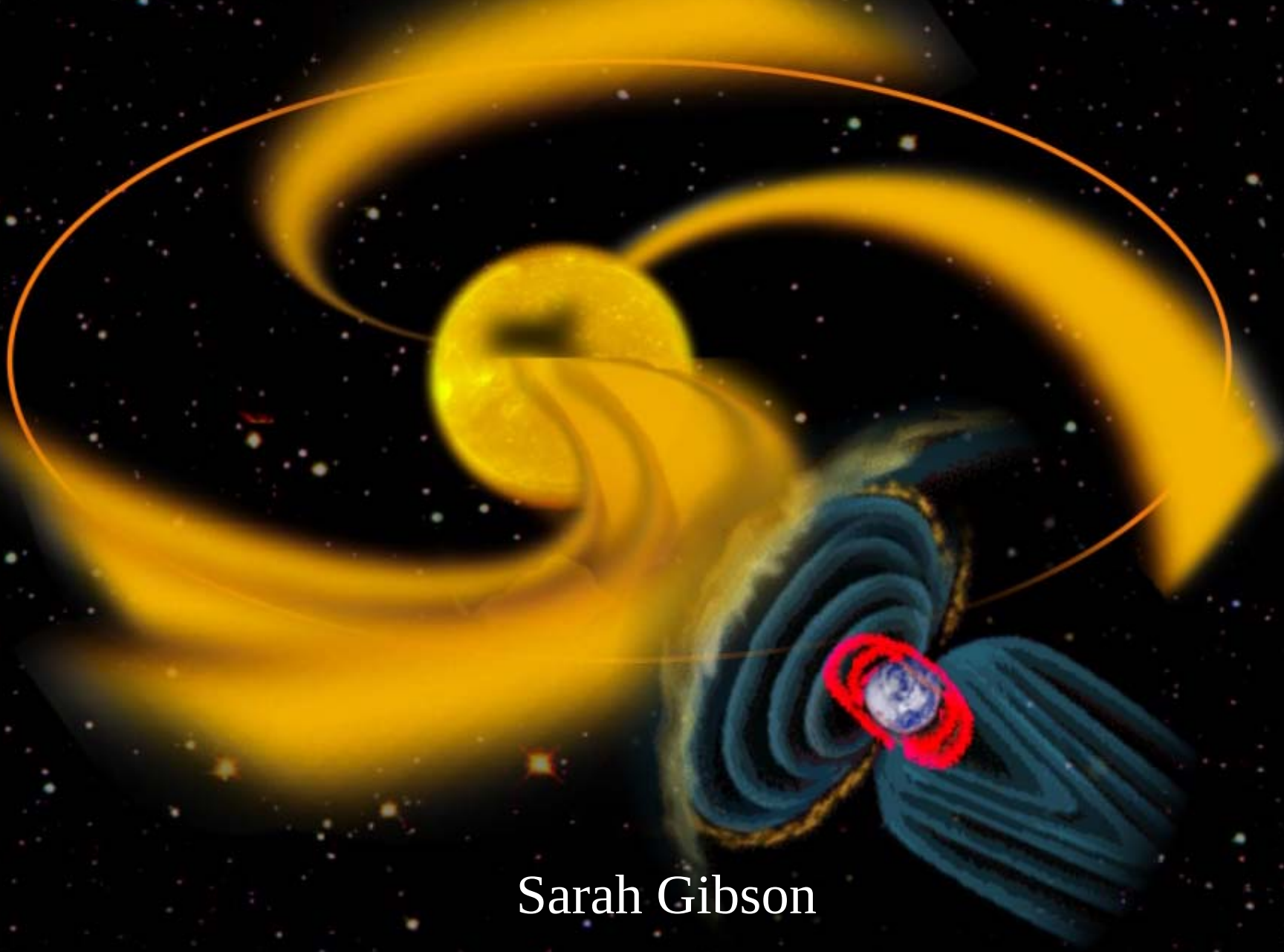
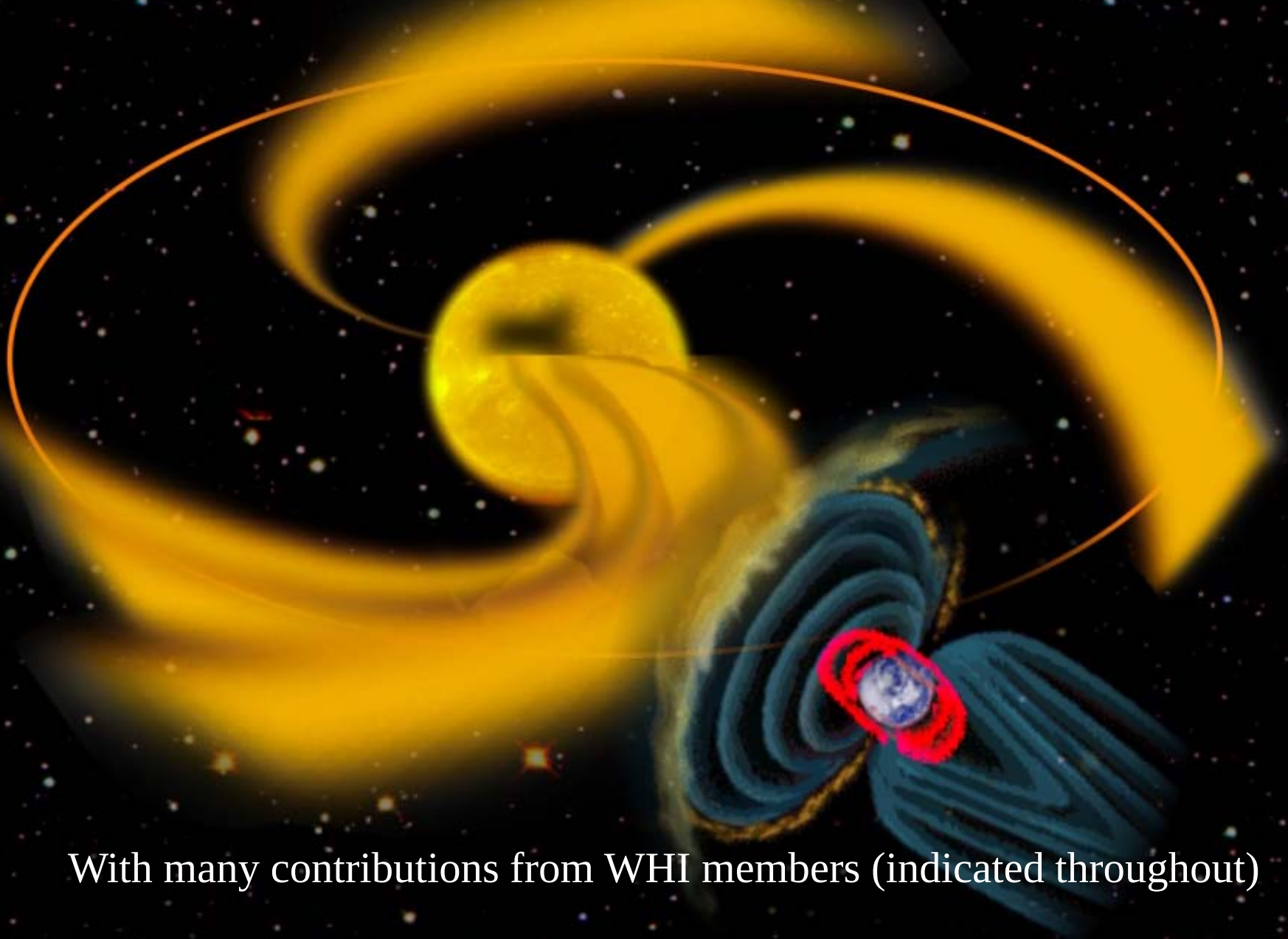


# A Multifaceted Minimum: from Sun to Earth in 2008-2009



Sarah Gibson

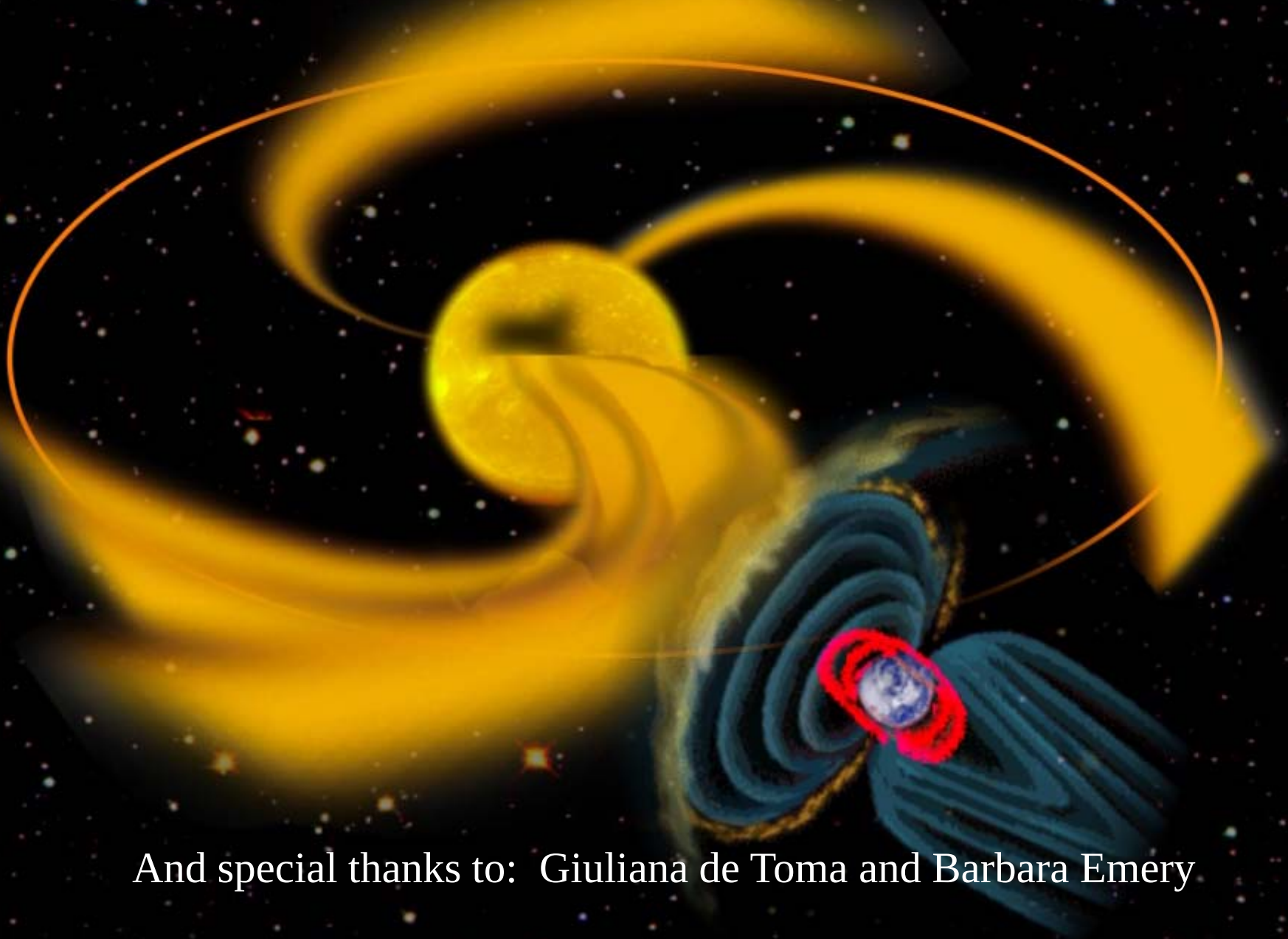
# A Multifaceted Minimum: from Sun to Earth in 2008-2009



With many contributions from WHI members (indicated throughout)



# A Multifaceted Minimum: from Sun to Earth in 2008-2009



And special thanks to: Giuliana de Toma and Barbara Emery



# Solar Minimum 2008-2009: Quiet, Complex, and Long

- 2008: A Deep Solar Minimum Begins...
  - *Whole Heliosphere Interval*
  - Sun Quiet but Complex
  - Heliosphere Still Ringing
- 2009: A Long Minimum Continues to Evolve..
  - Complexity Loses Coherence
  - Low-latitude Solar Open Flux Fades
  - Heliosphere Hits Bottom
- 2010: Activity Returns: Minimum is Over



# 2008

## Science News Headlines:

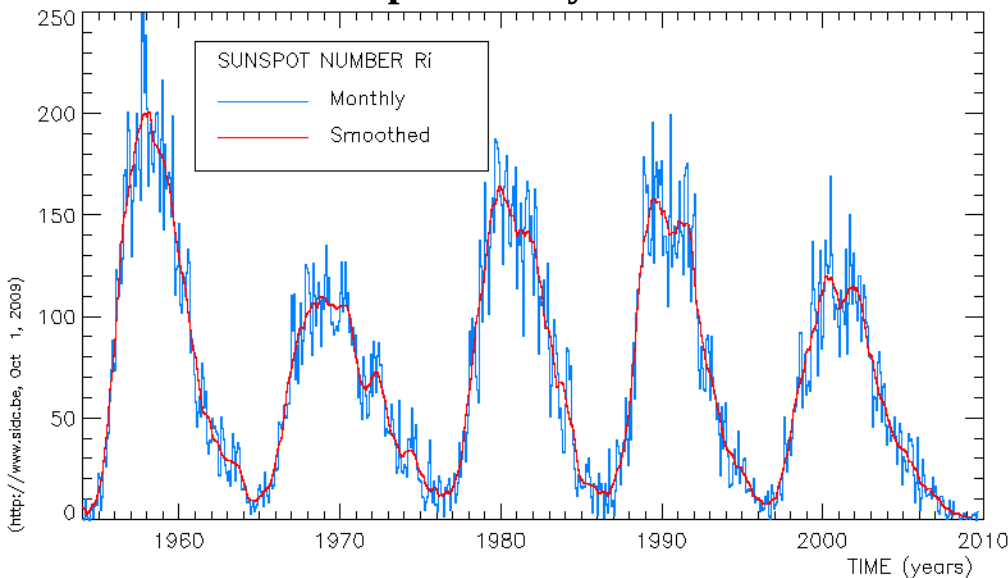
- "Blanket Year of the Space Age"
- "Solar Wind Loses Power, Hits 50-year Low"
- "Space Is Closer Than You Think!"



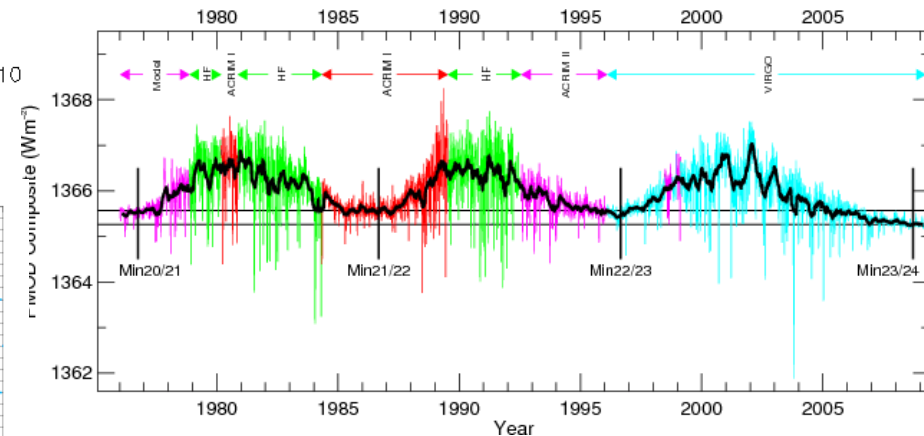
# Current solar minimum: unusually deep

**Sunspot Number: 2008 had 266 spotless days - most since 1913**

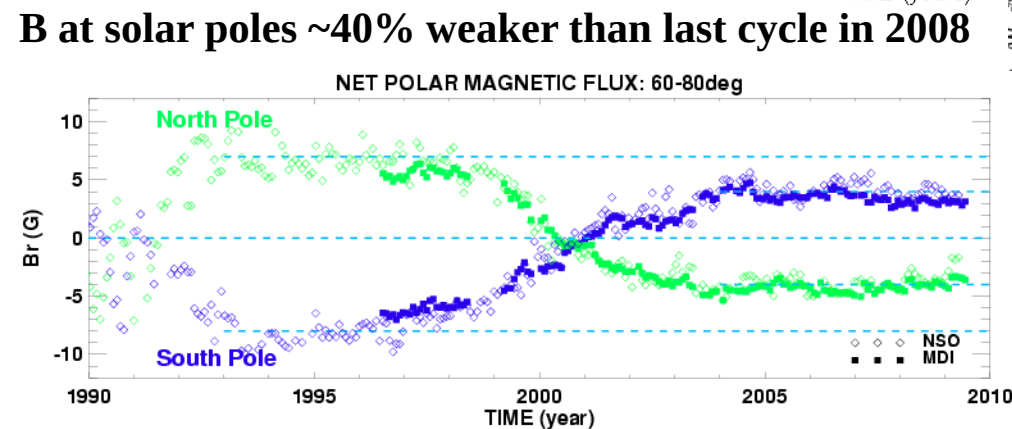
**At the Sun...**



**Solar irradiance: may be depleted relative to past minima** (note difference is still small relative to min-max variation)



Froelich, C, A&A, 501, L27, 2009

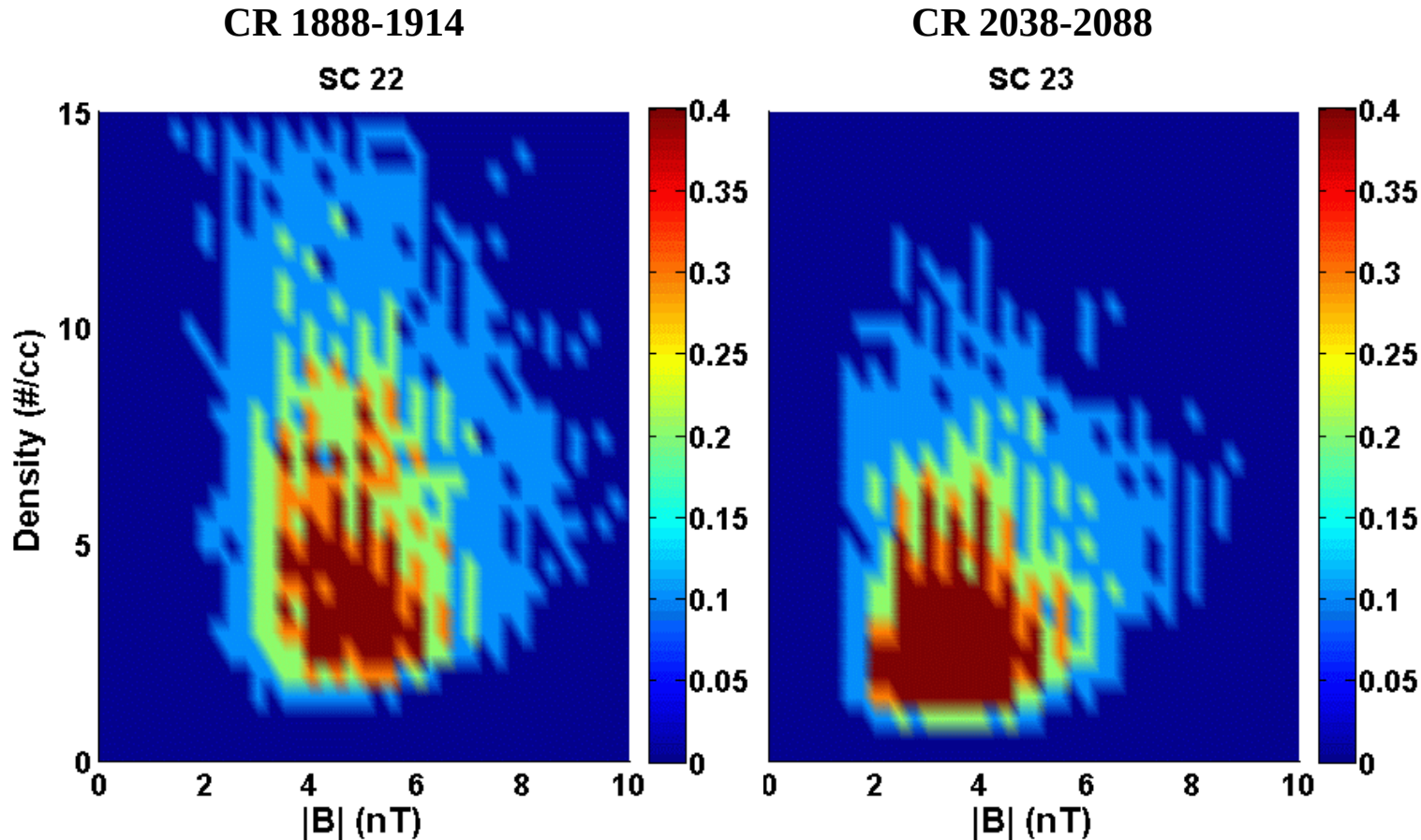


MDI data: Courtesy Giuliana de Toma



# Current solar minimum: unusually deep

In the solar wind...



Courtesy C. Lee et al., 2009: "The Observed Weaker Magnetic Flux of the Solar Cycle 23 Minimum Period ", in preparation".



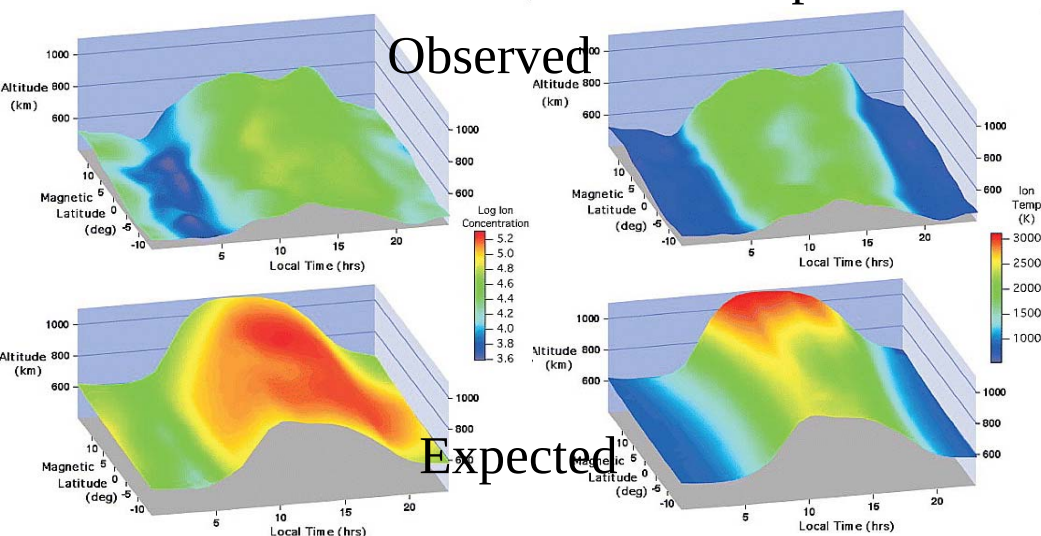


# Current solar minimum: unusually deep

**At the Earth.**

Ion concentration

Ion temperature

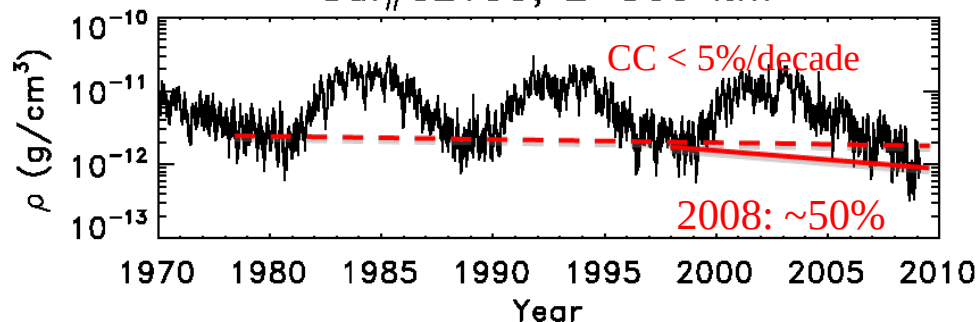


Earth's ionosphere thin and cool

Space "closer than you think" by about 100 miles (NASA-CINDI)

**Long-term satellite-drag data**

Sat#02150, Z=360 km



Earth's thermospheric density is ~10 times lower than can be accounted by climate change

Courtesy Stan Solomon, Tom Woods





# Whole Heliosphere Interval (WHI)

## Internationally coordinated observing and modeling effort

Focus on observations originating from **Carrington Rotation 2068**: March 20 - April 16, 2008

- **Synoptic observing programs:** Broad heliospheric coverage, provide context and baseline measurements
- **Targeted observing campaigns:** Coordinated observations run during CROT 2068
- Observational input from **27 solar, 19 heliospheric, and 21 geospace instruments**
- **~200 people** “officially registered”

## Science goals

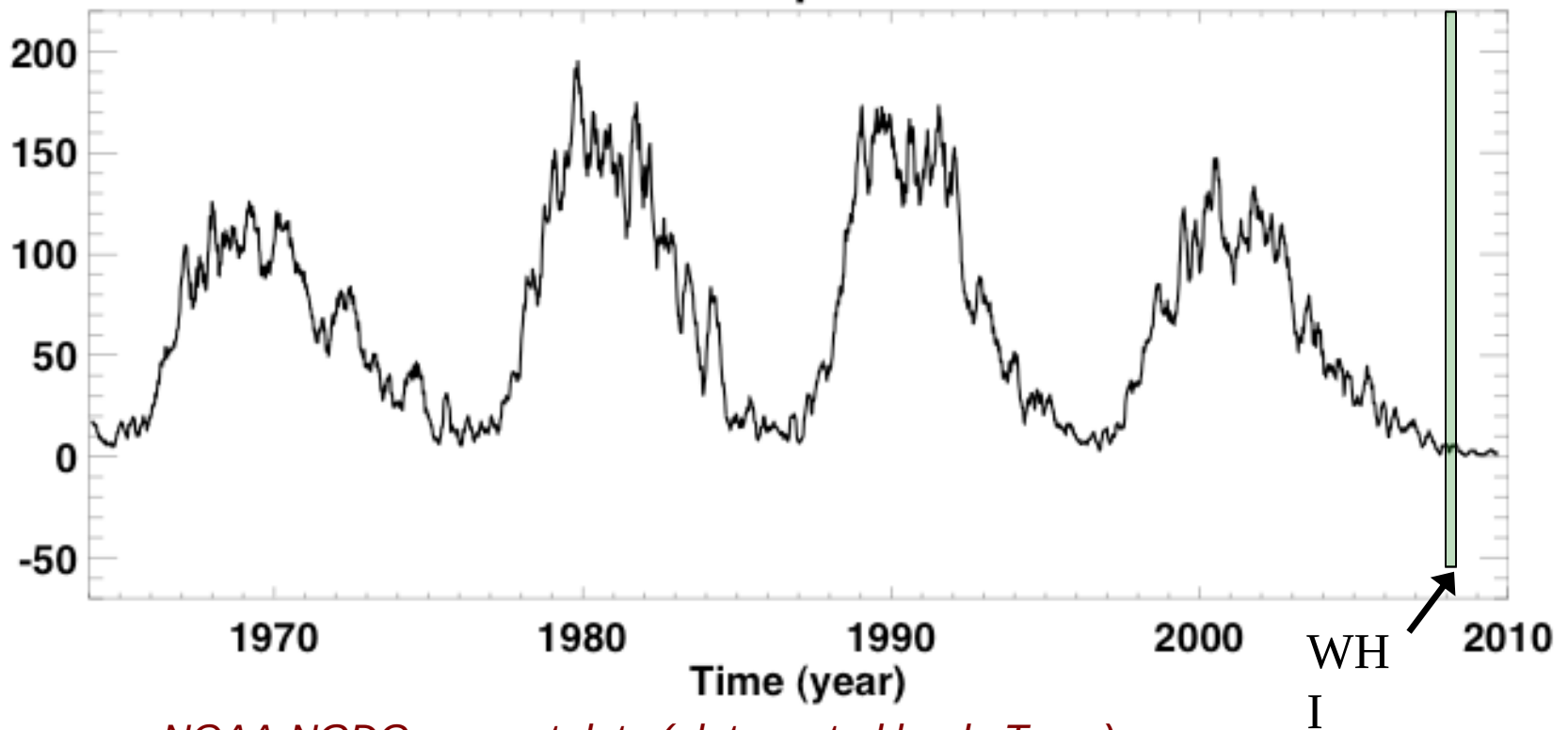
1. **Connect** the origins and effects of solar structure and activity through the solar wind to the Earth and other planetary systems
2. **Characterize** the 3-D solar minimum heliosphere



# Where WHI fits in to minimum....

Typical of the **early stage** of the recent minimum.

- WHI had minimum-level sunspot number



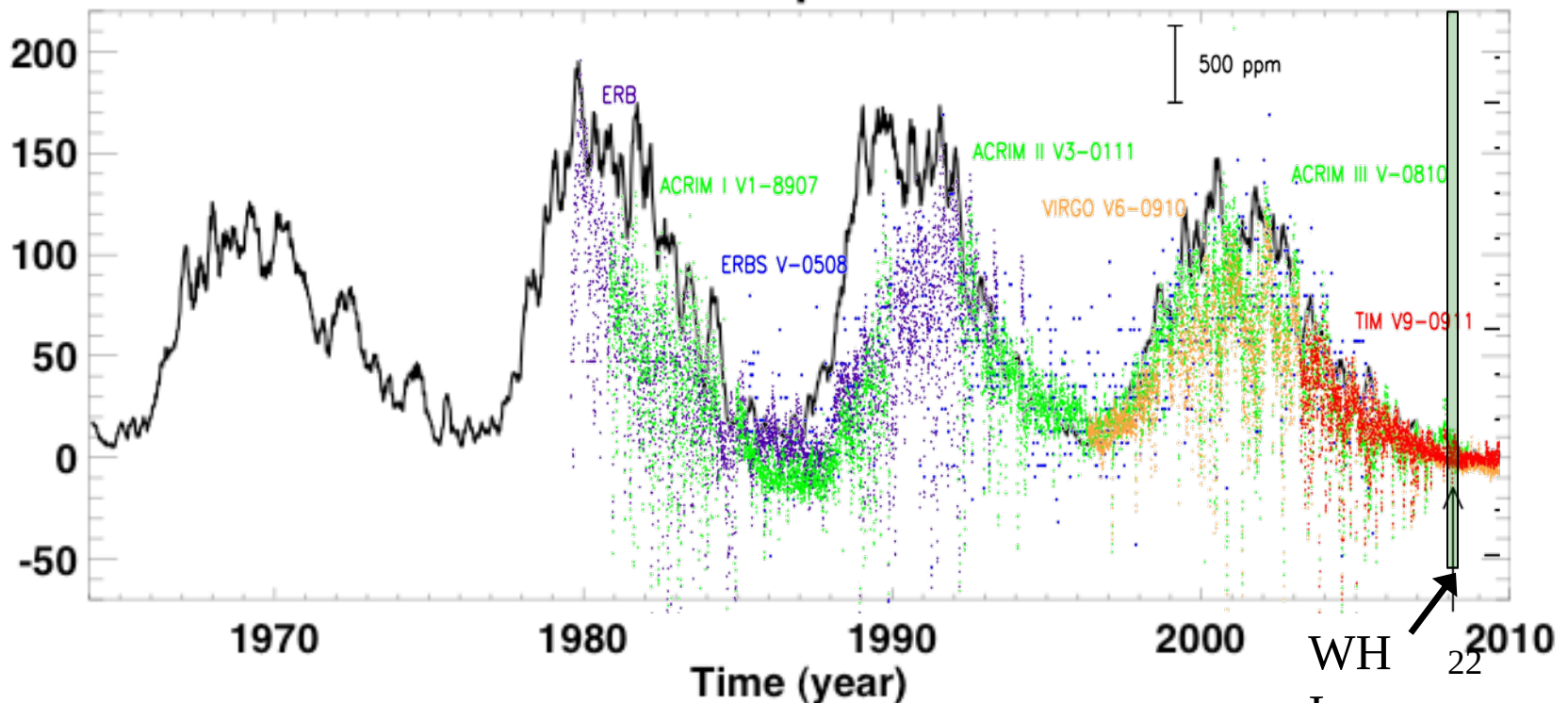
*NOAA-NGDC sunspot data (plot created by de Toma)*



# Where WHI fits in to minimum....

Typical of the **early stage** of the recent minimum.

- WHI had minimum-level irradiance



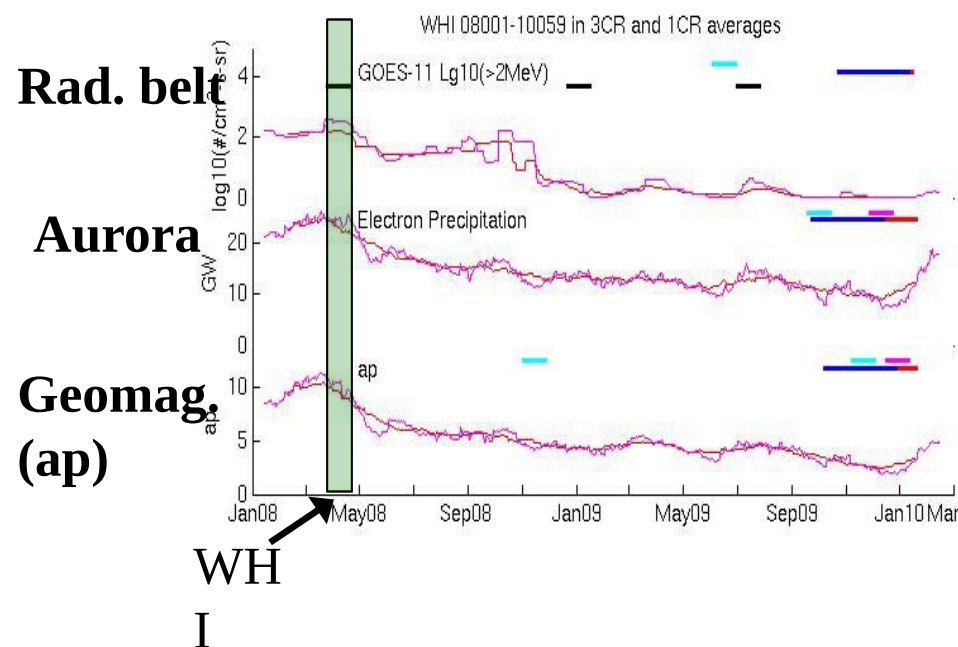
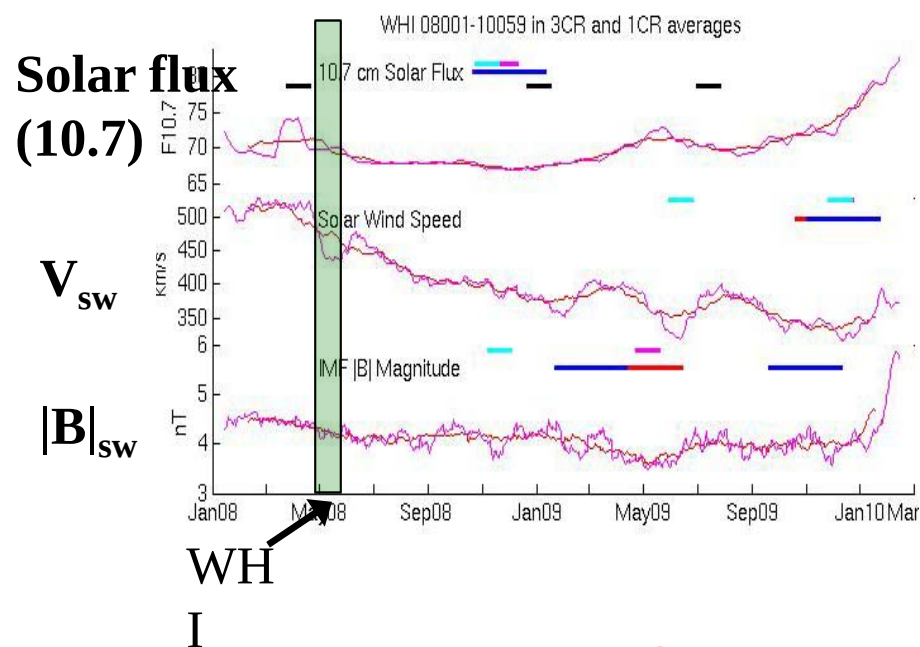
NOAA-NGDC sunspot data (Giuliana de Toma); Total solar irradiance composite (Greg Kopp)



# Where WHI fits in to minimum....

Typical of the **early stage** of the recent minimum.

- WHI solar wind speed, radiation belt population, and auroral/geomagnetic activity **still high** at the Earth during WHI compared to eventual minima (late in 2009)



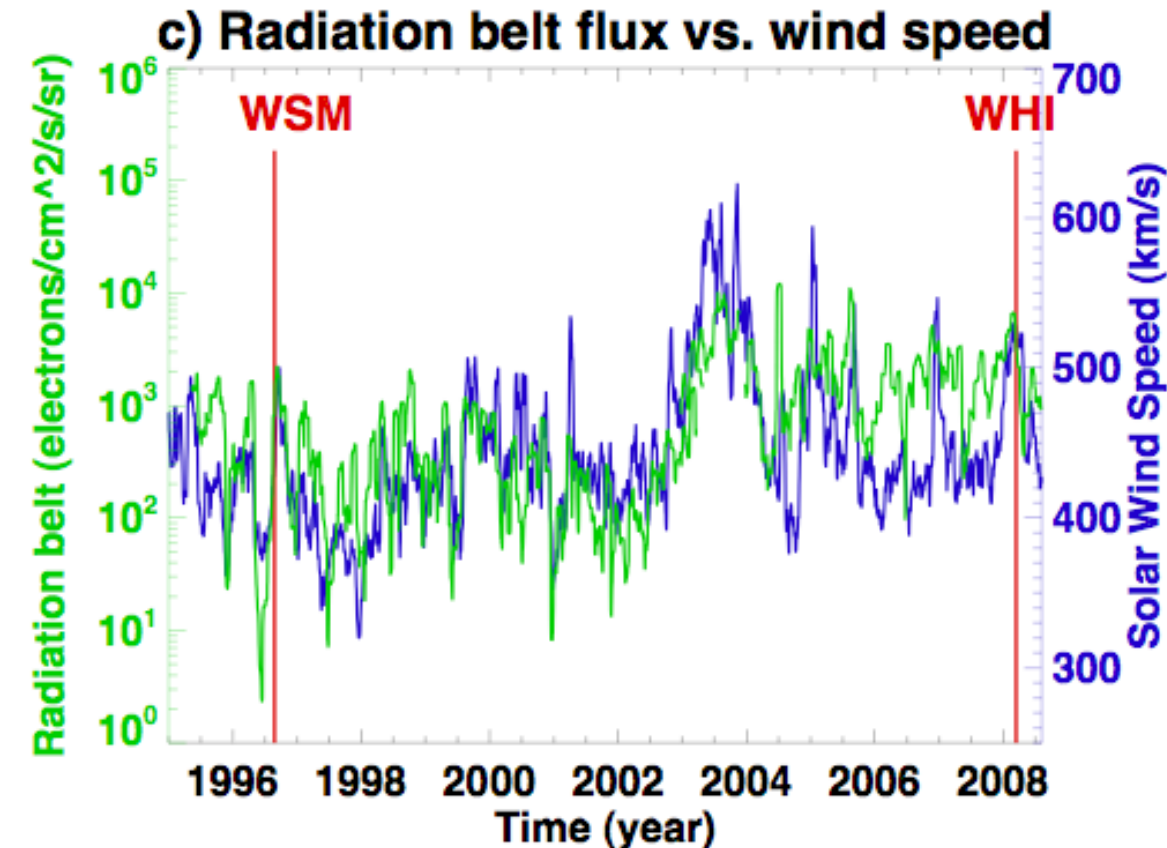
Courtesy Barbara Emery





# Where WHI fits in to minima in general!

- Wind speed and radiation belt flux **high compared to prior minimum**, too!



Solar wind speed at Earth

- **13% increase**

Radiation belt flux

- **340 % increase (71% log)**

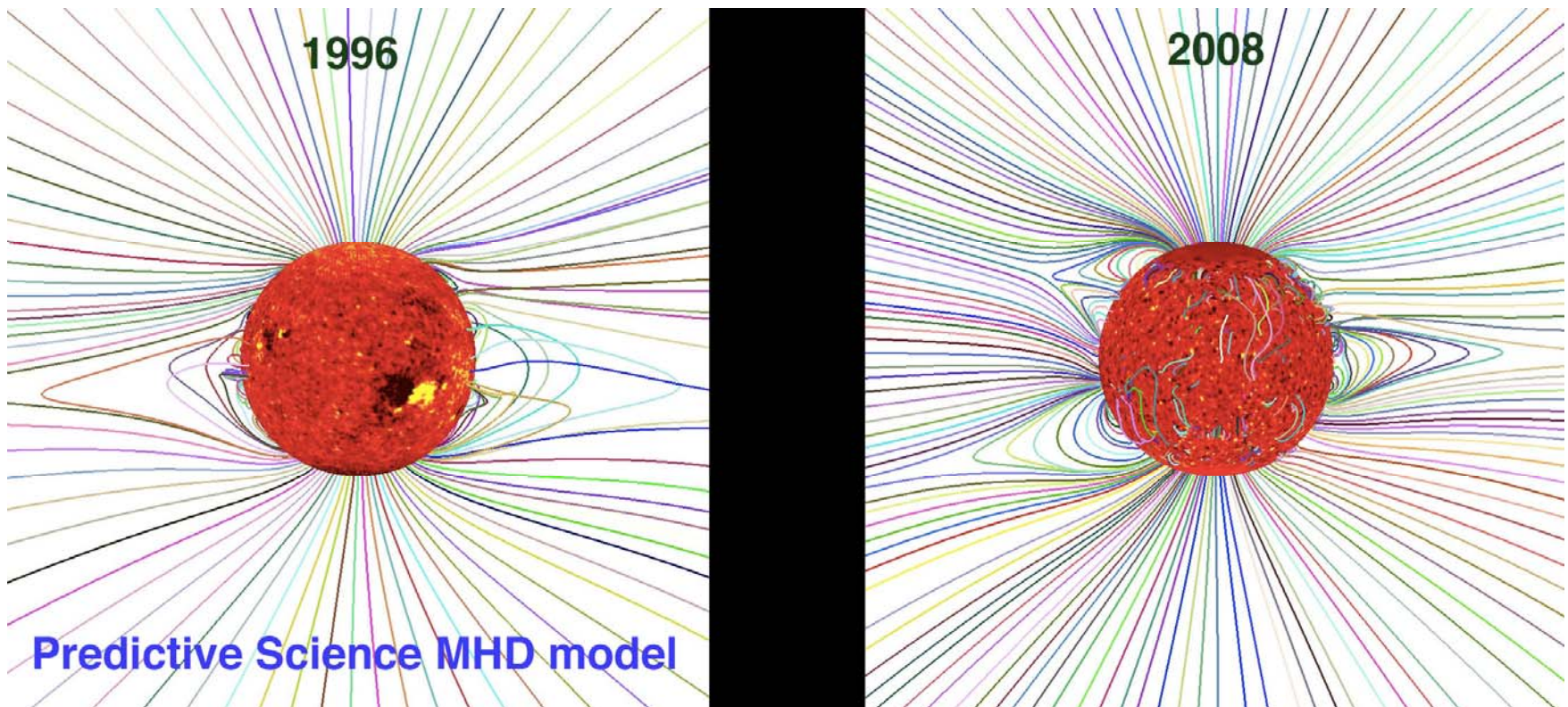
*Gibson et al., JGR, 114, A09105, 2009*



# Current solar minimum: unusually complex

## At the Sun...

More open magnetic flux at low latitudes in 2008 than in 1996; less dipolar.

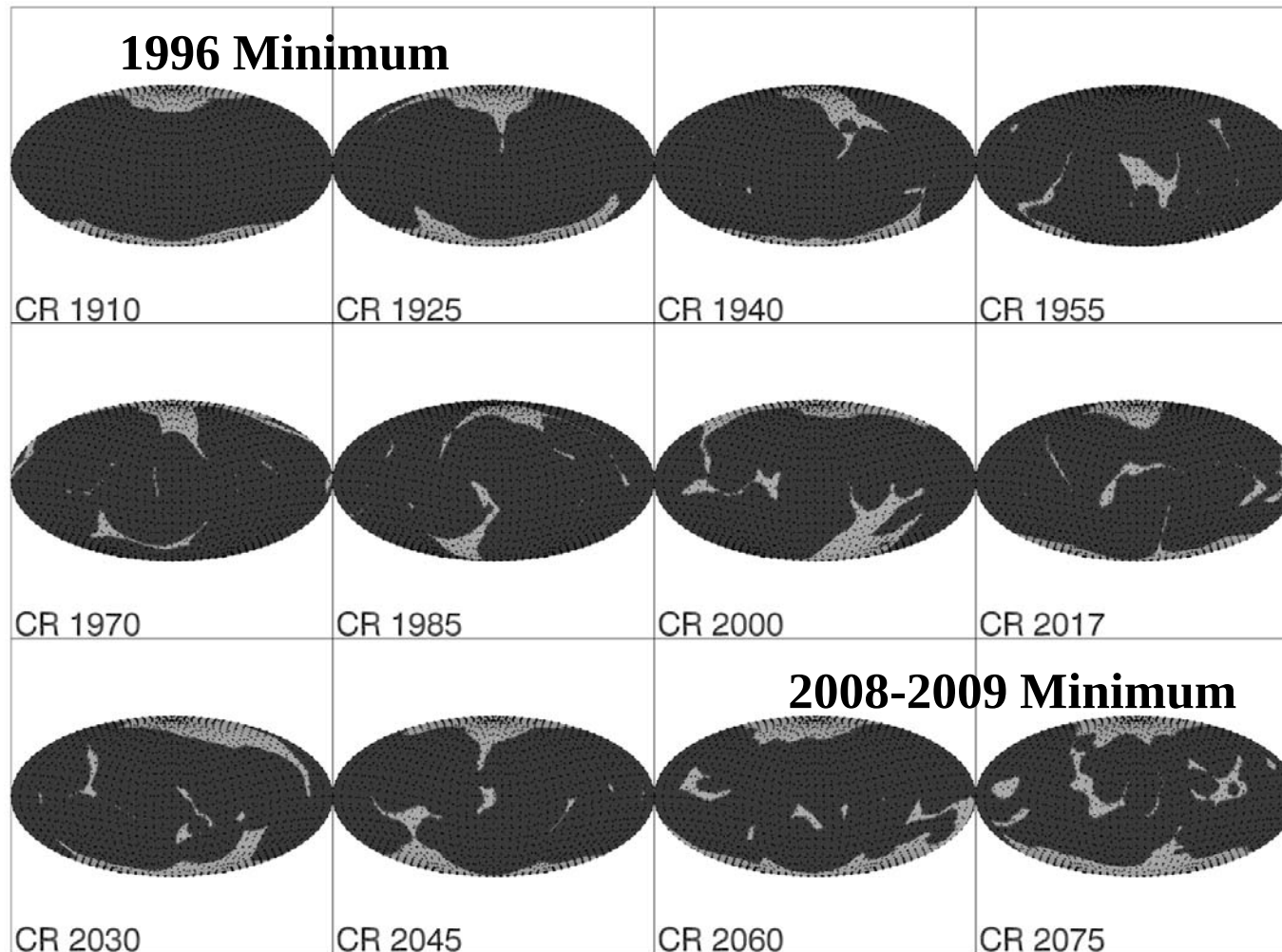




# Current solar minimum: unusually complex

At the Sun...

More low-latitude open flux – coronal holes



MAS coronal MHD model, open field line footpoint area

Courtesy Pete Riley



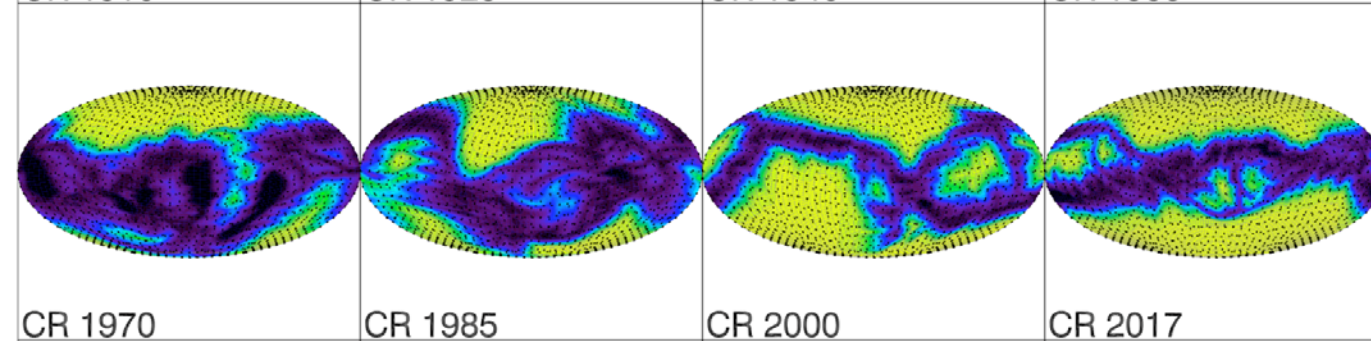
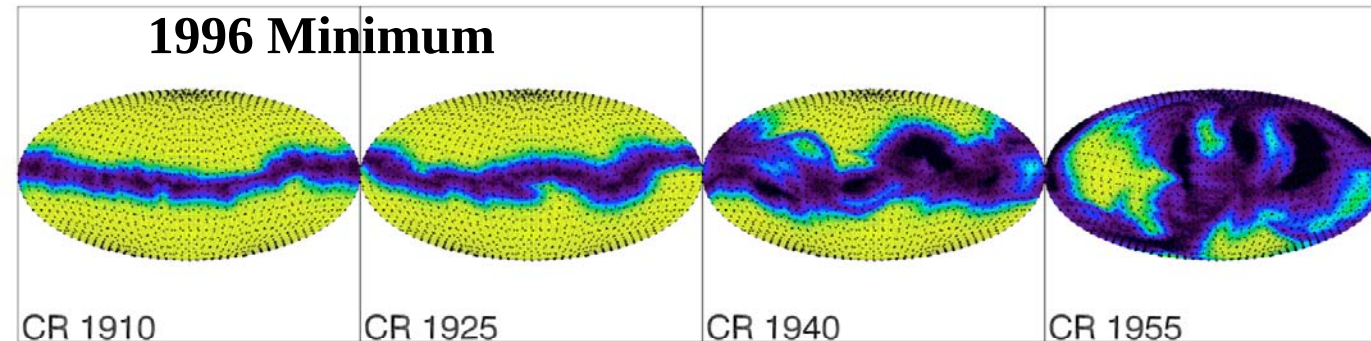


# Current solar minimum: unusually complex

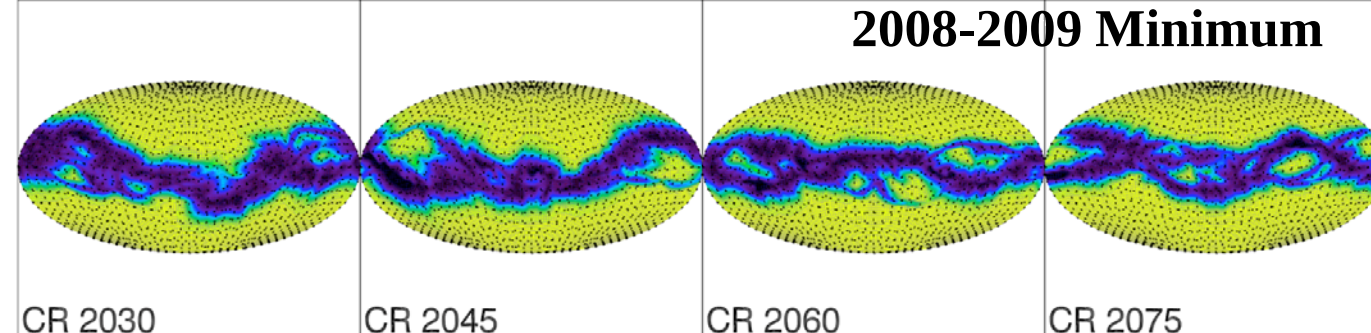
In the solar wind...

Warped heliospheric current sheet (HCS) and fast wind streams at low latitudes

## 1996 Minimum



## 2008-2009 Minimum



MAS coronal MHD model, solar wind speed at 30 R<sub>sun</sub>

Courtesy Pete Riley

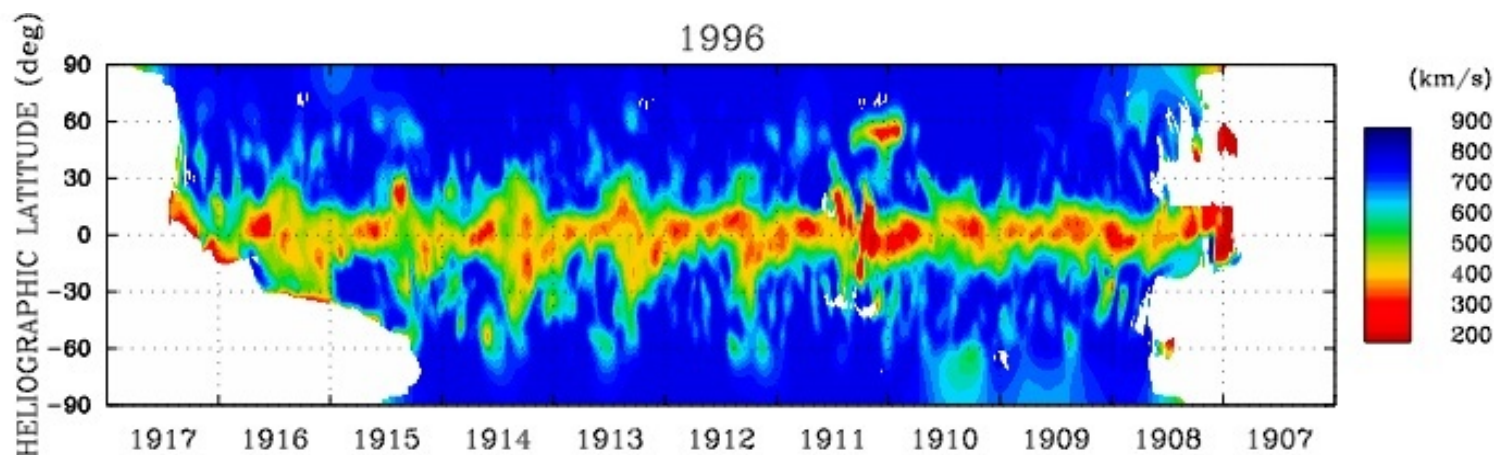


# Current solar minimum: unusually complex

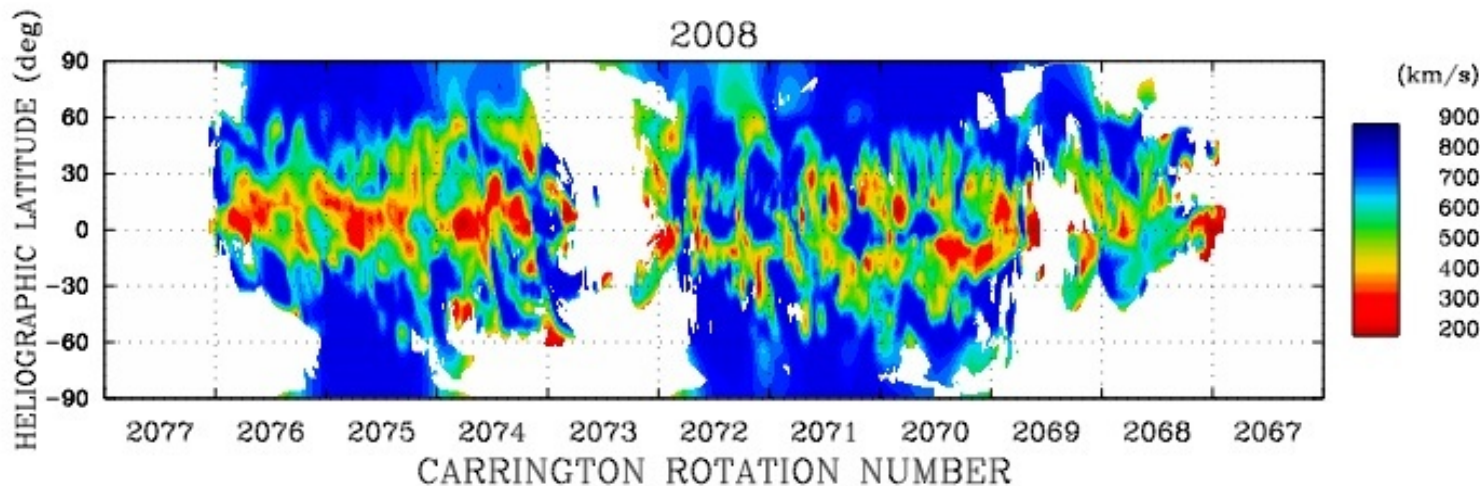
In the solar wind...

**Fast wind threads the ecliptic more commonly in 2008 than 1996.**

Solar wind  
velocity from  
STEL  
interplanetary  
scintillation data



a.





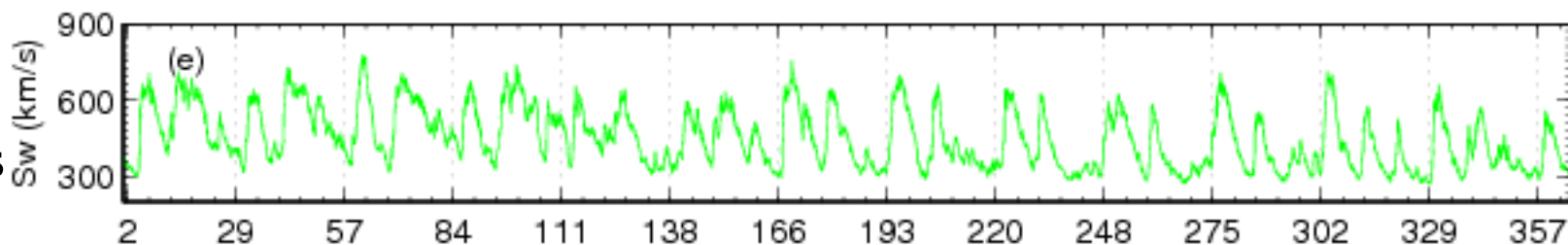


# Current solar minimum: unusually complex

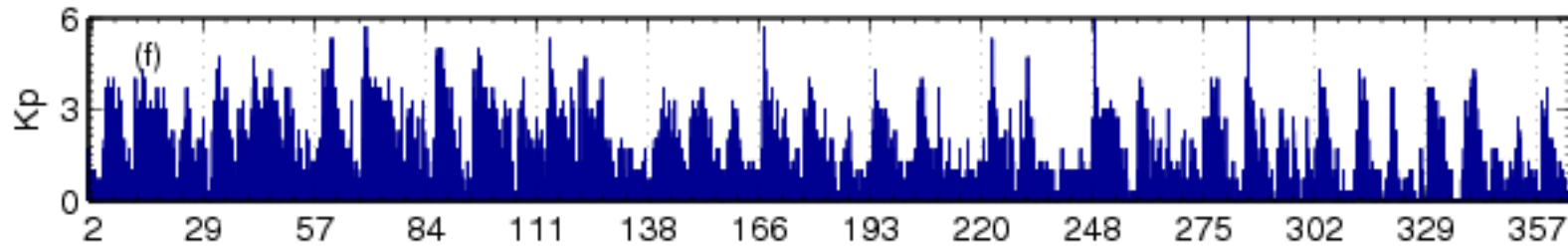
At the Earth...

Geospace was periodically driven **throughout 2008**

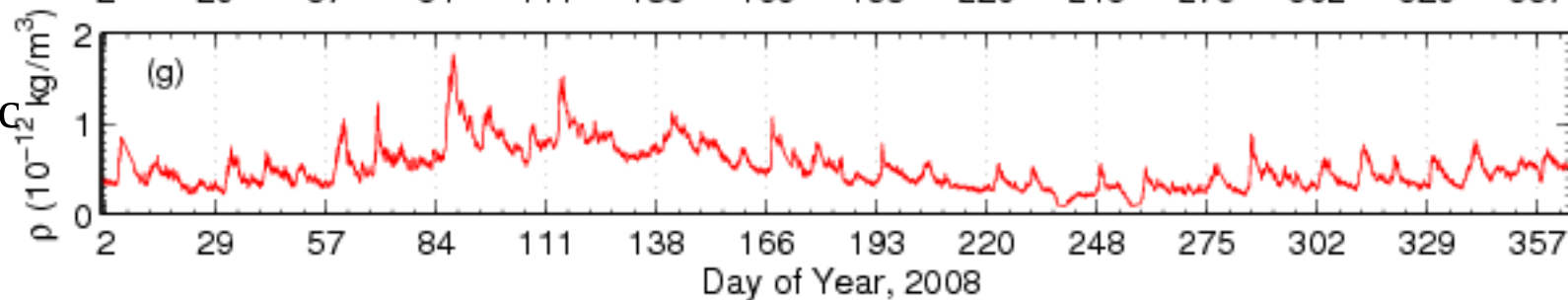
High-speed  
wind streams



Geomagnetic  
index Kp



Thermospheric  
density



Courtesy Jiuhou Lei



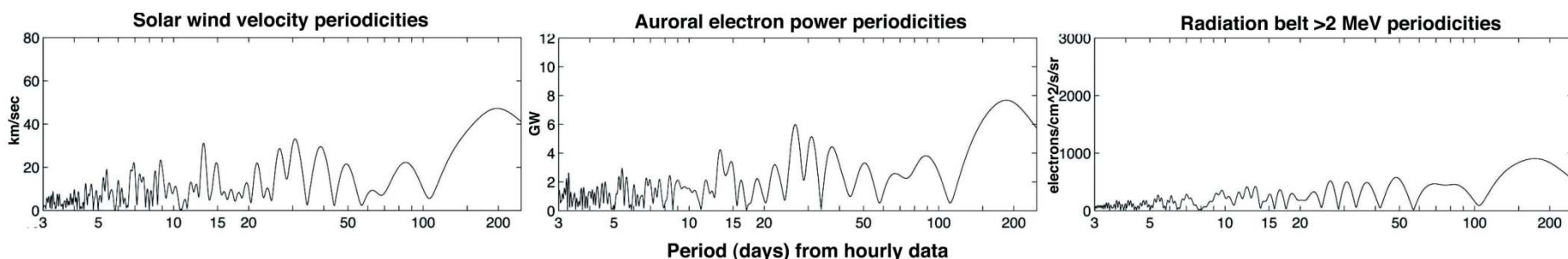
# Current solar minimum: unusually complex

**At the Earth.**

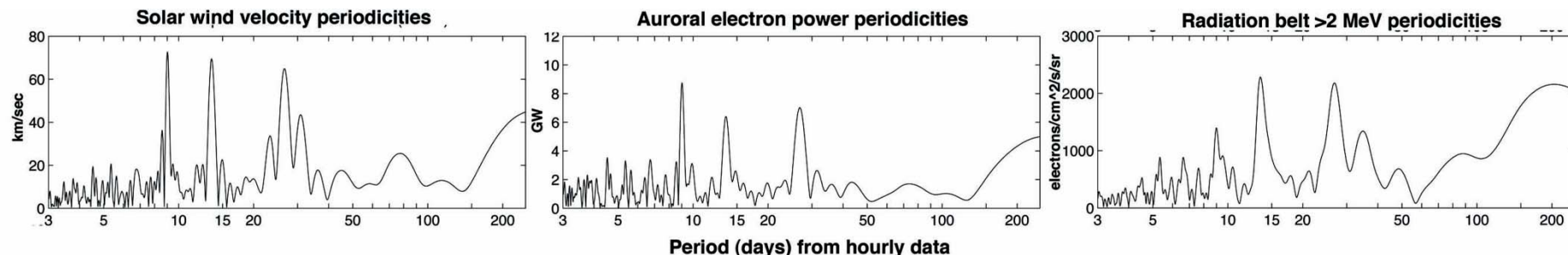
Periodicities (9, 13, 27 day) of wind → periodicities in aurora and radiation belt

**The Earth was ringing for most of 2008**

**WSM (1996)**



**WHI (2008)**

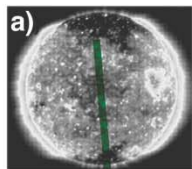


Periodicities determined for 9-months around WSM and WHI

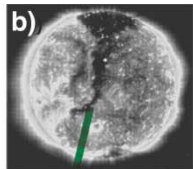


# End to end during WHI: analysis

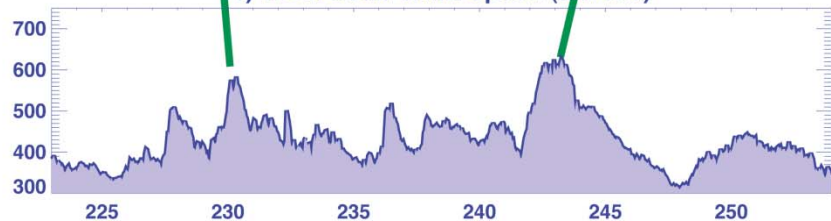
WHI: longitudinally-extended coronal holes -> long and strong HSS



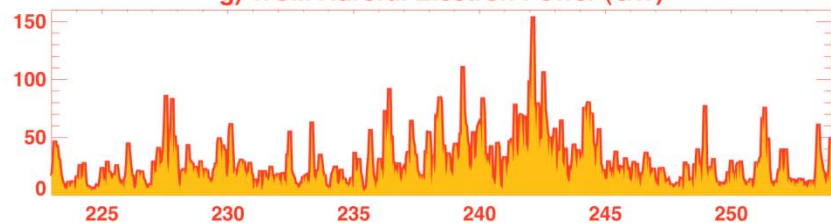
1996



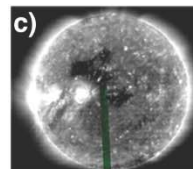
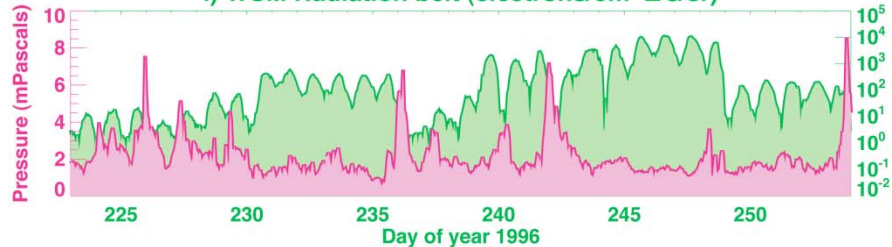
e) WSM Solar Wind Speed (km/sec)



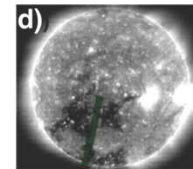
g) WSM Auroral Electron Power (GW)



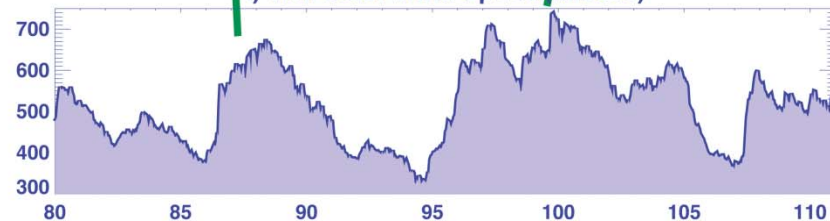
i) WSM Radiation belt (electrons/cm<sup>2</sup>/s/sr)



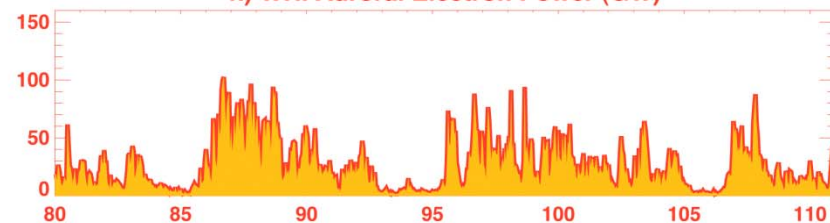
2008



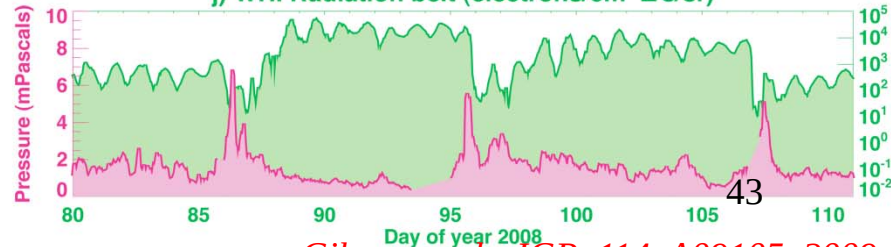
f) WHI Solar Wind Speed (km/sec)



h) WHI Auroral Electron Power (GW)



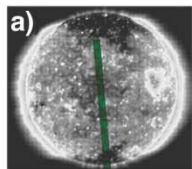
j) WHI Radiation belt (electrons/cm<sup>2</sup>/s/sr)



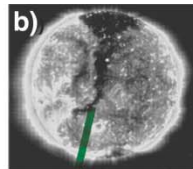


# End to end during WHI: analysis

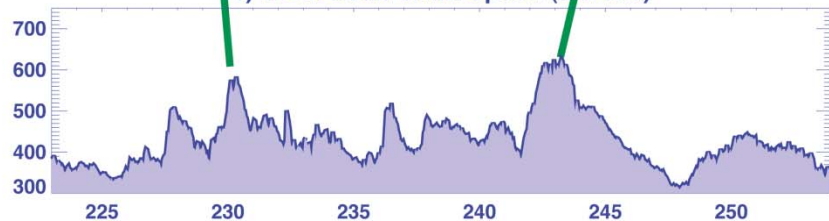
Auroral power correlates to  $B \cdot V$



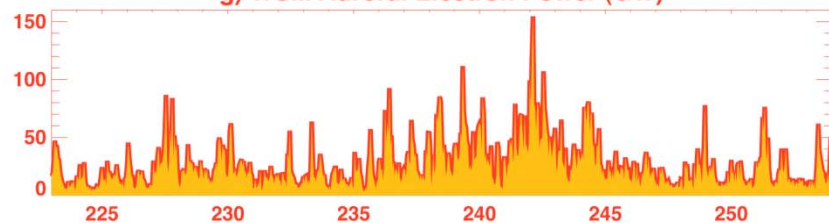
1996



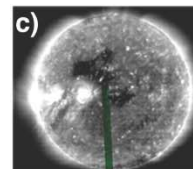
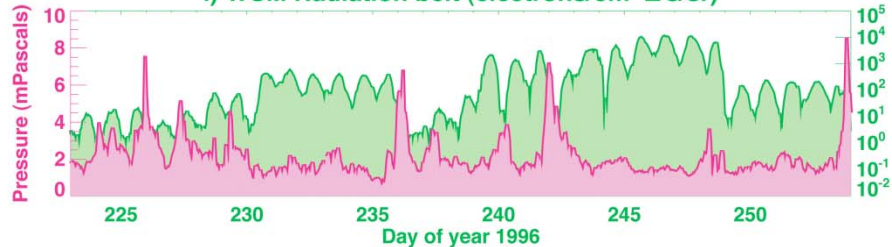
e) WSM Solar Wind Speed (km/sec)



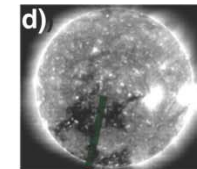
g) WSM Auroral Electron Power (GW)



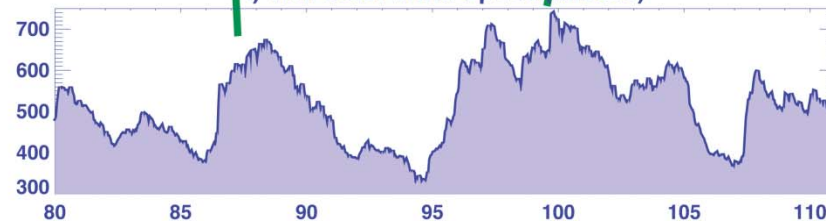
i) WSM Radiation belt (electrons/cm<sup>2</sup>/s/sr)



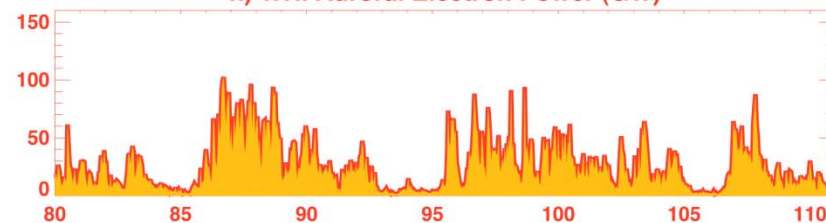
2008



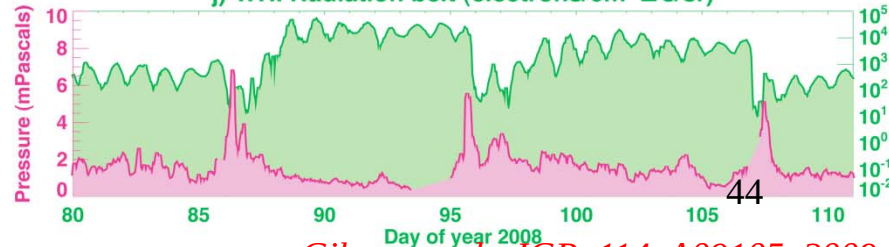
f) WHI Solar Wind Speed (km/sec)



h) WHI Auroral Electron Power (GW)



j) WHI Radiation belt (electrons/cm<sup>2</sup>/s/sr)

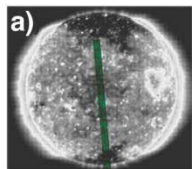




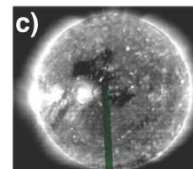
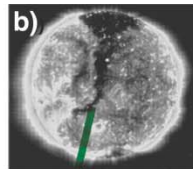


# End to end during WHI: analysis

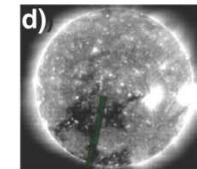
WHI: clearly modulated (but weak) aurora



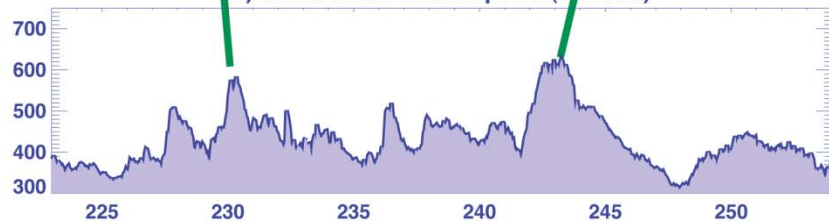
1996



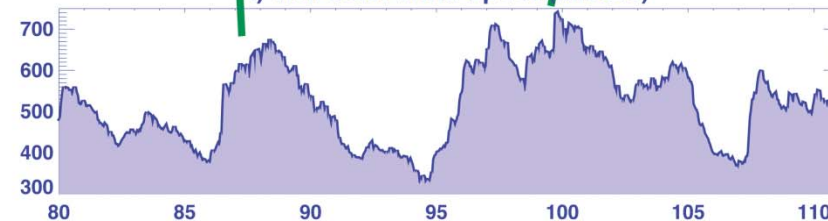
2008



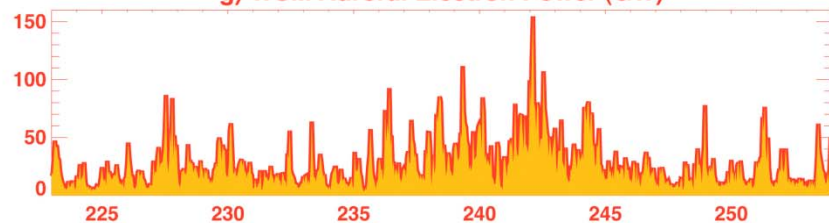
e) WSM Solar Wind Speed (km/sec)



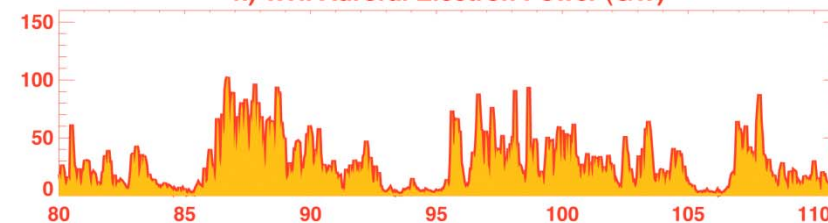
f) WHI Solar Wind Speed (km/sec)



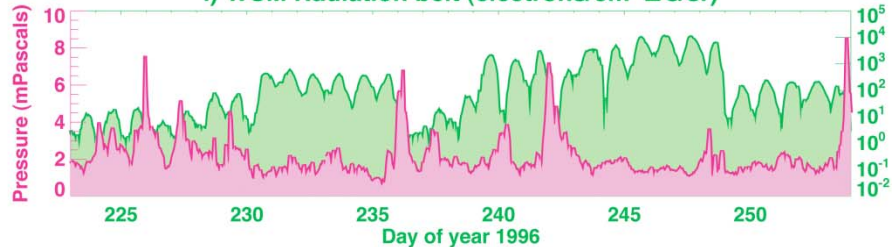
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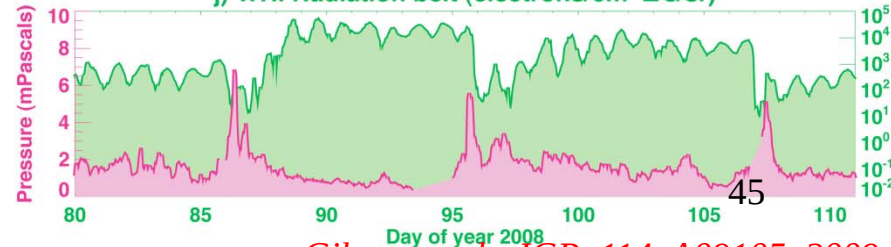
h) WHI Auroral Electron Power (GW)



i) WSM Radiation belt (electrons/cm<sup>2</sup>/s/sr)



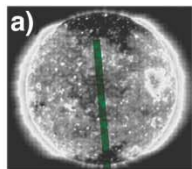
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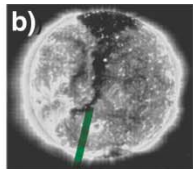


# End to end during WHI: analysis

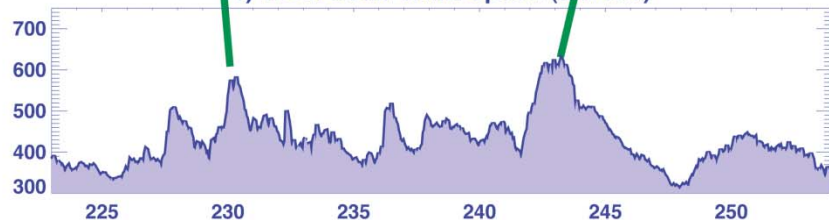
Solar wind primary driver of radiation belt (1-2 day lag)



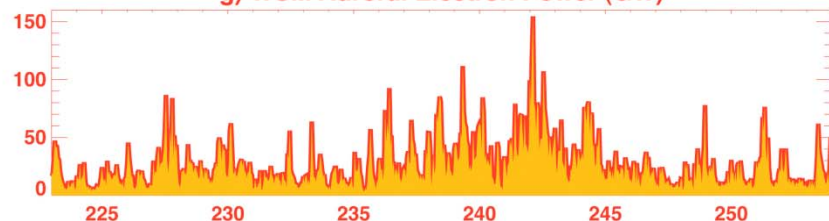
1996



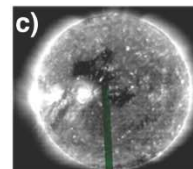
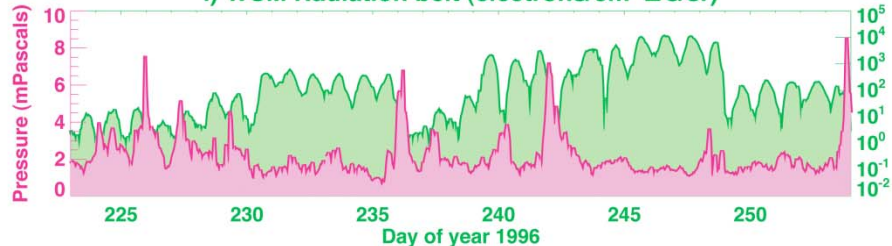
e) WSM Solar Wind Speed (km/sec)



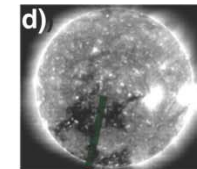
g) WSM Auroral Electron Power (GW)



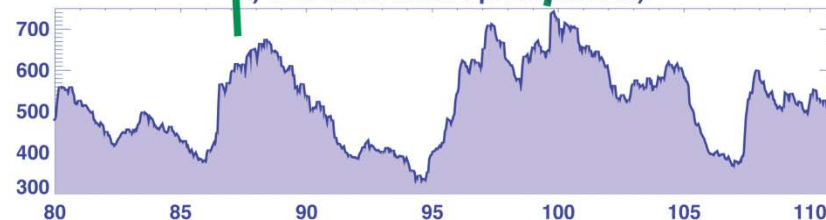
i) WSM Radiation belt (electrons/cm<sup>2</sup>/s/sr)



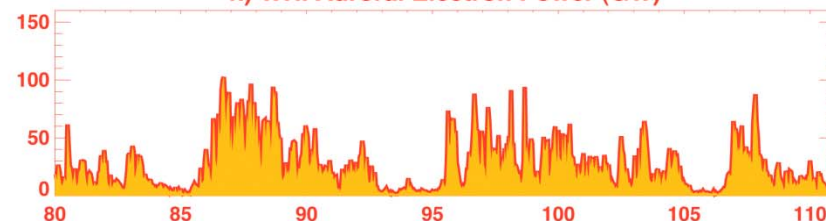
2008



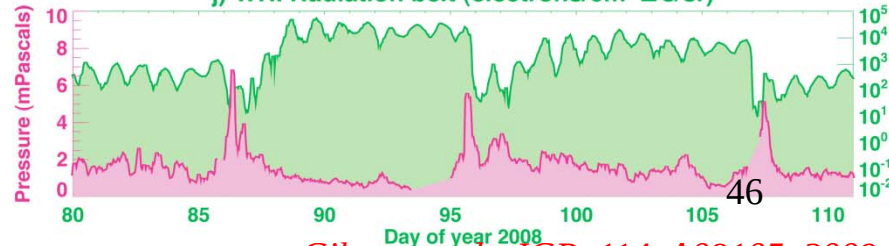
f) WHI Solar Wind Speed (km/sec)



h) WHI Auroral Electron Power (GW)



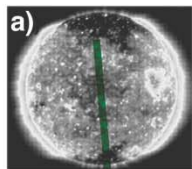
j) WHI Radiation belt (electrons/cm<sup>2</sup>/s/sr)



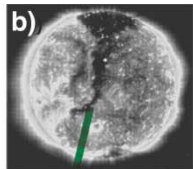


# End to end during WHI: analysis

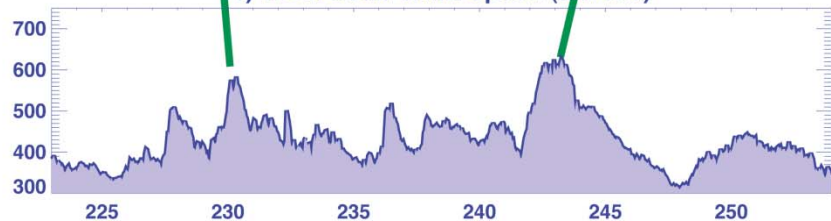
WHI: clearly modulated and enhanced radiation belt



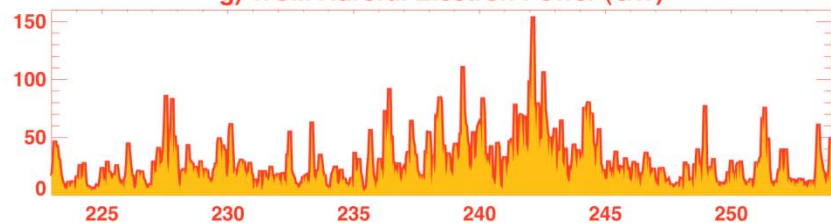
1996



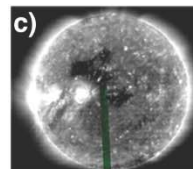
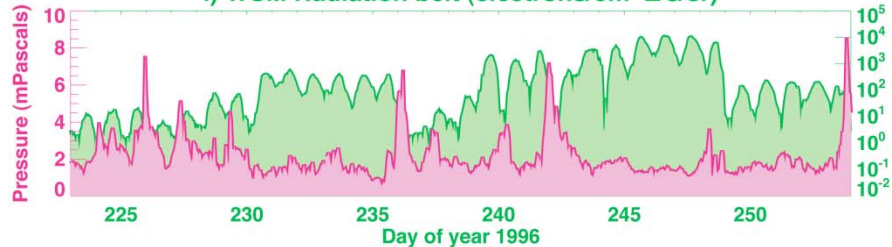
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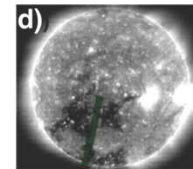
g) WSM Auroral Electron Power (GW)



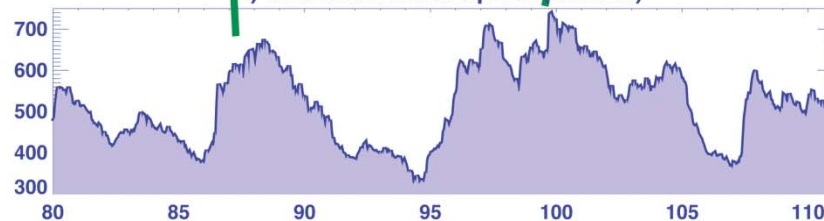
i) WSM Radiation belt (electrons/cm<sup>2</sup>/s/sr)



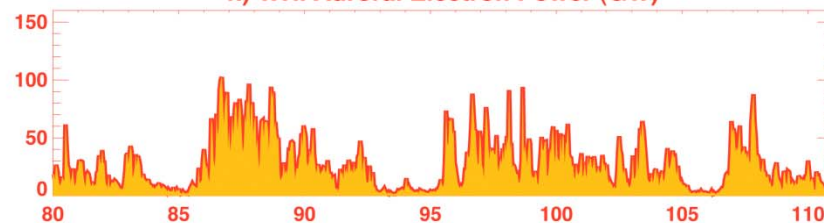
2008



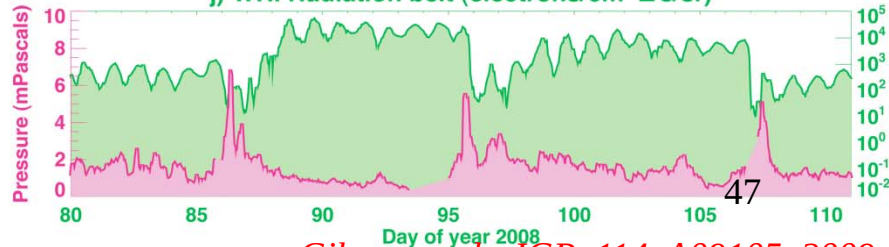
f) WHI Solar Wind Speed (km/sec)



h) WHI Auroral Electron Power (GW)



j) WHI Radiation belt (electrons/cm<sup>2</sup>/s/sr)





# 2009

## Science News Headlines:

- “Deep Solar Minimum”
- “Are Sunspots Disappearing?”
- “Cosmic Rays Hit Space-Age high”



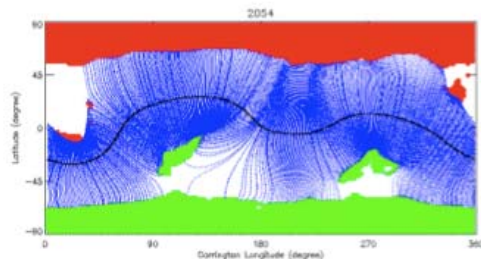


# Current solar minimum: evolution

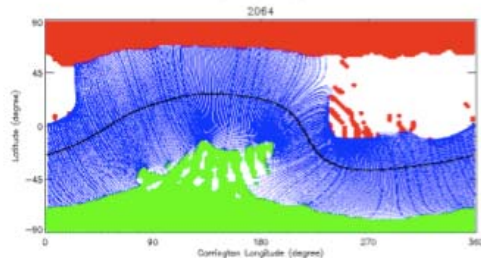
## At the Sun...

*GONG synoptic polarity maps from CR 2054 – 2083.*

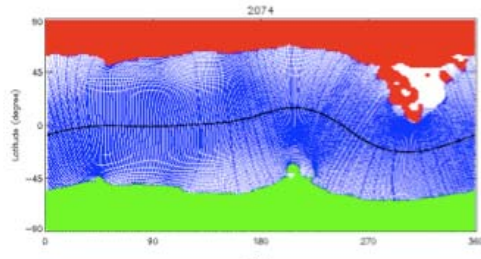
Towards the end of 2008, large low-latitude coronal holes disappeared, and HCS flattened



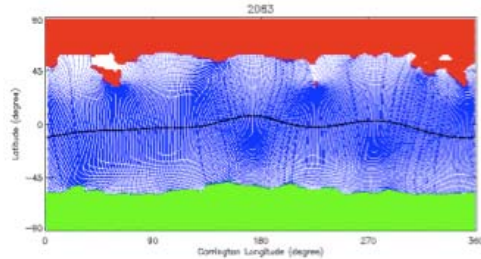
2054  
Feb. 07



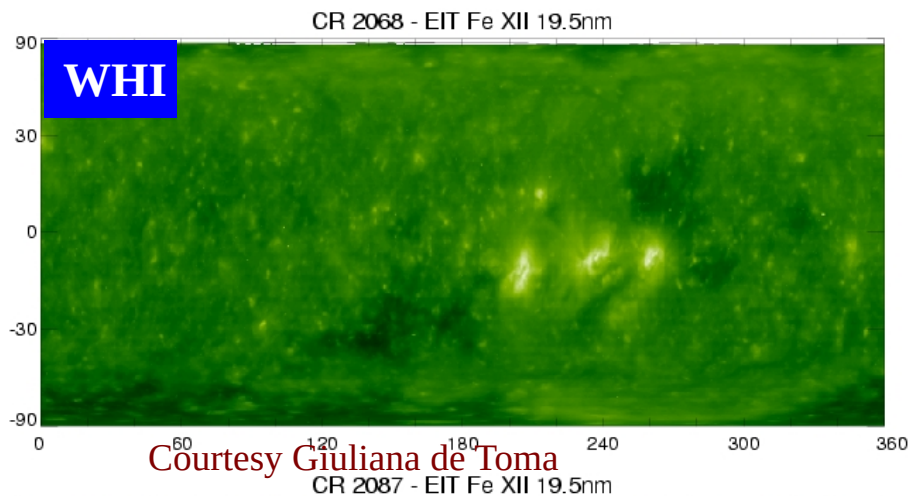
2064  
Dec. 07



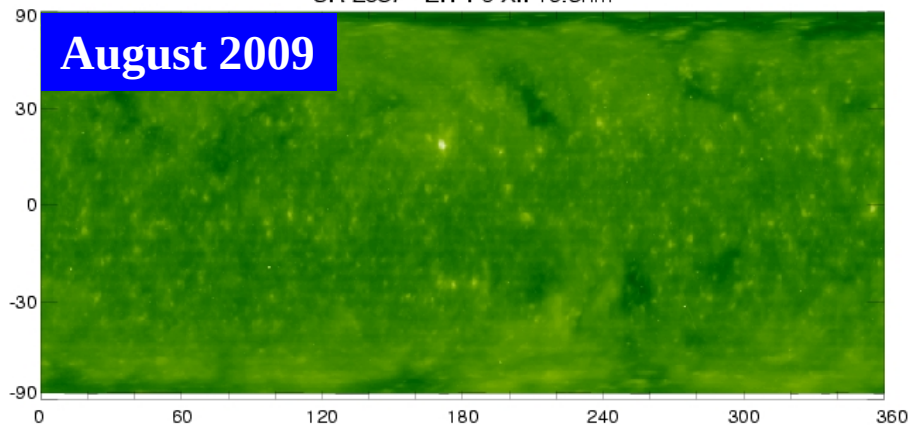
WHI  
2074  
Sep. 08



2083  
May 09



Courtesy Giuliana de Toma



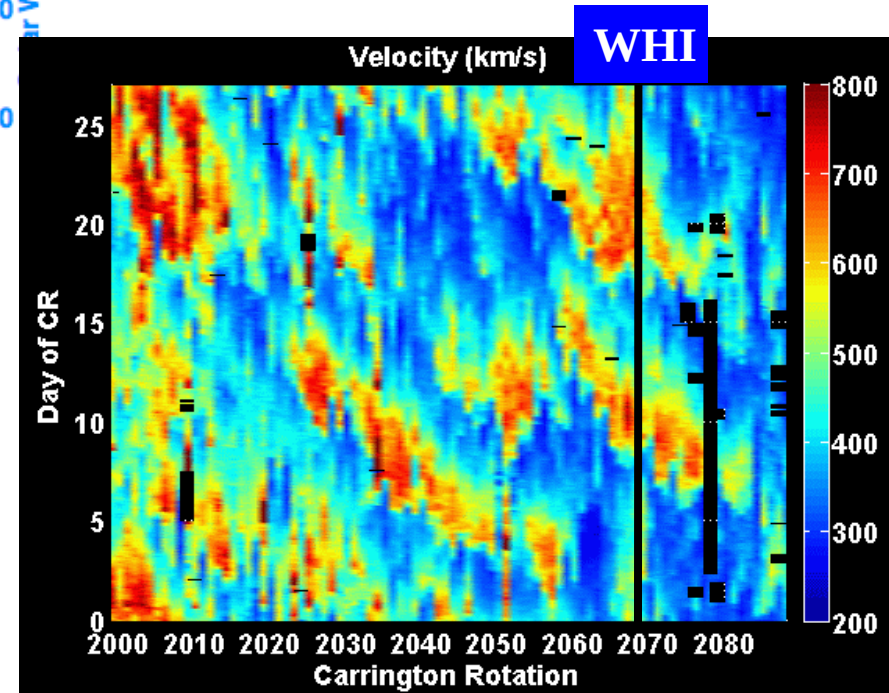
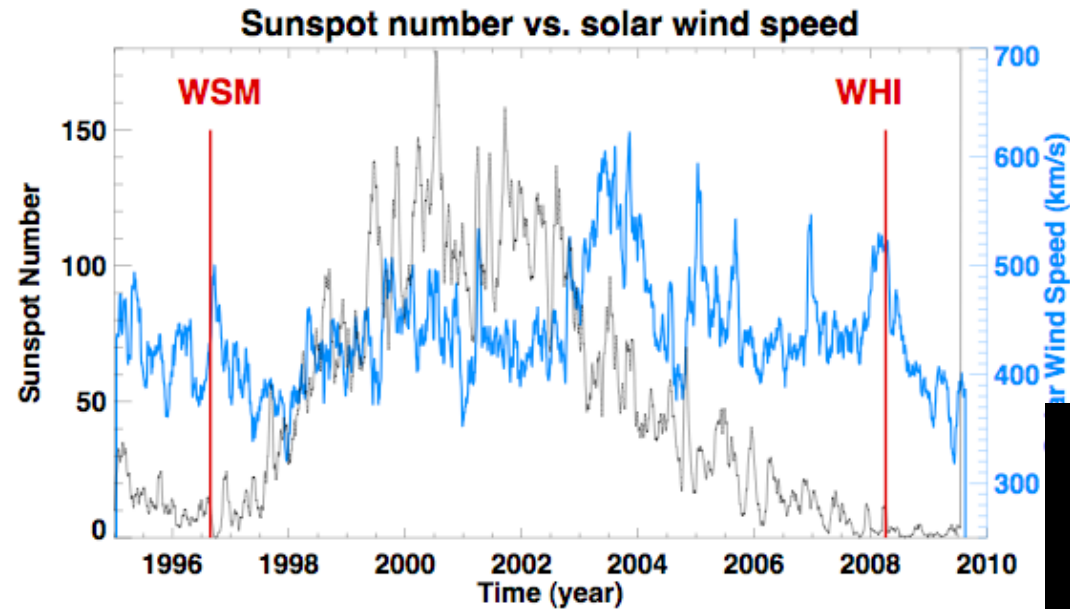
Note some small mid-latitude coronal holes are present: More on that in a moment.



# Current solar minimum: evolution

In the wind...

As low-latitude coronal holes diminished, **high-speed streams tapered off**



*Courtesy C. Lee et al., 2009: "Organization of Energetic Particles by the Solar Minimum Phase of Solar Cycle 23", in preparation".*

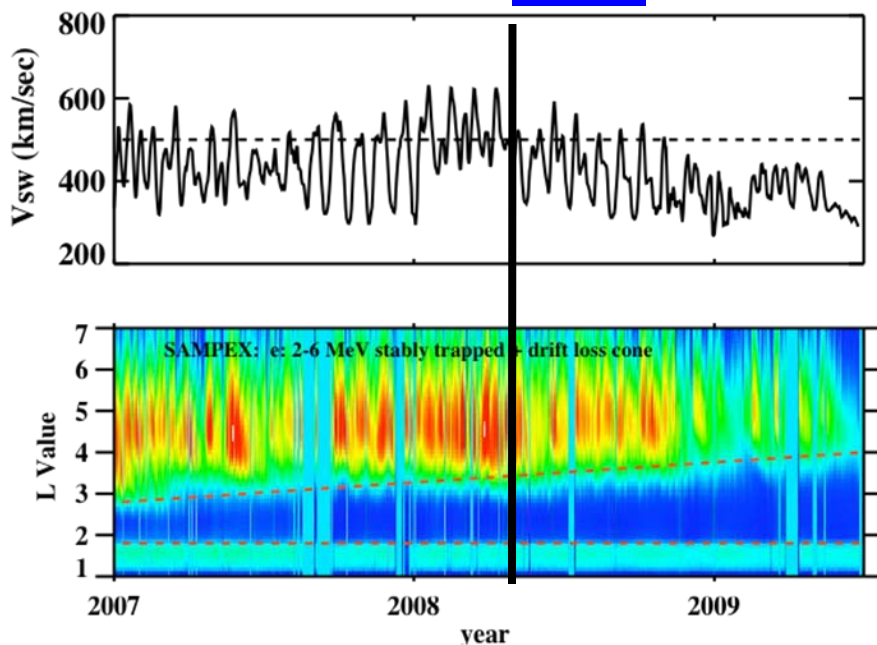


# Current solar minimum: evolution

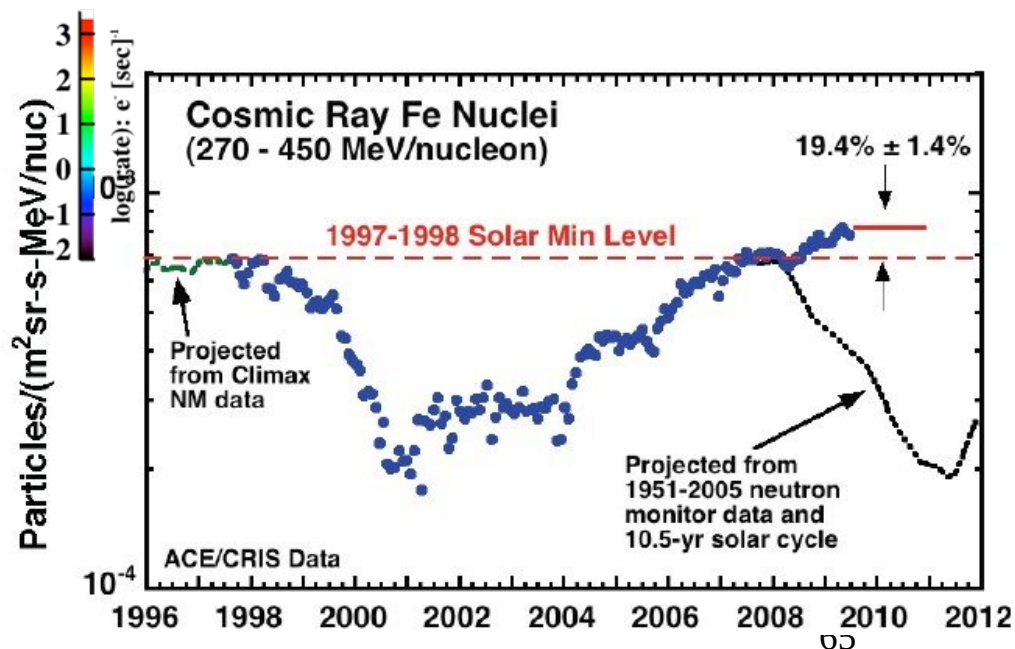
As the high-speed streams disappeared, **radiation belts fell to record lows**, and **cosmic rays reached record highs**

WHI

At the Earth.



Courtesy Dan Baker



Courtesy Dick Mewaldt

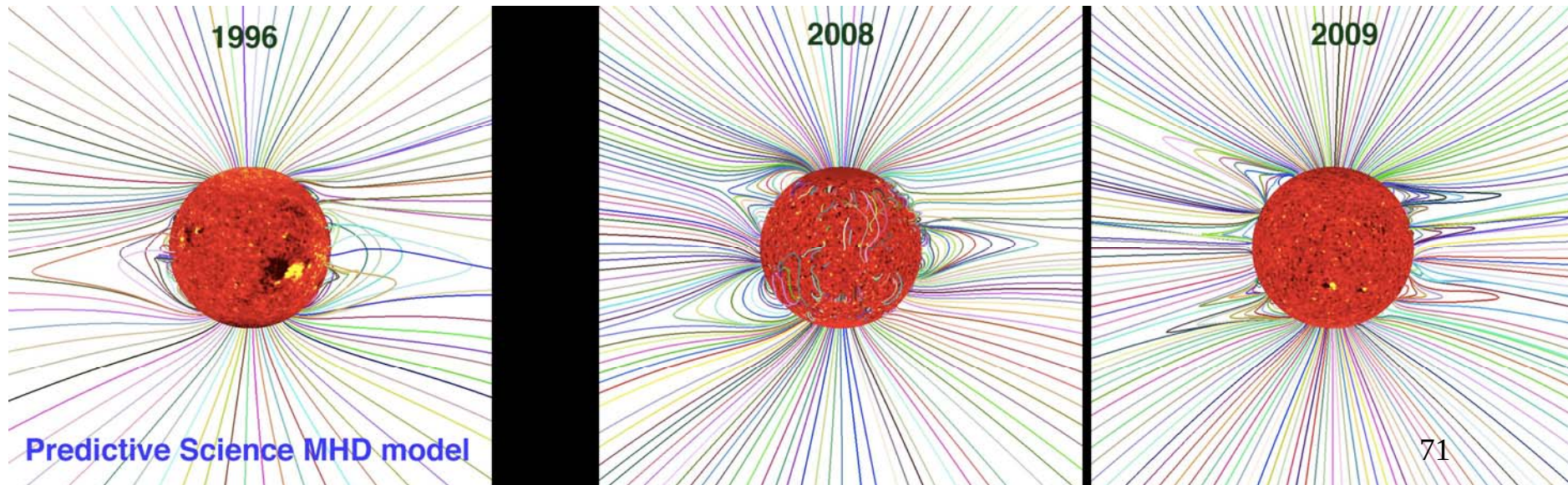




# Current solar minimum: evolution

However, the disappearance of large, low-latitude coronal holes in 2009 did not mean that the global field became completely dominated by the dipole as in 1996.

On the contrary, the MAS model shown below exhibited small open field regions at all latitudes in 2009.







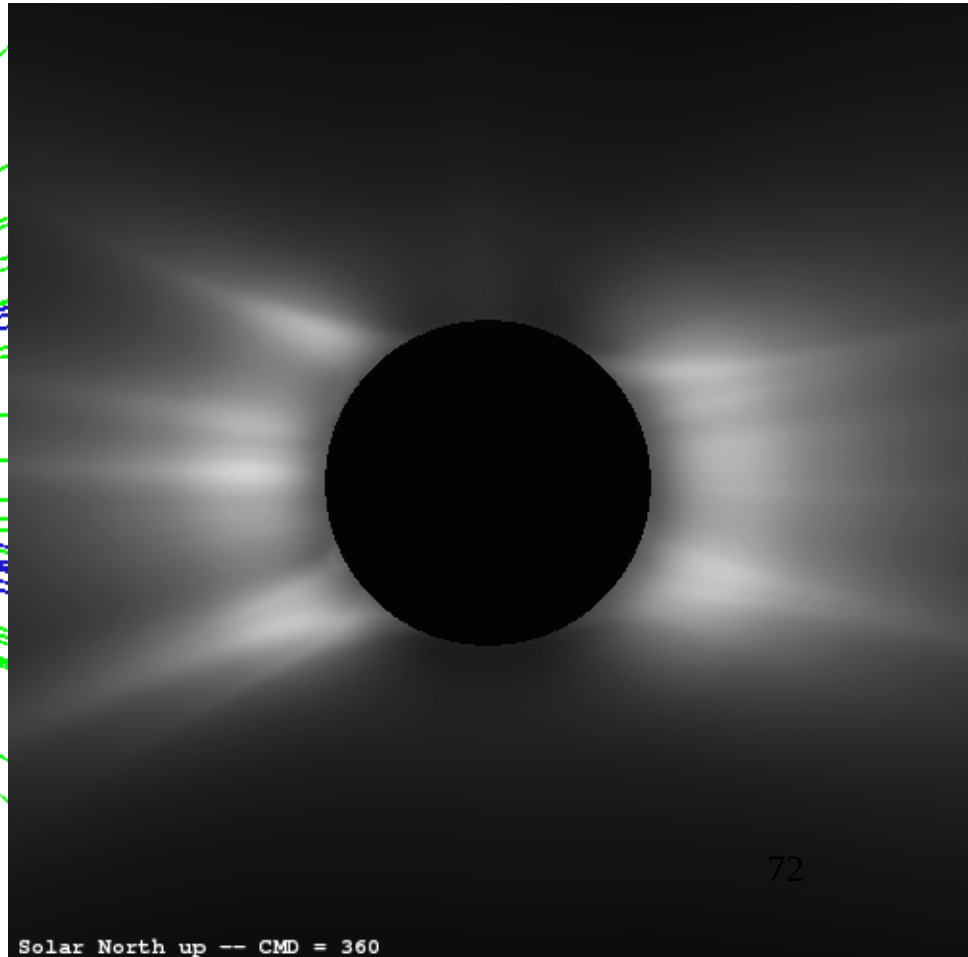
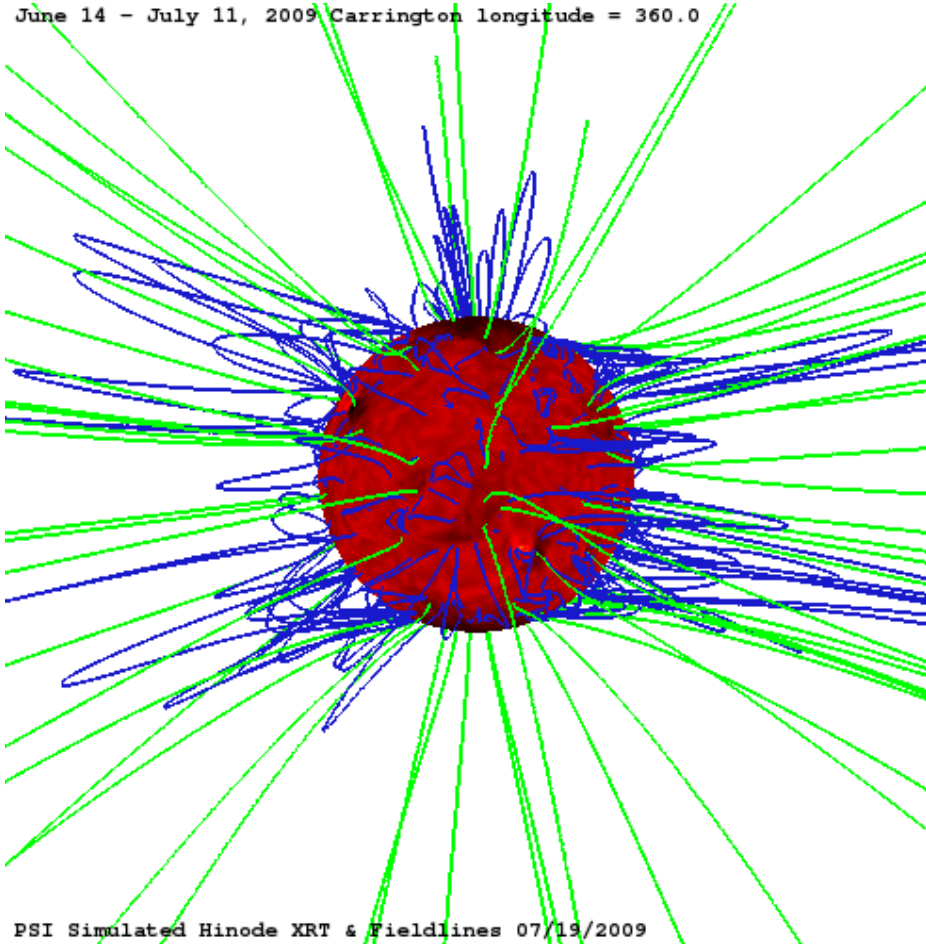
# Current solar minimum: evolution

The fire hose has become a sprinkler head!

June-July 2009 MAS modeled corona

Courtesy Jon Linker

June 14 - July 11, 2009 Carrington longitude = 360.0





# Summary

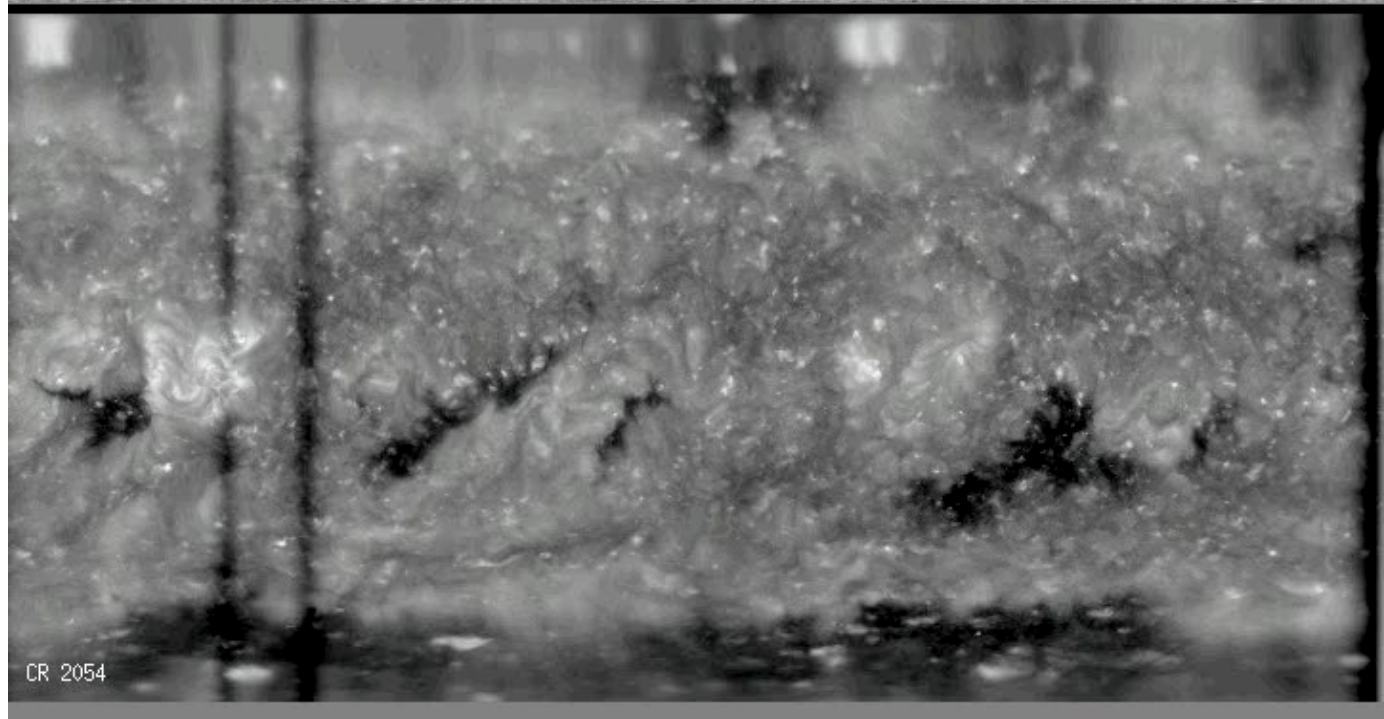
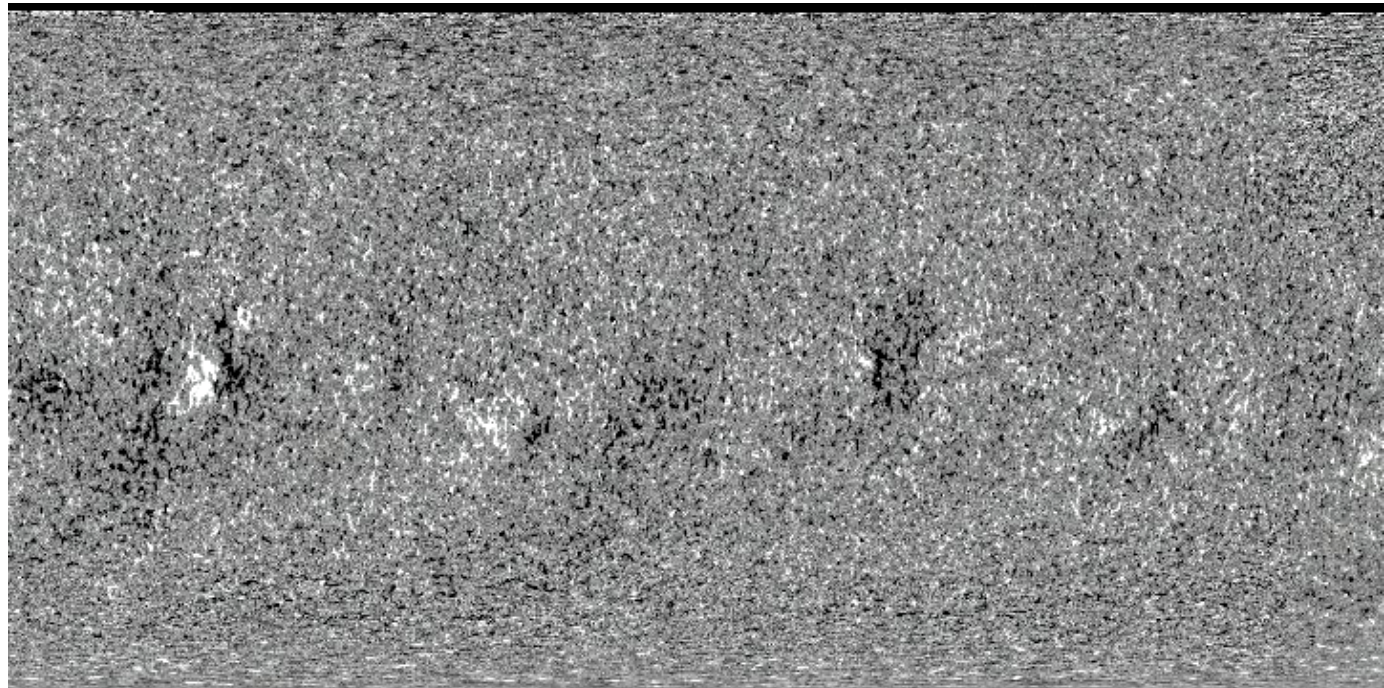
- The recent solar minimum was not just deep, but also long and complex
- WHI illustrates certain aspects of this solar minimum well:
  - “Quiet” side irradiance (as low as any this minimum)
  - Low-latitude coronal holes → high-speed streams → geospace periodicities
- The length of this cycle allows us to probe Sun-Earth physical processes
  1. In 2008 geospace was forced by high-speed streams, even though solar irradiance, activity, and IMF were lower than 1996 – *allows us to isolate the effects of fast solar wind*
  2. In 2009 low-latitude open flux diminished; high-speed streams no longer periodically forced the Earth – *allows us to study the Sun-Earth system at its “quietest”*
- WHI is a good example of #1 – more end-to-end modeling needed
- Mid-2009 good time to study #2



SOHO-MDI

Rotations  
spanning  
minimum

STEREO EUVIA+B



CR 2054

Courtesy Neal Sheeley



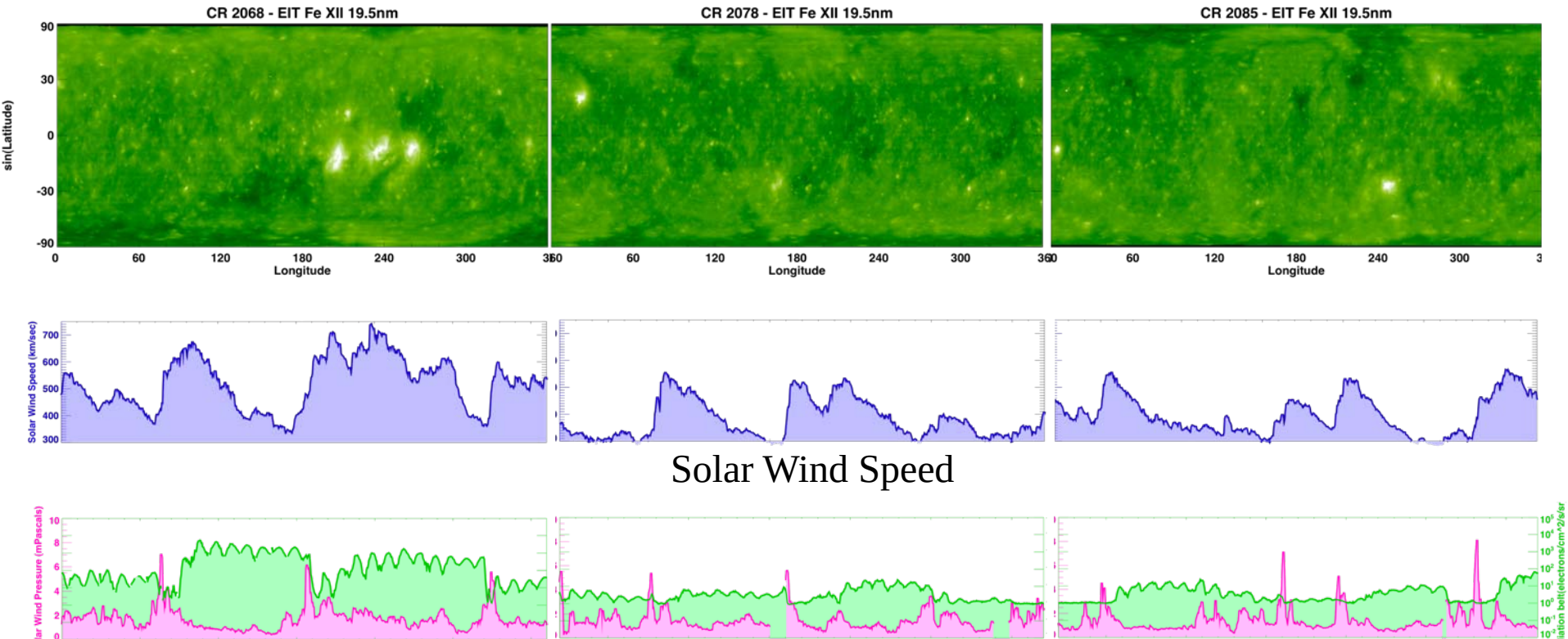


# Rotations spanning minimum

Mar 20-Apr 16 08 (CR2068)

Dec 17 -Jan 12 08/09 (CR2078)

Jun 26-Jul 22 09 (CR2085)



Solar Wind Speed

GOES radiation belt (green) and solar wind pressure (pink)



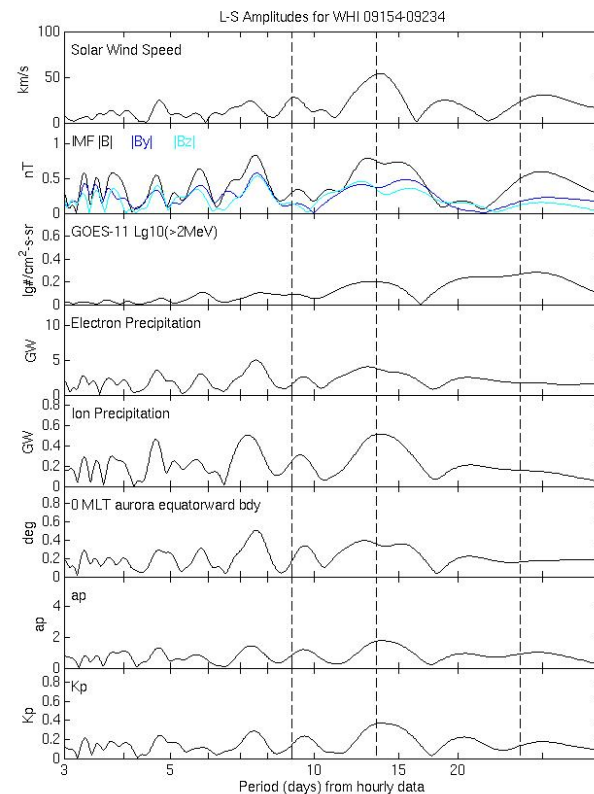
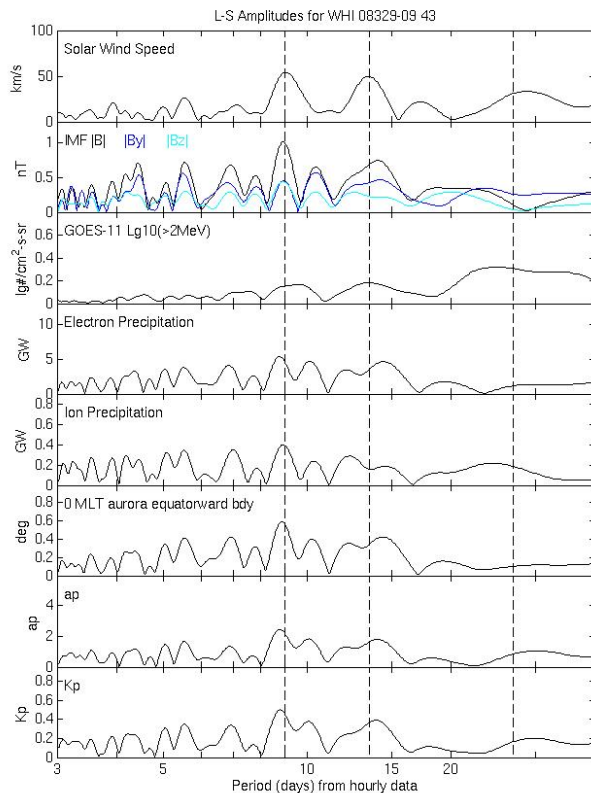
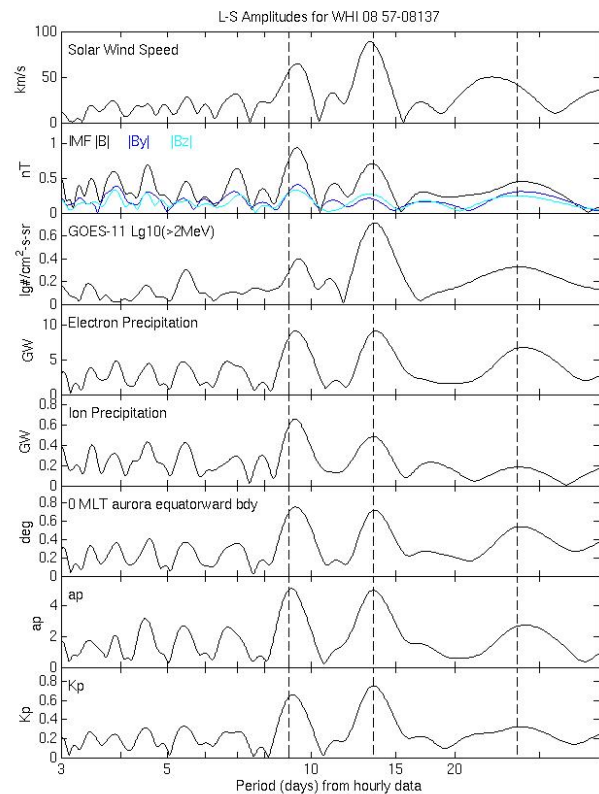


# Rotations spanning minimum

Mar 20-Apr 16 08 (CR2068)

Dec 17 -Jan 12 08/09 (CR2078)

Jun 26-Jul 22 09 (CR2085)



Courtesy Barbara Emery