18+ Years of Ulysses Observations: A Comparison of Two Solar Minima

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With thanks for material to…

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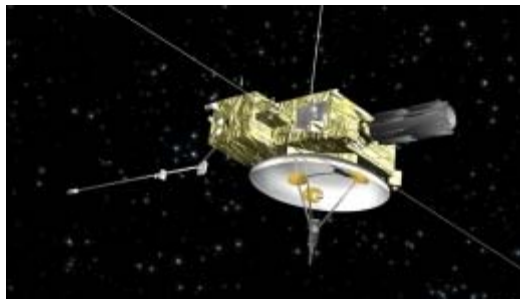
Imperial College London

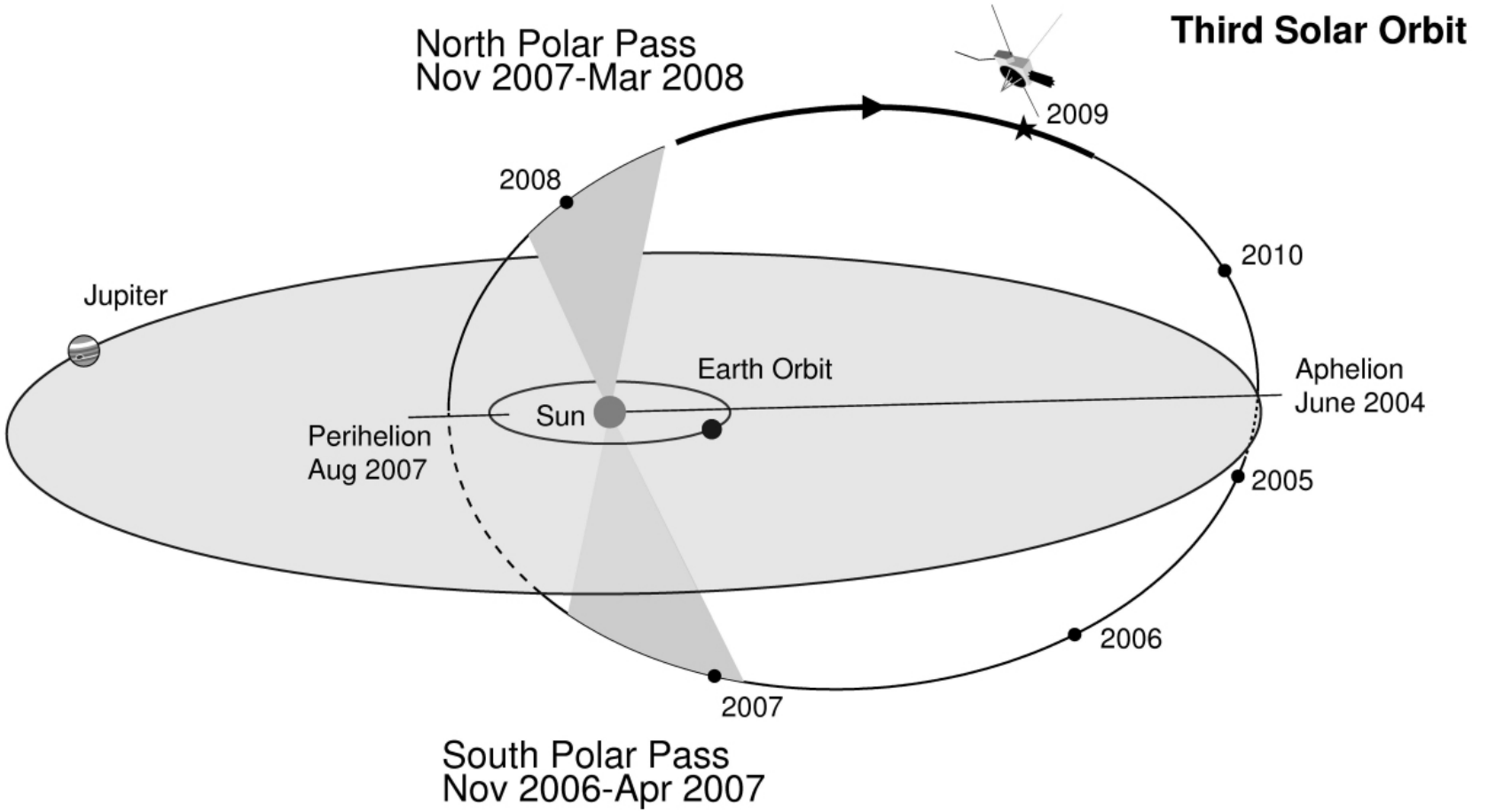
Outline



- Ulysses mission overview and final end of tracking
- A selection of scientific highlights
- Third orbit observations and the extended solar minimum

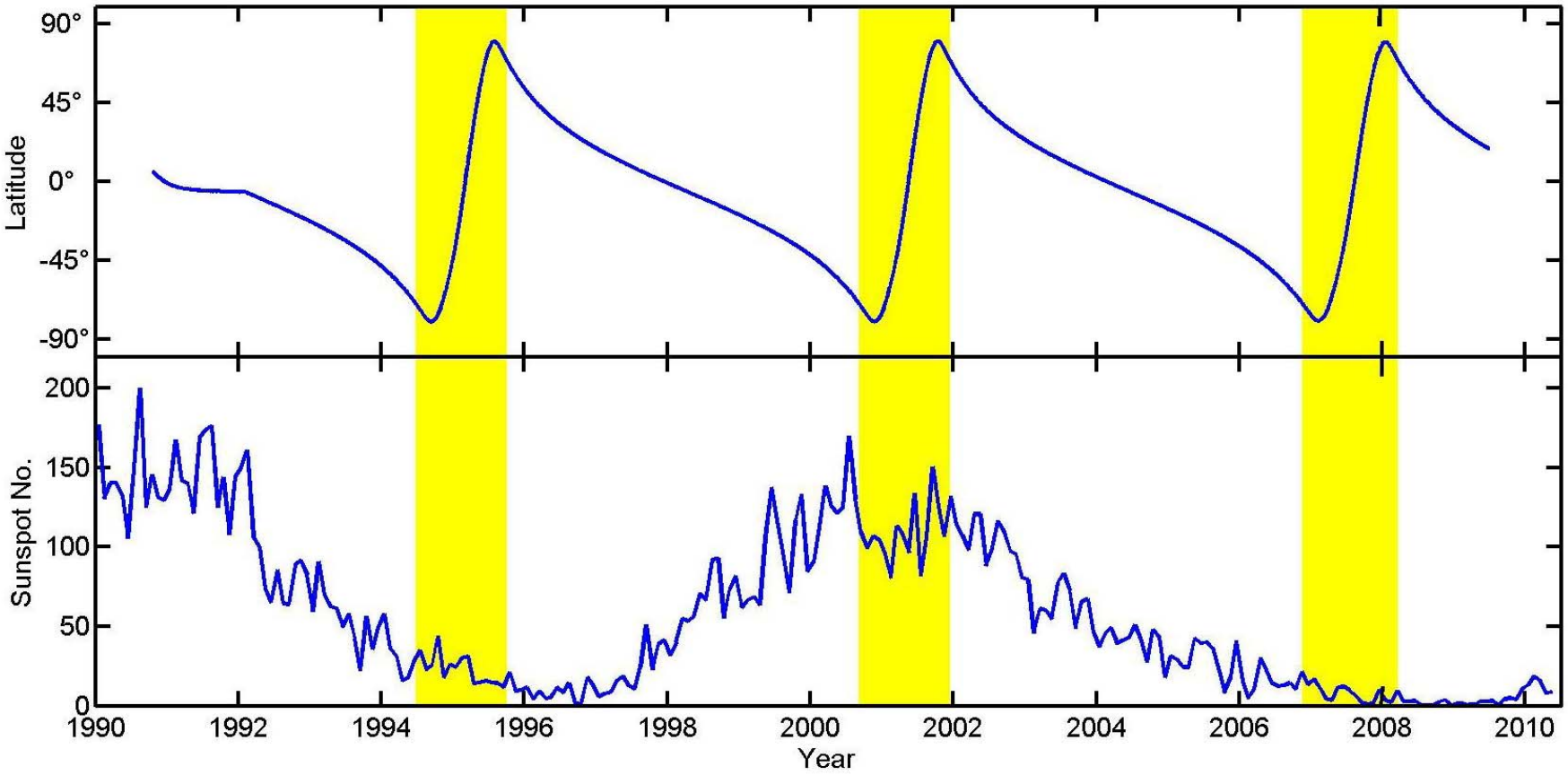
Ulysses

Third Solar Orbit



★ Ulysses position on 01.01.2009

Solar cycle context…



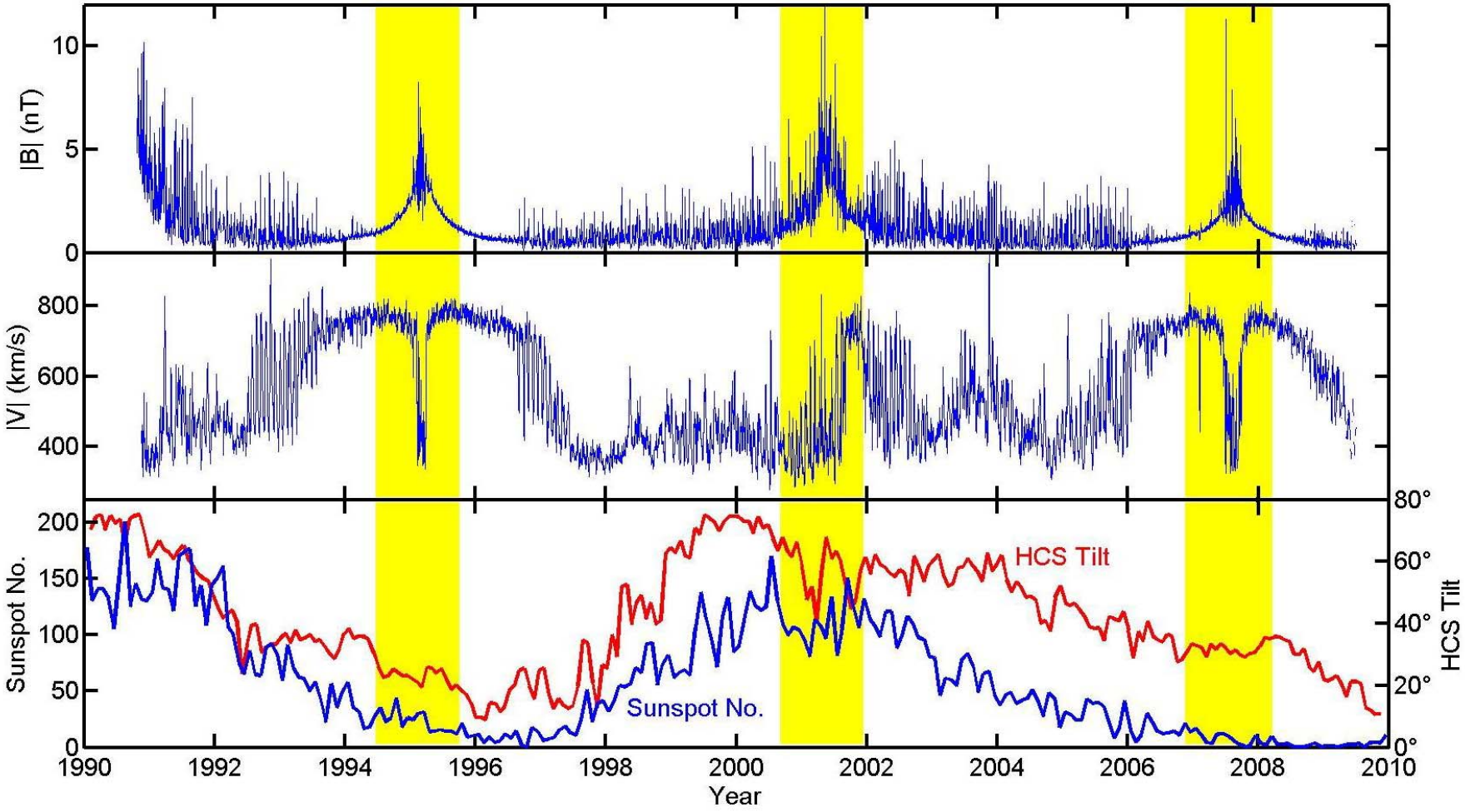
Yellow regions mark polar passes and fast latitude scans

End of Ulysses tracking

- X-band transmitter failed in January 2008
- Mission continued to operate at reduced data rate on low gain S-band transmitter
- Was keeping a crucial part of fuel system warm but ingenious ops gave 1.5 years further data
- Increasing distance led to pointlessly low data return by end of June 2009
- But we had an extremely successful 18 years and 9 months of operations!

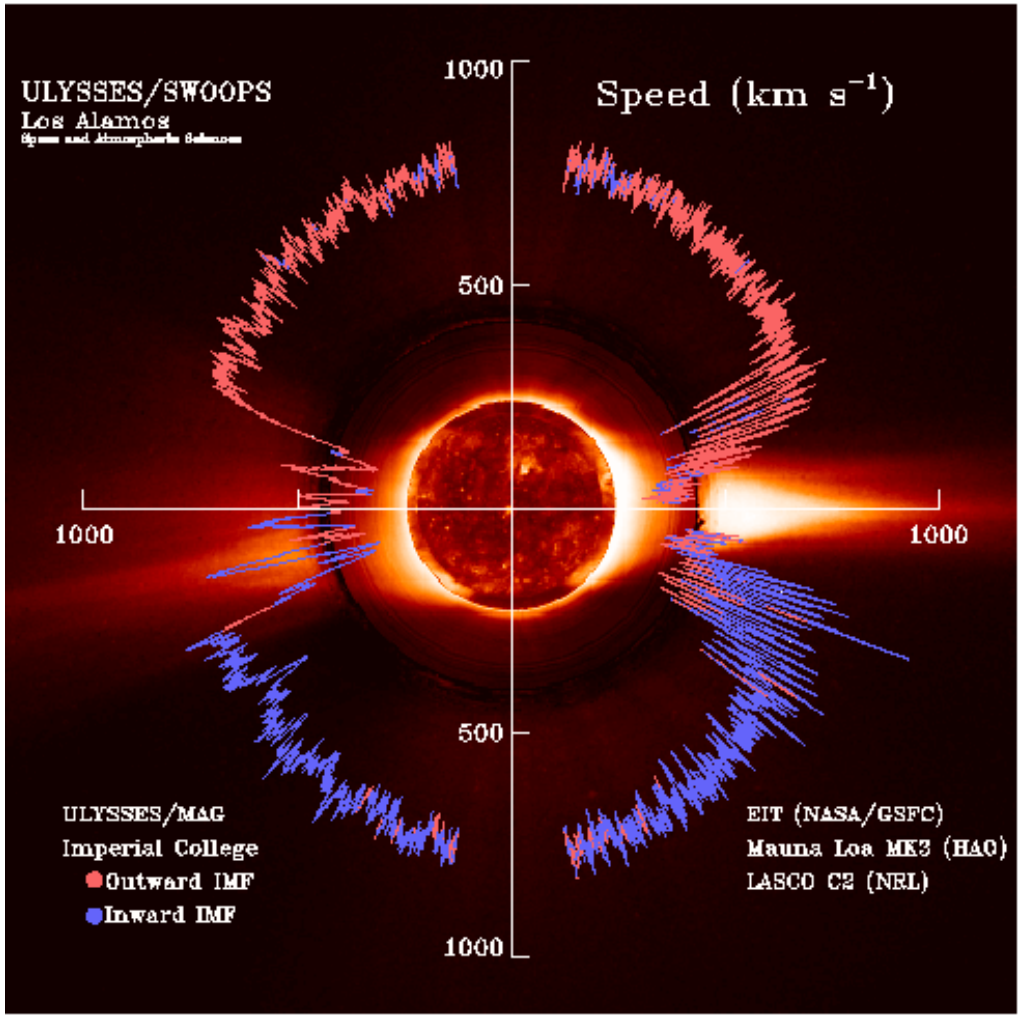
Ulysses mission overview…

18 years + 9 months of almost continuous data

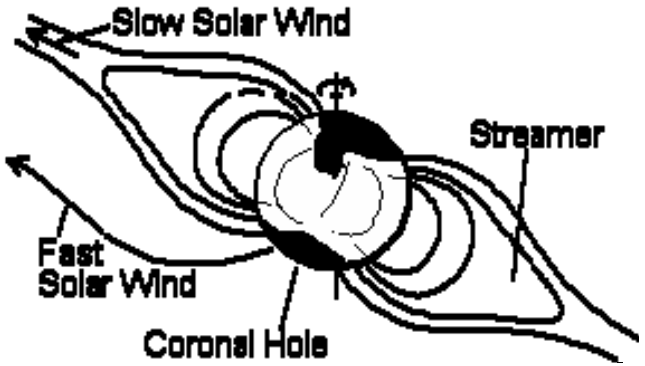


Yellow regions mark polar passes and fast latitude scans

Results from first solar orbit

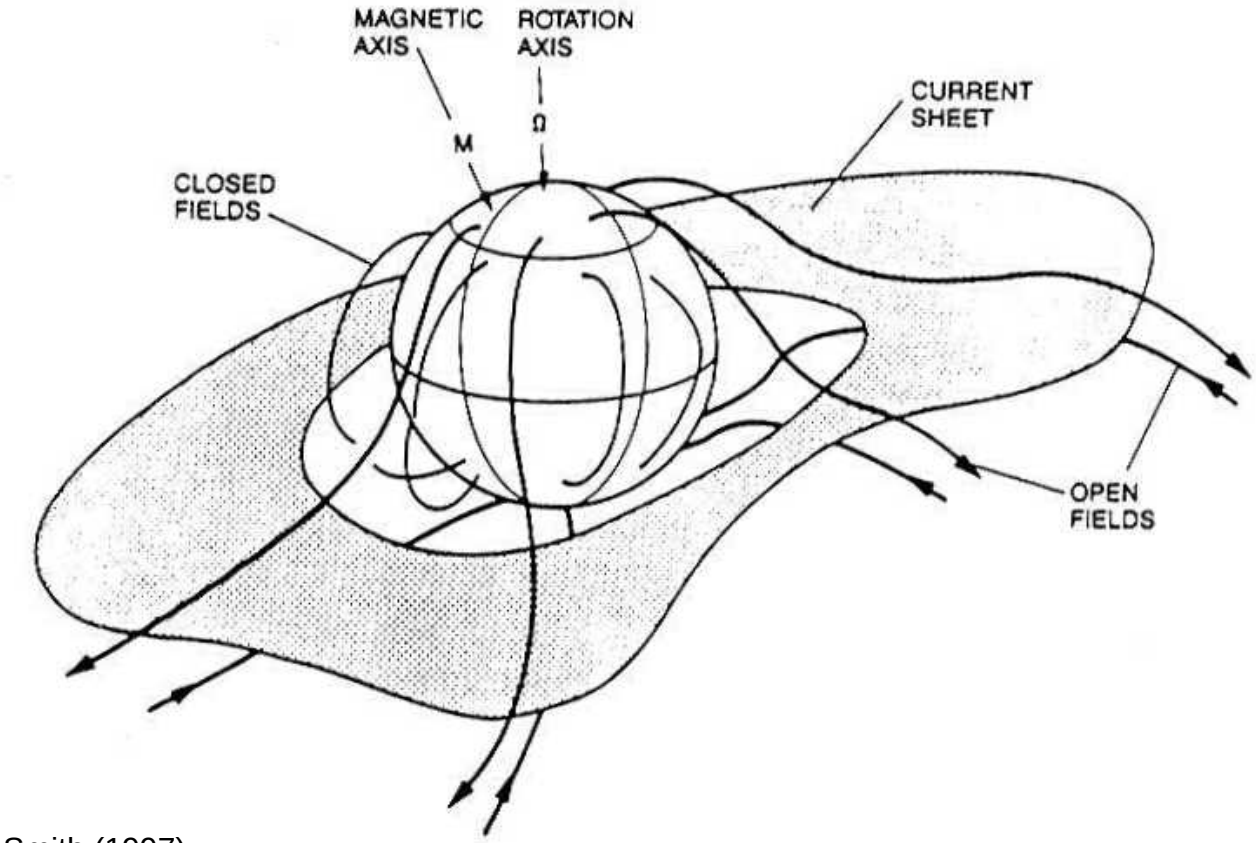


McComas et al, (1998)



Suess et al, (1998)

Formation of the heliospheric current sheet



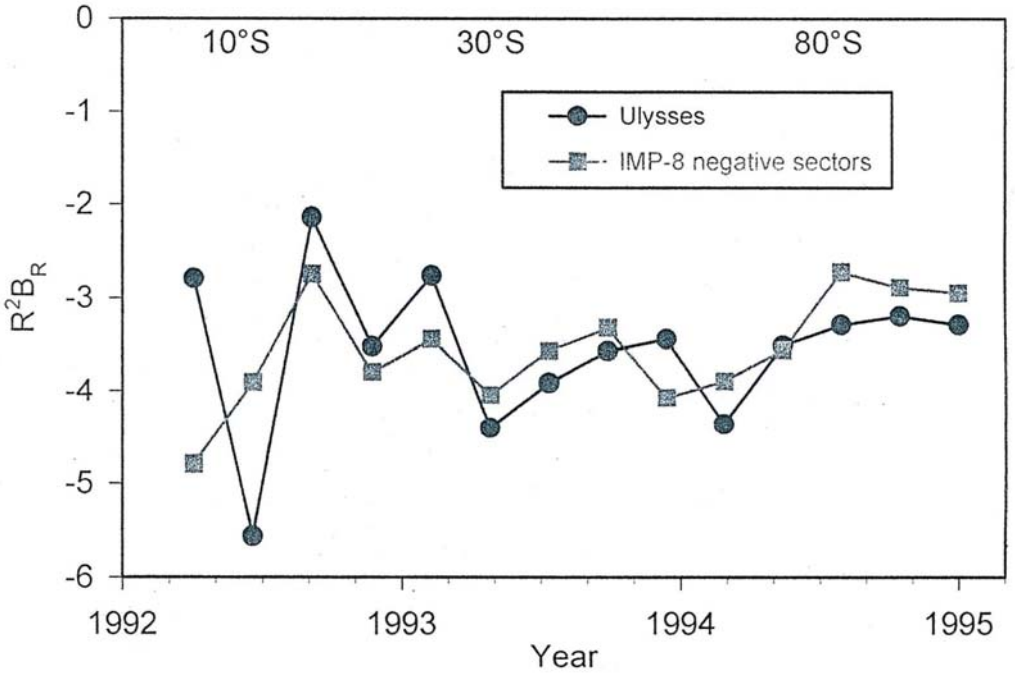
Smith (1997)

Ulysses first orbit discoveries

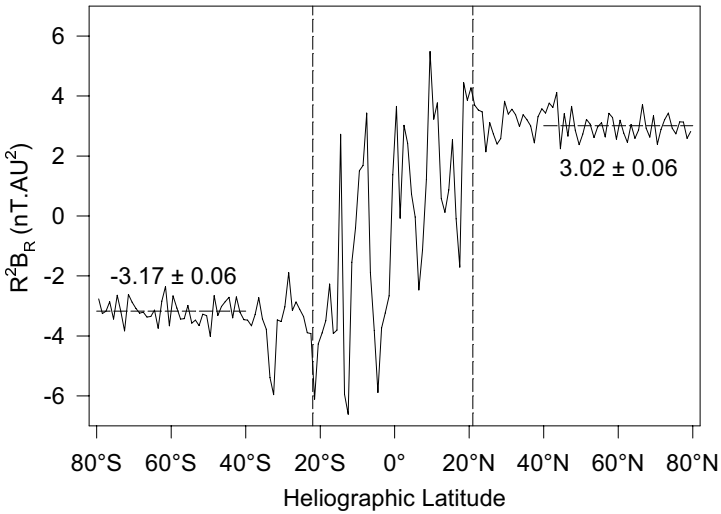
- Confirmation of continuous fast solar wind at high latitudes from polar coronal holes
- Latitude independence of r^2B_r
- Ubiquitous large amplitude Alfvén waves present in fast solar wind
- Composition signatures of the fast and slow wind
- Determination of the 3D structure of Corotating Interaction Regions

Dependence of Field Strength on Latitude

- Assuming that the magnetic field is radial at the ‘source surface’, the radial component of the magnetic field can be used to infer the field strength near the Sun since r^2B_r is a constant.
- Ulysses observations showed that r^2B_r had no dependence on latitude.
- This implies that the latitudinal magnetic pressure gradient associated with strong photospheric polar fields must have relaxed by the outer corona.



Smith and Balogh (1995)



Forsyth et al (1996)

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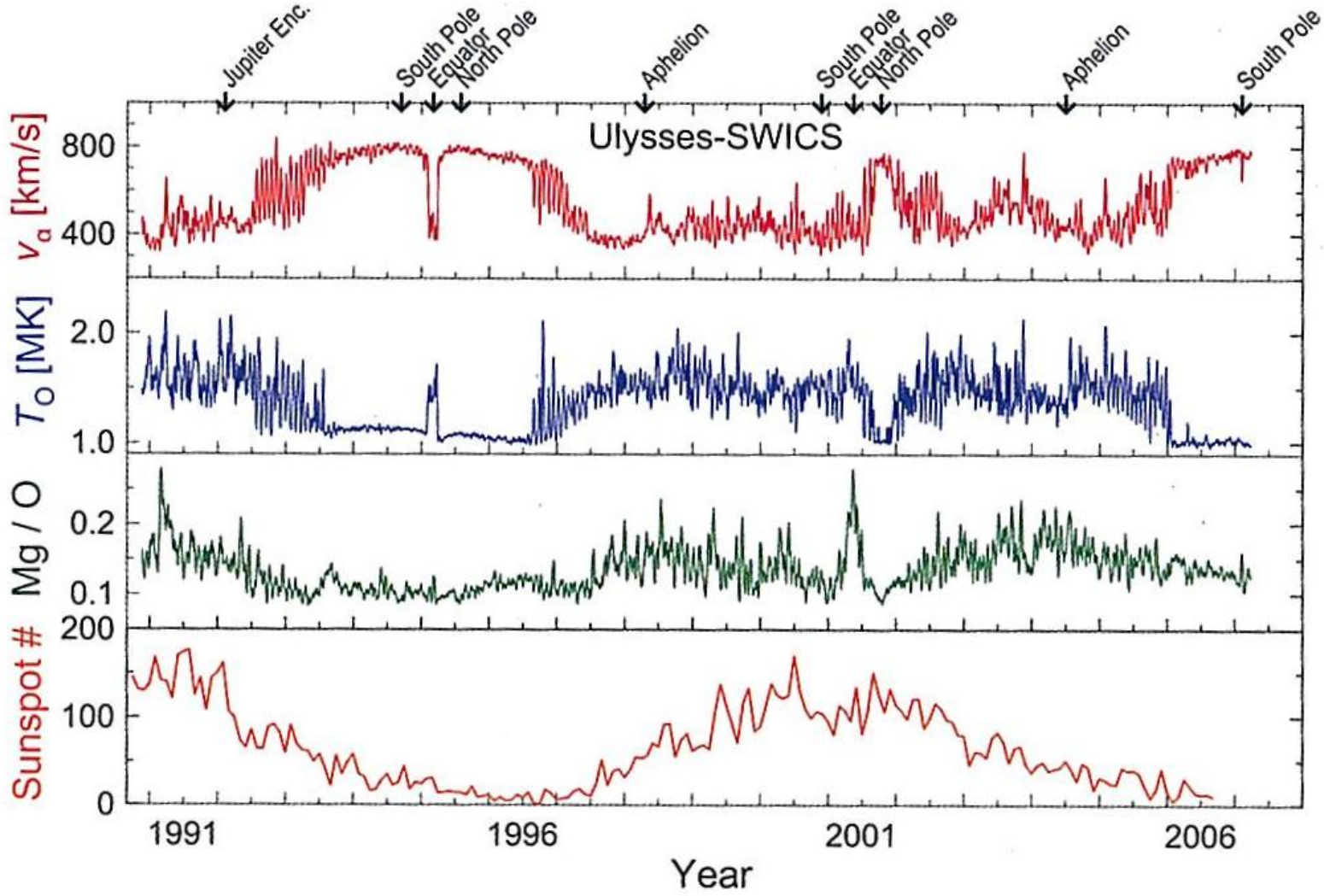
Solar wind composition



von Steiger (2008)

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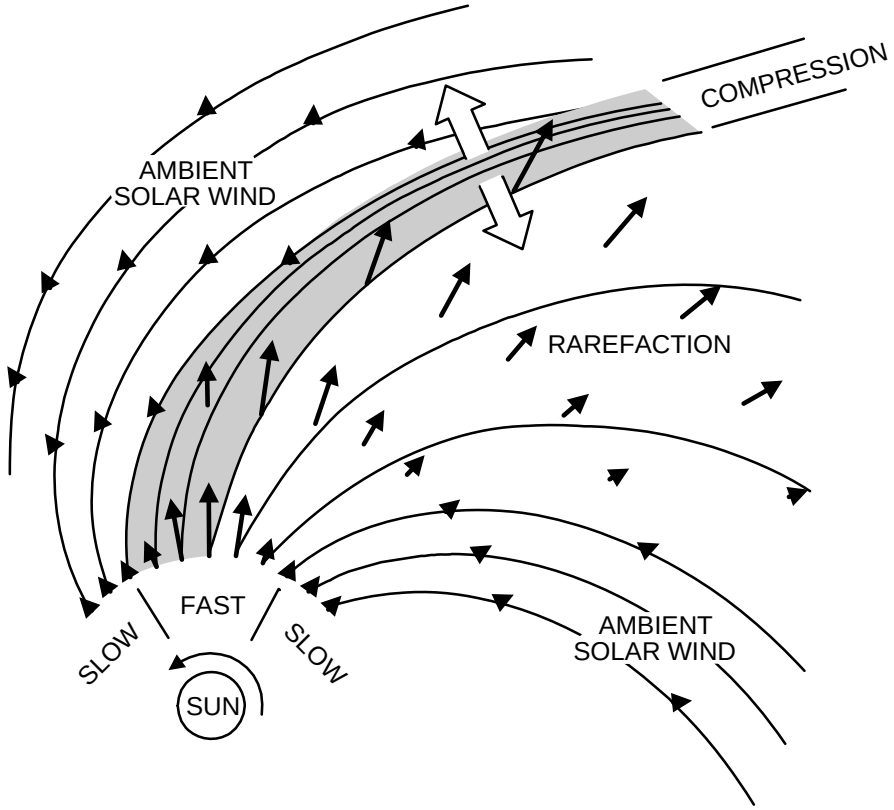
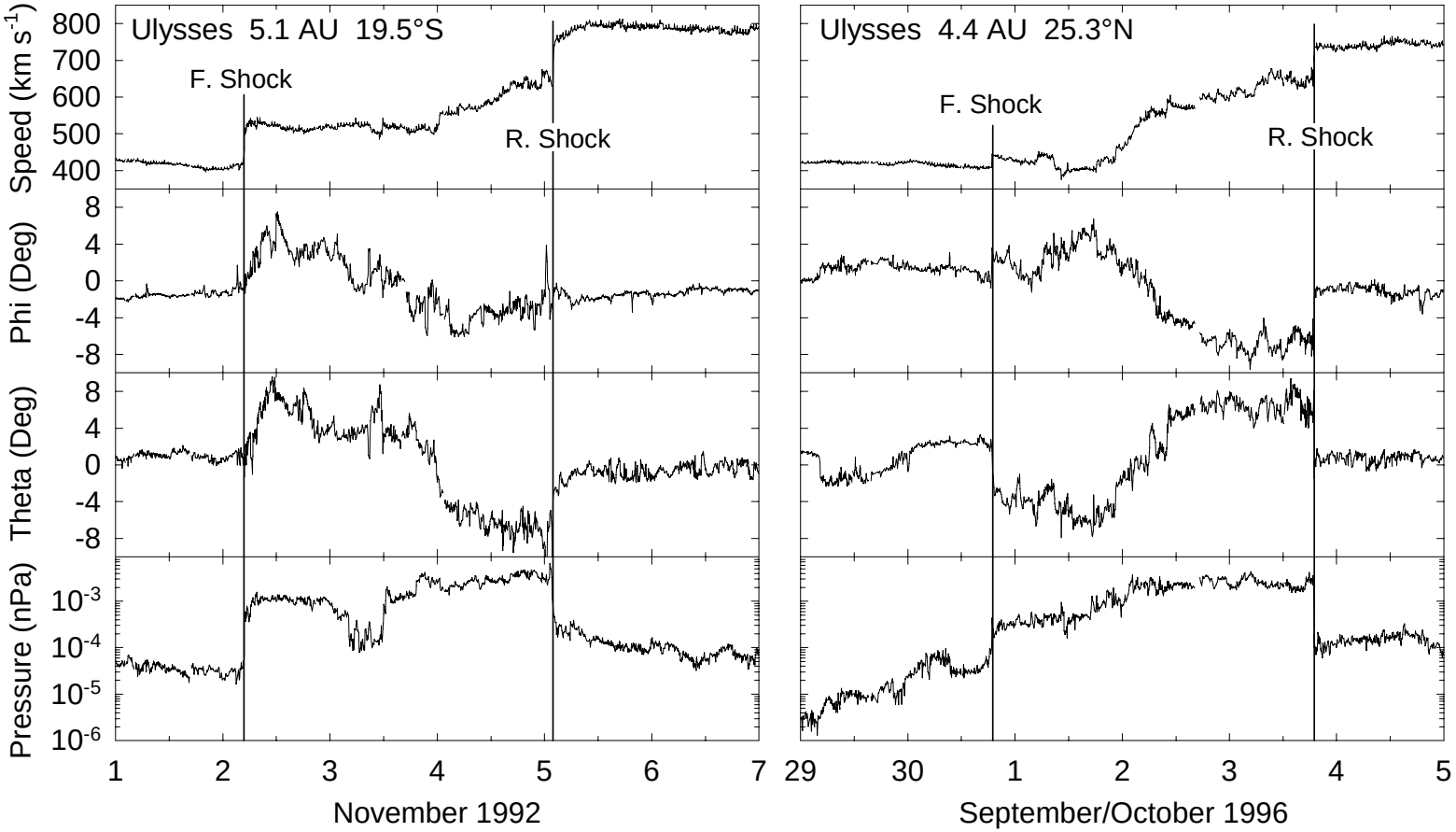
Corotating Interaction Regions

- Interaction regions form wherever fast solar wind ‘catches up’ with slower wind ahead of it.
- A compression region forms where the magnetic field lines and plasma ‘pile up’. The resulting pressure waves can steepen into shocks.
- When a fast solar wind stream originates from a stable coronal hole persisting over many solar rotations, the resulting interaction region pattern corotates with the Sun.

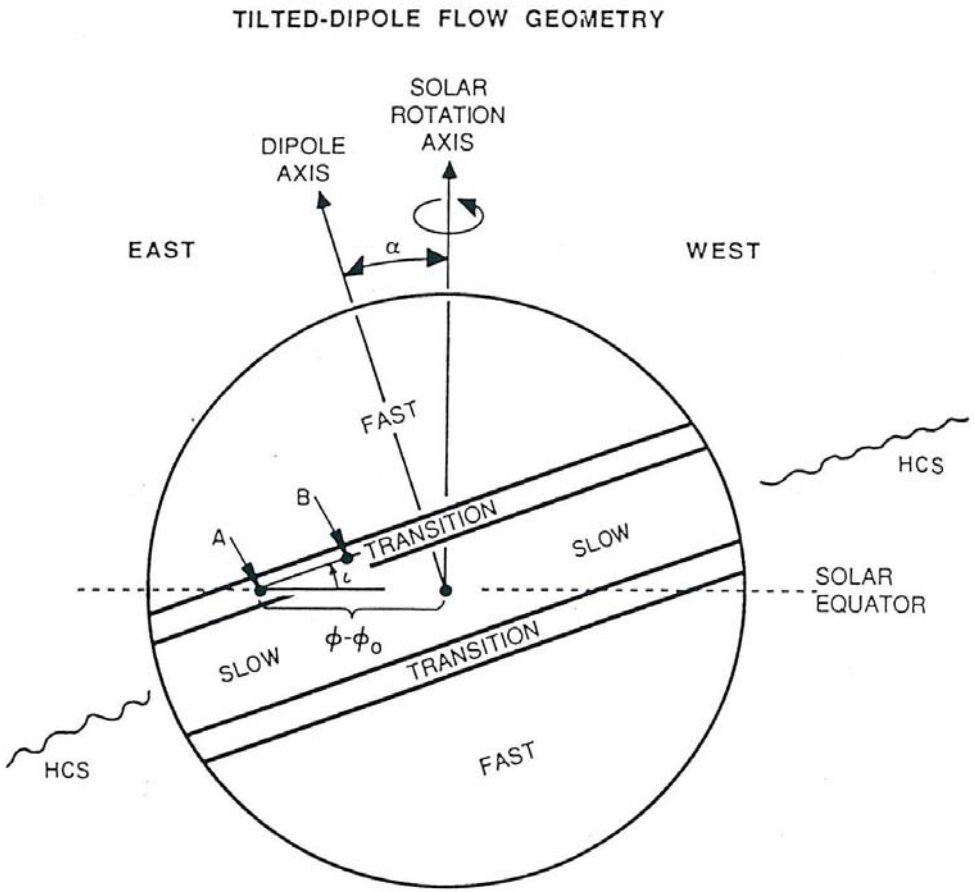


Pizzo (1985)

- Ulysses discovered north-south flow deflections associated with interaction regions implying that the forward waves/shocks propagate equatorwards while reverse waves/shocks propagate polewards.



Pizzo and Gosling (1999)

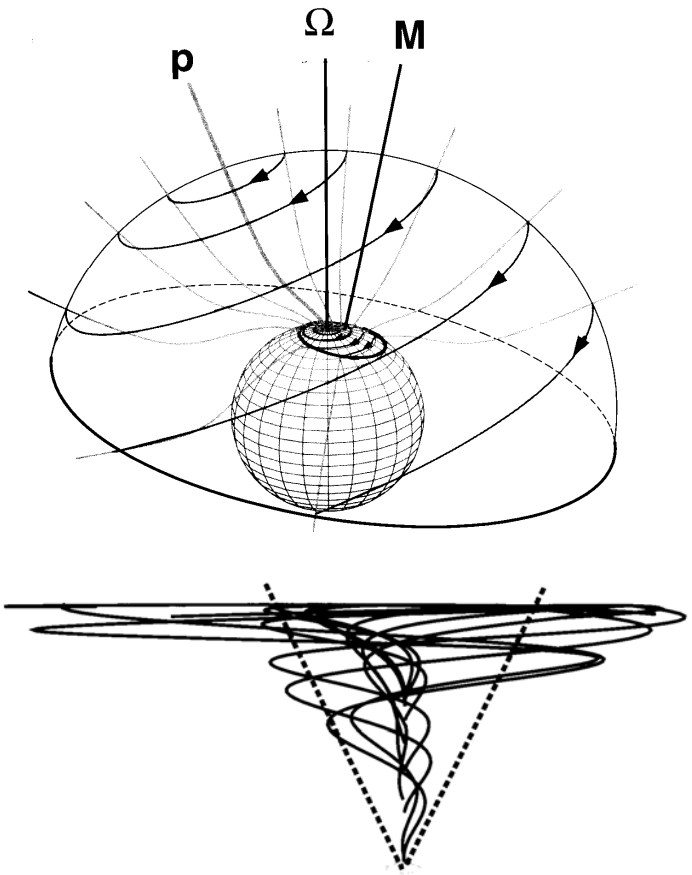

TILTED-DIPOLE FLOW GEOMETRY
SOLAR
ROTATION
AXIS
DIPOLE
AXIS
EAST
WEST
α
FAST
HCS
B
A
TRANSITION
SLOW
SOLAR
EQUATOR
ι
SLOW
φ-φo
TRANSITION
HCS
FAST

Pizzo (1991)

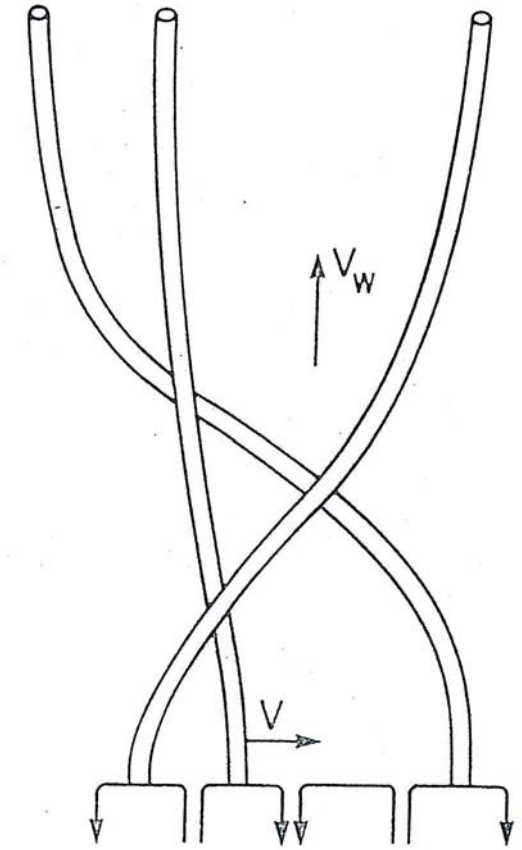
Ulysses first orbit discoveries

- Identification of over-expanding ICMEs embedded in the fast solar wind
- Energetic particles at high latitudes
- Cosmic ray latitude gradients
- Radio and plasma waves, dust, neutral atoms,…

How do energetic particles reach high latitudes?



Fisk (1996)



Jokipii and Kota (1989)

Ulysses first orbit discoveries

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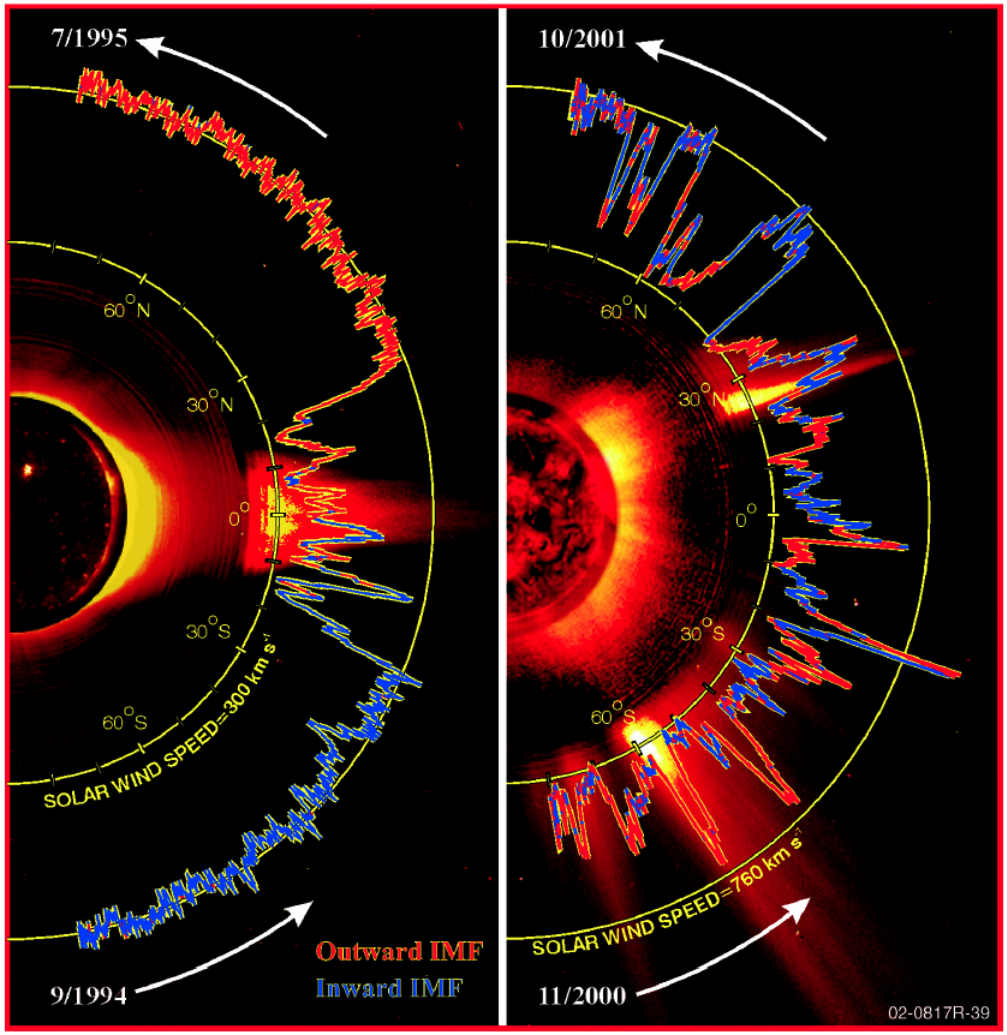
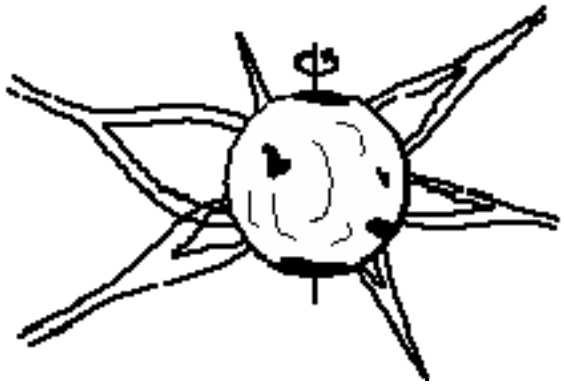
- Radio and plasma waves, dust, neutral atoms,…

Second fast latitude scan

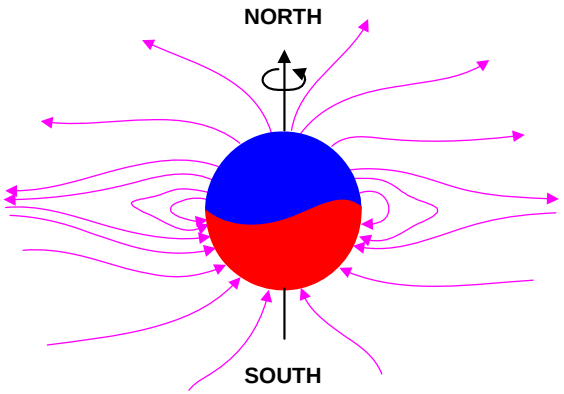


McComas et al, (2002)

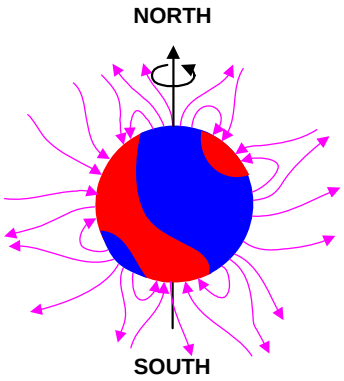


Suess et al, (1998)

Solar cycle evolution of the coronal magnetic field



CORONAL MAGNETIC FIELD LINES AT SOLAR MINIMUM ACTIVITY



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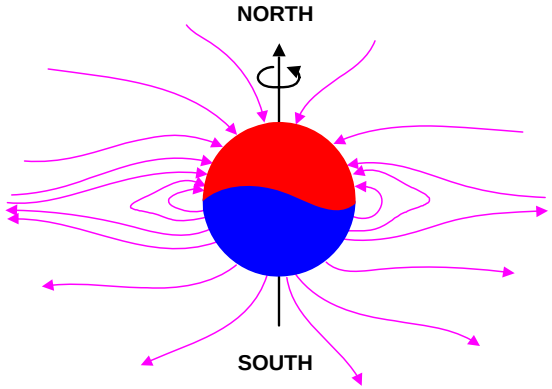
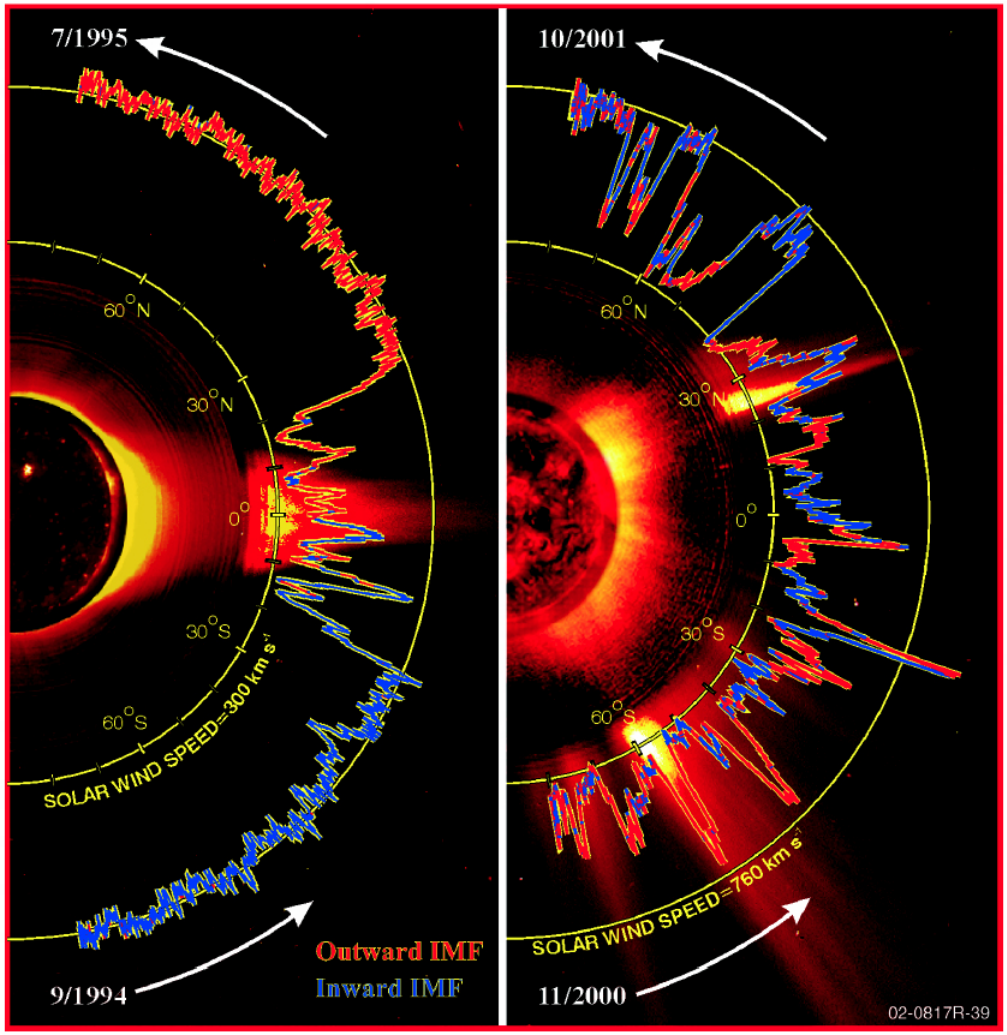


CORONAL MAGNETIC FIELD LINES AT NEXT SOLAR MINIMUM

Second fast latitude scan



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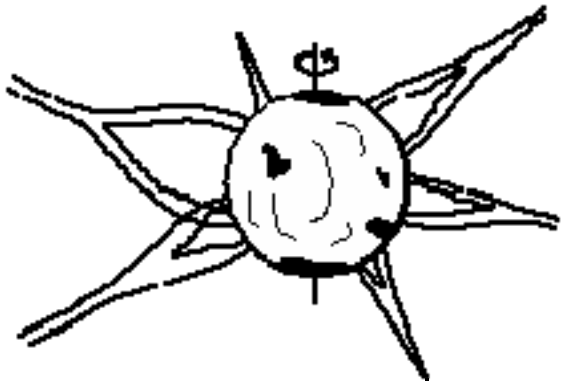
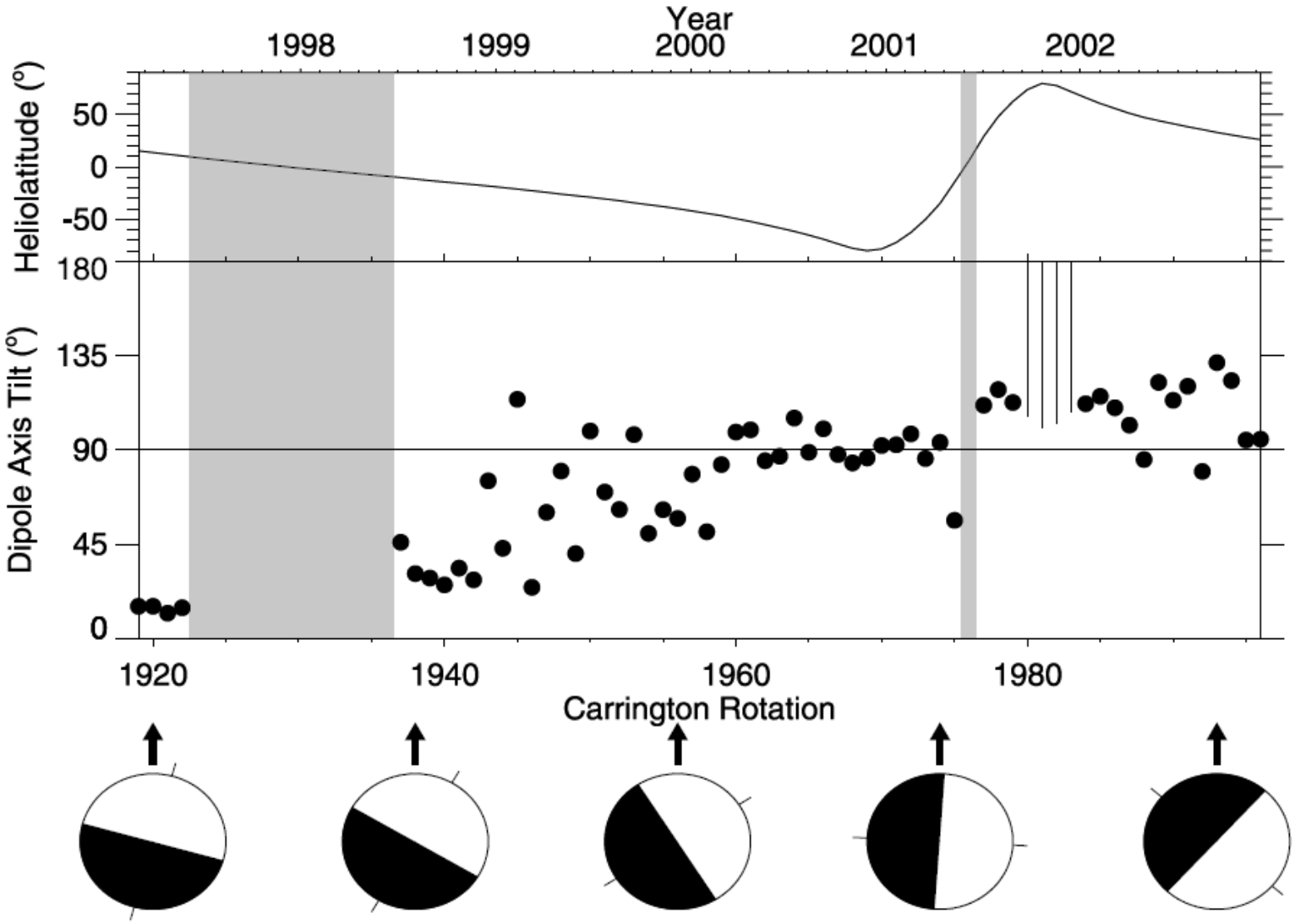


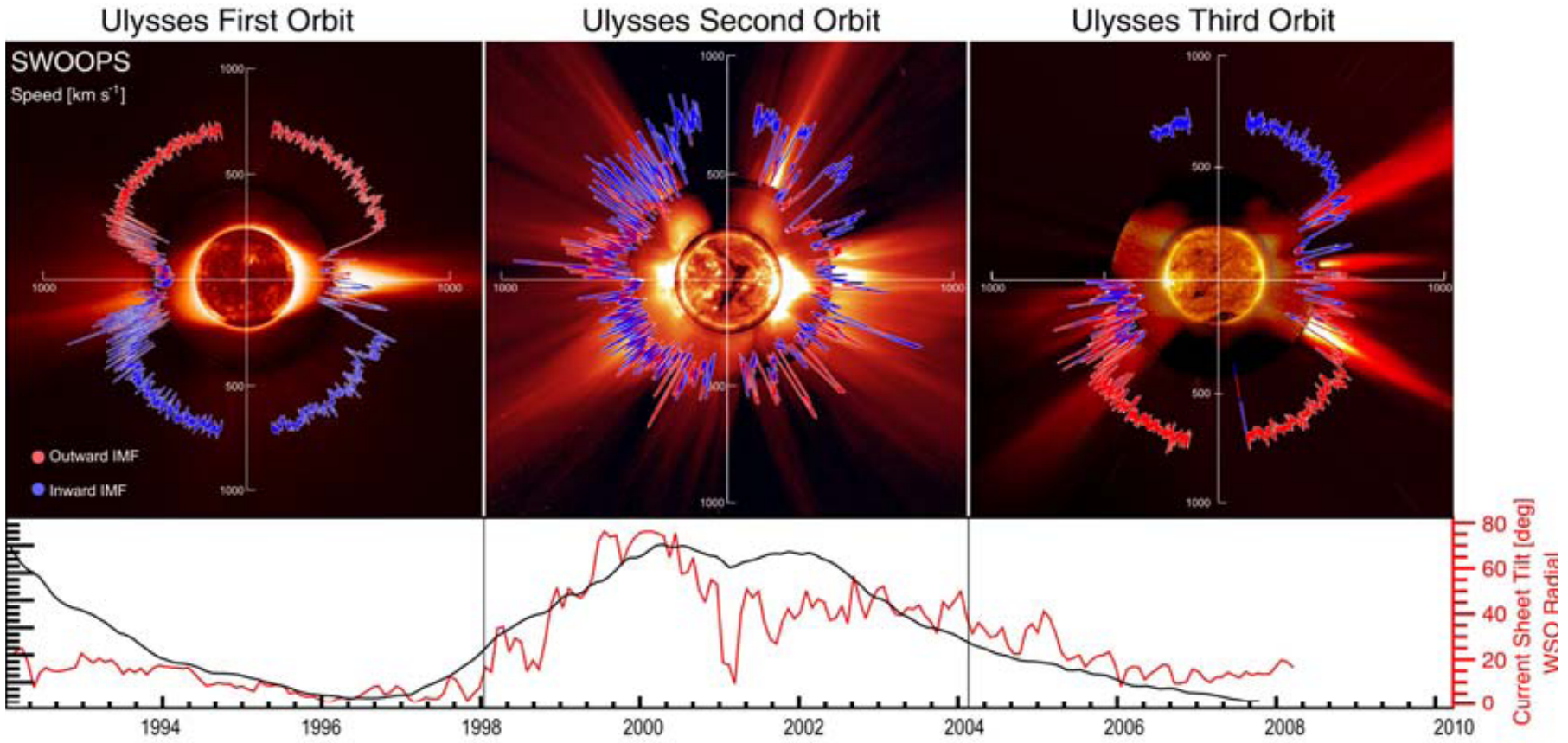
Suess et al, (1998)

Magnetic field polarity reversal

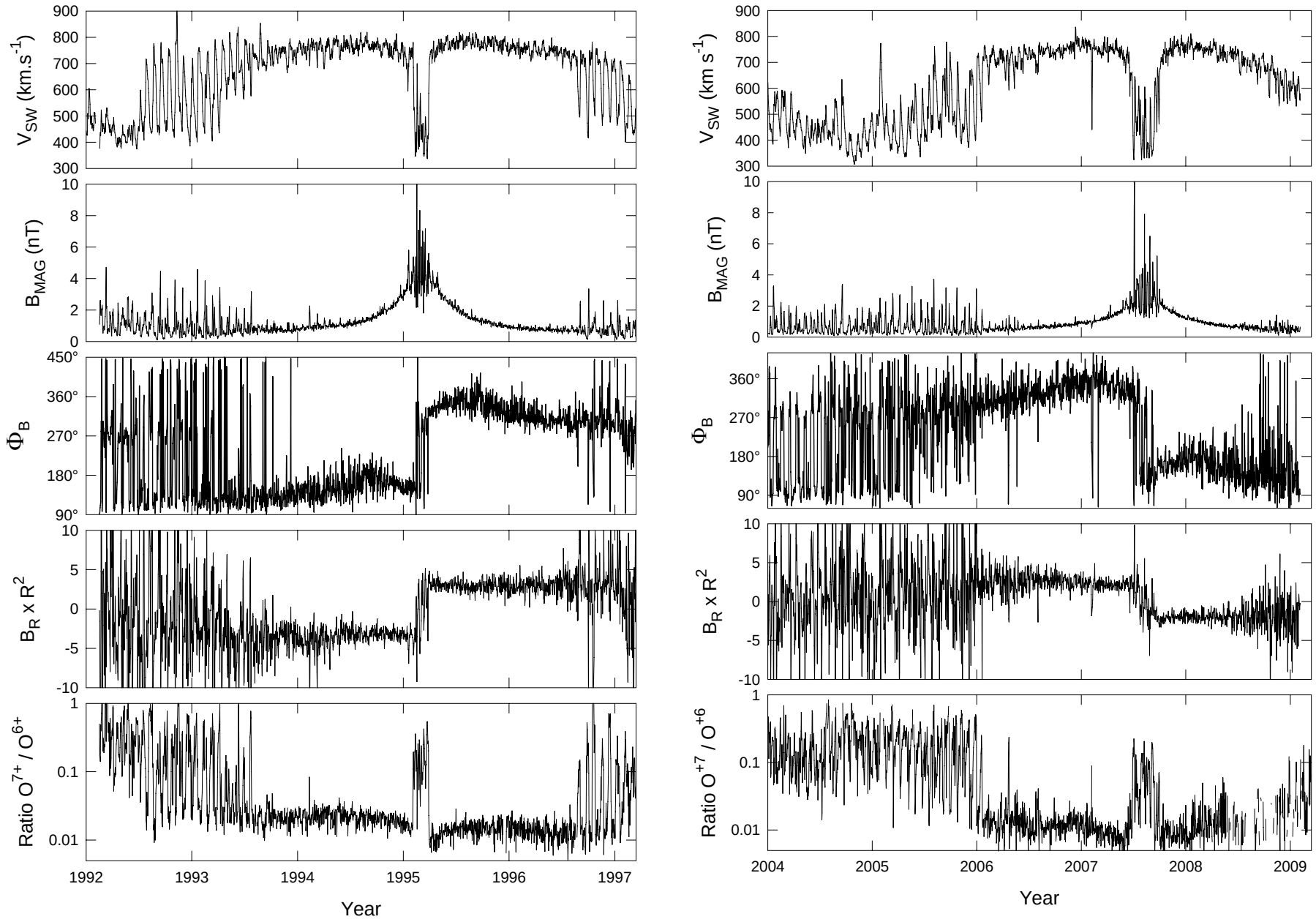


Jones et al, (2003)

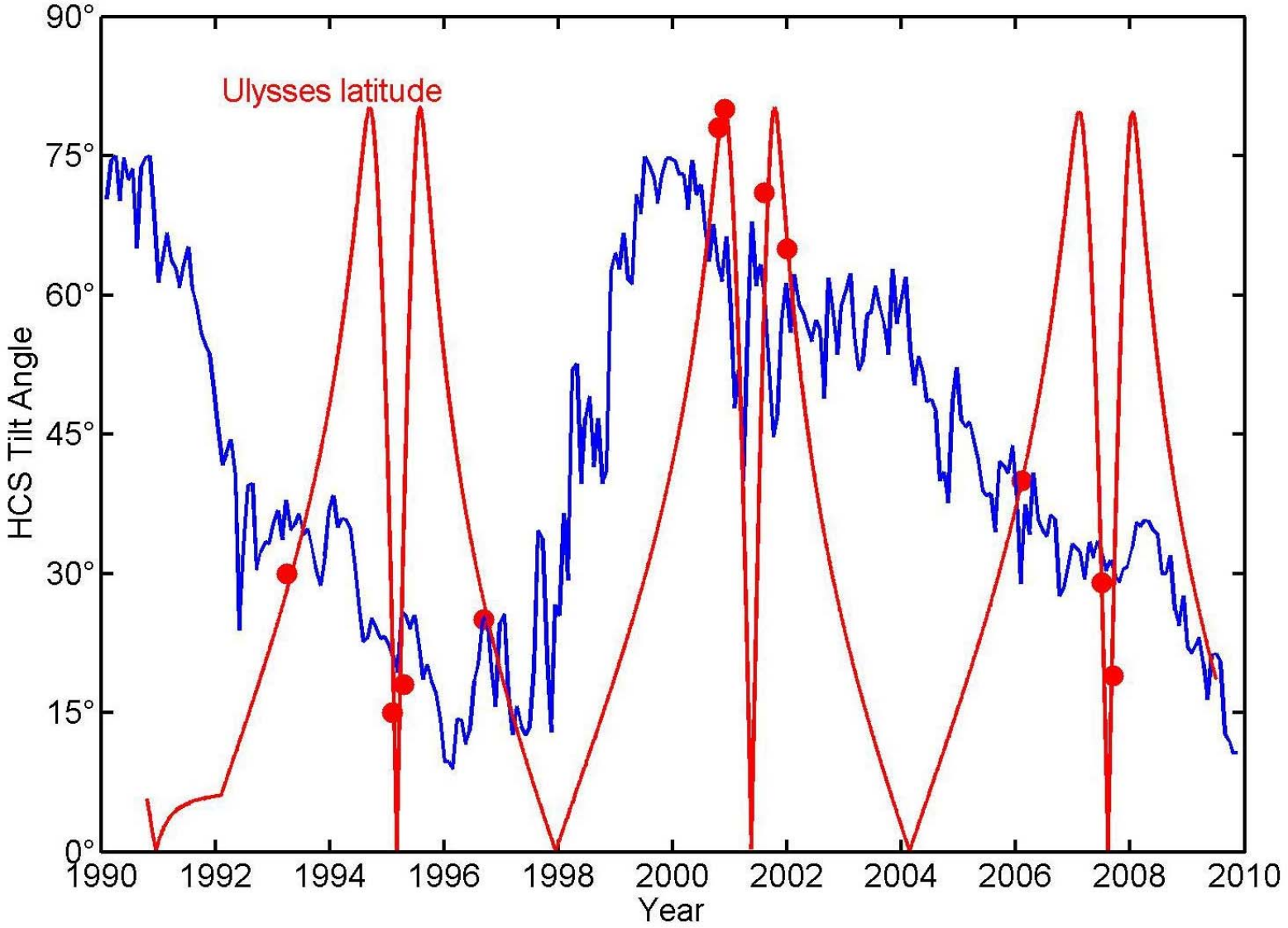
Comparison of three Ulysses orbits



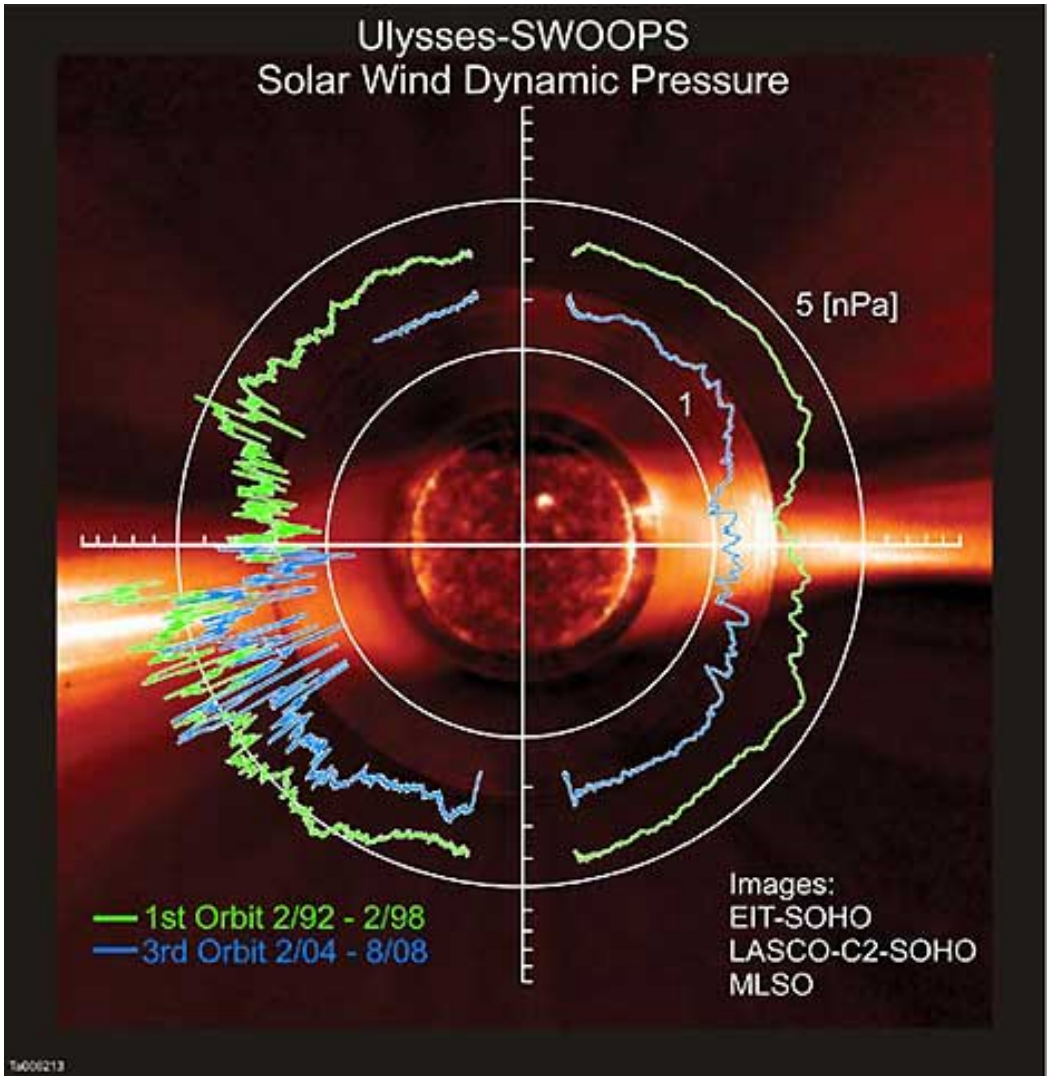
McComas et al, (2008)


1992 – 1997
2004 – 2009
V_{SW} (km.s^{-1})
V_{SW} (km s^{-1})
B_{MAG} (nT)
Φ_B
B_R x R^2
Ratio O^{7+} / O^{6+}
Ratio O^{+7} / O^{+6}
Year
Year

HCS tilt greater in 2007 than in 1995…



~22% reduction in solar wind dynamic pressure



Solar wind changes

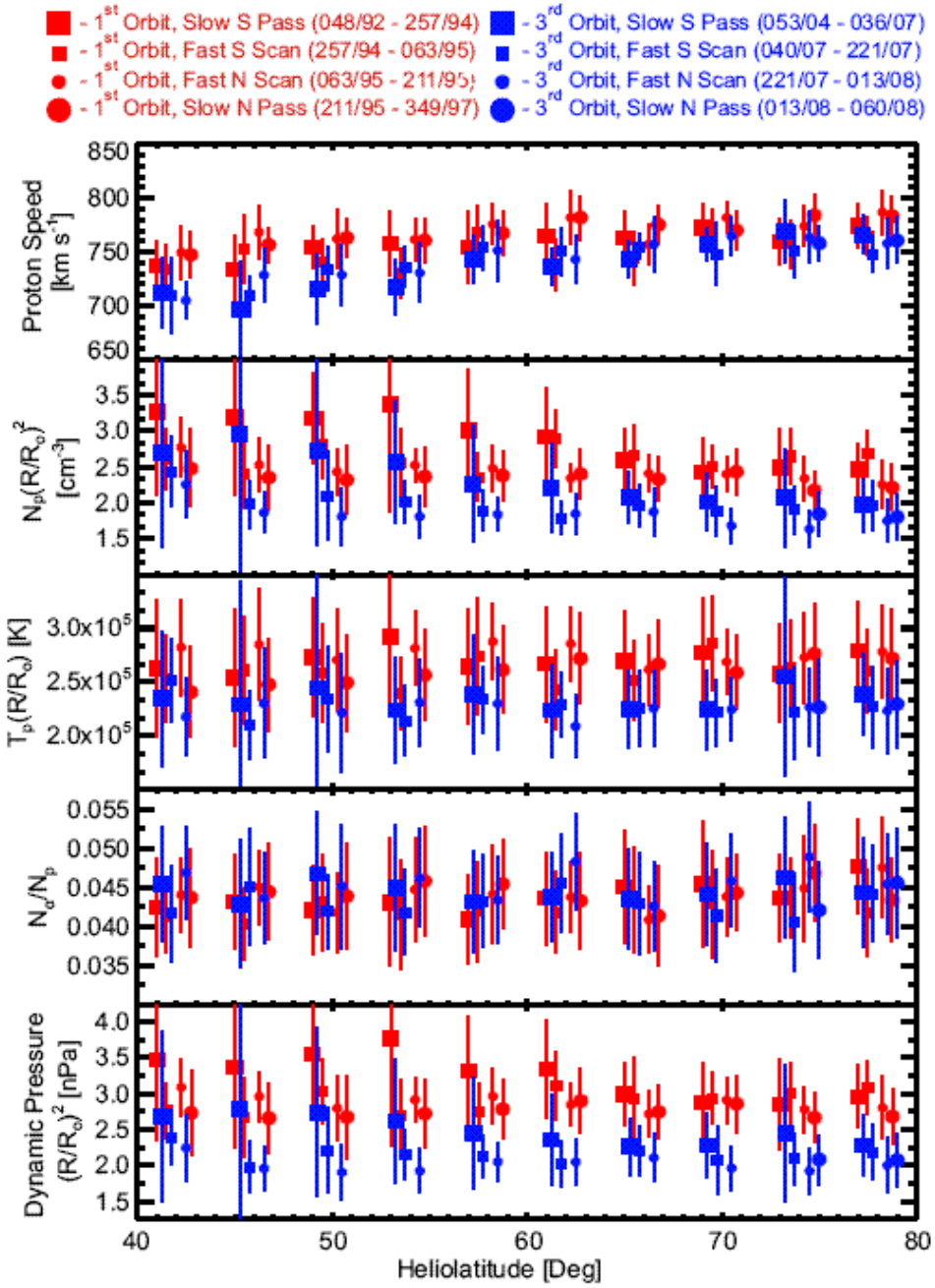
Proton speed

Scaled proton density

Scaled proton temperature

Alpha to proton ratio

Dynamic pressure



–3%

–17%

–14%

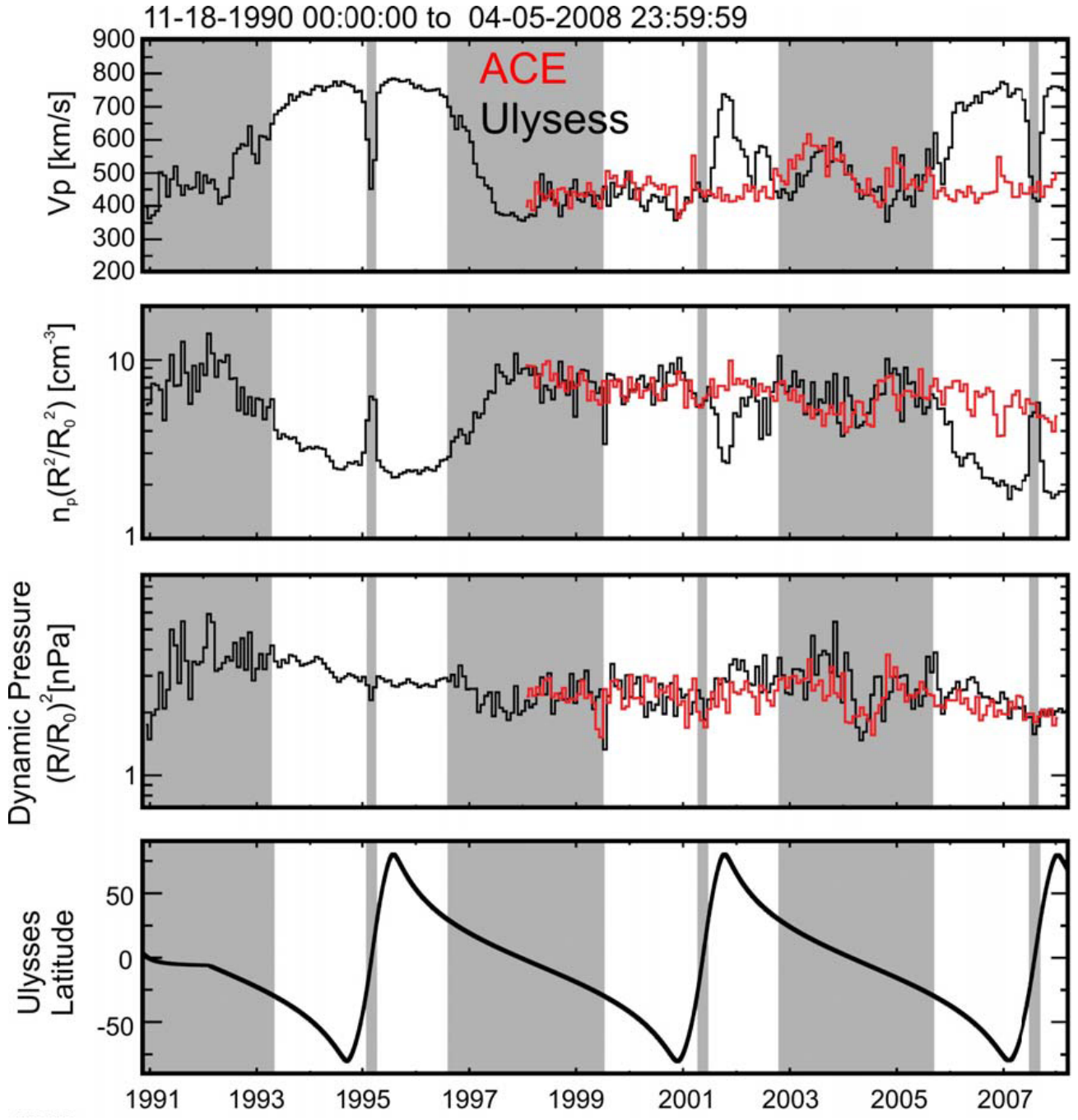
0%

–22%

McComas et al, (2008)

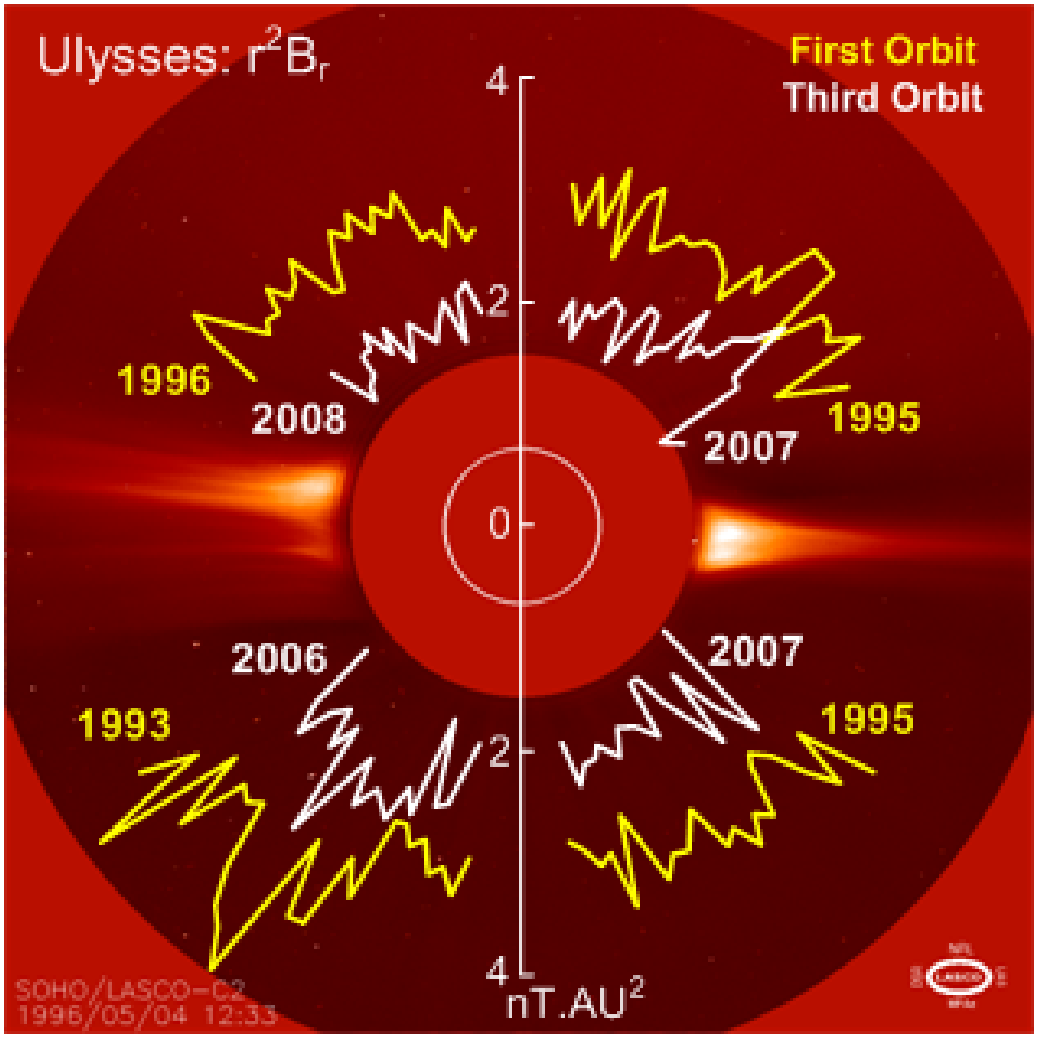
A global effect

Grey areas are where Ulysses is within ±30° of the equator

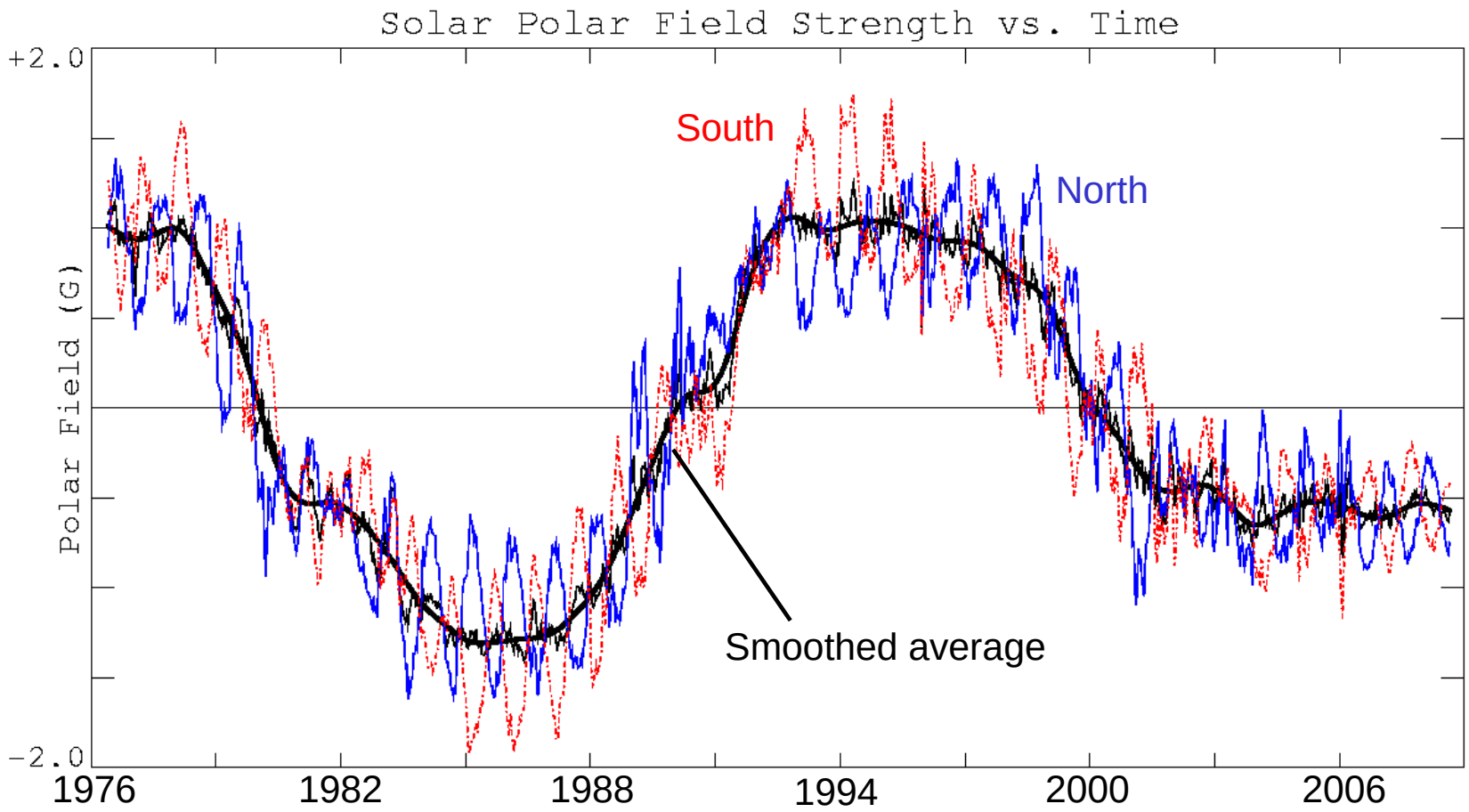


McComas et al, (2008)

~33% reduction in polar magnetic flux

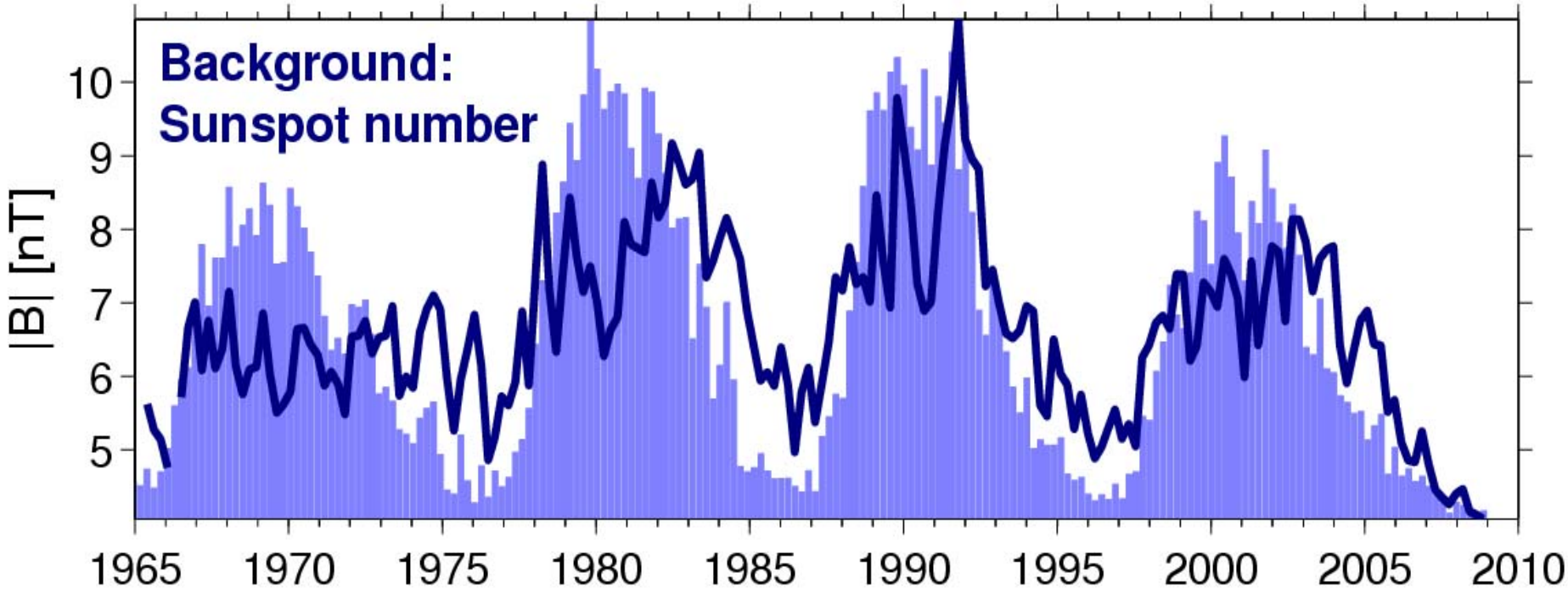


Photospheric field also reduced

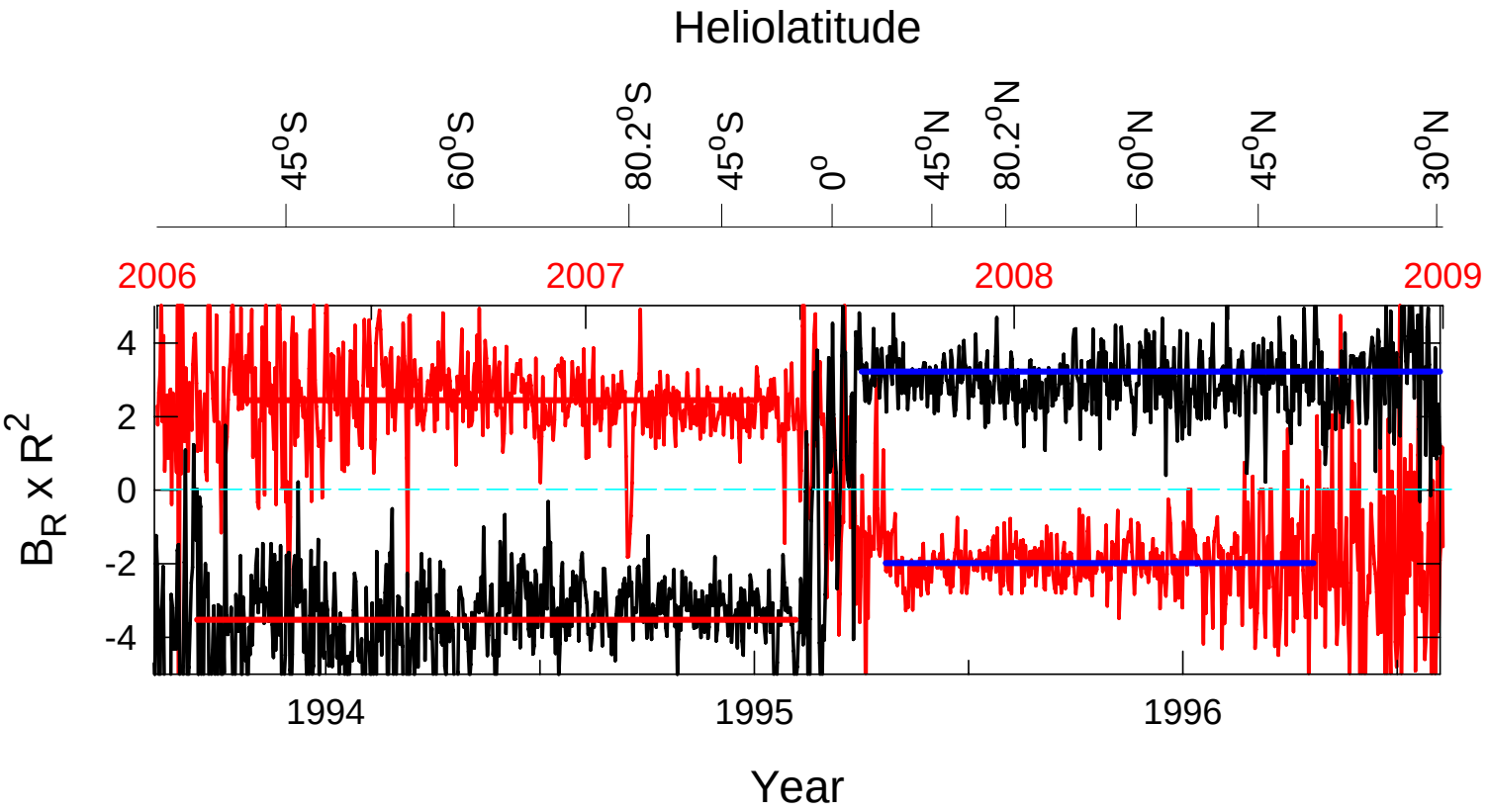


Wilcox Solar Obsevatory (http://wso.stanford.edu)

Heliospheric magnetic field at 1 AU

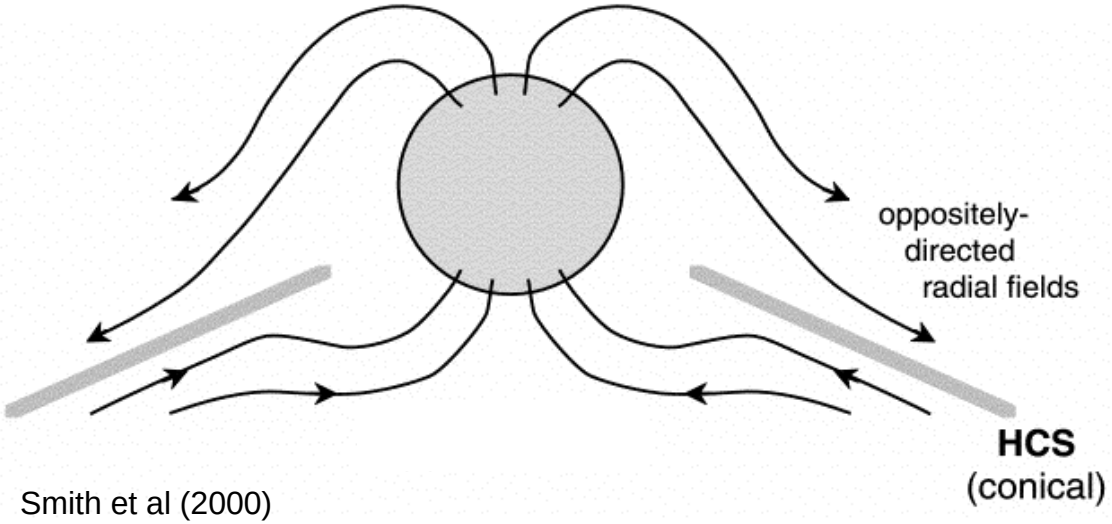


[Owens et al., 2008]



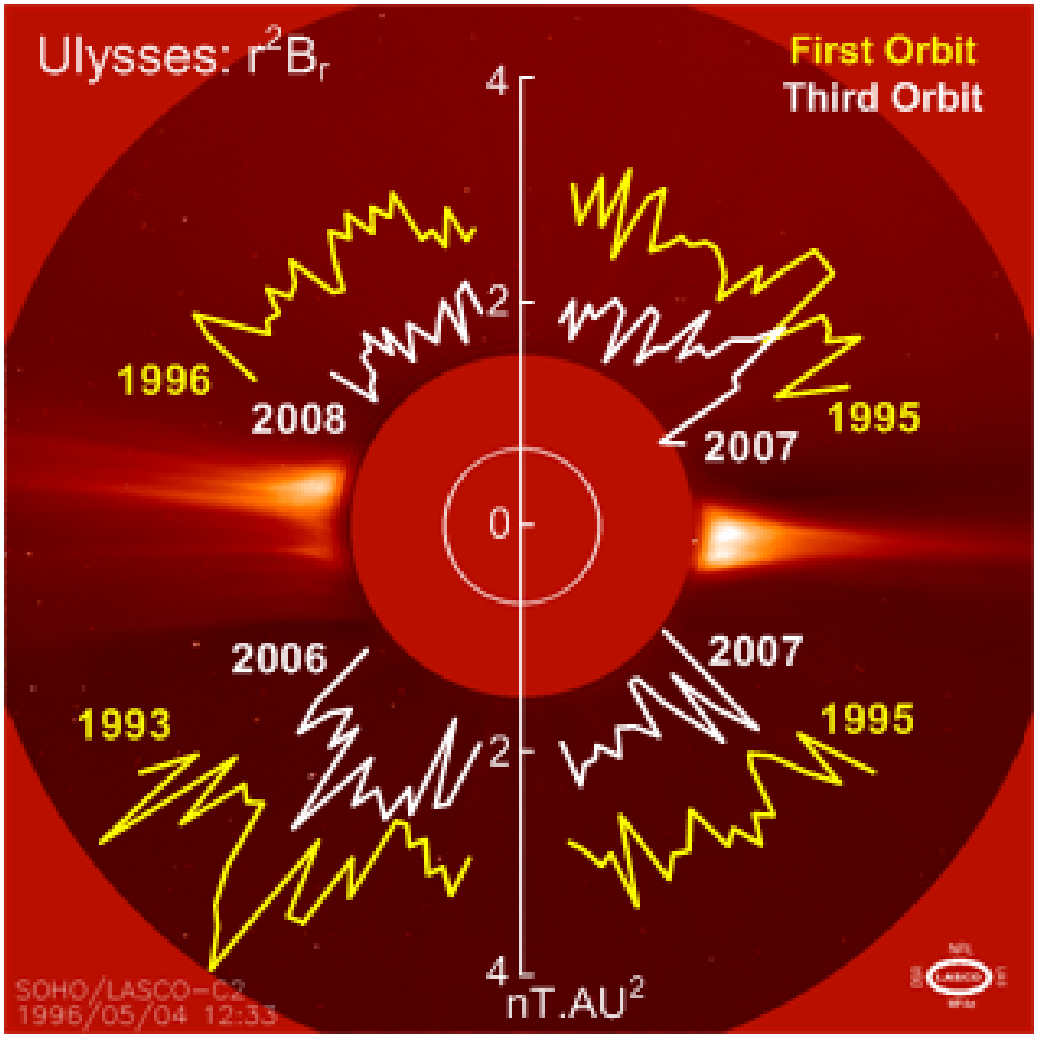
	1993.7-1995.1 (511d)	1995.25-1996.6 (494d)	2006.2-2007.4 (437d)	2007.7-2008.7 (359d)
	South	North	South	North
Mean (nT)	-3.5254	2.9739	2.4167	-2.0039
Median (nT)	-3.3426	2.9845	2.4234	-2.0234
Std. Dev. (nT)	1.3900	0.9096	1.1753	0.8748
Std. Err. (nT)	0.0615	0.0409	0.0562	0.0462

North – south asymmetry ?

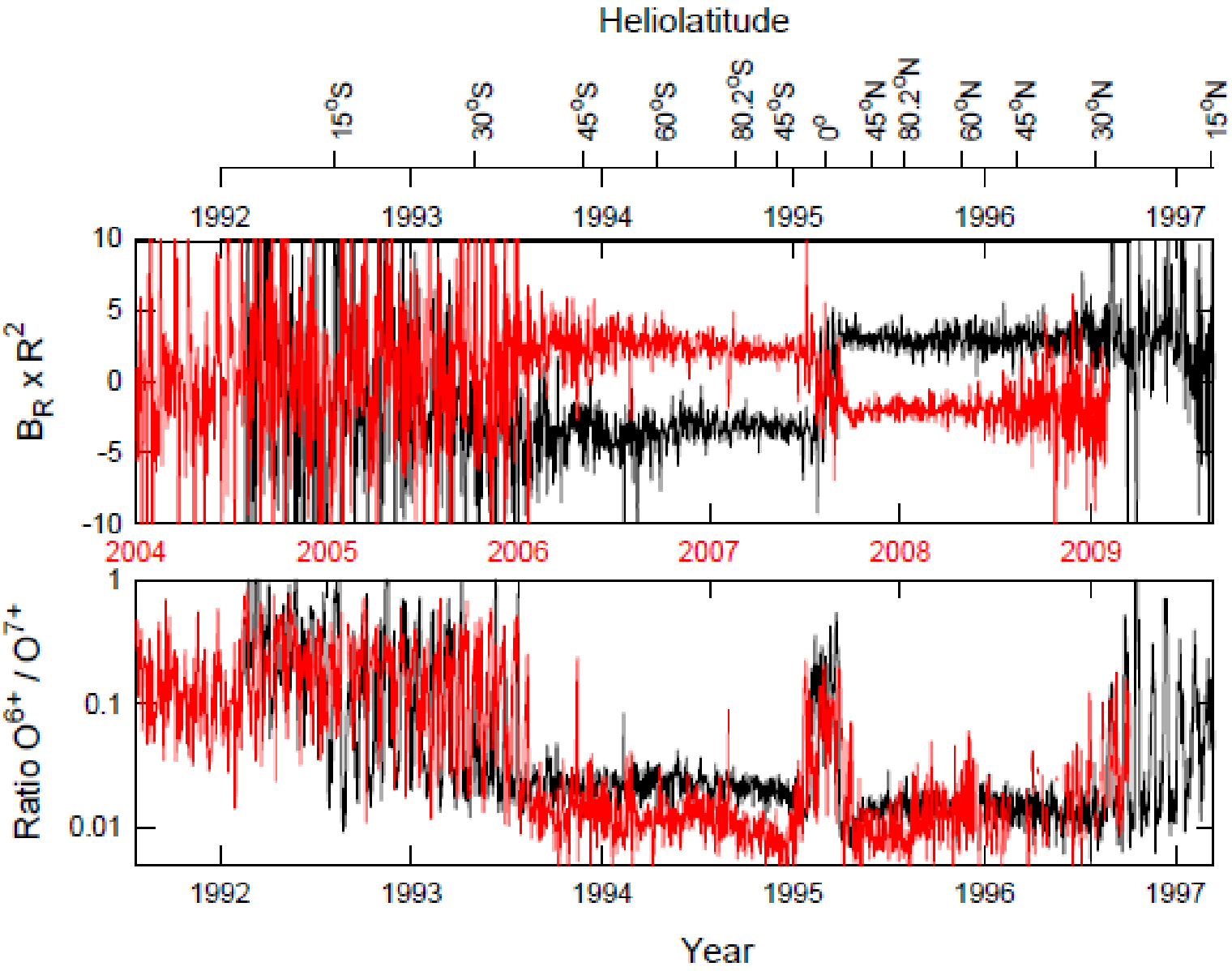


Smith et al (2000)

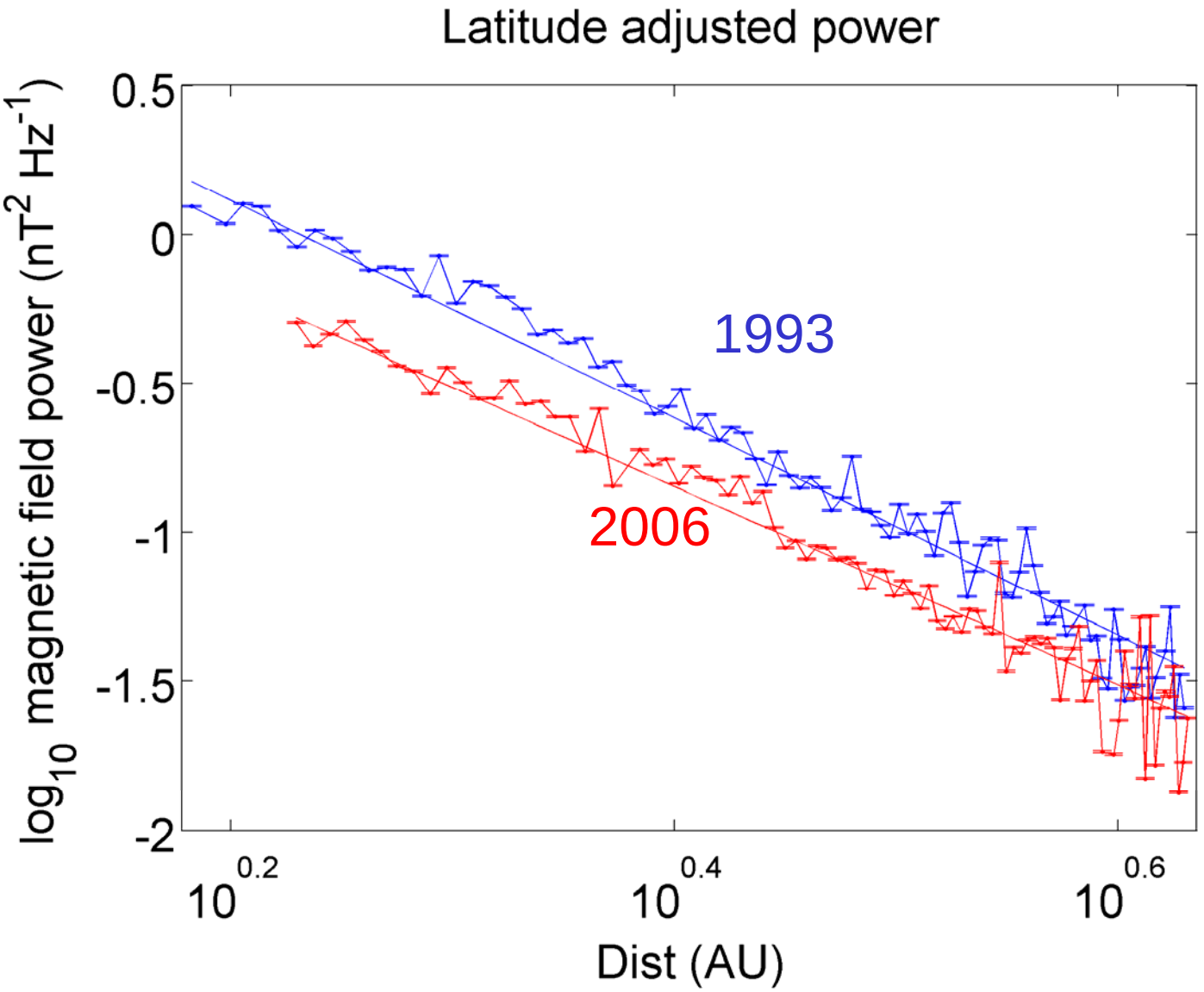
Role of time variations...?



Composition signatures…



Reduced magnetic field wave power

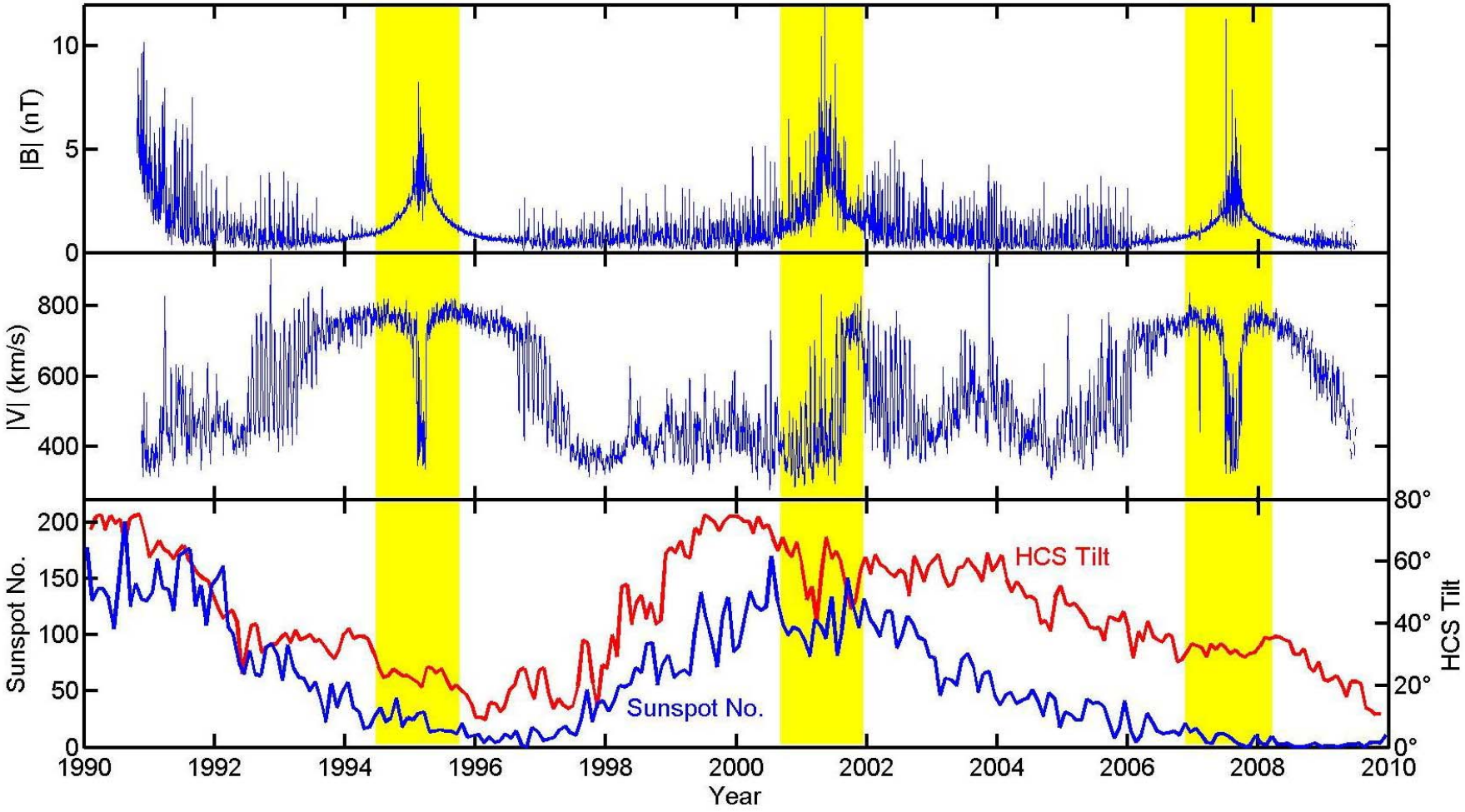


Discussion

- Weaker photospheric fields and less open flux are consistent with smaller polar coronal holes.
- Recent models powering the solar wind through emerging magnetic flux predict that the solar wind power should be proportional to the magnetic flux of the open field.
- Less heating is consistent with lower coronal temperatures.
- Lower dynamic pressure implies that the size of the heliosphere is smaller this solar minimum.

Ulysses mission overview…

18 years + 9 months of almost continuous data

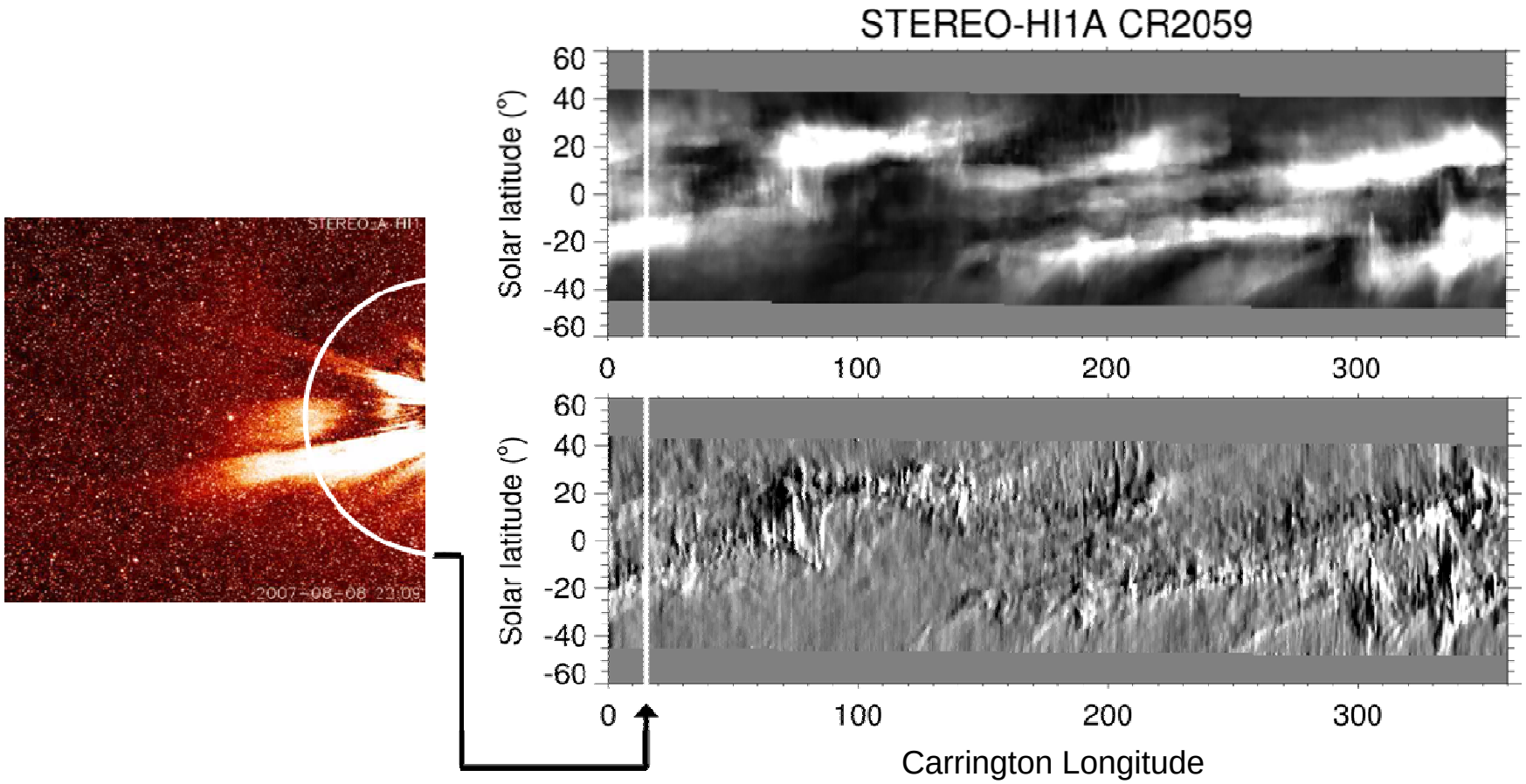


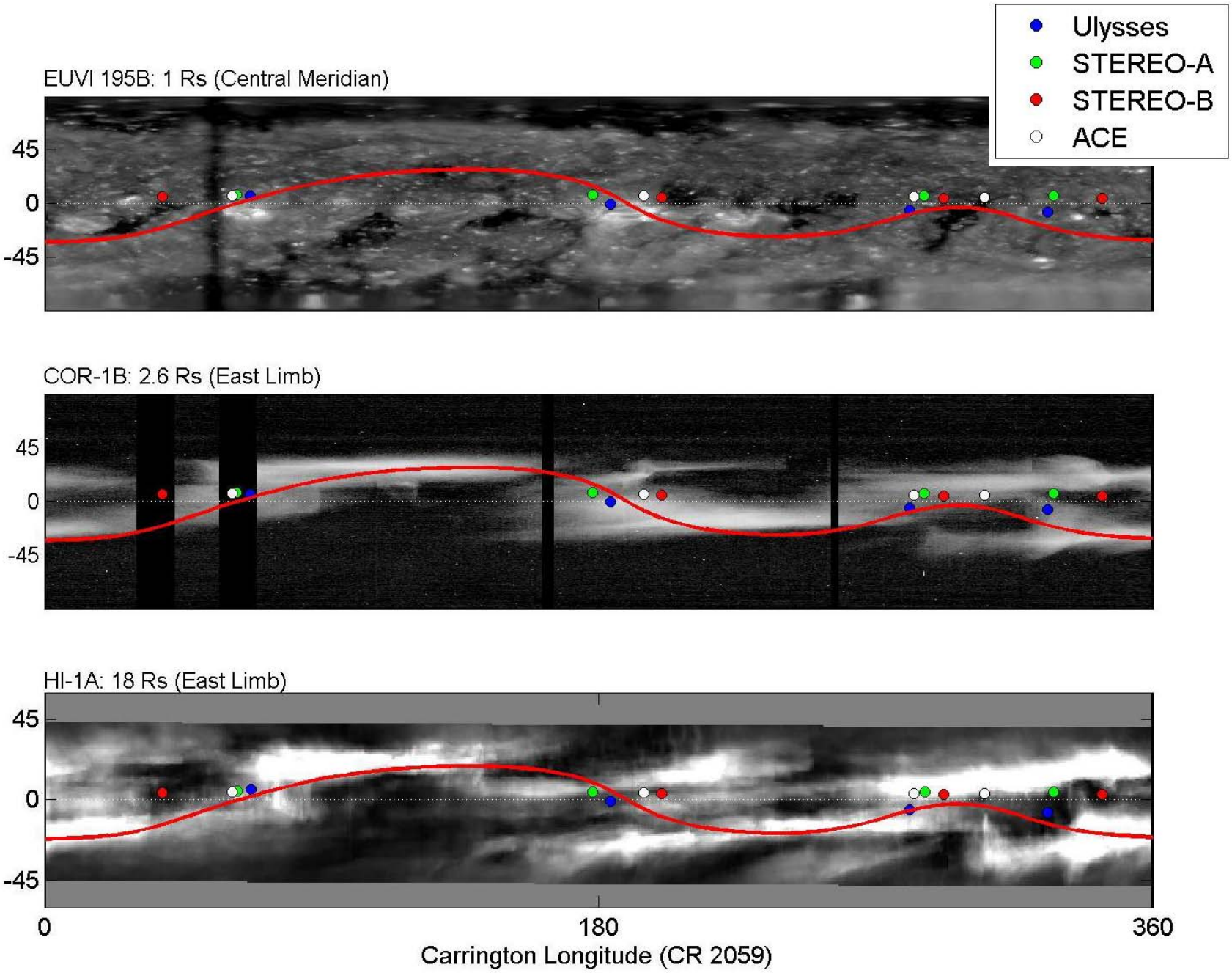
Yellow regions mark polar passes and fast latitude scans

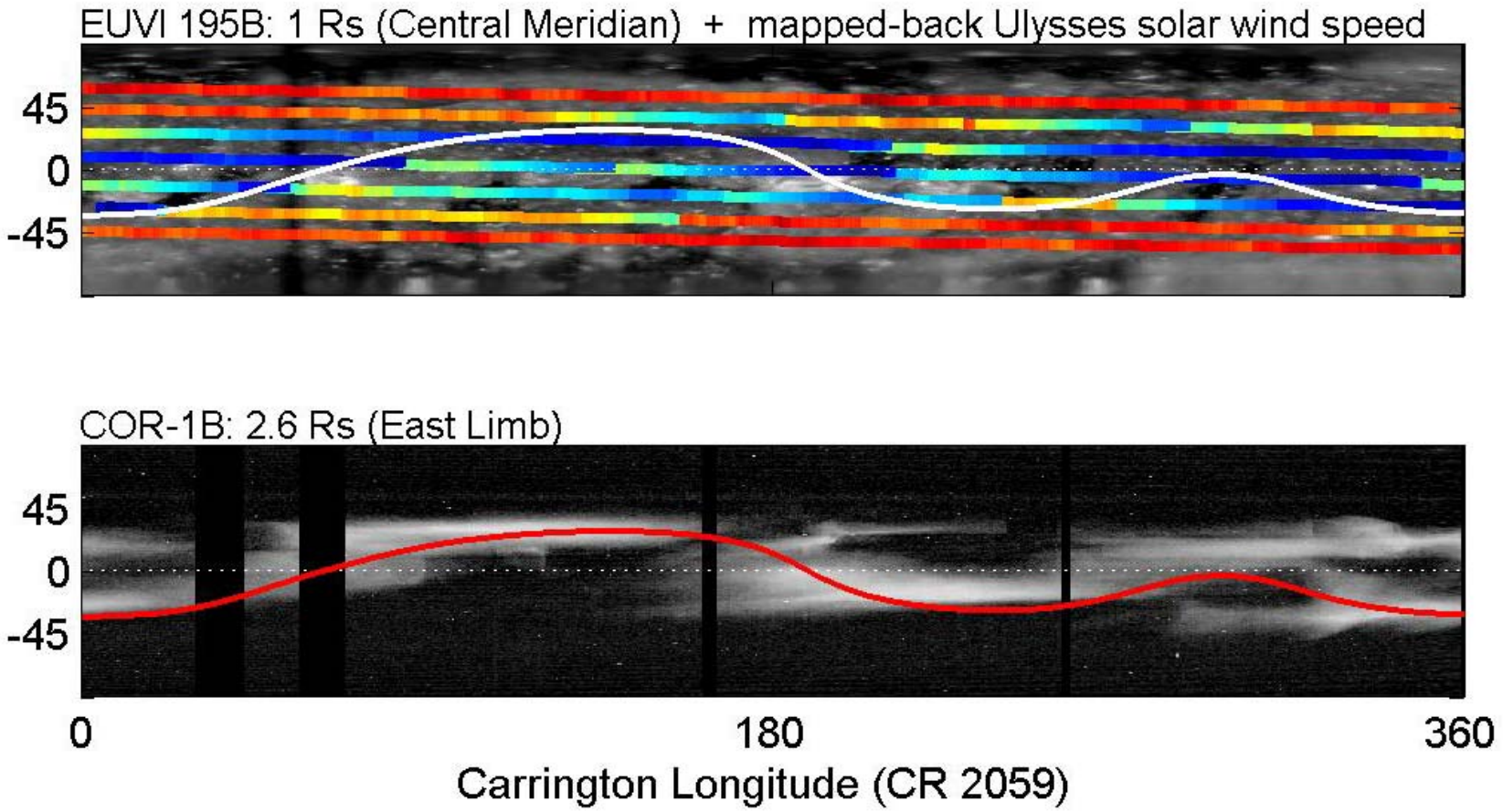
Summary

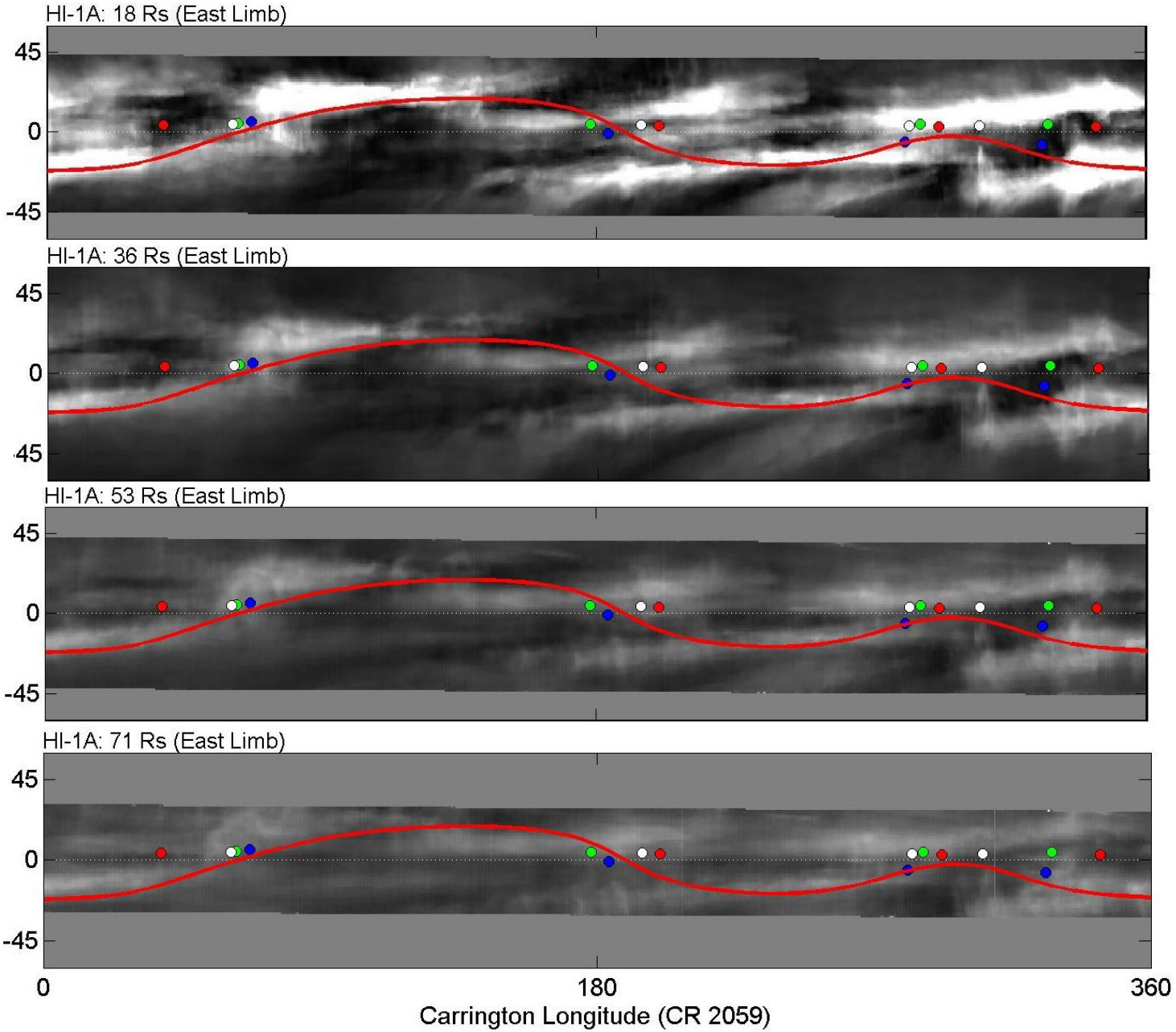
- The Ulysses mission has provided a unique 18+ year dataset characterising the 3D structure and solar cycle evolution of the heliosphere
- Comparisons of the solar minima of cycles 22 and 23 reveal weaker polar magnetic fields both at the photosphere and in the heliosphere
- Solar wind density, temperature and dynamic pressure are all significantly reduced this solar minimum
- Comparison with in-ecliptic observations show that these are global effects.

Heliospheric Imager synoptic maps




Ulysses
STEREO-A
STEREO-B
ACE
EUVI 195B: 1 Rs (Central Meridian)
COR-1B: 2.6 Rs (East Limb)
HI-1A: 18 Rs (East Limb)
45
0
-45
0
180
360
Carrington Longitude (CR 2059)


EUVI 195B: 1 Rs (Central Meridian) + mapped-back Ulysses solar wind speed
45
0
-45
COR-1B: 2.6 Rs (East Limb)
45
0
-45
0
180
360
Carrington Longitude (CR 2059)


HI-1A: 18 Rs (East Limb)
45
0
-45
HI-1A: 36 Rs (East Limb)
45
0
-45
HI-1A: 53 Rs (East Limb)
45
0
-45
HI-1A: 71 Rs (East Limb)
45
0
-45
0
180
360
Carrington Longitude (CR 2059)