - Solomon et al. (GRL, 2010)
- Thermospheric density at 400 km is about 28% lower in 2008 than in 1996
  - Emmert et al. (GRL, 2010)
  - ~3% is from long-term CO$_2$ increase (IR cooling)
TSI 1996-2008 range is -224 to +48 ppm

- SOHO VIRGO PMOD (Fröhlich) and ACRIM (Willson) composites indicate 2008 TSI is lower than 1996 level

- SOHO VIRGO RMIB (DeWitte) and SORCE TIM model (Lean) composites indicate 2008 TSI is higher

- Uncertainty for 2008-1996 trend is about 100 ppm

Figure from Woods, ASP, 2010
Less Solar Activity Can Affect Earth’s Global Temperature

- Maunder Minimum (MM) period in late 1600s has lower solar activity
  - How much of the colder temperature (-0.4 K) during MM was driven by solar irradiance change?
- Even if cycle minimum did not change during MM, Georg Feulner’s climate model (GRL, 2011) predicts a colder period because of cycle maxima being low during MM and enhanced volcanic aerosols blocking more solar radiation
Could we have a “Maunder Minimum” soon?

- SC-24 has much lower solar activity in SC-24
- Some predictions suggest low activity for 2-3 more solar cycles
- Low solar activity is only expected to slow down global warming
Congratulations HAO
for a rich 75-year history of solar
and atmospheric studies !