

How Low is Low?

Putting Our Latest Solar
Cycle Minimum in Context
with Secular Variations

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Many Contributions: Phil Chamberlin, Julianna deToma, Leonid Didkovsky, Frank Eparvier, Juan Fontenla, Claus Fröhlich, Sarah Gibson, Jerry Harder, David Hathaway, Rachel Hock, Andrew Jones, Judith Lean, Bill McClintock, Mark Rast, Erik Richard, Leif Svalgaard, Neil Sheeley, Marty Snow, Dave Webb



A photograph of a sunrise over a body of water, with mountains visible in the background. The sun is a bright white circle in the center, surrounded by a red and orange glow. The water is dark and reflects the light. The mountains are silhouetted against the bright sky.

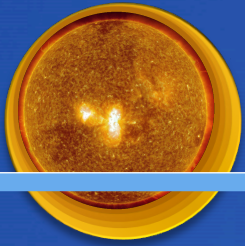
SOHO-23 Workshop, Sept. 21-25, 2009

Understanding a Peculiar Solar Minimum

SORCE Workshop, May 19-21, 2010

**Solar and Anthropogenic Impacts on Earth:
The Current Solar Minimum and Predictions for
Future Decades**

Sunrise seen from Cadillac Mountain



Key Points & Research Topics

● Key Points

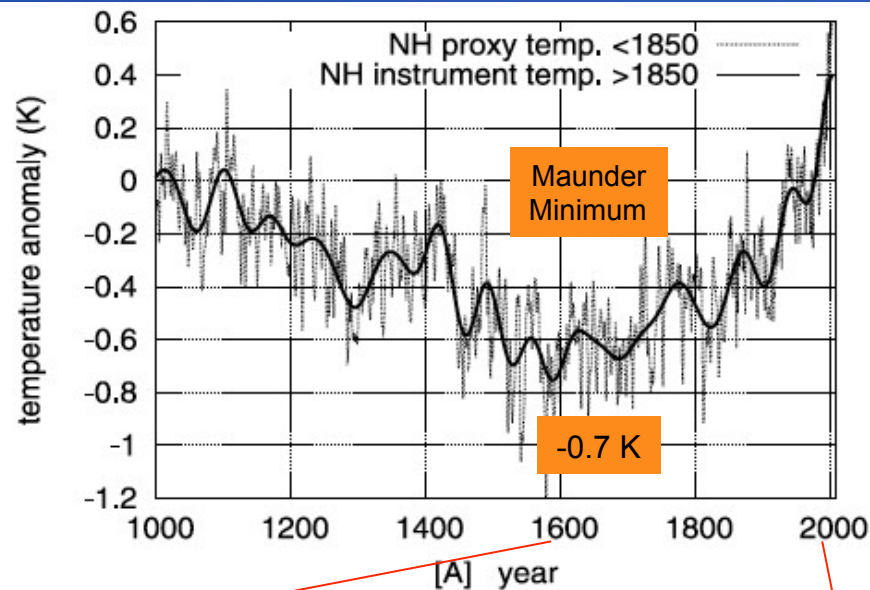
- This recent solar cycle minimum in 2007-2009 is more extended and has lower activity (irradiance, solar wind, magnetic field) than the 1996 cycle minimum.
- Furthermore, this 2007-2009 minimum appears to be similar to those in the early 1900s (named the Gleissberg Minimum ?).
- Most studies have been completed to relate how the Earth system has responded to this low minimum. One study on the thermosphere (Emmert et al., GRL, 2010) reports 28% less density at 400 km.

● Key Research Topics

- How does low solar cycle impact the Earth system in 2007-2009?
- Solar physics on how / why the solar activity is lower
 - Is the quiet sun radiance lower in 2007-2009 than in 1996?
 - Can solar dynamo theory / modeling explain this solar cycle?
- Can we extrapolate these lessons to the Maunder Minimum period?

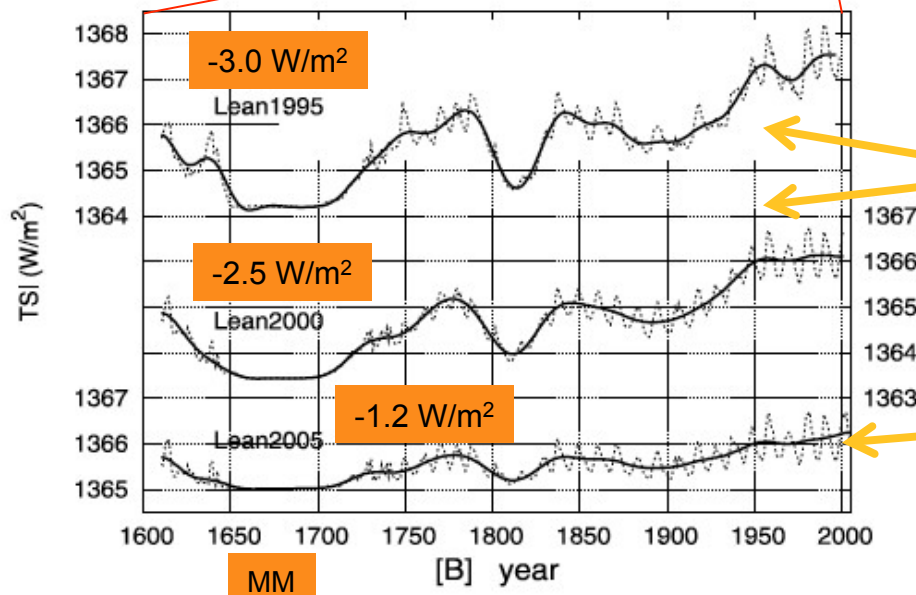
**Why do we care what the solar
cycle minimum level is?**

Solar Forcing on Long-term Climate Change



Global temperature change at Maunder Minimum is about -0.4 K. Shown is Northern Hemisphere.

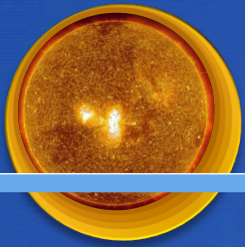
Secular (long-term) changes of solar irradiance can be estimated by trending results at the cycle minima



1970-2000 estimates for MM total solar irradiance (TSI) are mostly based on sun-like stars and are considered too high now.

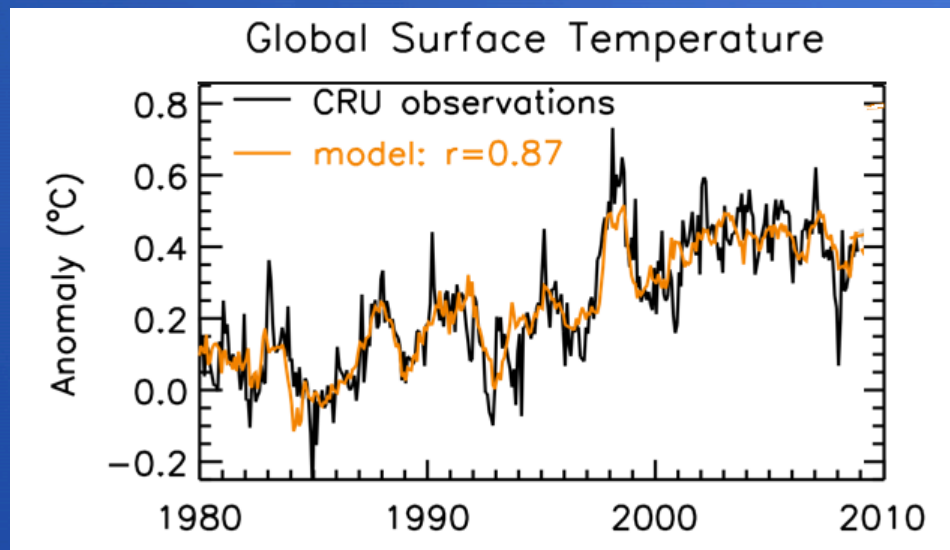
Recent MM TSI estimates are based on magnetic field changes and are about 1-2 W/m^2 (0.15-0.3 K).

[figures from Scafetta and West, *GRL*, 2006]

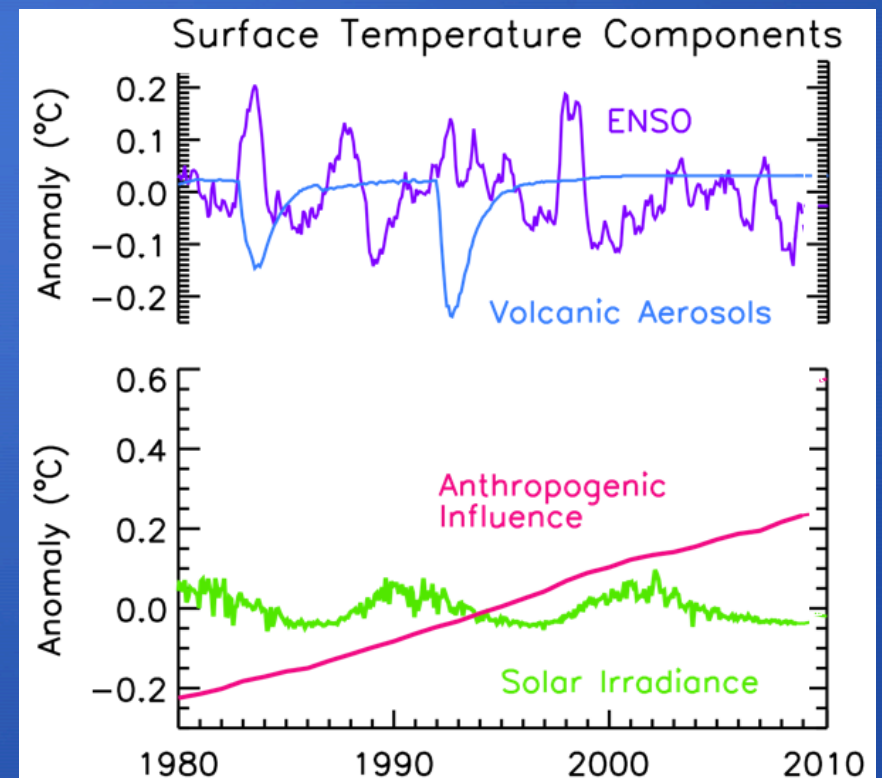


Recent “Cooling” Trend

- The total solar irradiance (TSI) is known to vary about 0.07% over the 11-year solar cycle
- Expect Earth’s global temperature to change by 0.1 K over solar cycle
- This includes positive feedbacks with factor of ~2
 - Empirical analysis, e.g. Lean & Rind, *GRL*, 2008
 - GCM models, e.g. NCAR and GISS, Shindell *et al.*, *J. Climate*, 2003

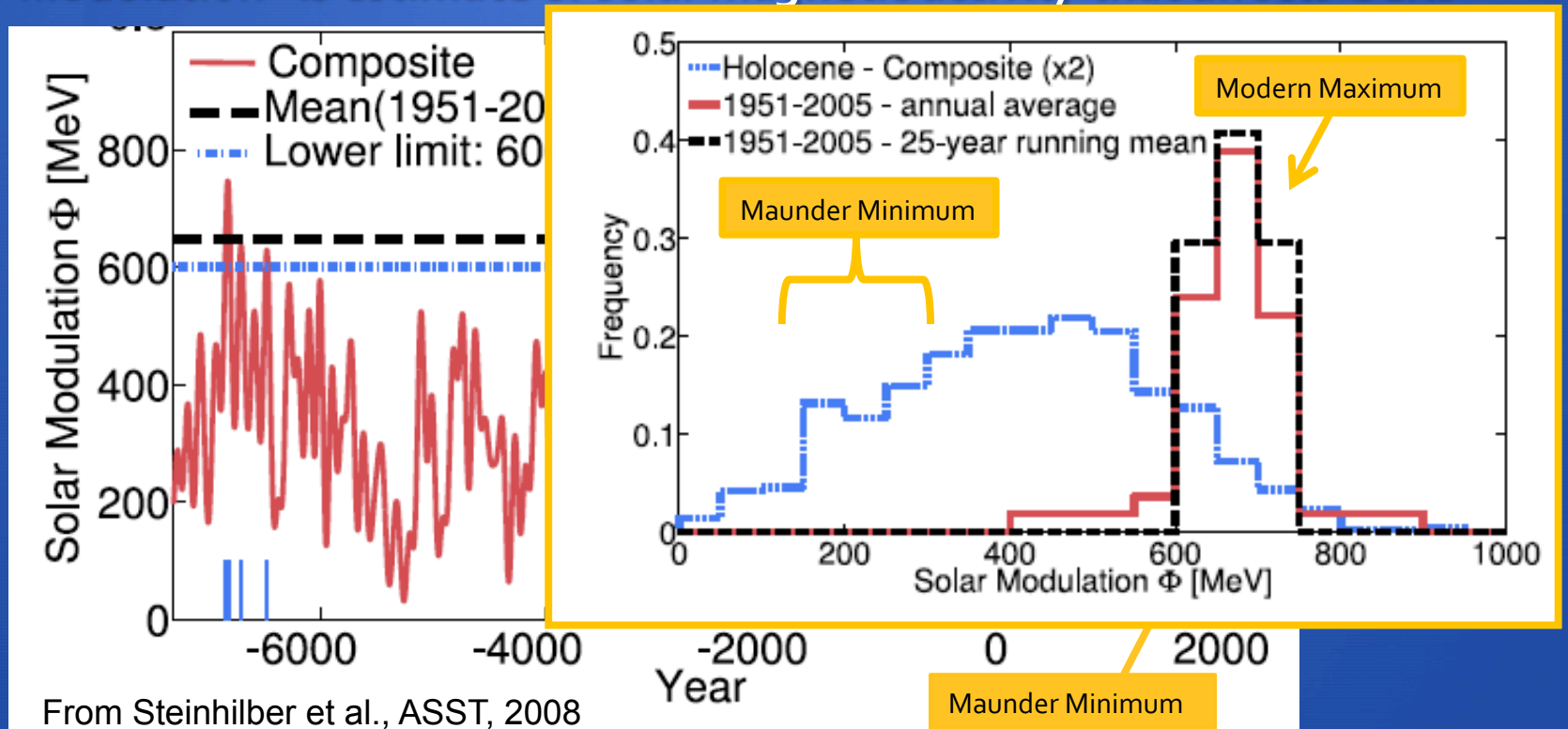


Figures from Judith Lean (Lean & Rind, *GRL*, 2008)



What does secular (long-term) trend indicate for extreme minimum?

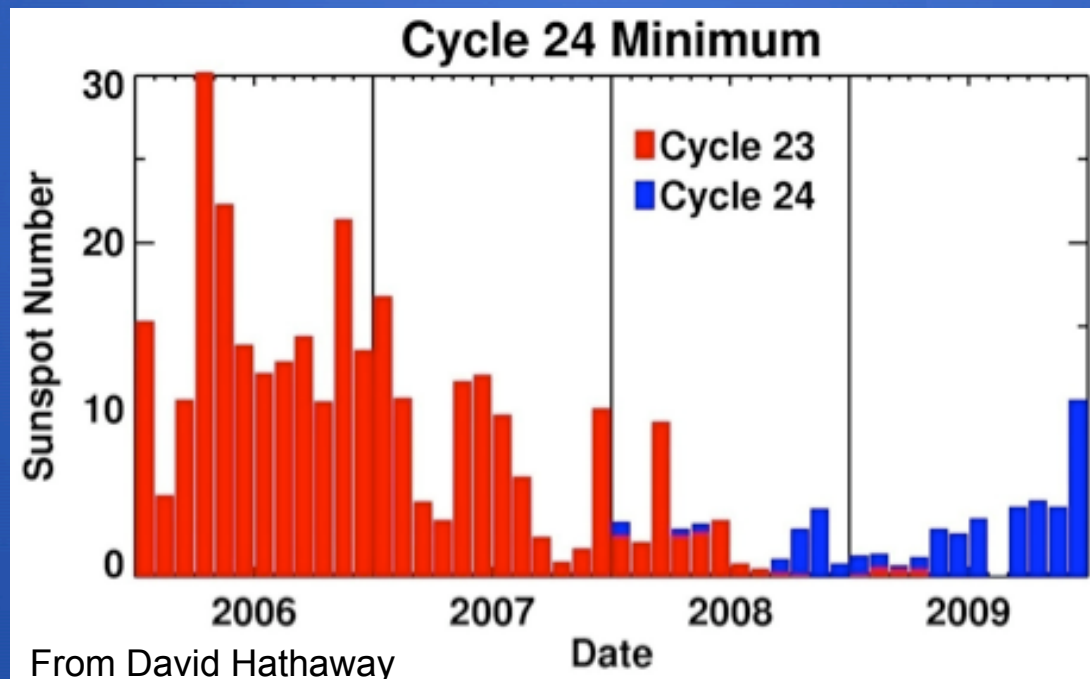
- Tree-rings ^{14}C and ice-cores ^{10}Be provide indication of solar magnetic fields affecting galactic cosmic rays (GCRs)
 - NOTE: There are more GCRs at Earth during solar minimum.
- “Solar Modulation” is estimate of solar magnetic activity that affects GCRs

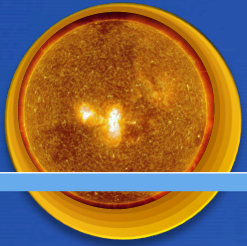


**What do we know about this
latest solar cycle minimum level?**

What is Solar Minimum?

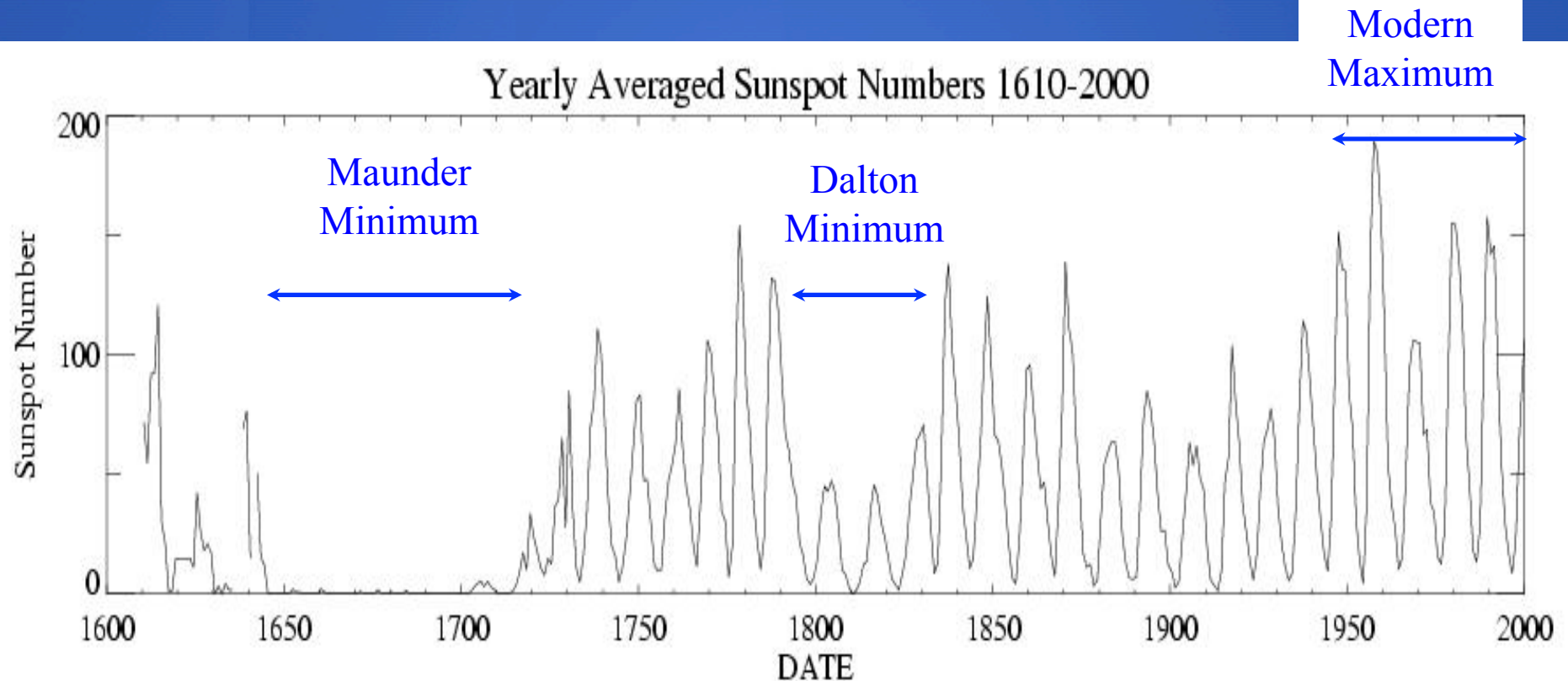
- Minimum of what?
- What time period / smoothing for minimum?
- Smoothed sunspot number minimum = Nov/Dec 2008
- Smoothed spotless days maximum = Nov/Dec 2008
- Irradiance minimum = Aug 2008
- New cycle sunspots (reversed magnetic polarity) > Old cycle sunspots = Sep 2008

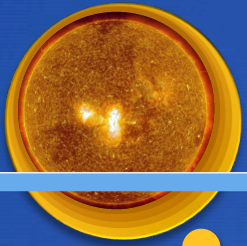




What does the sunspot record tell us?

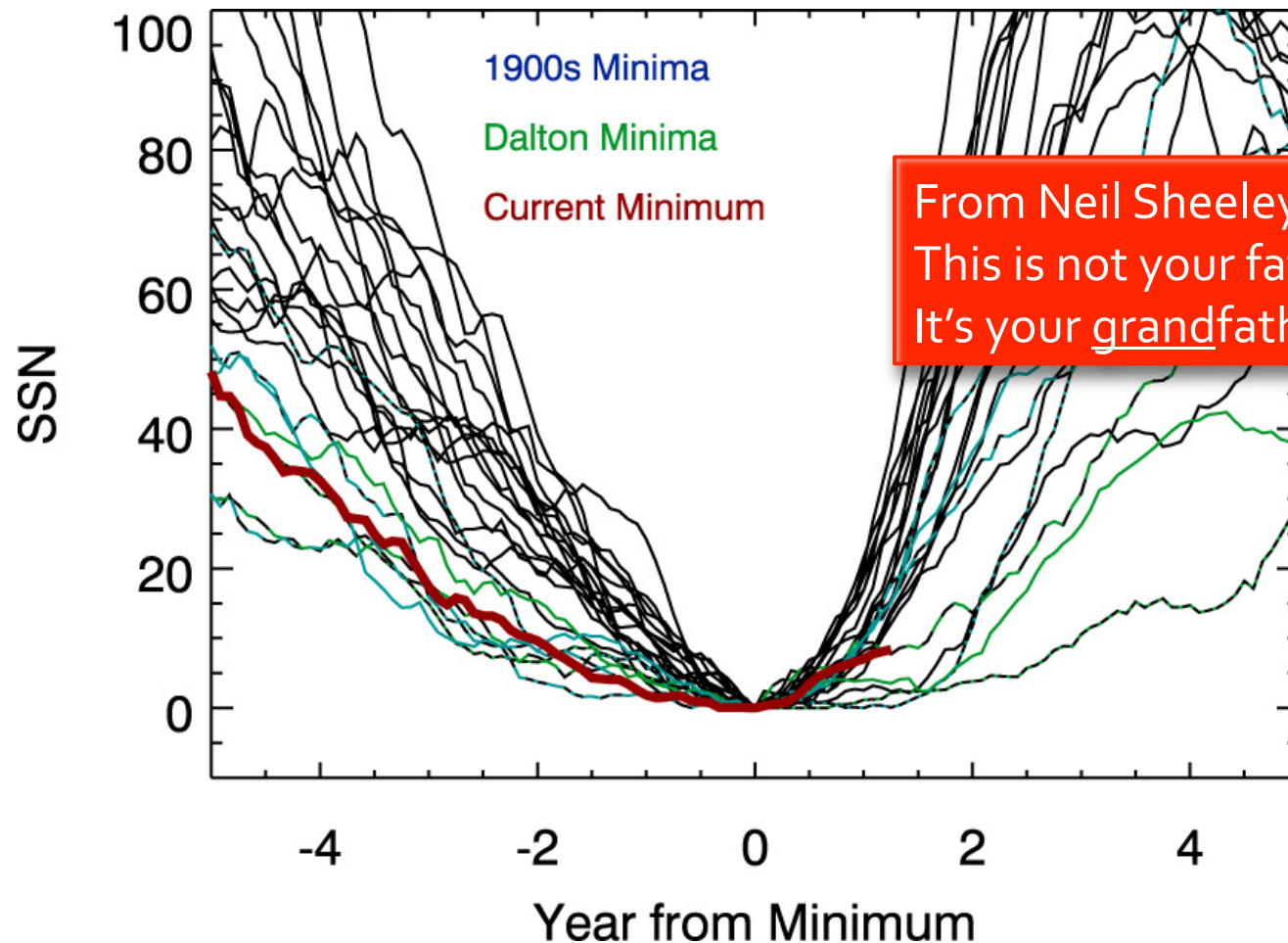
- Sunspot Number (SSN) provides the longest, direct measurement of solar activity since the 1600s



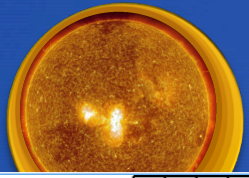


What does the sunspot record tell us?

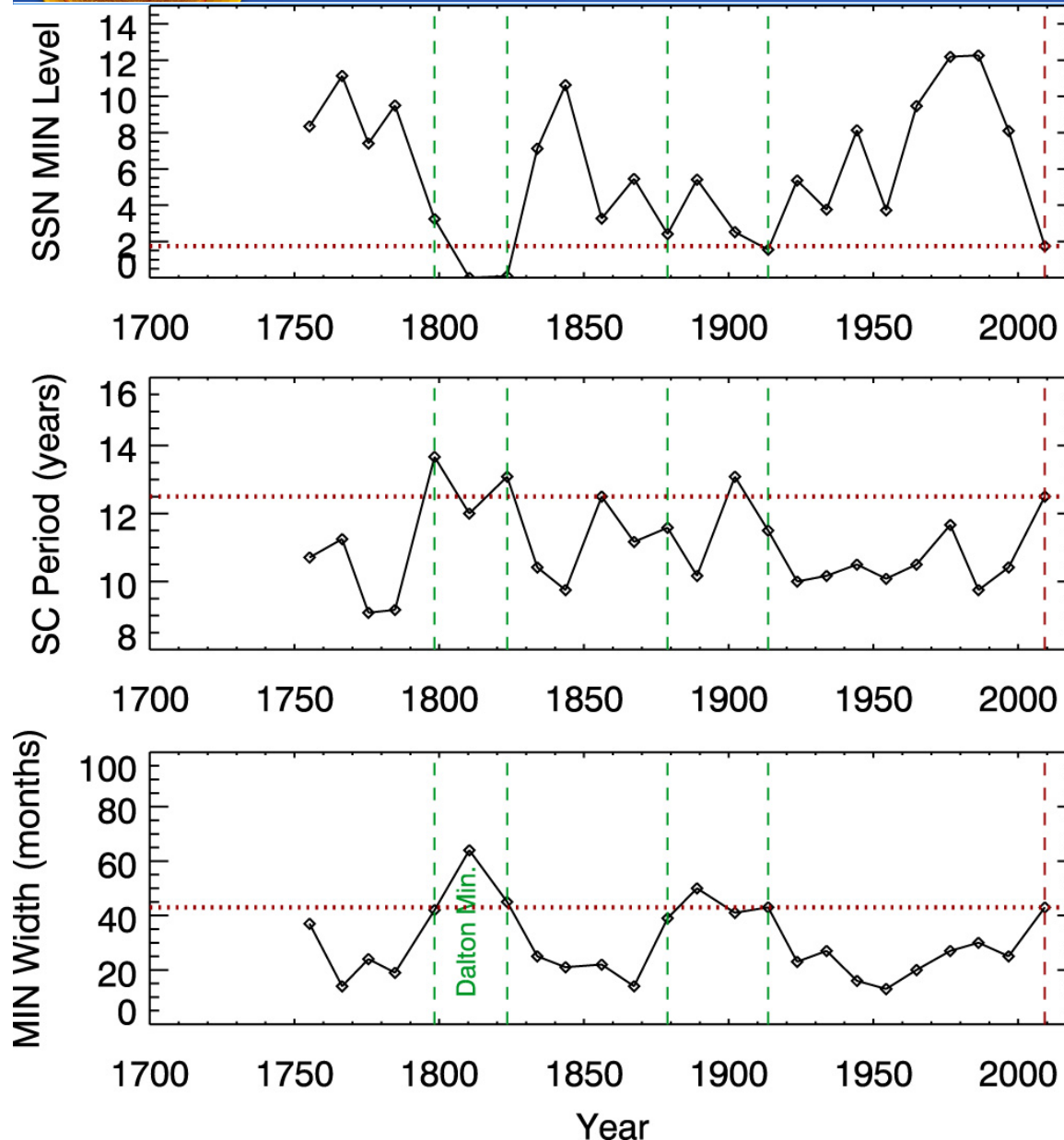
- Latest cycle minimum appears similar to those in early 1900s and Dalton Minimum in early 1800s



From Neil Sheeley's SOHO Keynote Talk:
This is not your father's solar minimum.
It's your grandfather's solar minimum!



What does the sunspot record tell us?

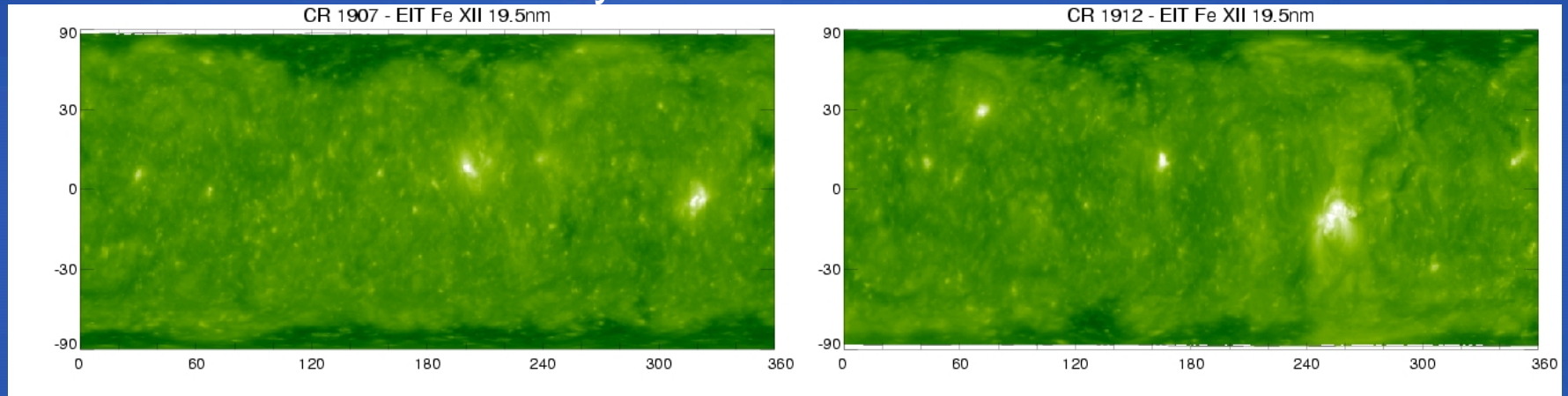


- SSN Minimum Level
 - **Lowest since 1920s**
 - (3 of 24 are lower)
- SC Period Length
 - **Longest since 1900**
 - (4 of 24 are longer)
- Minimum Duration
 - **Widest since 1920s**
 - (4 of 24 are wider)

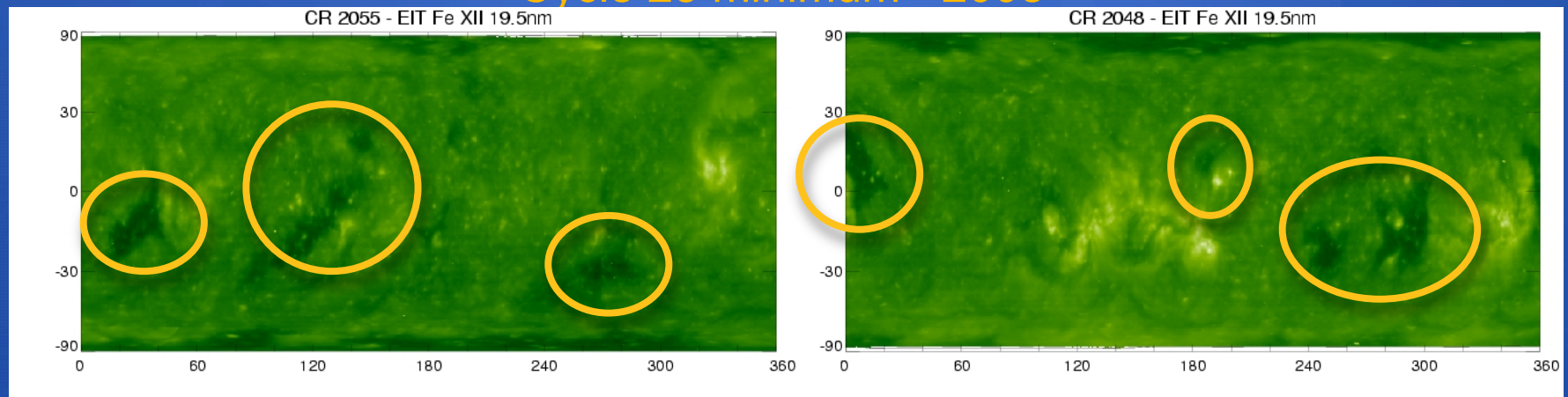
What's Different on the Sun?

SOHO EIT Images from Giuliana de Toma

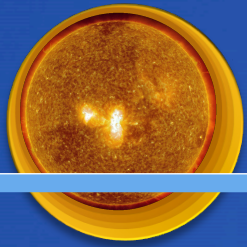
Cycle 22 minimum - 1996



Cycle 23 minimum - 2008

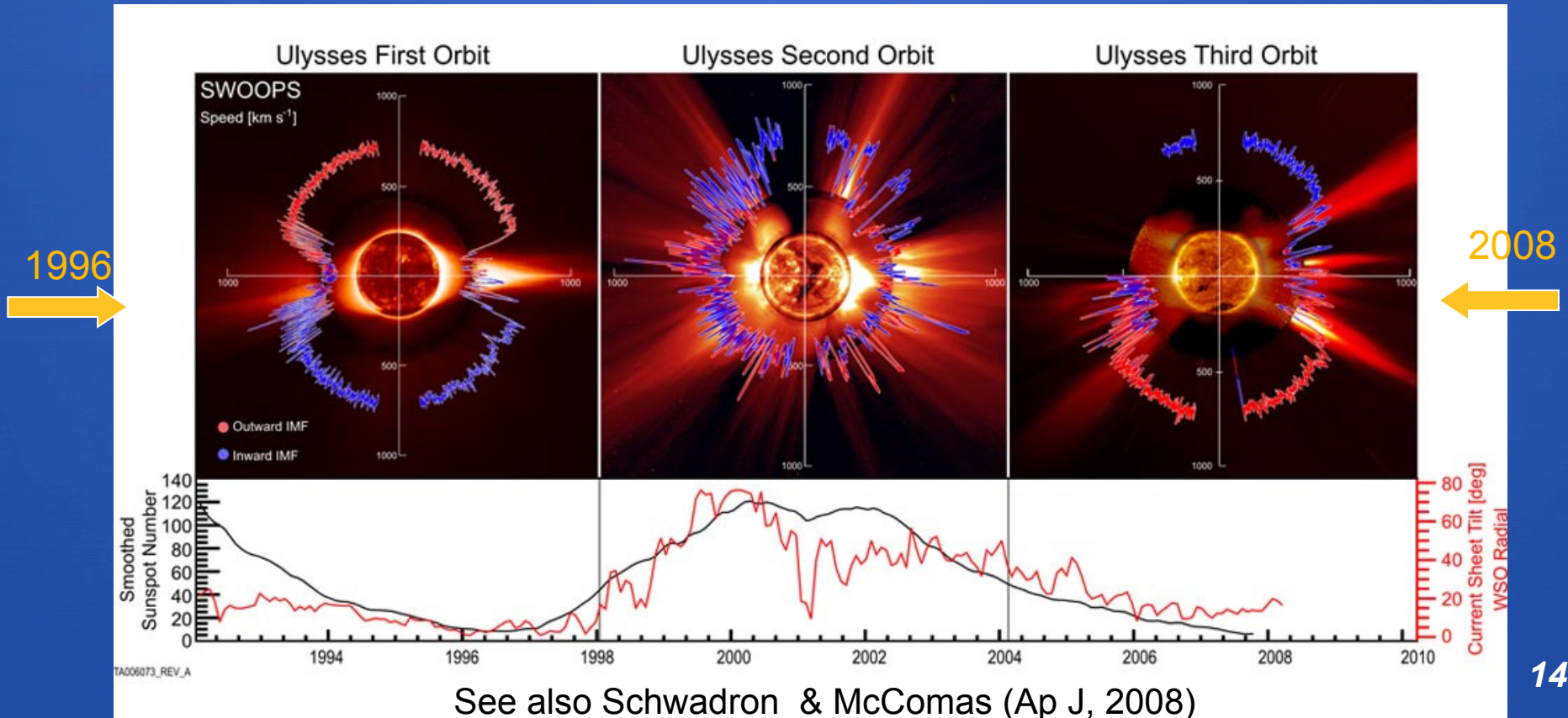


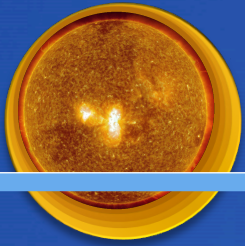
- polar coronal holes are smaller (by ~40-50%) than in 1996
- large, mid- and low-latitude coronal holes persisted for most of the minimum phase



Heliospheric Current Sheet (HCS) is not flat from Sarah Gibson (WHI comparison)

- Solar wind density (near ecliptic) is 45% lower
- But solar wind speed is 13% higher and number of fast solar wind periods is more [Gibson et al., JGR, 2009]

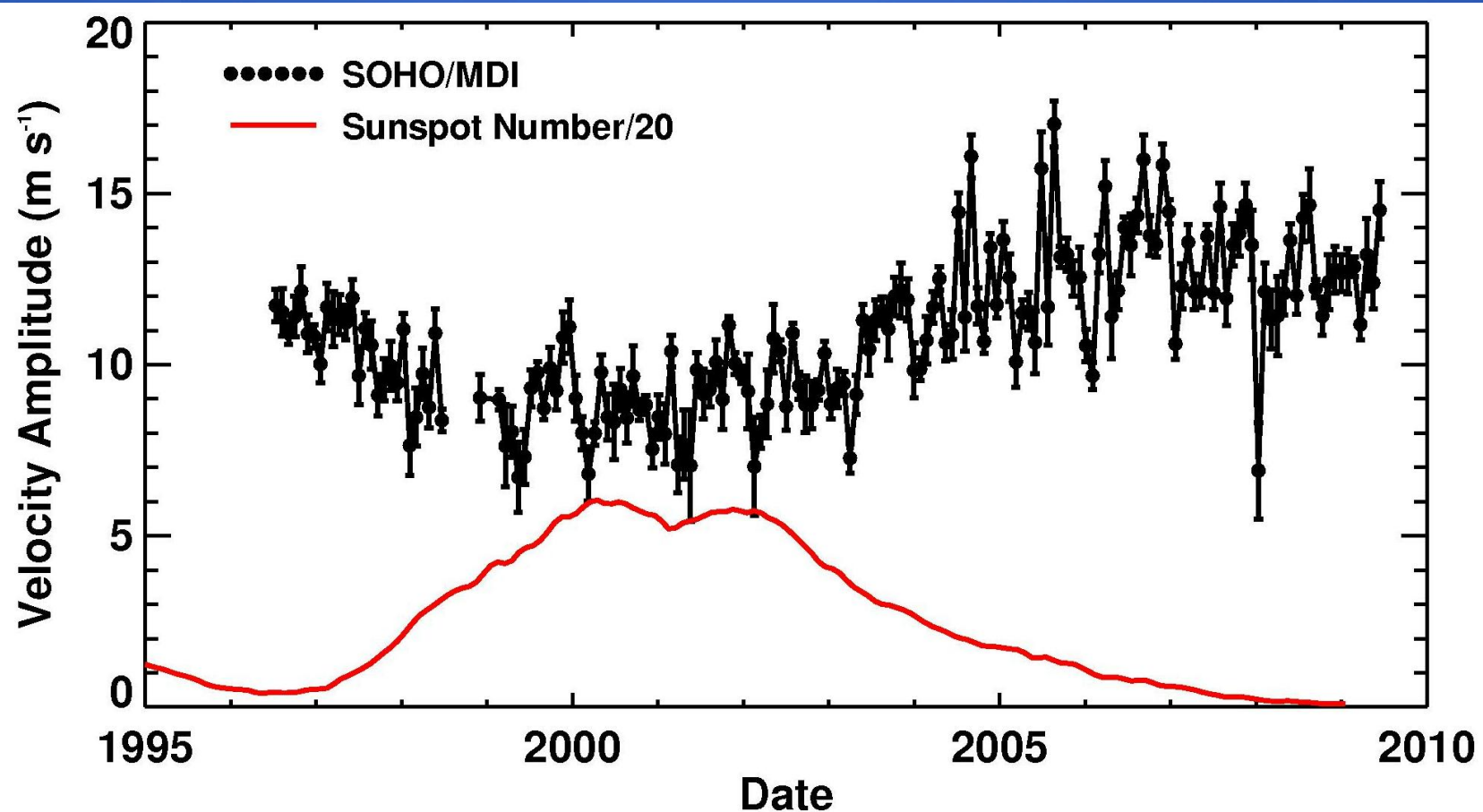


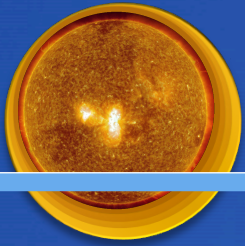


Meridional Flow is Now Faster

from David Hathaway

The Meridional Flow slowed from 11.5 m/s in 1996 to 8.5 m/s in 2001 (cf. Basu & Antia, 2003) but then rapidly increased in speed to 13.0 m/s by 2004.





Solar Rotation During Maunder Min

- Jack Eddy's 1976 paper about Maunder Minimum discusses how the solar rotation was faster and how the differential rotation was more enhanced

SOLAR ROTATION DURING THE MAUNDER MINIMUM

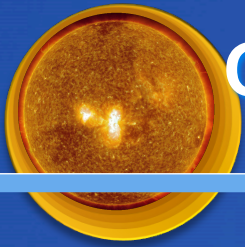
J. A. EDDY, P. A. GILMAN, and D. E. TROTTER

High Altitude Observatory, National Center for Atmospheric Research,
Boulder, Colo. 80303, U.S.A.*

(Received 8 December, 1975)

Abstract. We have measured solar surface rotation from sunspot drawings made in A.D. 1642–1644 and find probable differences from present-day rates. The 17th century sunspots rotated faster near the equator by 3 or 4%, and the differential rotation between 0 and $\pm 20^\circ$ latitude was enhanced by about a factor 3. These differences are consistent features in both spots and groups of spots and in both northern and southern hemispheres. We presume that this apparent change in surface rotation was related to the ensuing dearth of solar activity (the Maunder Minimum) which persisted until about 1715.

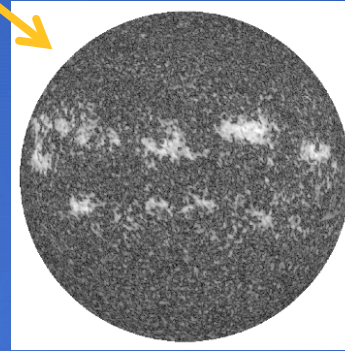
Is the solar irradiance level lower?



Can irradiance be different at each minimum?

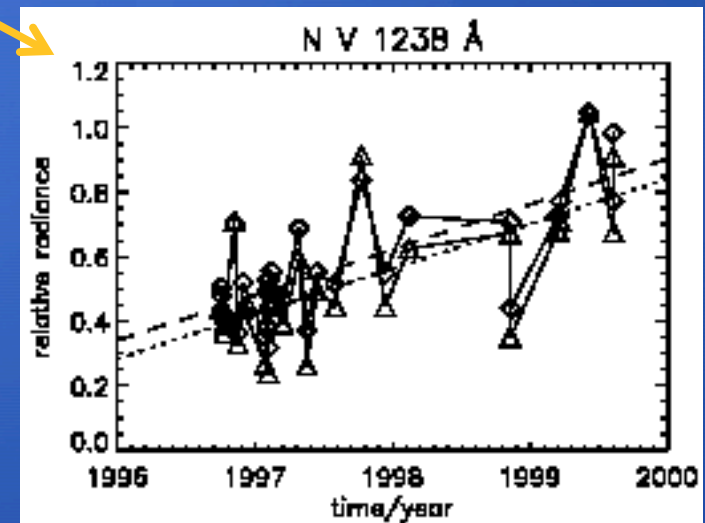
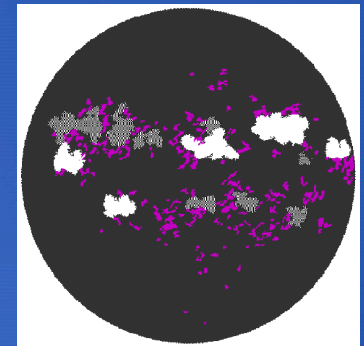
- Fractional area of active network and quiet network is **not** zero at minimum
 - e.g. Worden *et al.*, *Ap J*, 1998, 1999, 2001
- Quiet Sun radiance **changes** with solar activity
 - e.g. Schuhle *et al.*, *A & A*, 2000 using SOHO SUMER data
- Luminosity changes
 - e.g. Foukal *et al.*, *Nature*, 2006
 - PICARD mission: solar diameter
- Dynamo changes
 - Faster rotation rate and/or meridional flow rate
 - e.g. Eddy *et al.*, *Solar Phys.* 1976

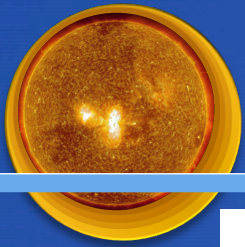
Ca II K line
6/03/1992



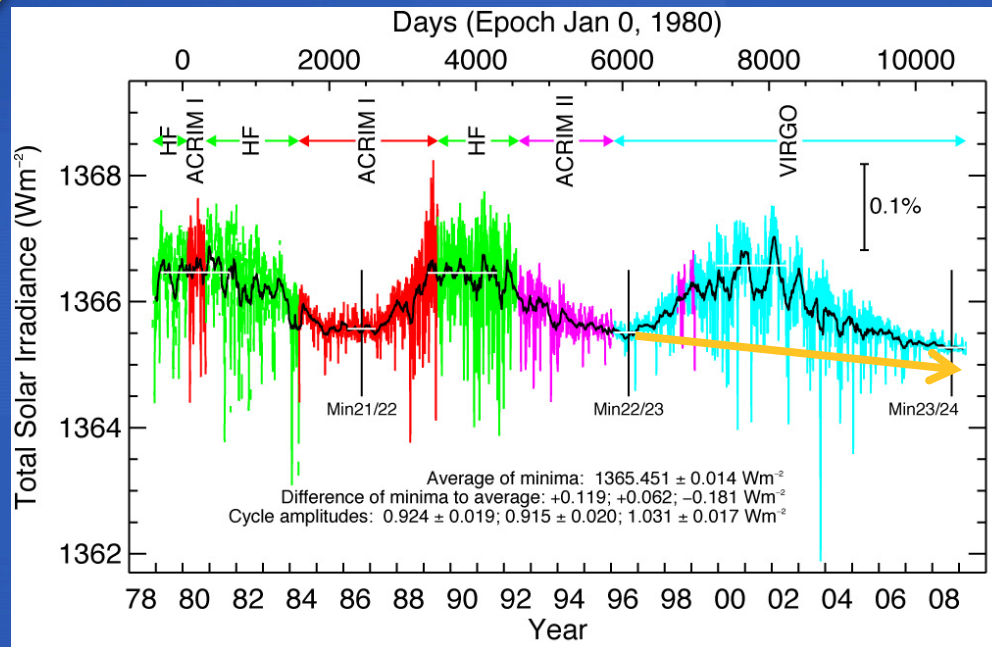
Map

- Black: Quiet-Sun
- Purple: Active Network
- Grey: Enhanced Network
- White: Plage



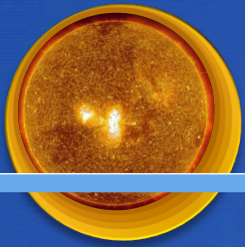


Is the solar irradiance lower now?



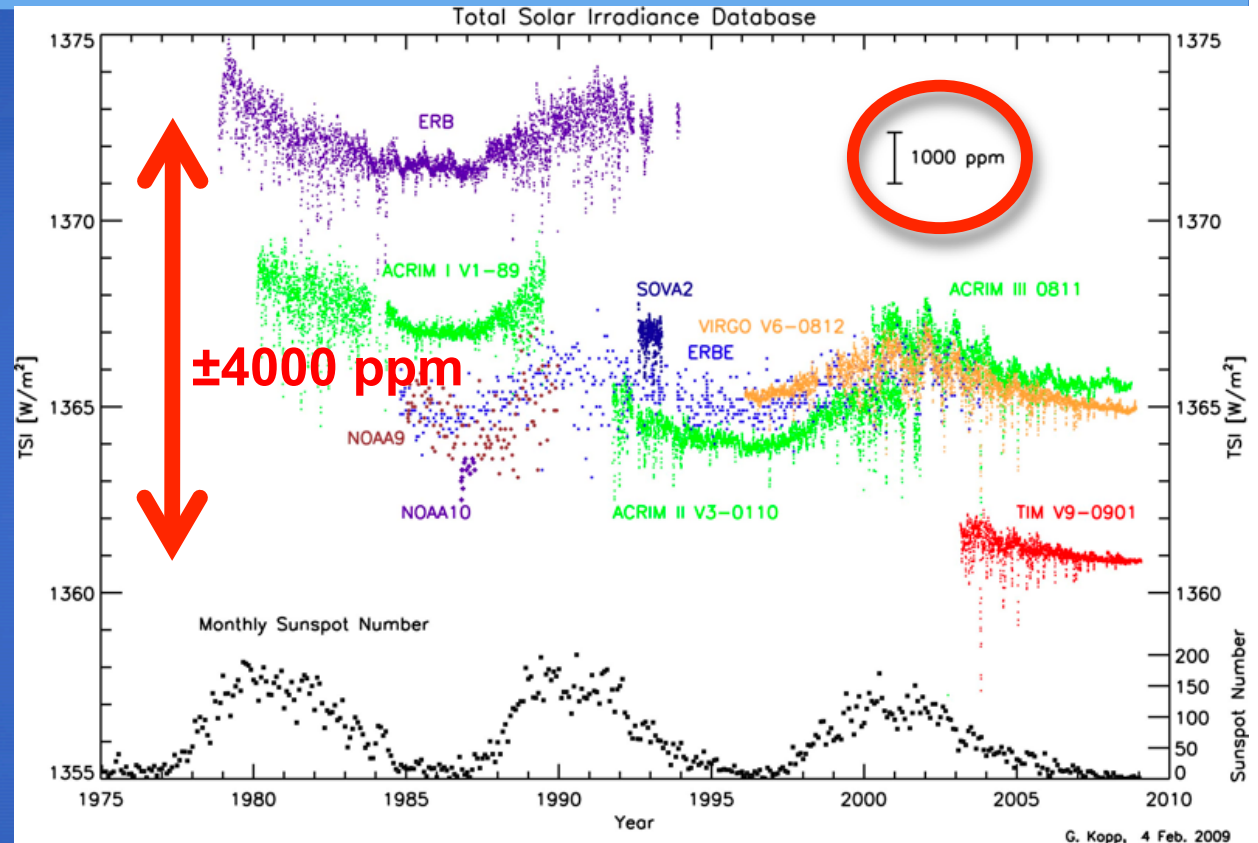
For example, Claus Fröhlich's composite TSI indicates lower irradiance for 2008.

- Our most common technique to look for solar secular (long-term) trends is to examine the irradiance at one minimum to that at other minima.
- **HOWEVER**, understanding instrument degradation trends and possible calibration offsets between different instruments make this task challenging.

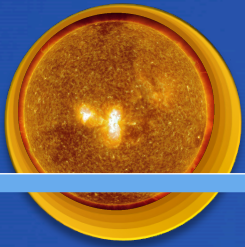


Challenges with TSI Data / Trends

- TSI Differences are much larger than ~ 1000 ppm estimated accuracy
- Hope to resolve these differences with new TSI Radiometric Facility (TRF) built for Glory TIM [accuracy ~ 300 ppm]
- PICARD PREMOS has also used TRF in July 09. ACRIM is planning visit to TRF too.

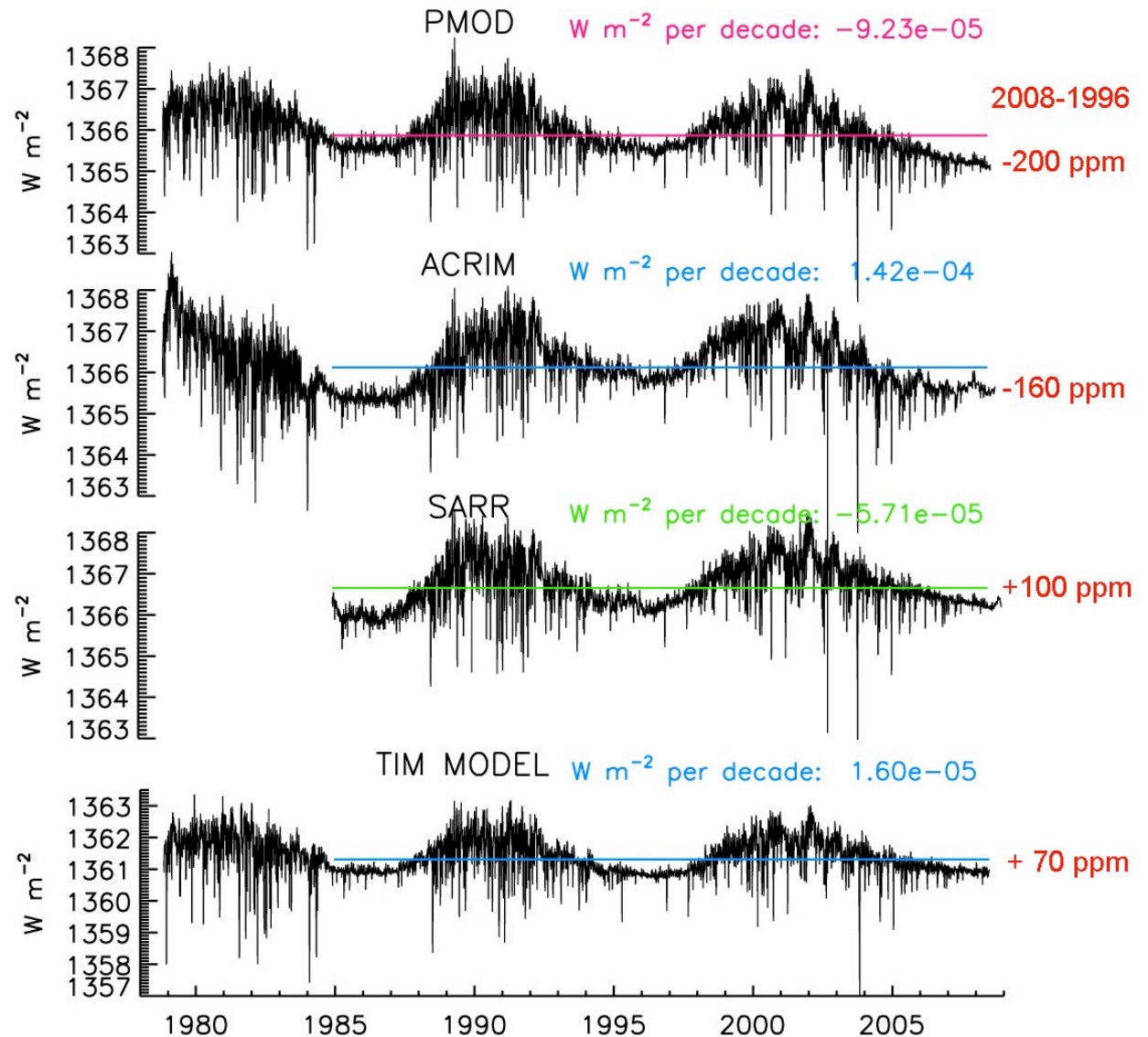


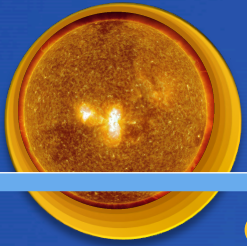
- Composite TSI time series are created by adopting reference TSI level
- Instrument degradation trends are critical for the long-term variations



4 TSI Composites: Conflicting Results

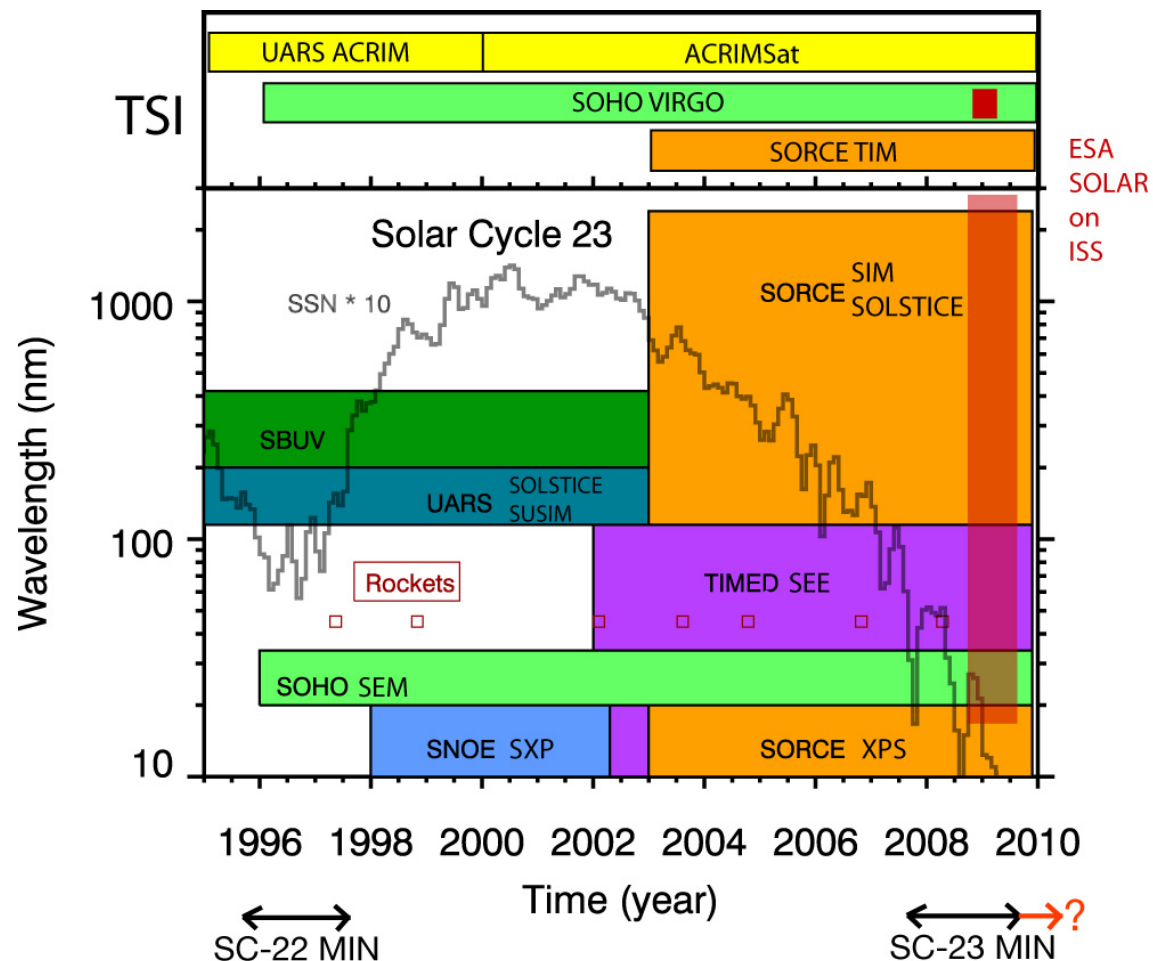
- SOHO VIRGO PMOD (Fröhlich) and ACRIM (Willson) composites indicate 2008 TSI is lower than 1996 level
- SOHO VIRGO DIARAD (DeWitte) and SORCE TIM / Model (Lean) composites indicate 2008 TSI is higher
- Uncertainty for 2008-1996 trend is about 100 ppm

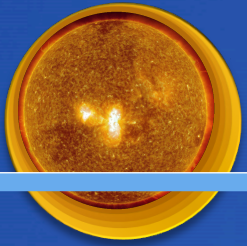




Irradiance Data Sets for 1996 & 2008

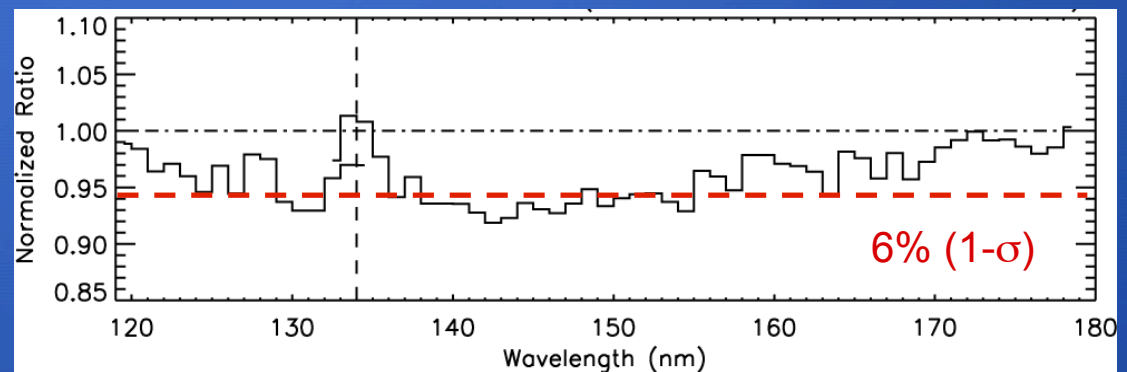
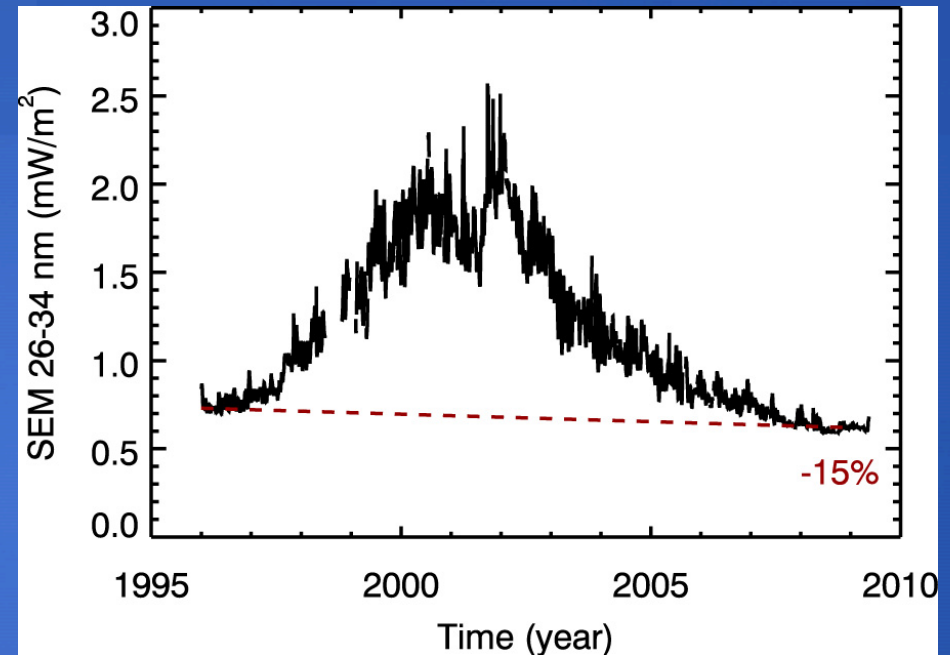
- Multiple sets of Total Solar Irradiance (TSI)
- Limited Solar Spectral Irradiance (SSI) before 2003

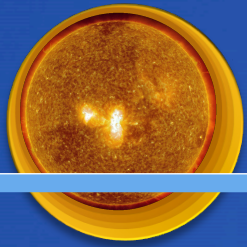




Lower Solar EUV Irradiance

- SOHO SEM 26-34 nm is about 15% less in 2008 than in 1996 (Leonid Didkovsky, '09 SPD 18.07)
 - Uncertainty is ~6%
- SORCE SOLSTICE FUV is about 1-6% less than UARS in 1996 (Marty Snow, '09 SPD 11.12)
 - First corrects for offsets using stellar irradiances
- **HOWEVER...**
these are only about 1- σ results

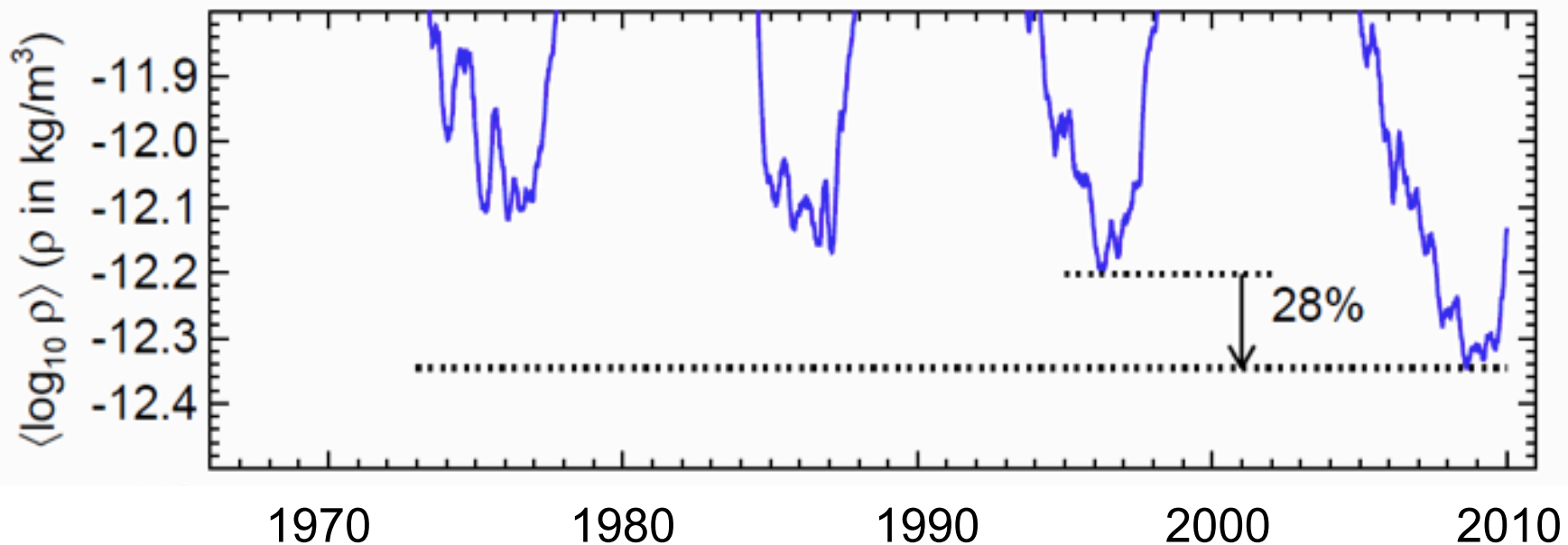




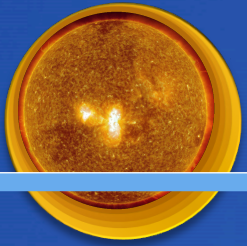
Are there changes on Earth that indicate lower irradiance in 2007-2009?

- Thermospheric density is about 28% lower in 2008 than in 1996
 - based on satellite drag data analysis (J. Emmert, et al., 2010)

Density at 400 km

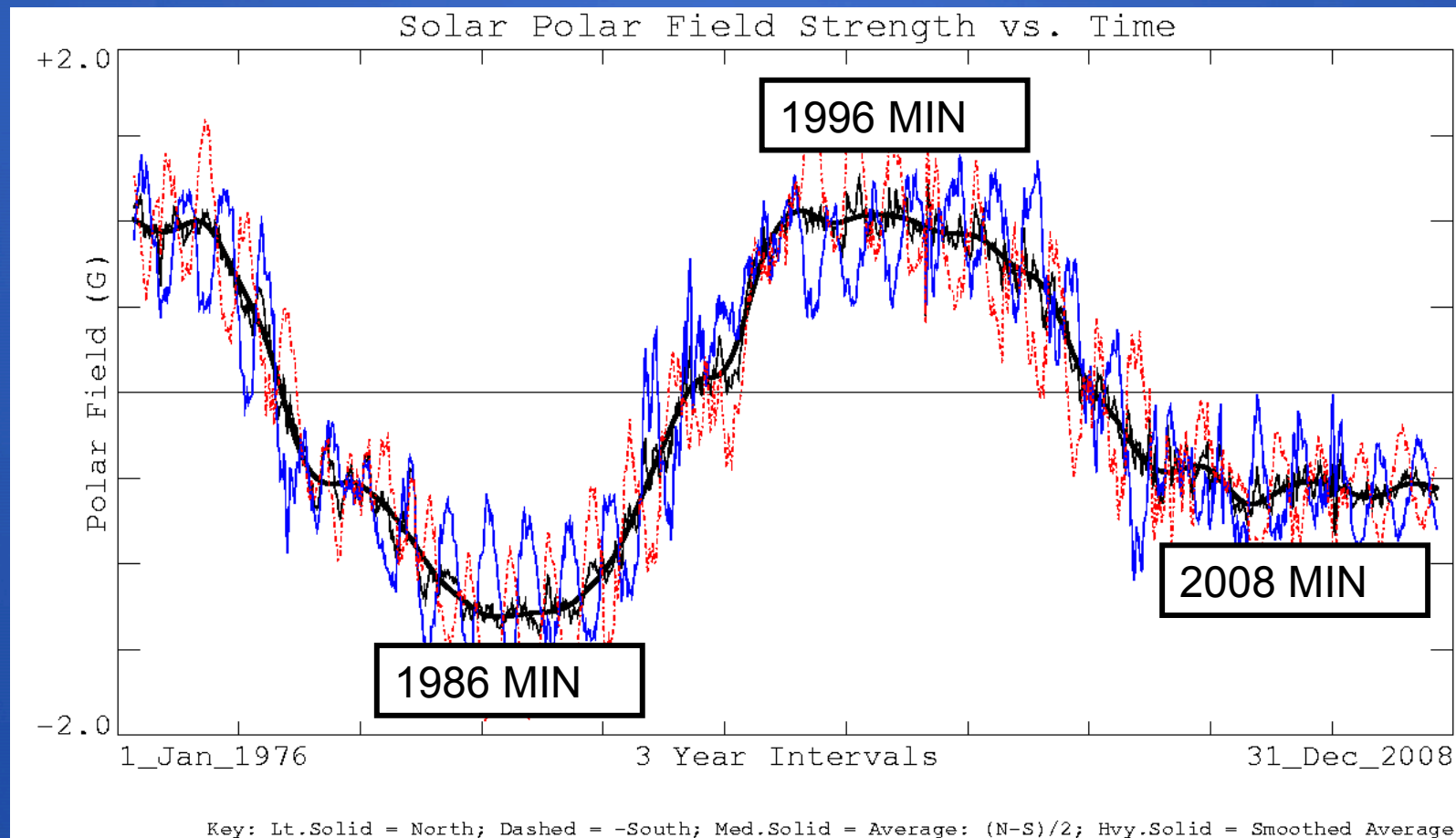


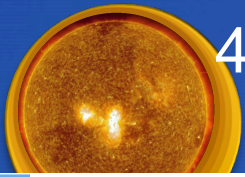
Is the solar magnetic field lower?



Weaker Polar Magnetic Field

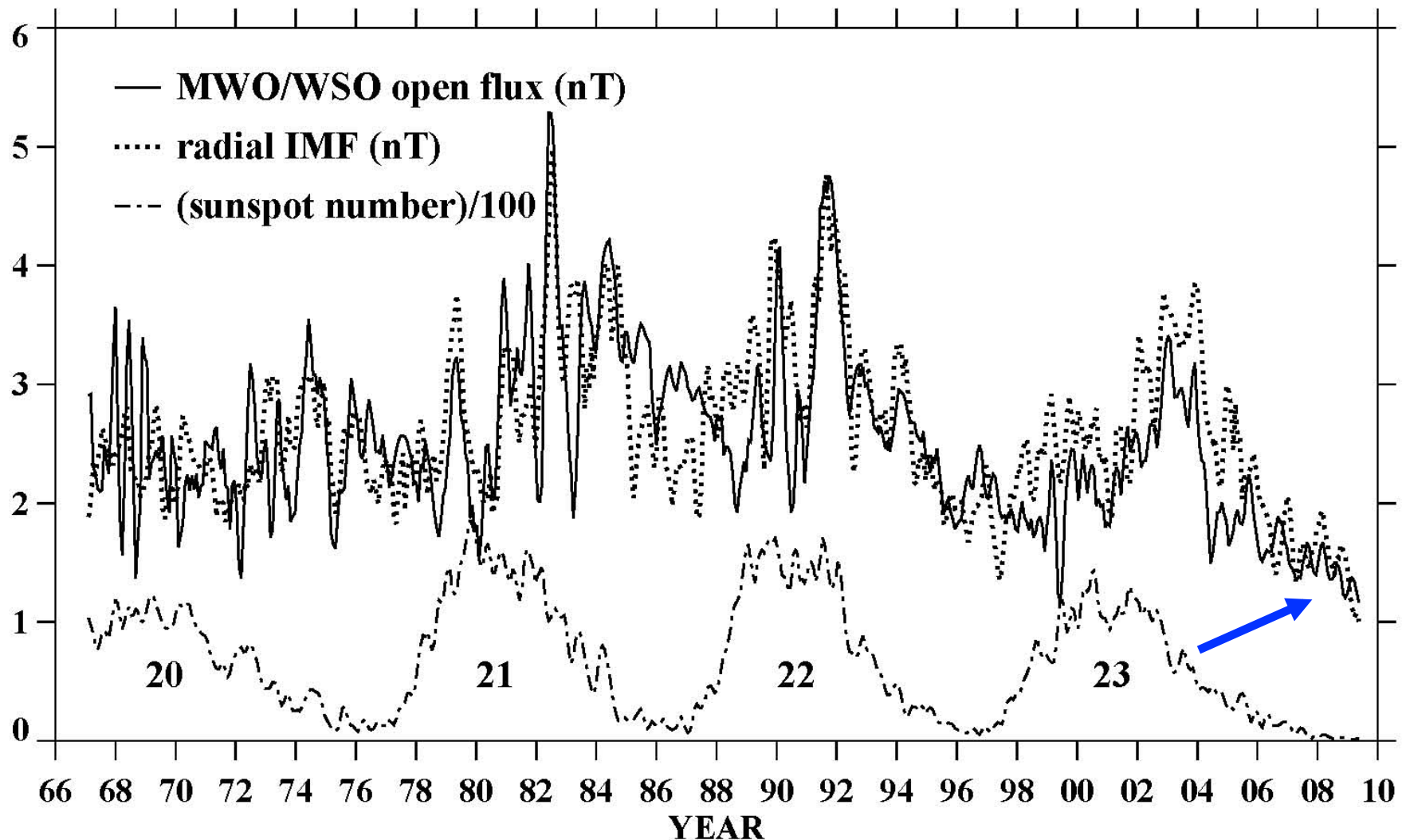
- Solar polar magnetic field (PMF) during this minimum is 40% lower than the last few solar cycles



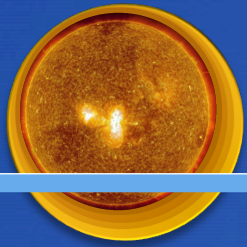


45% Less Open Flux than Any Cycle in the Past 40 Years

from Neil Sheeley – Solar Magnetic Field

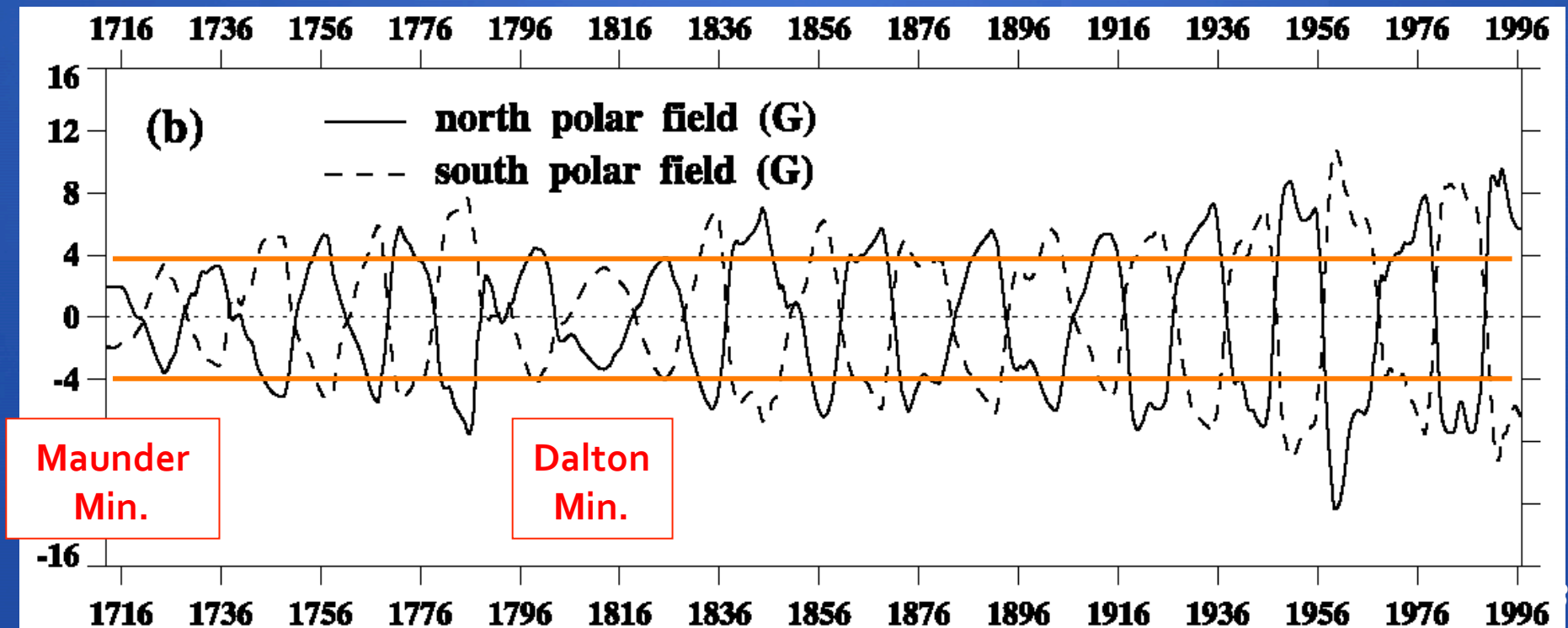


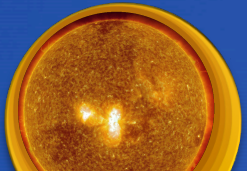
In contrast: Lin Fisk et al. reported that total Magnetic Flux ($B \cdot \text{Area}$) is conserved over the solar cycle. In part, the low-latitude coronal holes compensate for the smaller polar coronal holes.



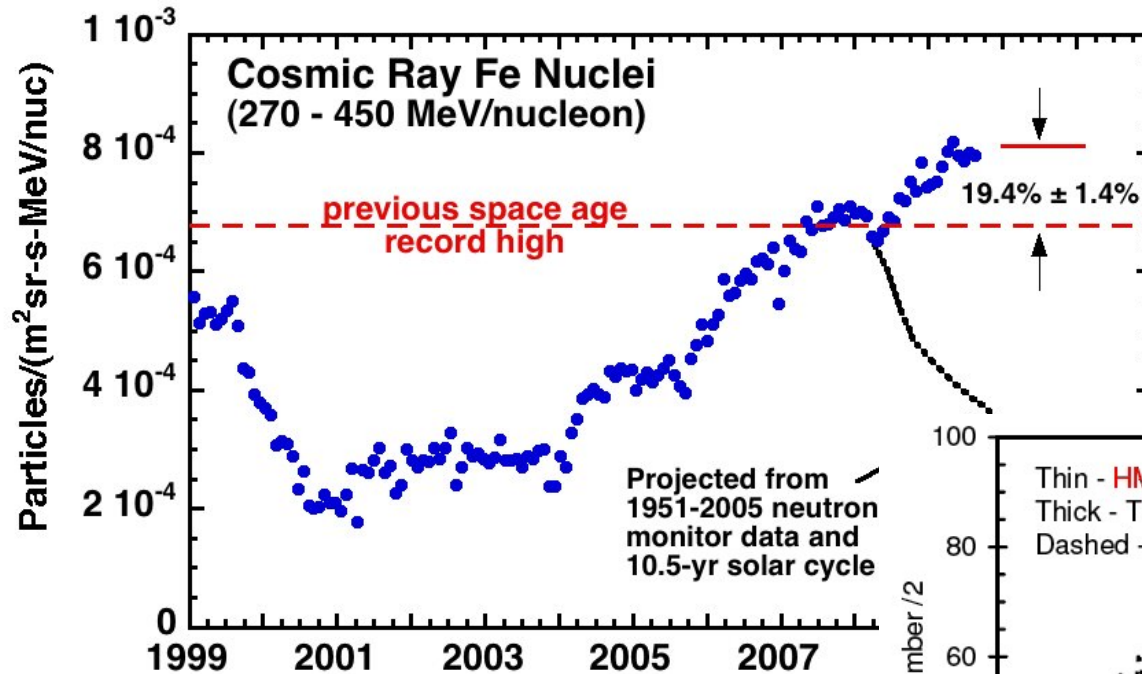
Reconstructed Polar Magnetic Field

- **Latest Minimum level is similar to that before 1920**
- **Maunder Minimum and Dalton Minimum levels are lower**
 - Polar magnetic field is reconstructed by Wang, Lean, and Sheeley [Ap. J., 2005]
- Polar magnetic field is used in some predictions of the next solar cycle maximum, so those predictions are expecting next maximum to be small



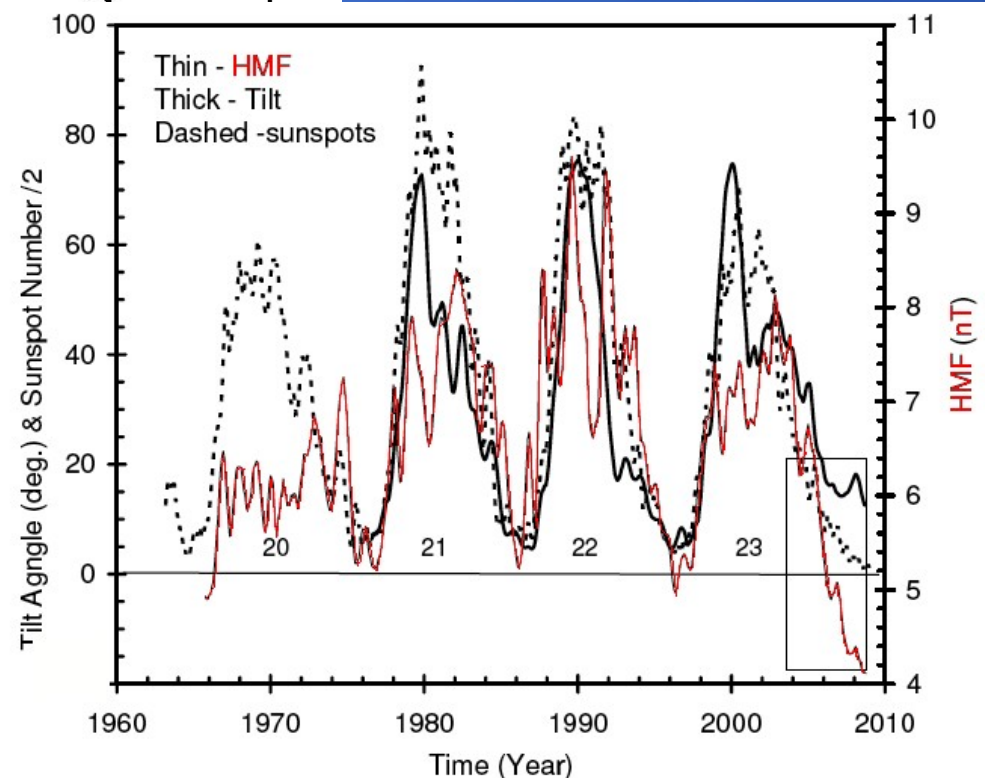


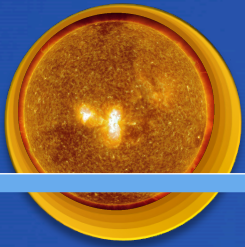
Record Low Heliospheric Magnetic Field (HMF) → Record High Cosmic Rays



- Dick Mewaldt: highest level of cosmic rays in the 54 year record

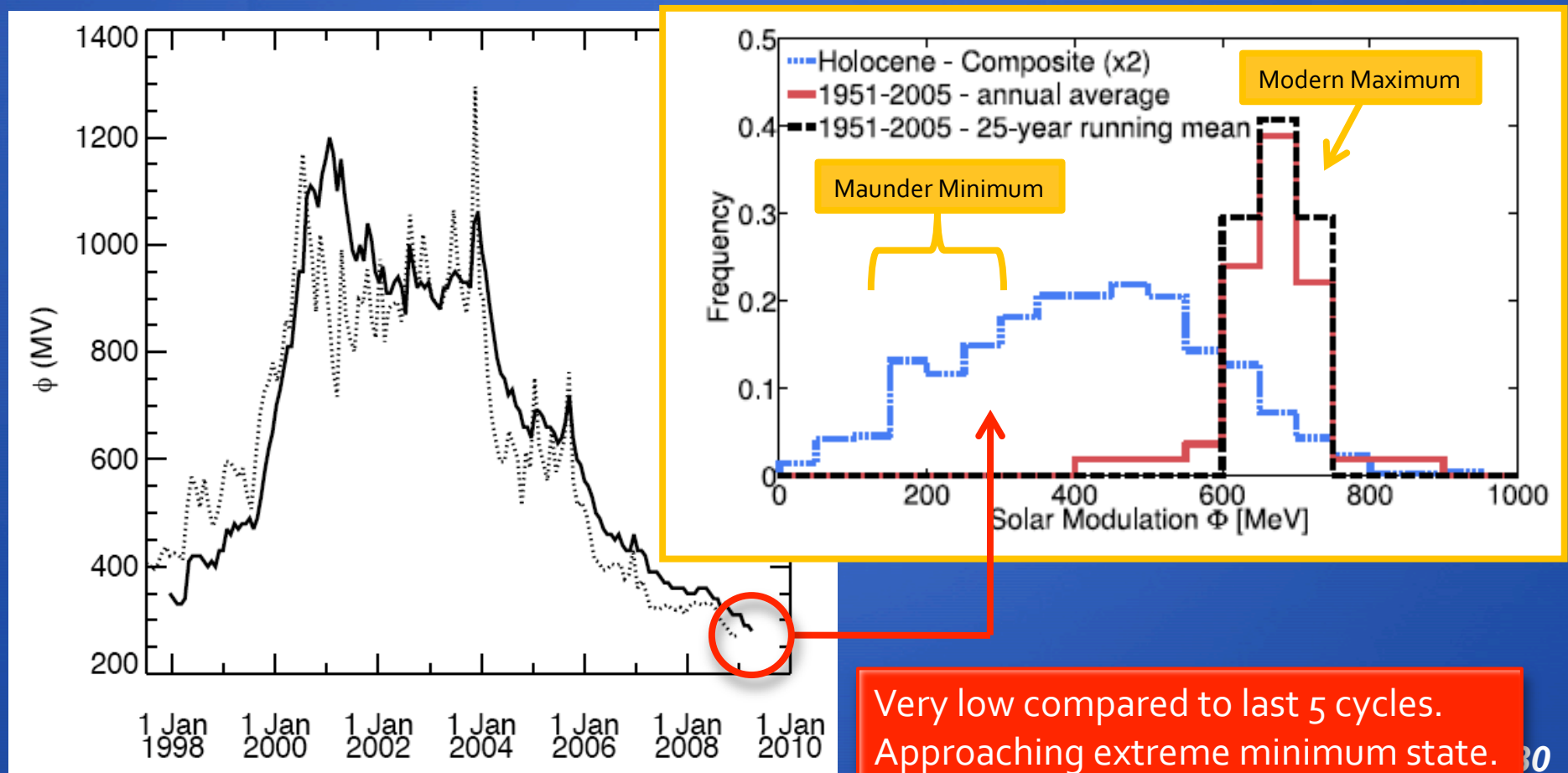
- Moraal et al. (2009) report that record high Galactic Cosmic Rays is consistent with standard modulation theory for GCRs
- That is, high GCRs are consistent with low HMF



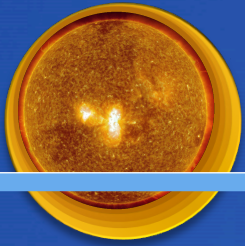


High GCRs → Low Solar Modulation

- Solar Modulation is < 300 MeV and still declining
- Figure from Wiedenbeck et al. (2009): dashed line is neutron monitor GCRs



**Summaries from
SOHO 23 Workshop (2009) and
SORCE Workshop (2010)**



SOHO 23 Workshop Question

● Is this latest cycle minimum peculiar?

Solar Surface Features

Peculiar

Low SSN wrt last 8 cycles
Longer cycle wrt last 8 cycles
Duration longer wrt last 8 cycles

More low-latitude coronal holes
Smaller polar coronal holes

Normal

Similar SSN as 1900s & Dalton Min.
Similar length as 1900s & Dalton Min.
Similar duration as 1900s & Dalton Min.
Similar active network area as 1996

Solar Magnetic Fields

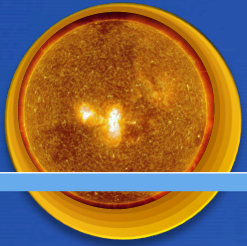
Peculiar

Low PMF wrt last few cycles
Low Open Field wrt last 7 cycles

More low-latitude coronal holes
Smaller polar coronal holes

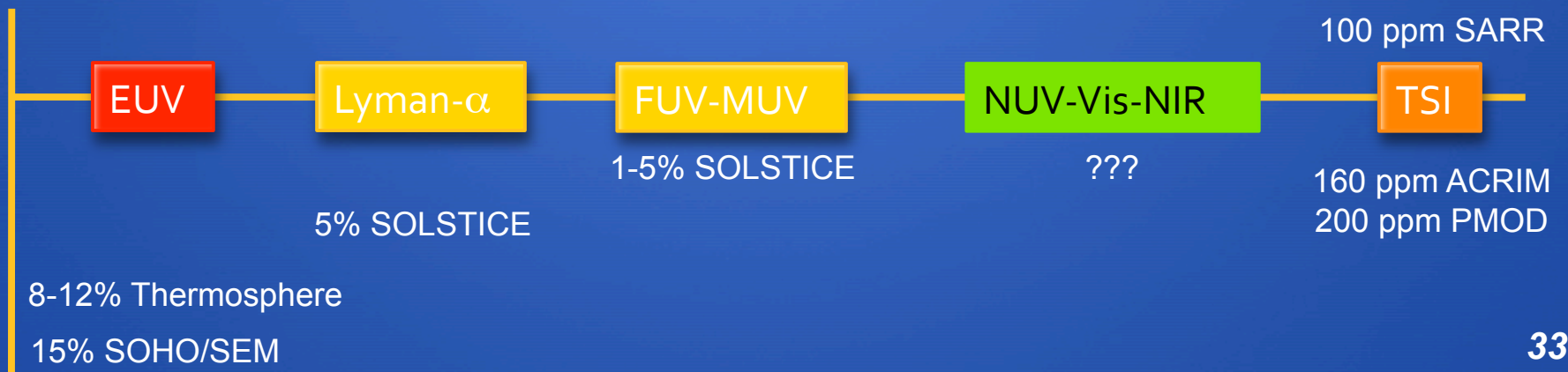
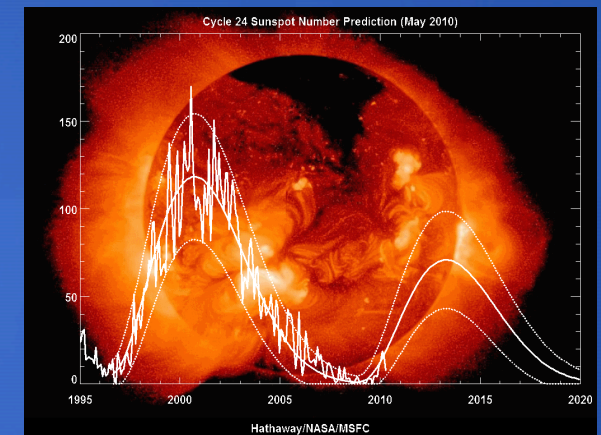
Normal

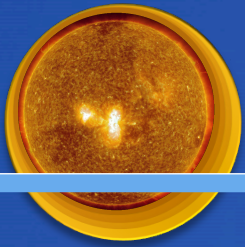
Similar Open Field as 1900s & Dalton Min.
Similar Magnetic Flux ($B \times \text{Area}$) as 1996



SORCE Workshop Question 1

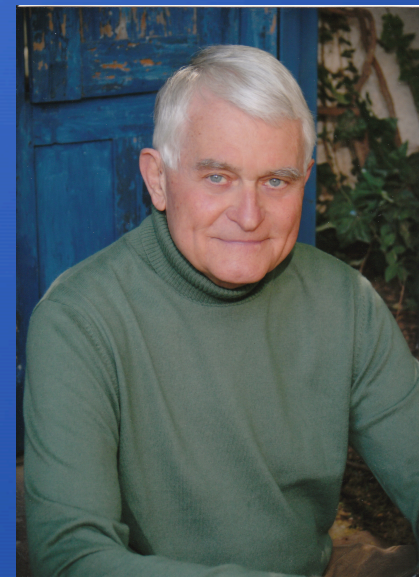
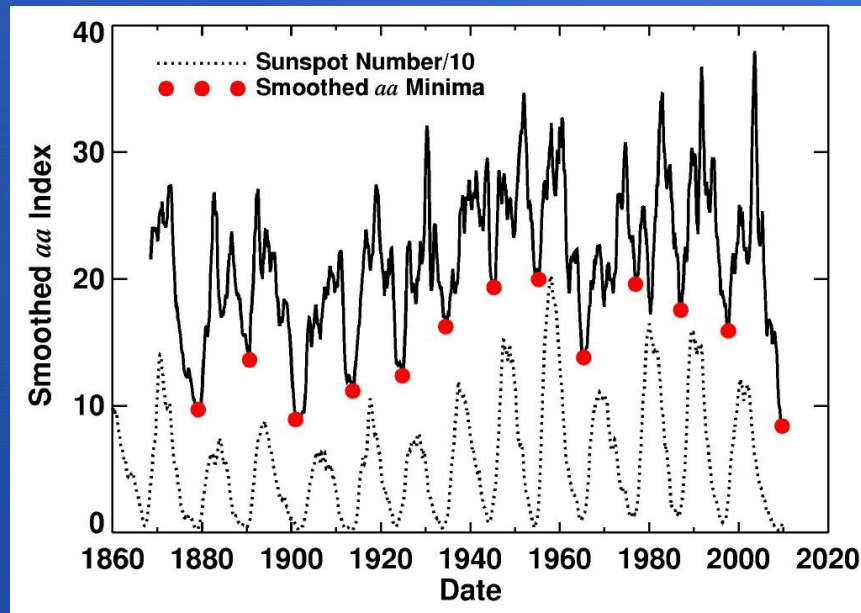
- Are spectral and total solar irradiance levels lower now than during past minima, and how much will they increase during solar cycle 24?
 - SSI UV: lower by 1-15%
 - TSI: ranges from 200 ppm lower to 100 ppm higher
 - SC 24 MAX: small cycle with SSN ~ 70





SORCE Workshop Question 2

- Are we entering a new prolonged period of anomalously low activity such as the Dalton Minimum in the early 1800s?
 - This minimum appears similar to early 1900s minima
 - Wait and see for Solar Cycle 24 ...
- *If so, should this cycle 23/24 minimum have a name? (e.g., Eddy Minimum)*
 - *AAS-SPD Petition already submitted for “Eddy Minimum”*

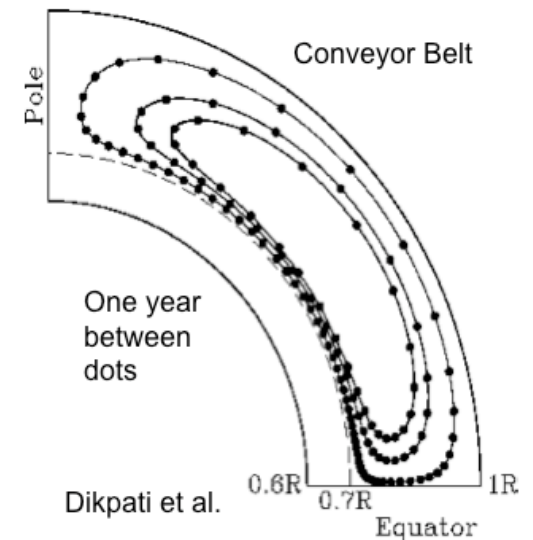
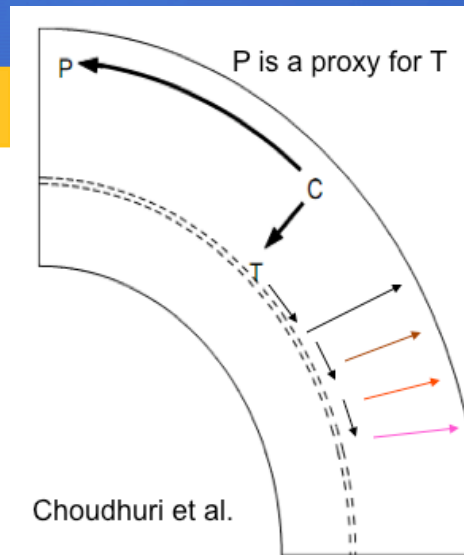
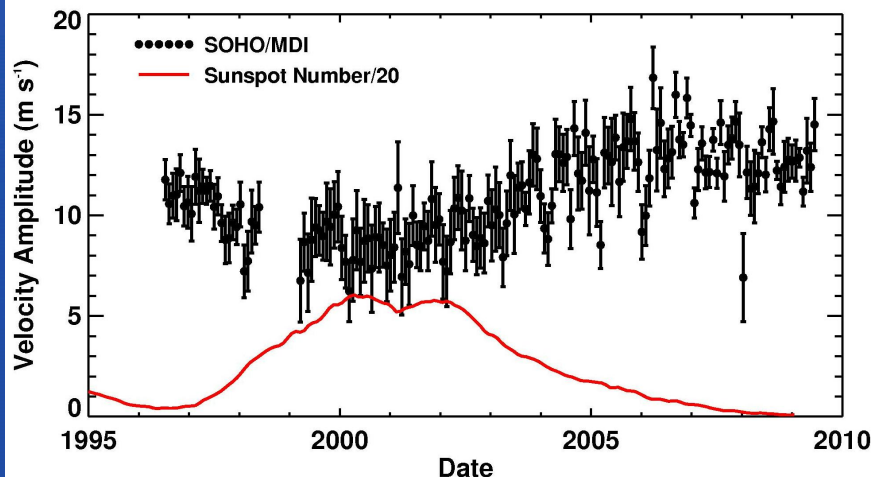


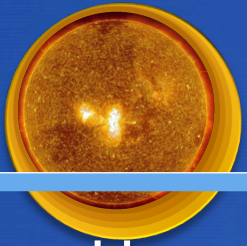


SORCE Workshop Question 3

- Can we identify anomalous behavior in the solar dynamo and surface flux transport during the latest minimum?
 - Weaker Polar Magnetic Field
 - Weaker / smaller / fewer sunspots – trending for weaker magnetic fields started before 2000
 - Faster Meridional Flow during this minimum – but the flow rate over the entire cycle needs to be considered

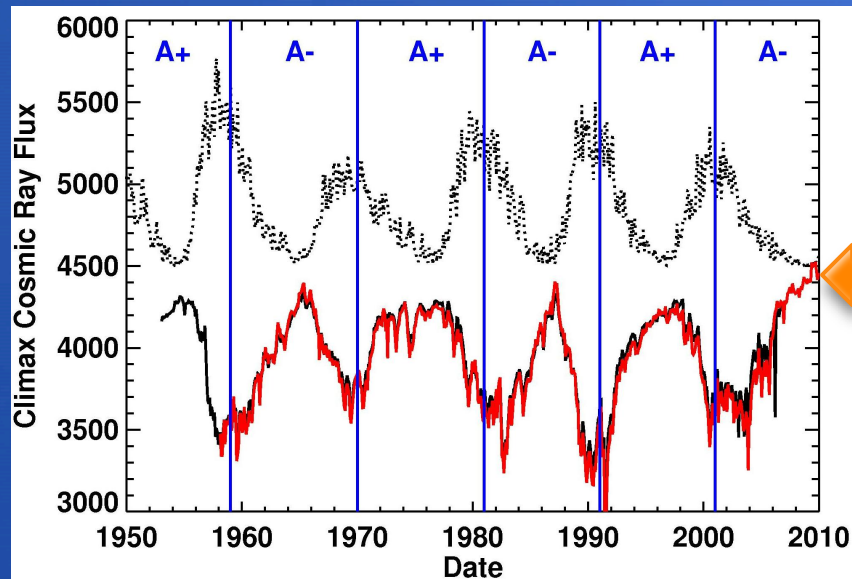
Faster Meridional Flow (Hathaway)



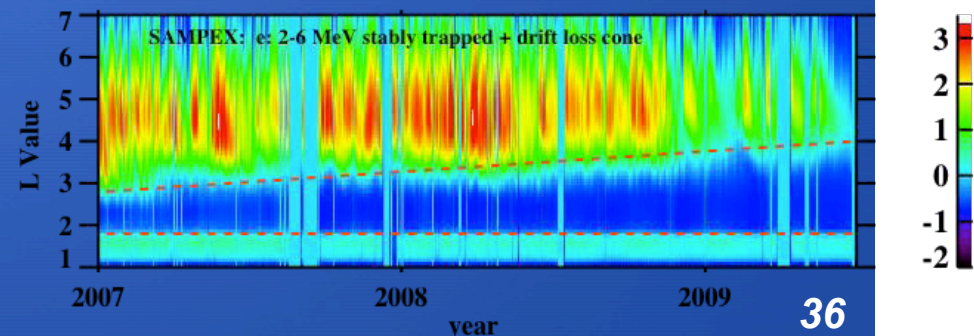
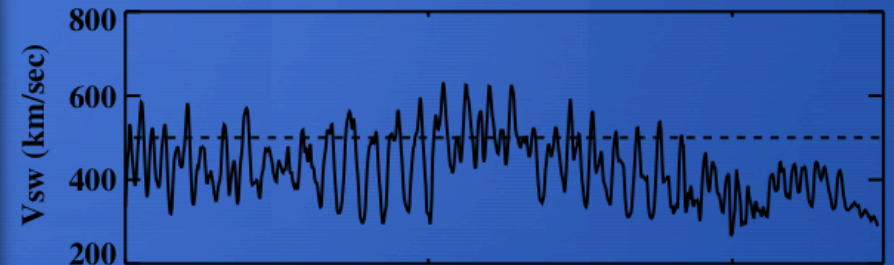


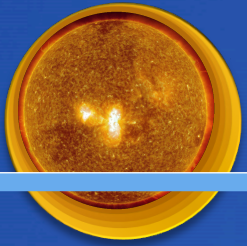
SORCE Workshop Question 4

- How are heliospheric changes altering incident cosmic ray fluxes and the Earth's near-space environment?
 - Highest level of cosmic ray fluxes
 - Lack of strong dipole during 2008 – high speed solar wind dominated for much of this recent cycle minimum



High Cosmic Ray Flux

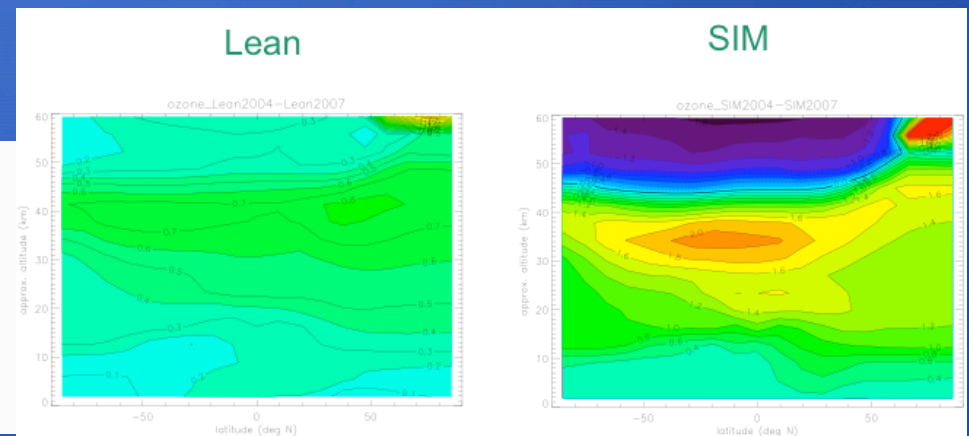
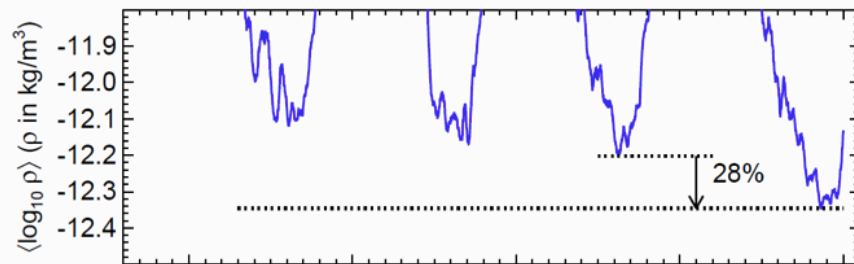


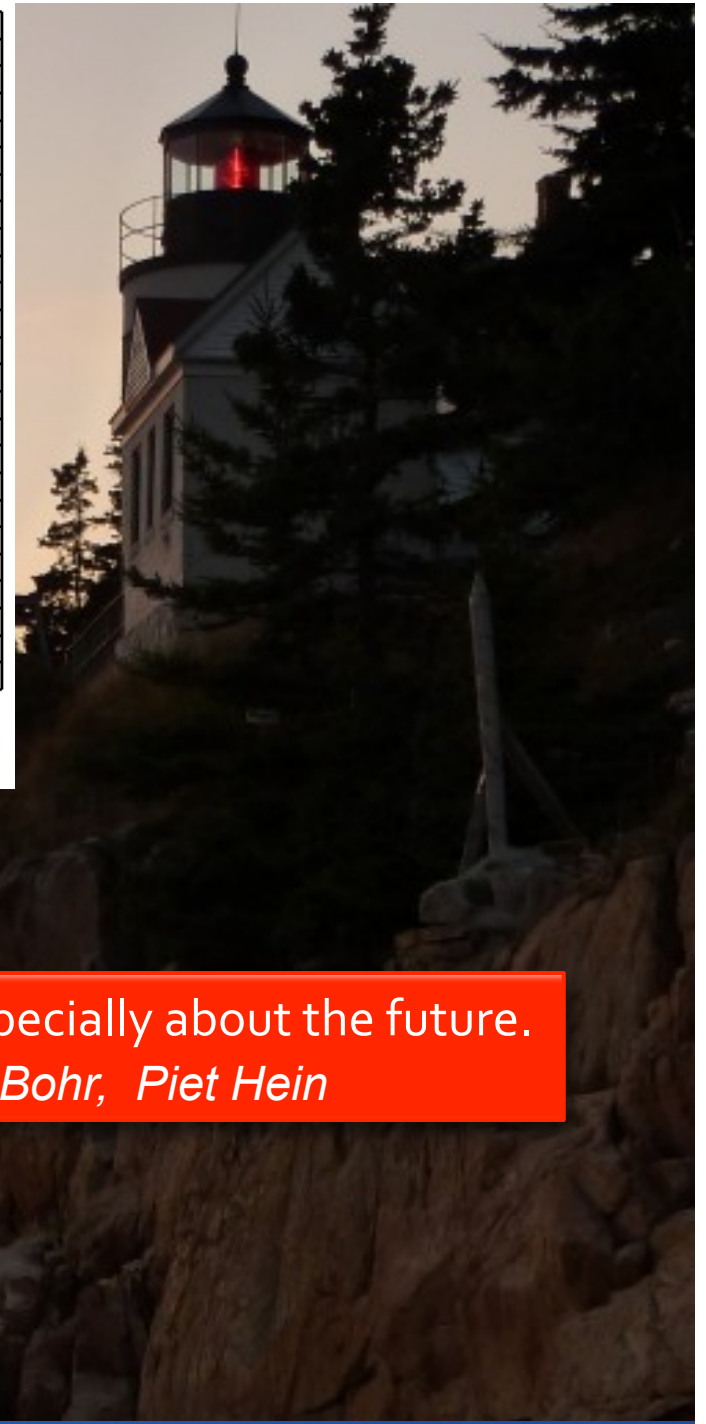
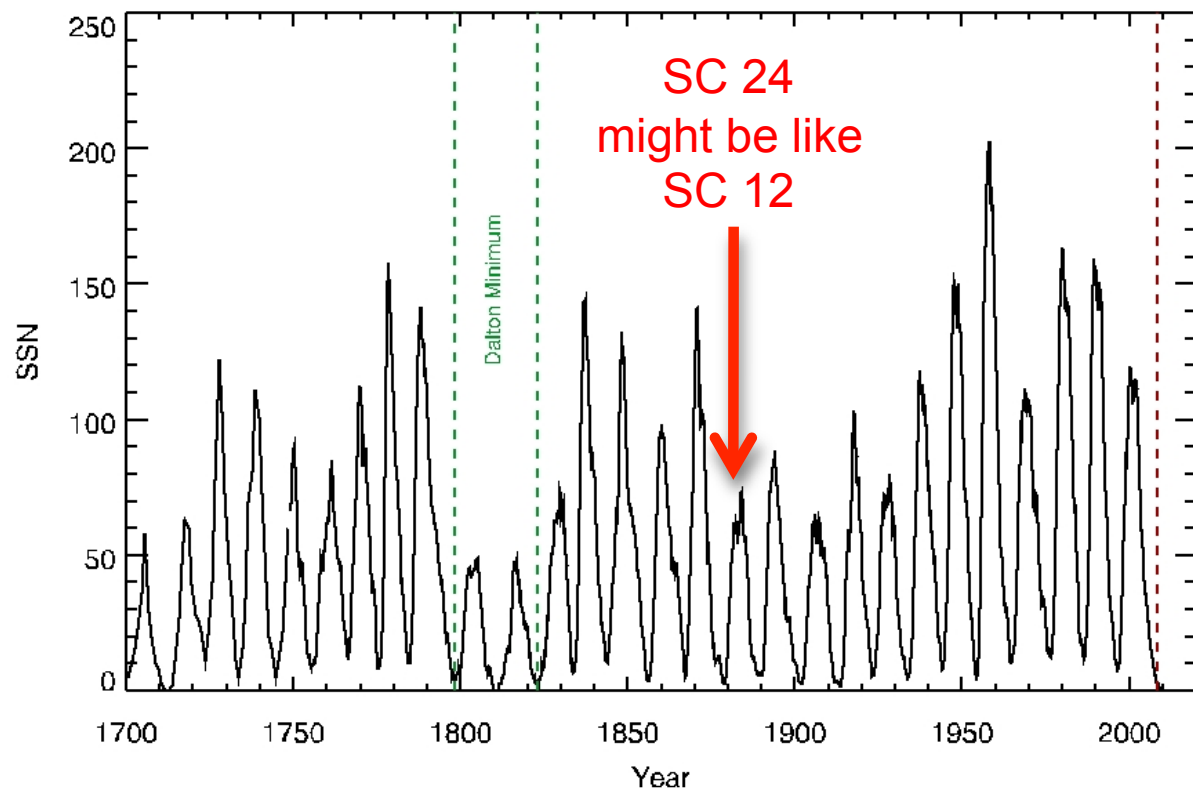


SORCE Workshop Question 5

- Can we reliably discern the terrestrial signatures of the current solar inactivity – at the surface, in the stratosphere, and in space weather?
 - Lower thermospheric density (28% at 400 km)
 - No clear change to ionosphere
 - New (unexpected) results for stratosphere and surface variations when SIM (Harder et al.) spectral variations are used in atmosphere-climate models

Density at 400 km





Prediction is very difficult, especially about the future.
Yogi Berra, Niels Bohr, Piet Hein

Sunset seen from Bass Harbor Head Light