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FINNISH METEOROLOGICAL INSTITUTE

Aalto University

HCS shift over 100 years

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OR: The collected adventures of the Bashful ballerina

K. Mursula[1], I. Virtanen[1], J. Koskela[1], M. Vokhmyanin[2], B. Zieger[3]

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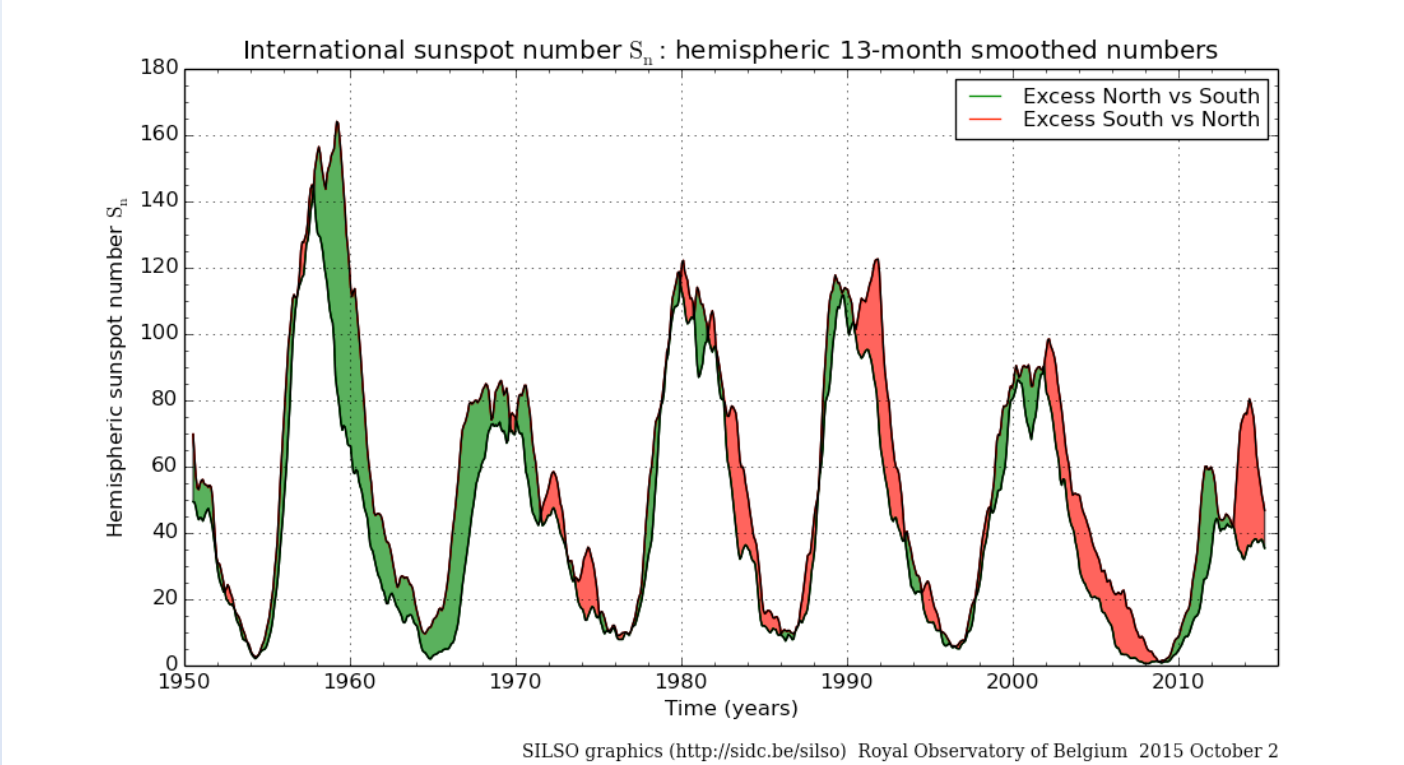
Hemispherical asymmetry in solar magnetic fields

- Sunspot activity is often north-south asymmetric
- Polar fields often develop differently in the two hemispheres
- Northern and southern hemispheres are connected, but not strictly. Therefore, magnetic fields are (slightly) asymmetric.



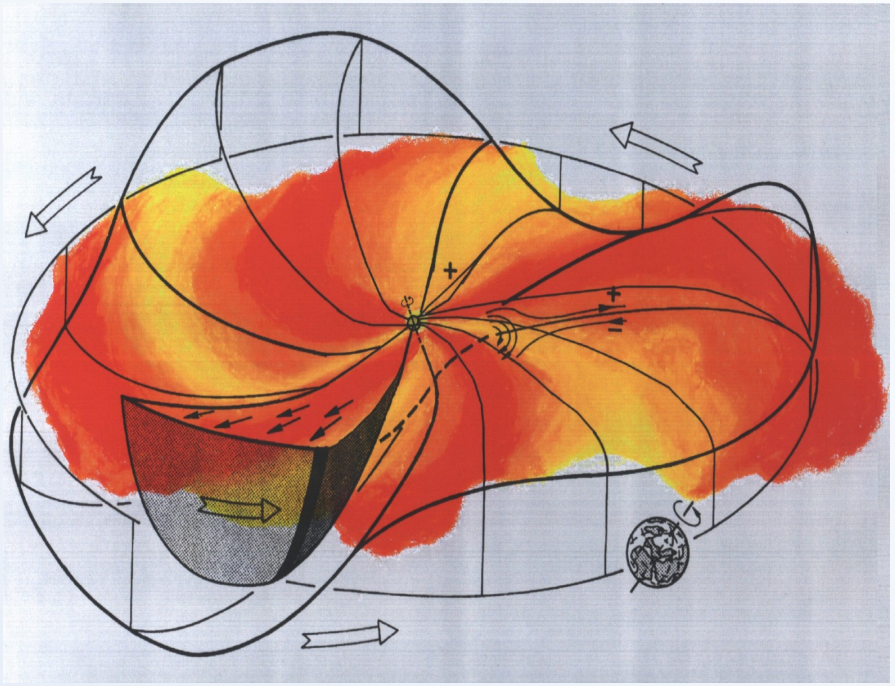
HCS = Magnetic equator = Ballerina skirt

Heliospheric current sheet (HCS) is the heliospheric magnetic equator that separates the two magnetic hemispheres (or HMF sectors).

Because of its wavy structure, HCS is often called the Ballerina skirt.

NOTE: It has always been tacitly assumed so far that the longitudinally averaged **HCS location coincides with the heliographic equator.**

However, this is not true!!

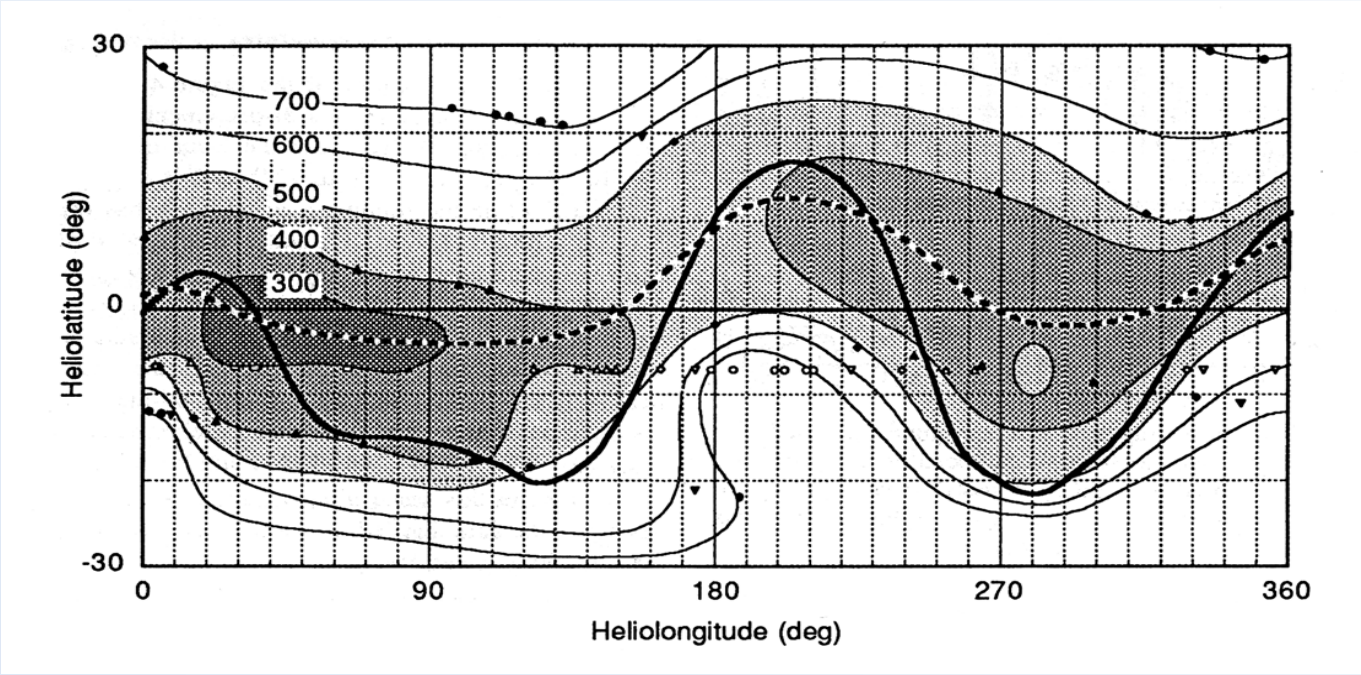


HCS and streamer belt: Ulysses

Ulysses probe on its first fast latitude scan over the ecliptic in 1995:

- SW speed distribution is shifted northwards

- HCS (heliospheric current sheet) is shifted southwards



HMF T/(T+A) ratio in Fall and Spring

Study the fraction of one HMF magnetic hemisphere in separately in Fall and Spring.

T= toward sector = magnetic south

A= away sector = magnetic north

T/(T+A) ratio in Fall

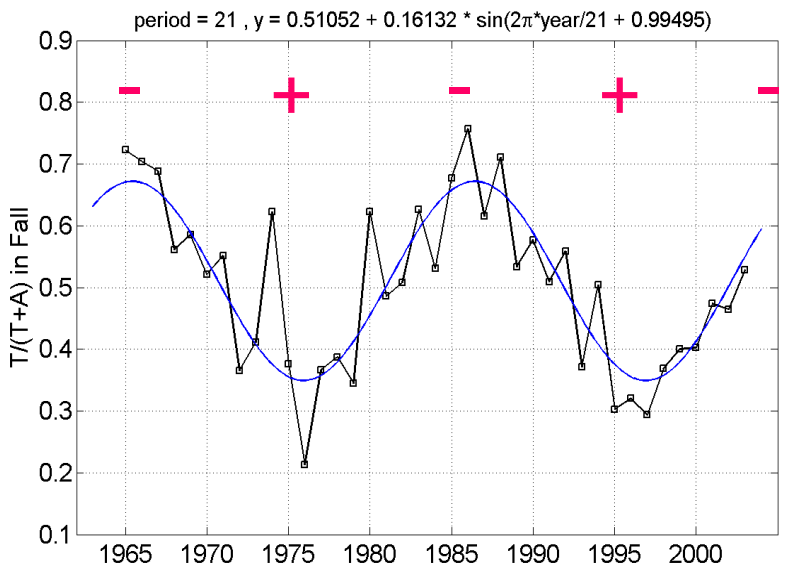
Despite some scatter, there is a clear dominance of the magnetic hemisphere coming mainly from the northern heliographic hemisphere.

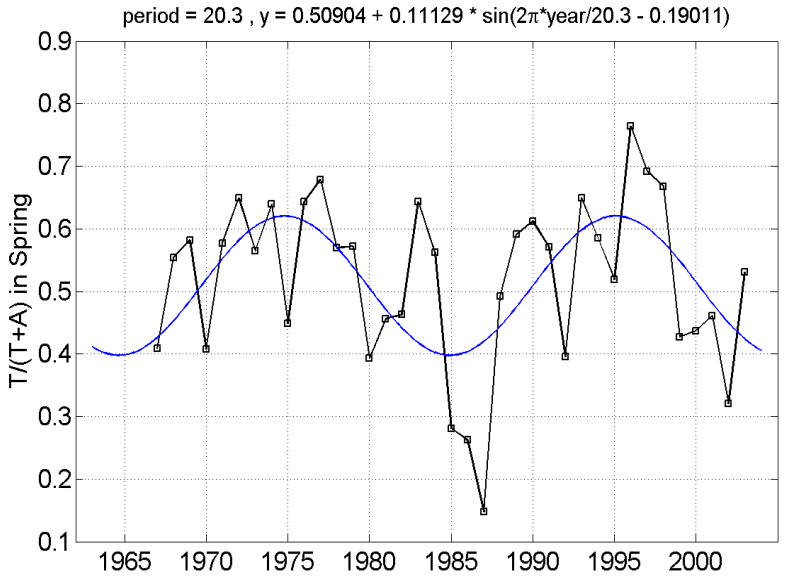
T/(T+A) ratio in Spring

There is more scatter, and the average level of dominance in Spring is lower than in Fall.

Still, clearly systematic 22-year variation of the baseline.

Rosenberg-Coleman rule is very well valid for the northern heliographic hemisphere but slightly less clear in the southern hemisphere.

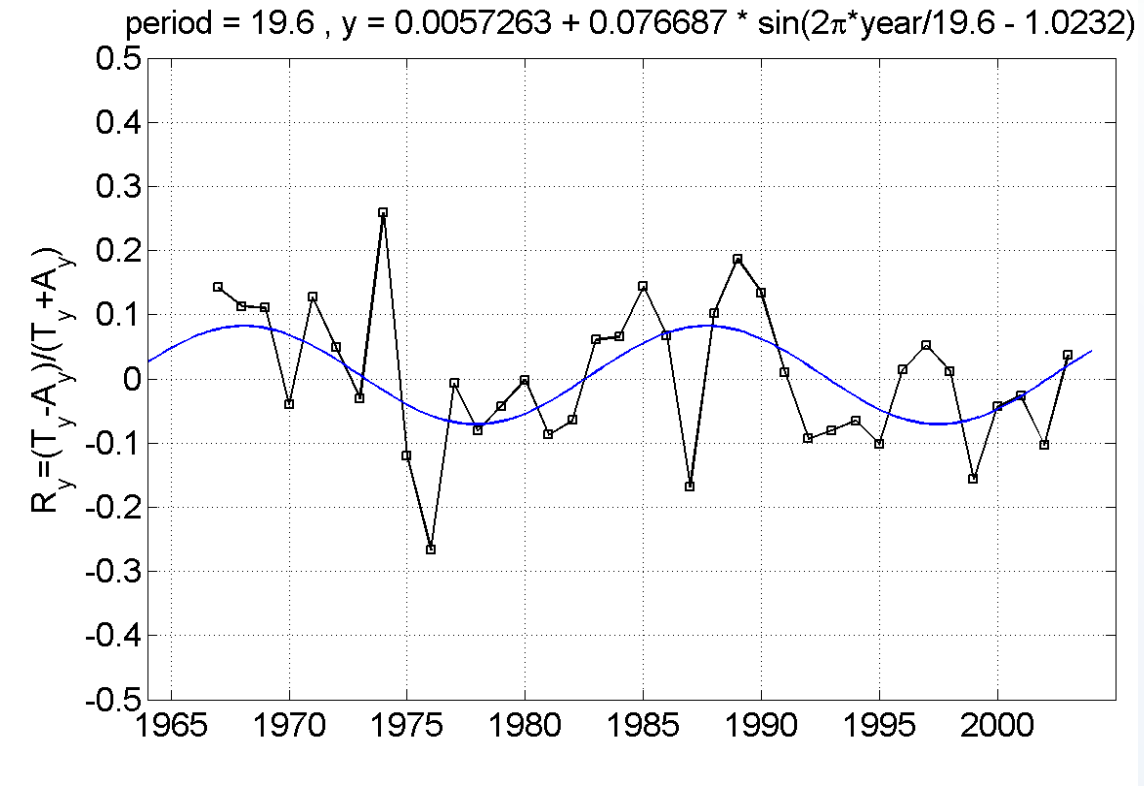




Annual (T-A)/(T+A) ratio (OMNI data)

The annual (or equinoctial) average of the (T-A)/(T+A) ratio reveals the asymmetry of the heliospheric current sheet at 1AU.

Despite considerable scatter, there is an overall significant 22-year baseline oscillation. The magnetic hemisphere of the northern heliographic hemisphere dominates at 1 AU.



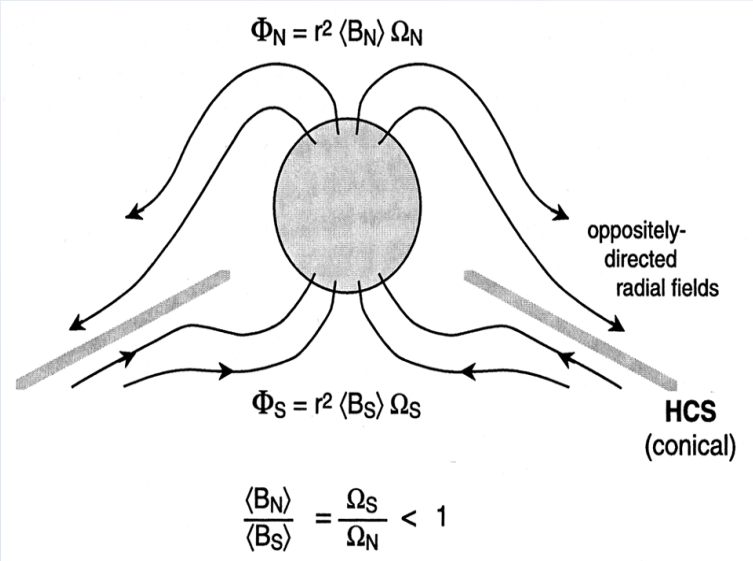
Mursula, and Hiltula, Geophys. Res. Lett., 30, 2003.

HCS is, on an average, shifted southward (towads the southern heliographic hemisphere) around solar minima. (Significant deviations also not random).

Since the Rosenberg-Coleman rule (latitudinal variation of sector dominance) still works both in Fall and Spring, the average shift must be less than 7.2°.

Southward shifted HCS = Bashful Ballerina

So rather than symmetric, the ***HCS is southward shifted or coned*** at these times and looks like this:



Smith et al., ApJ, 2000

As an amusing and natural continuation to the early naming practice, we called ***the Sun with its shifted heliospheric current sheet a Bashful Ballerina*** who is pushing her excessively high flaring skirt downward whenever her activity is fading out.

Mursula, and Hiltula, Geophys. Res. Lett., 30, 2003.

First solar observation of HCS shift

Zhao et al., JGR, 2005

Top Figure: Mean field in open regions

Field in north weaker than in south

(Hoeksema, 1995)

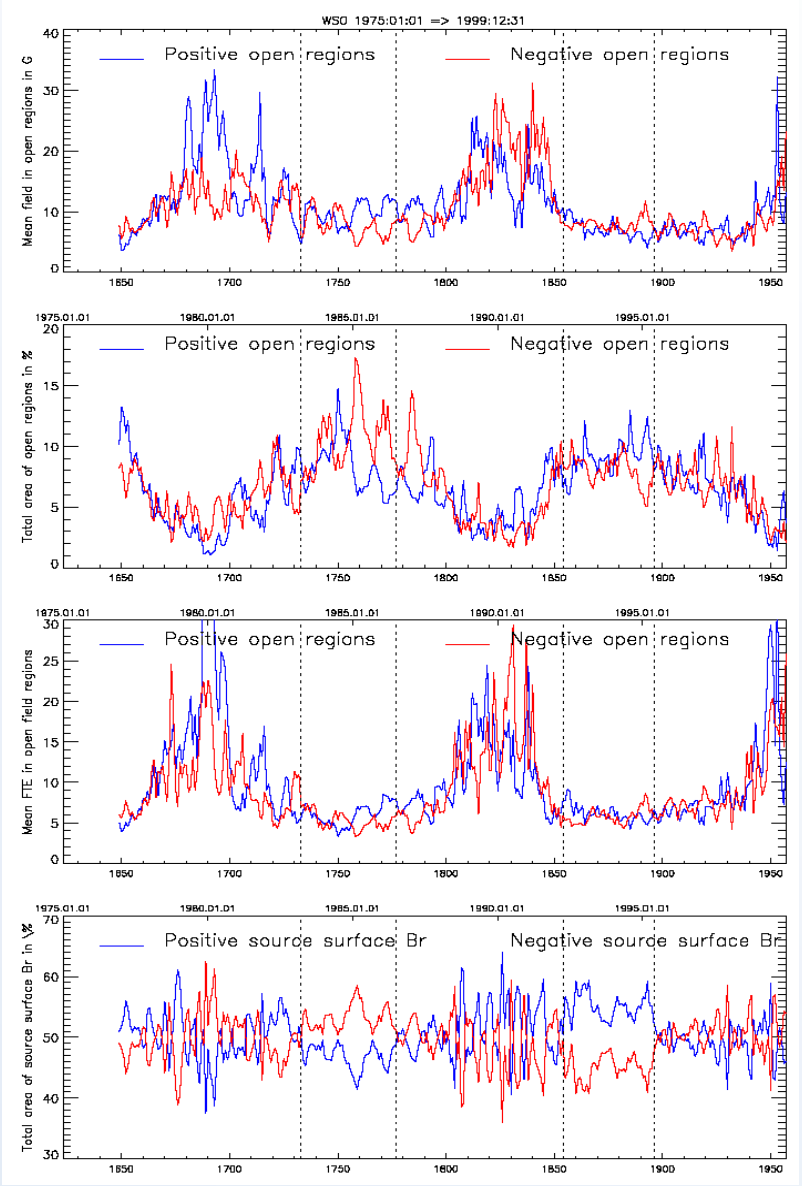
Second: Total area in open regions

Area in north larger than in south

Bottom: Total area in % of source surface Br

Area in north larger than in south

Area in north larger than in south during 3 years before minimum

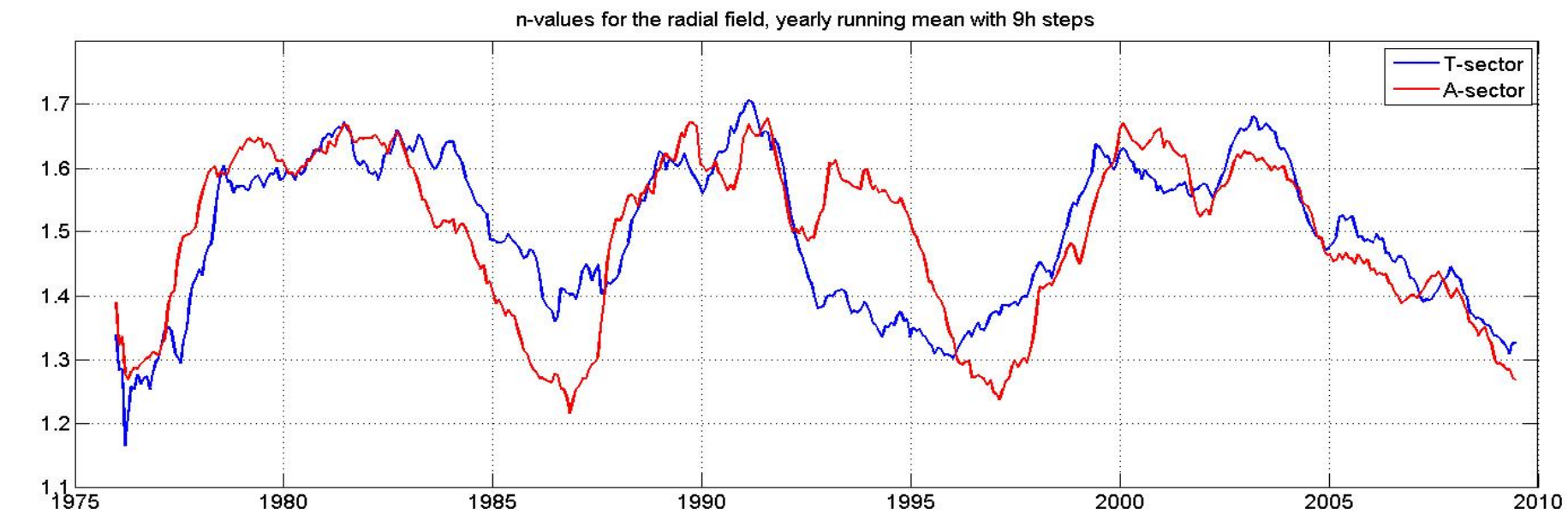


Radial profile of radial field: HMF vs. WSO

- n varies strongly with solar cycle because of variable HCS proximity.

- During the Ballerina times n is larger for the northern hemisphere field because magnetic equator is shifted south and the northern footpoint is located further away from HCS. This is clearly valid for SC 21 and 22.

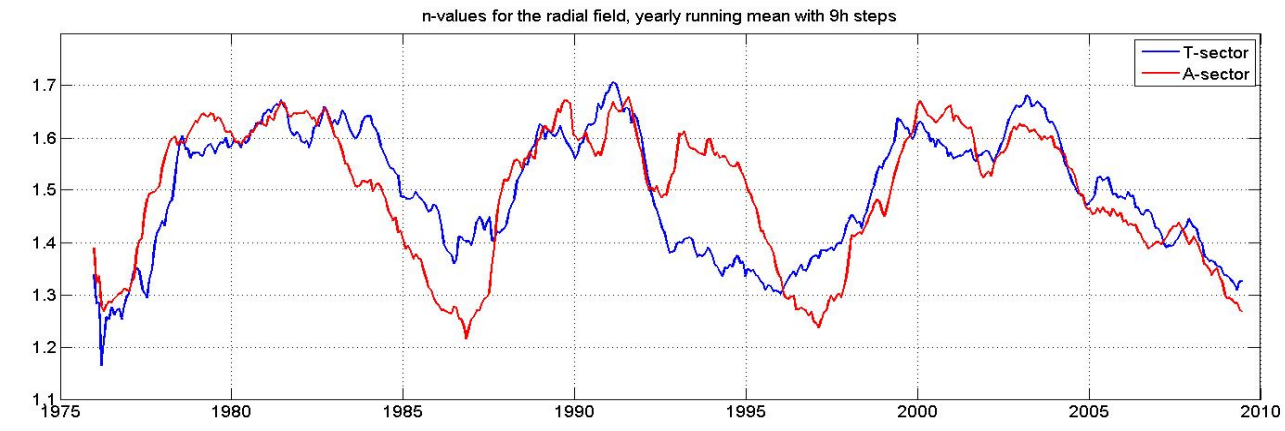
- During SC 23 Ballerina is also bashful but less than in earlier minima.

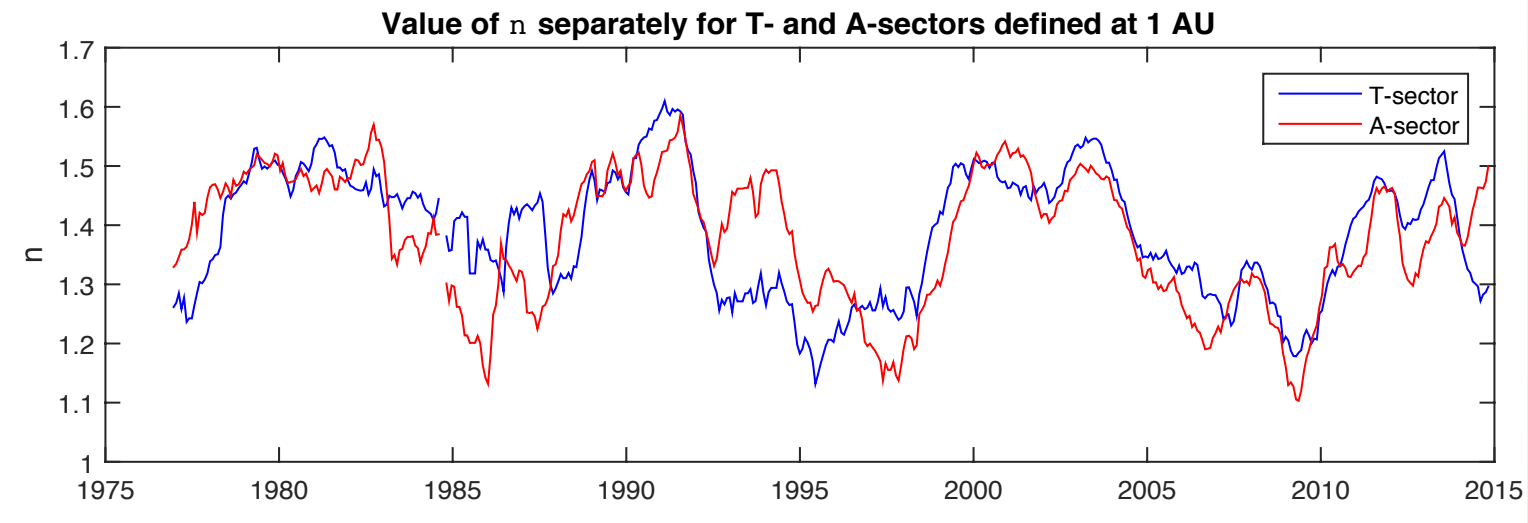


Mursula, and Virtanen, A&A, 2011.

Radial profile of radial field: HMF vs. WSO

Asymmetry during descending phase of SC24 starts showing up..



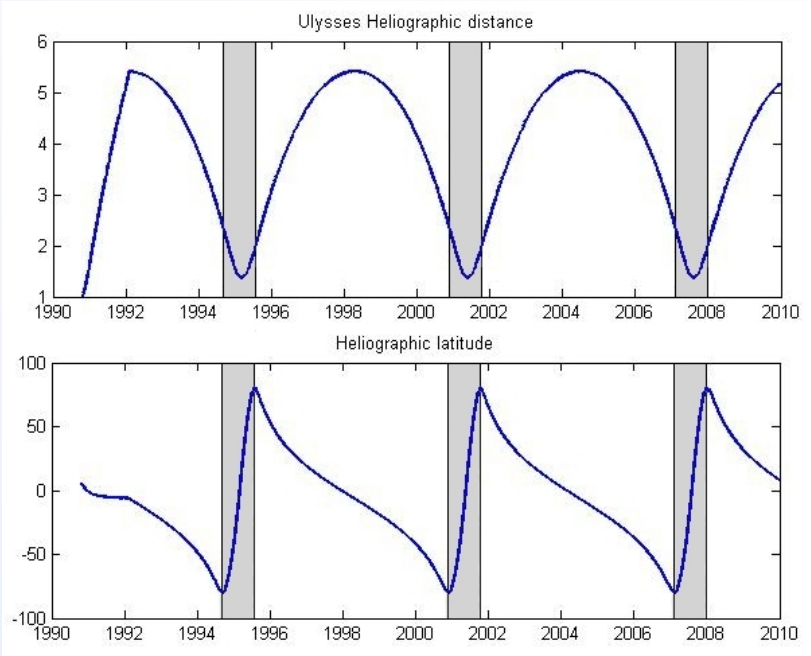


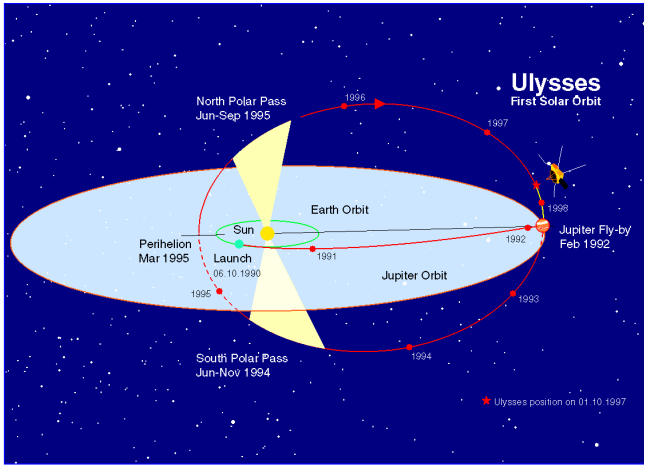
Ulysses mission

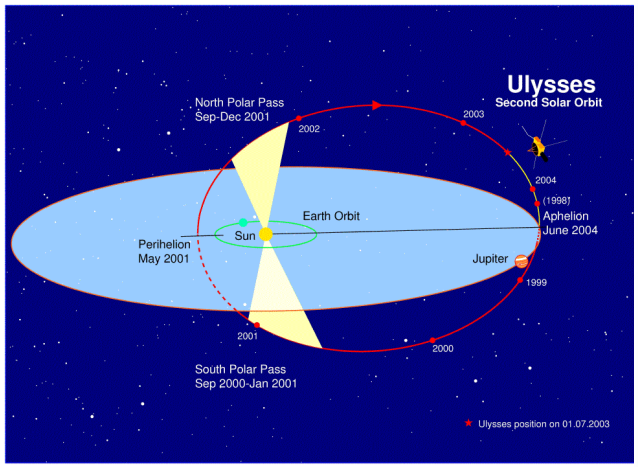
- Ulysses was flying on a polar orbit from 1991 until 2008, making three orbits around the Sun.

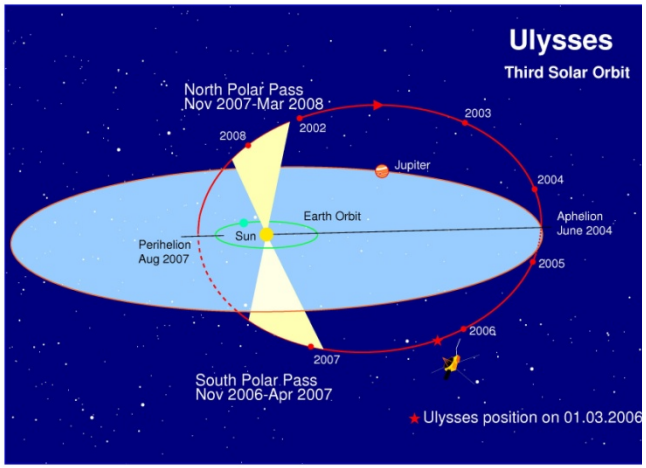
- The three fast latitude scans at the perigee took place in 1994-1995, 2001-2002 and 2007. Thus, the first and the third fast latitude scans were in solar minimum conditions and the second at the maximum of SC 23.

- During the fast latitude scans the latitude of Ulysses changes almost linearly in time.





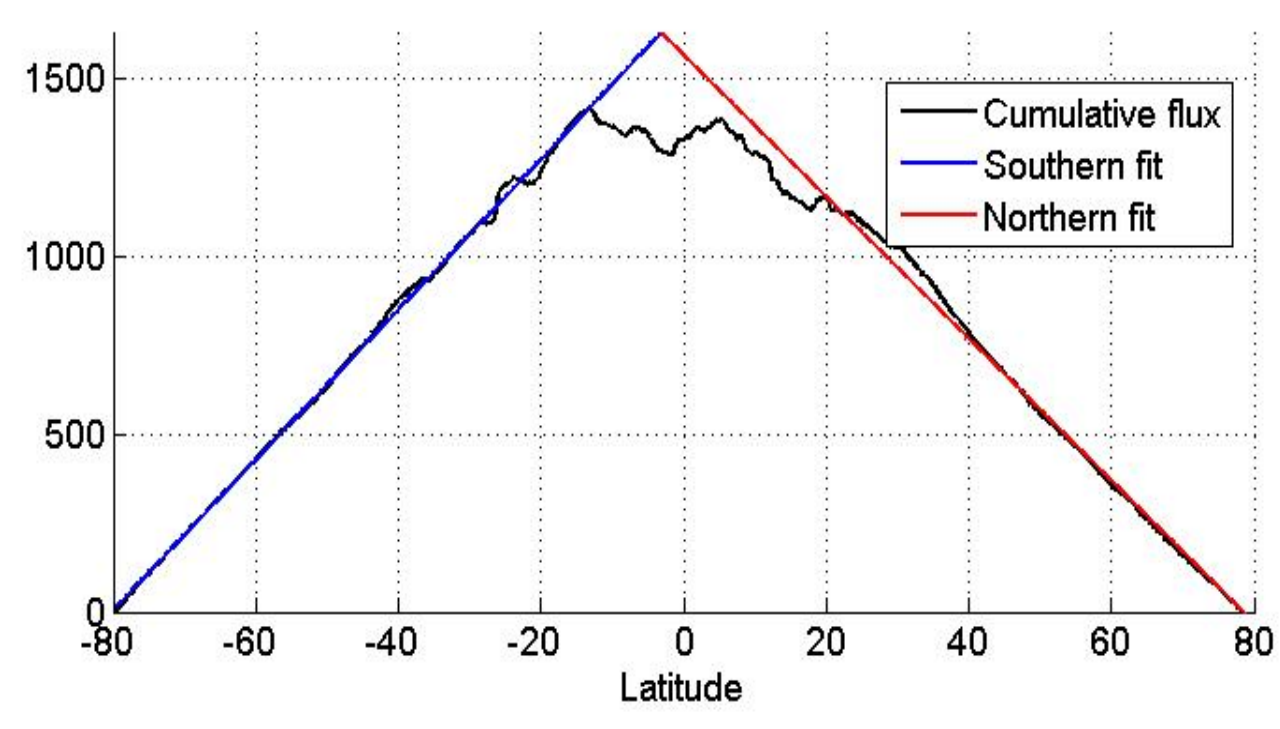




Best fit lines and slopes in 1994/1995

- Calculate the best-fit line to the cumulative flux density curve from high-latitude close to the equator.

- The slope of the best-fit line gives the average magnetic field over this latitude range if Br remains constant in latitude and time.



- The red and blue lines in figure correspond to a fit from ± 79.7° to ±14°.
- Equatorward extent of the fitting range is a (rather) arbitrary parameter.
- Reliable estimates of slopes should not depend on this limit.

High-latitude fields as a function of equatorial extent

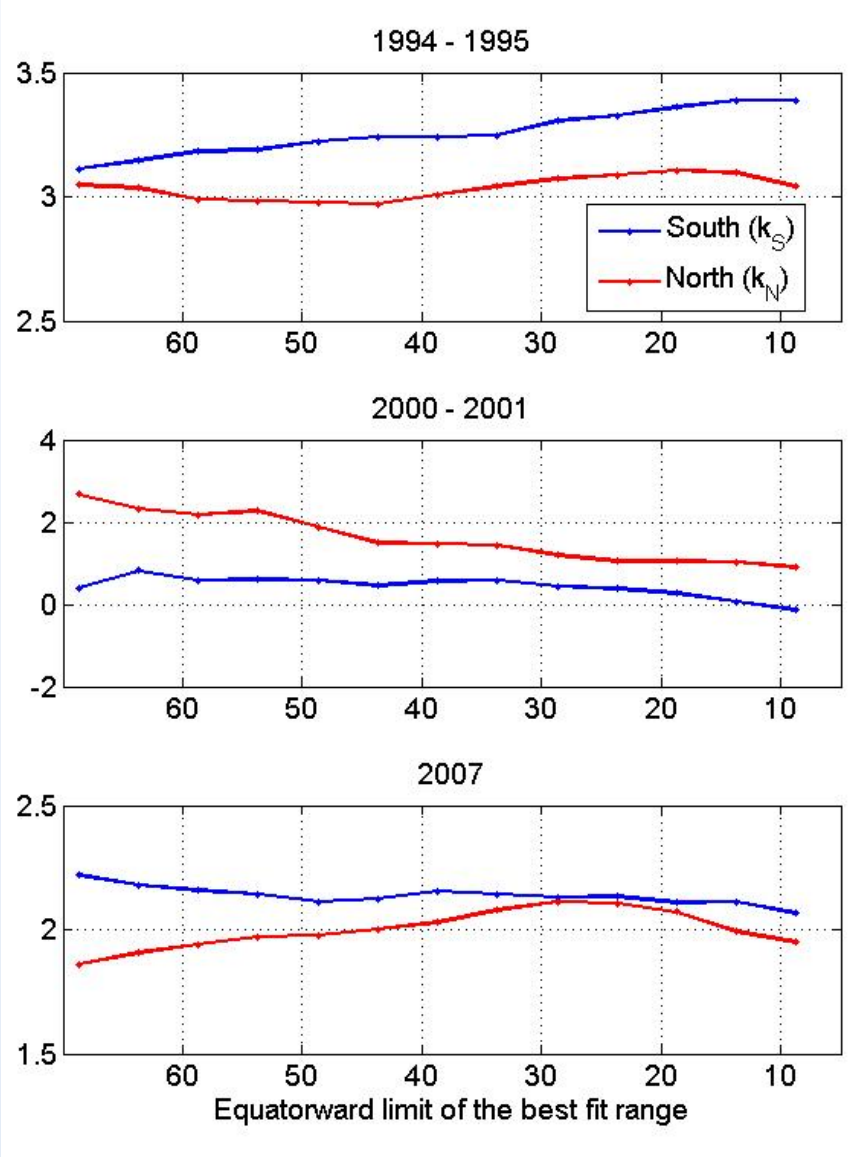
- Figure shows the slopes of the best fit lines as a function of the equatorial limit of the fitting range starting from ±79.7°.

- During both minimum time fast latitude scans in 1994-1995 and 2007 the magnitude of the northern field is significantly smaller than magnitude of the southern field.

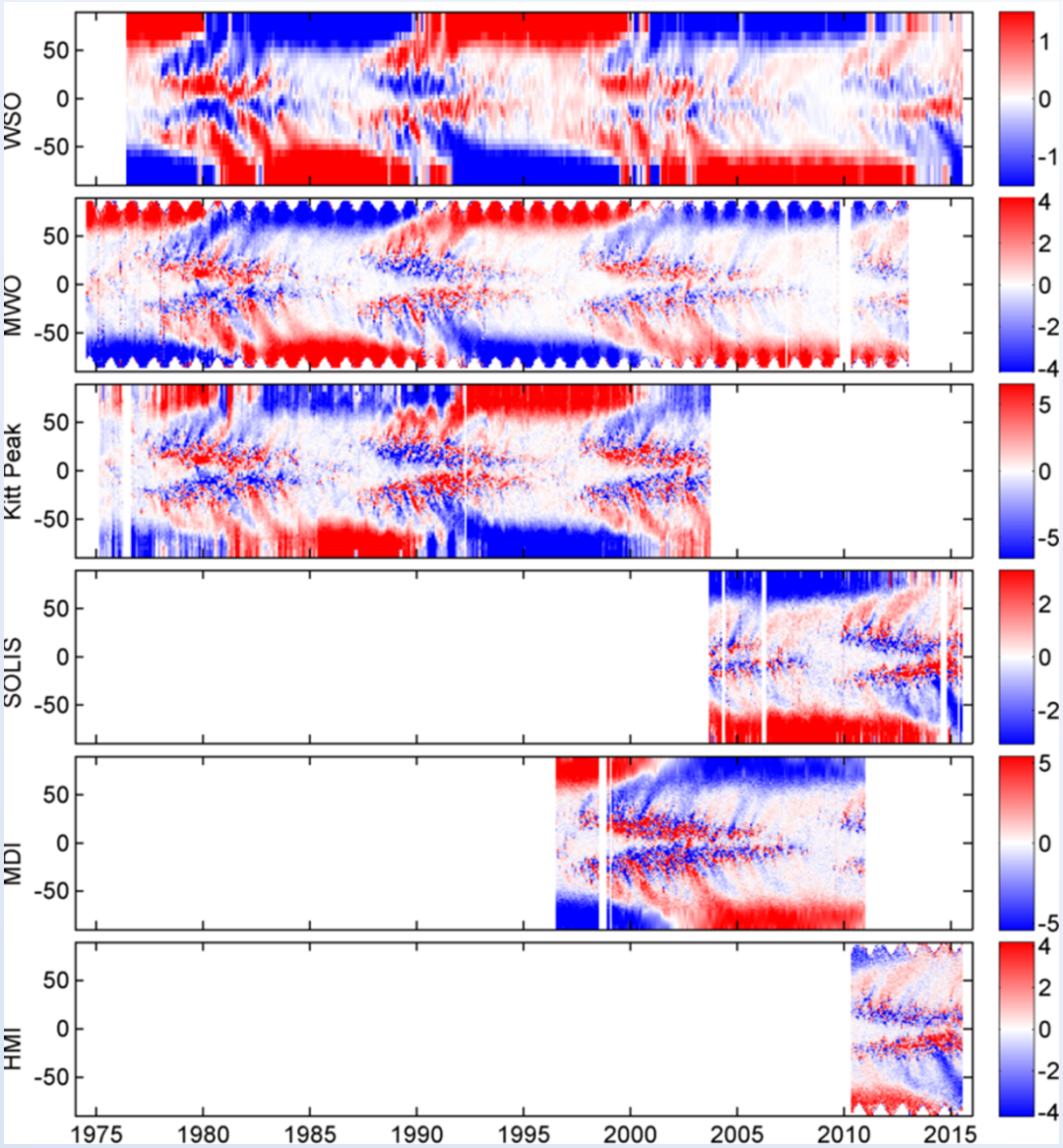
- In 2007 the magnitude of the field is roughly 1 nT smaller than in 1994-1995.

- In 2000-2001 the southern slope is close to zero and the northern slope is larger because the northern field is observed later in time when unipolar coronal hole had already developed by the time when satellite reached high northern latitudes.

Virtanen and Mursula, JGR., 2010.



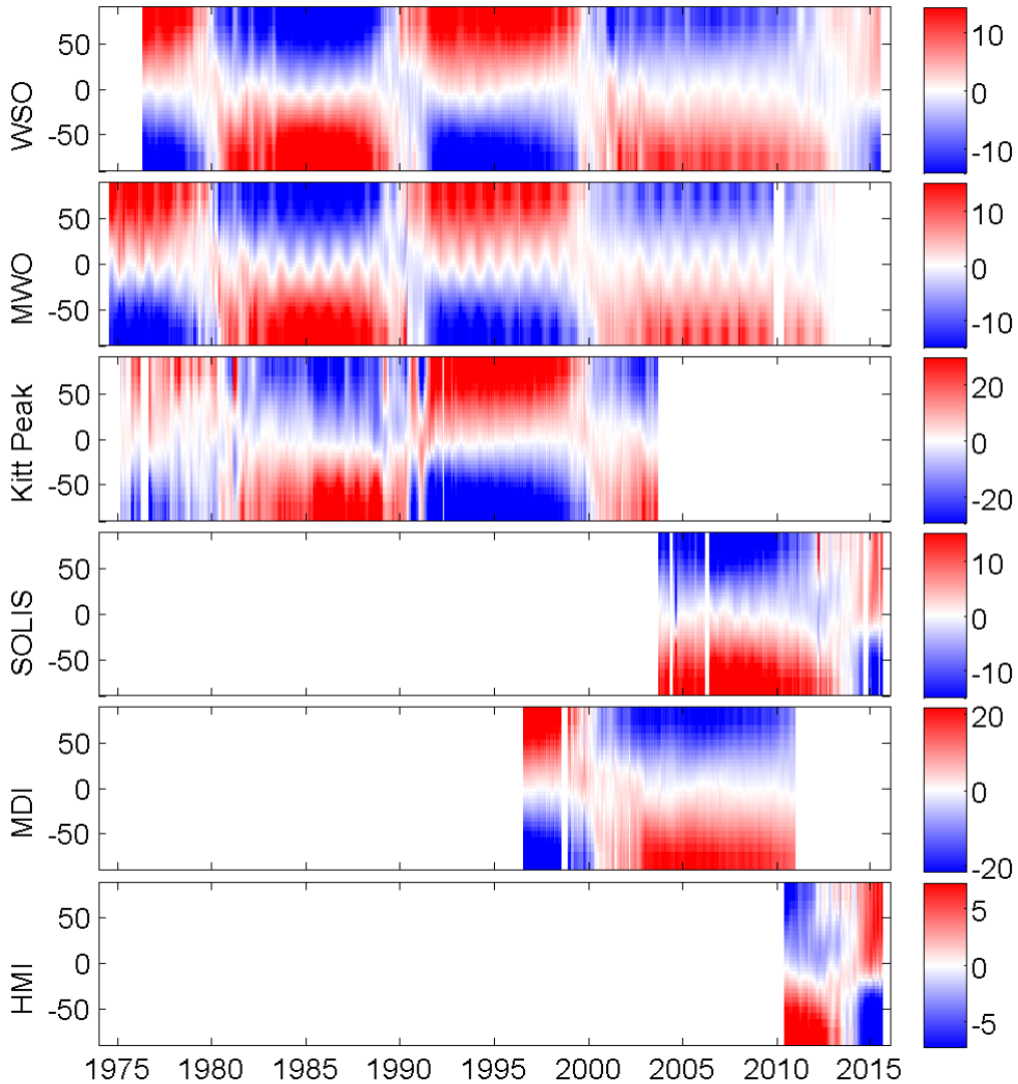
Photospheric magnetic field observations



- Longitudinal averages show similar large scale structures and solar cycle evolution in all six data sets.
- Higher resolution data show more complicated structures, especially in active regions.
- Even polar fields appear slightly differently in high resolution data.
- Differences between polar fields are largest during polarity reversals. Low resolution instruments indicate earlier reversal.

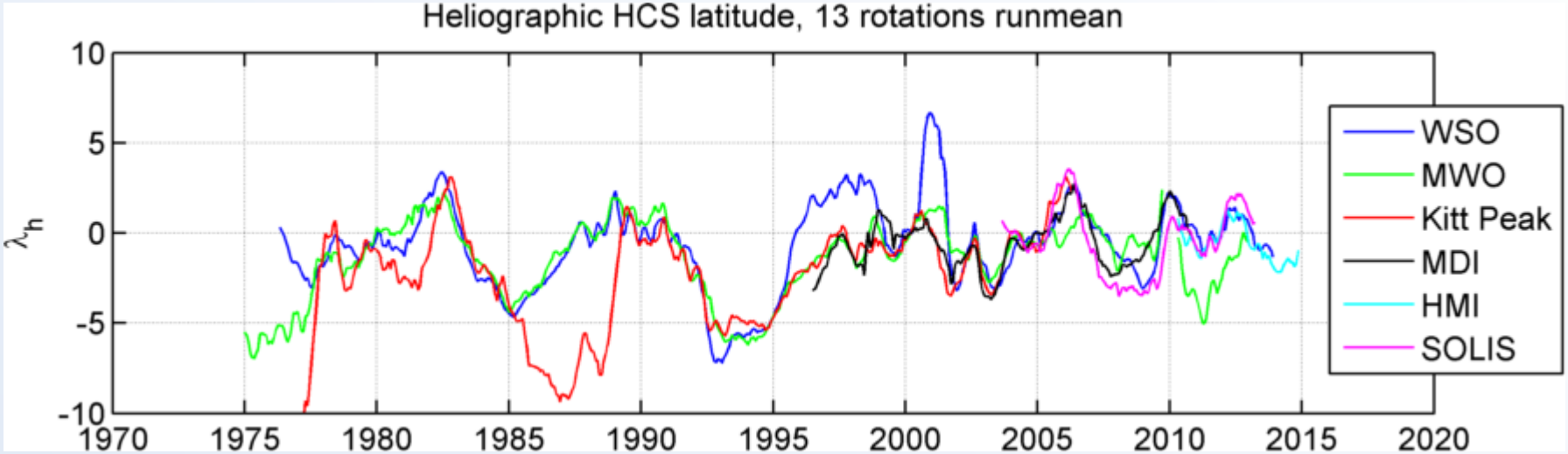
Virtanen and Mursula, A&A., 2016.

Coronal magnetic field



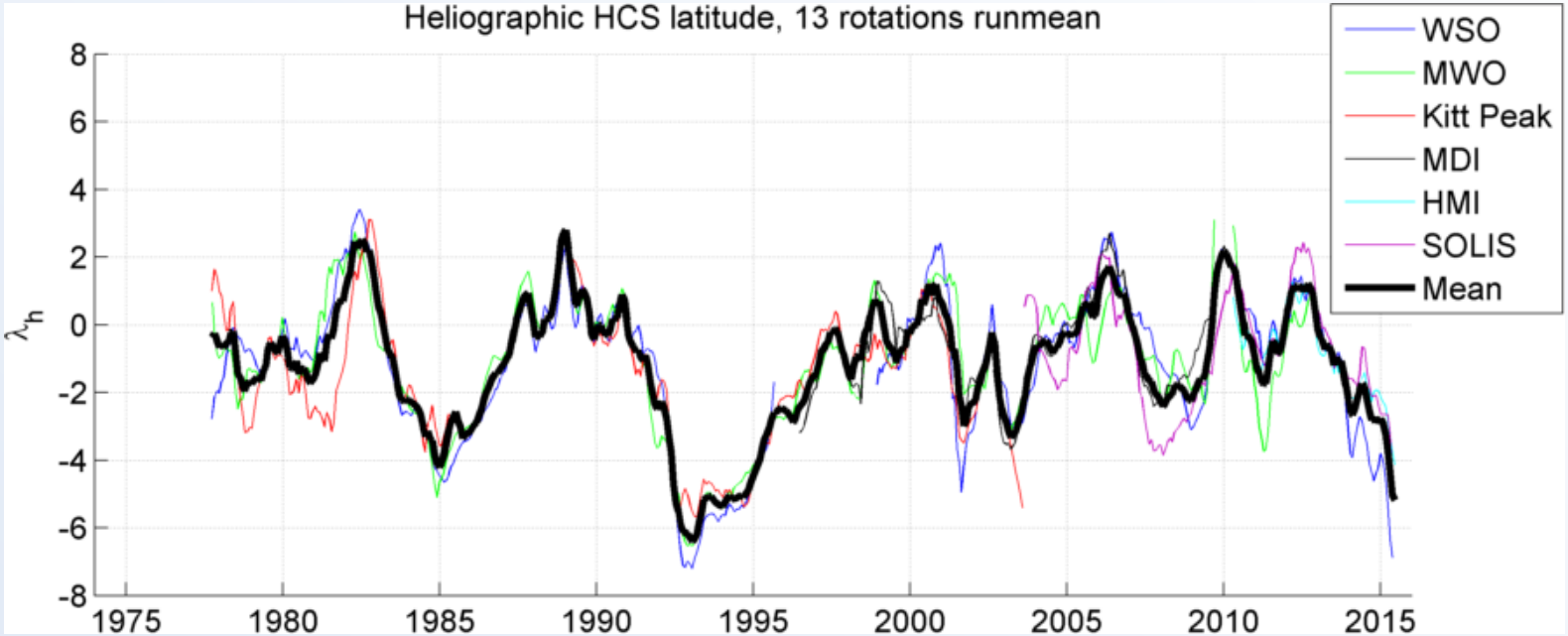
- We calculate the coronal magnetic field using PFSS model and photospheric observations of the six data sets.
- Longitudinal averages show
  - Solar cycle evolution
  - Hemispheric asymmetries
  - Vantage point (b_0) effect
  - Some obvious errors
  - Scaling between data sets is different than in photospheric magnetic field

Heliographic latitude λ_h of HCS



- Rotationally averaged latitude of HCS in heliographic coordinates
- Southward shifted HCS during the declining to minimum phase of solar cycles (20,) 21, 22 and 23.
- Shift is weaker and less systematic during cycle 23
- Weak, preliminary evidence for southward shift during SC24

λ_h of HCS, erroneous data removed



- Same as previous plot but Kitt Peak has been removed in 1985-1989, WSO in 1995-1998 and in 2000-2001 and MWO after 2010.
- Shows very systematic agreement between different data.
- Overall a clear dominance of s negative HCS location, especially in the declining to minimum phase of the solar cycle

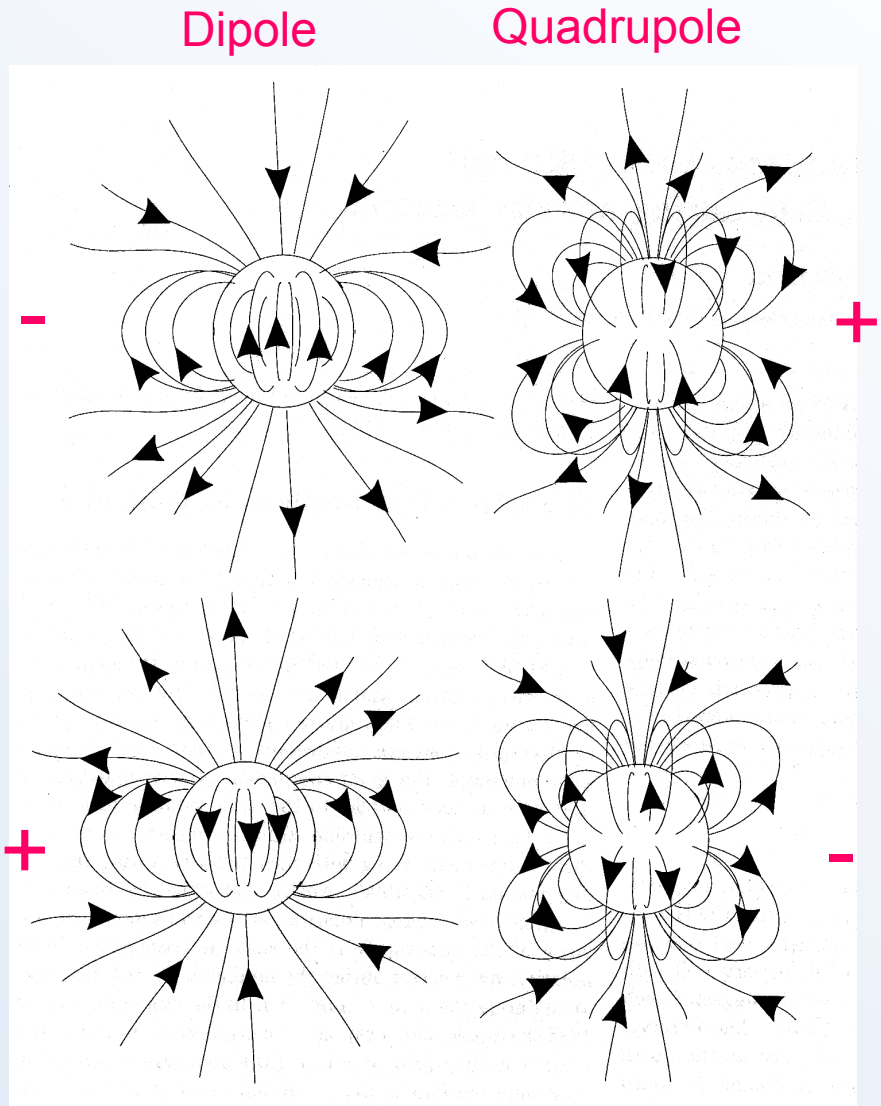
Virtanen and. Mursula, A&A, 2016

Dipole vs. quadrupole

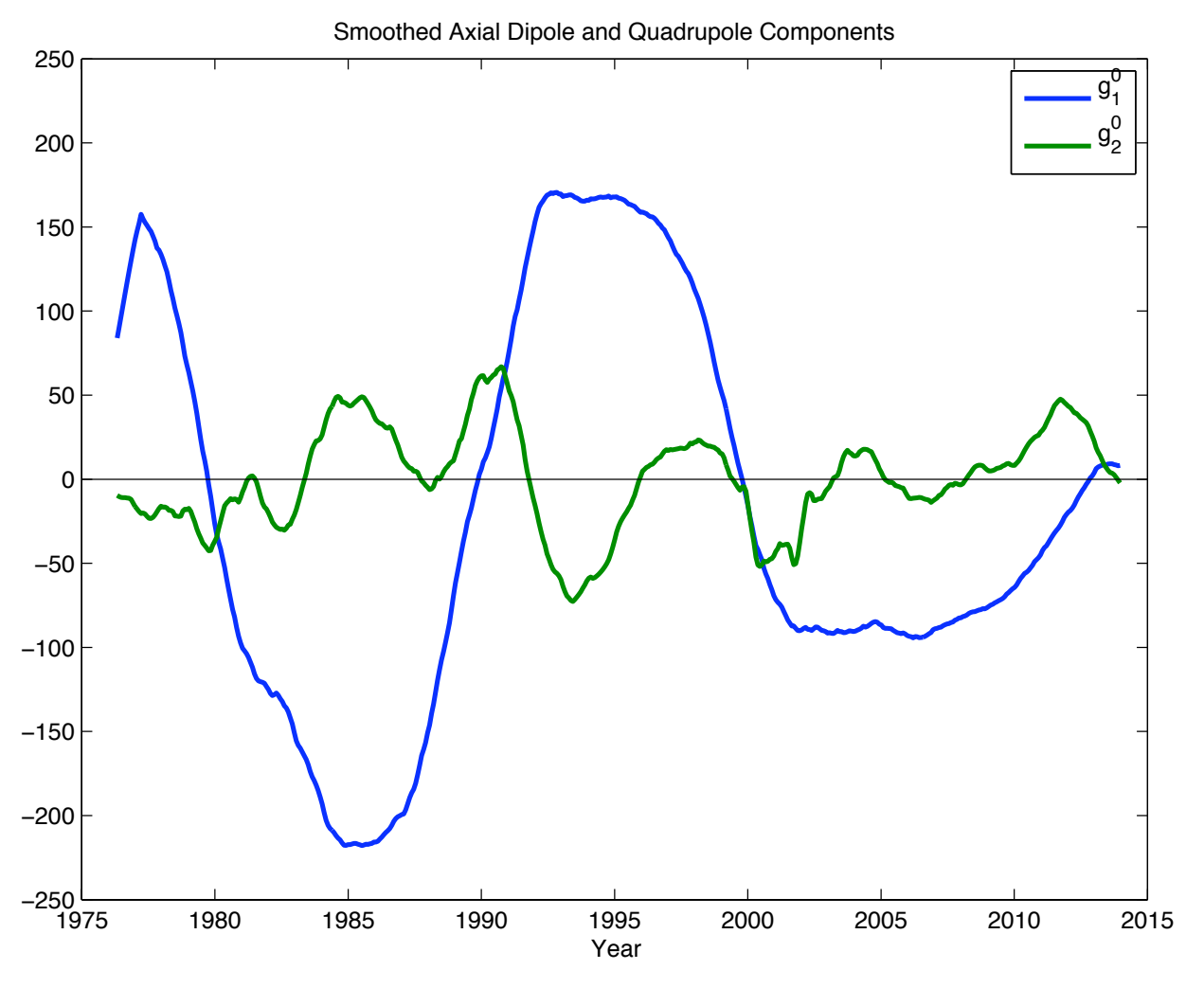
Quadrupole term has same polarity in both polar regions (Bravo and Gonzalez-Esparza, 2000).

A significant quadrupole term can produce the observed north-south differences in field strengths, areas and HCS asymmetry.

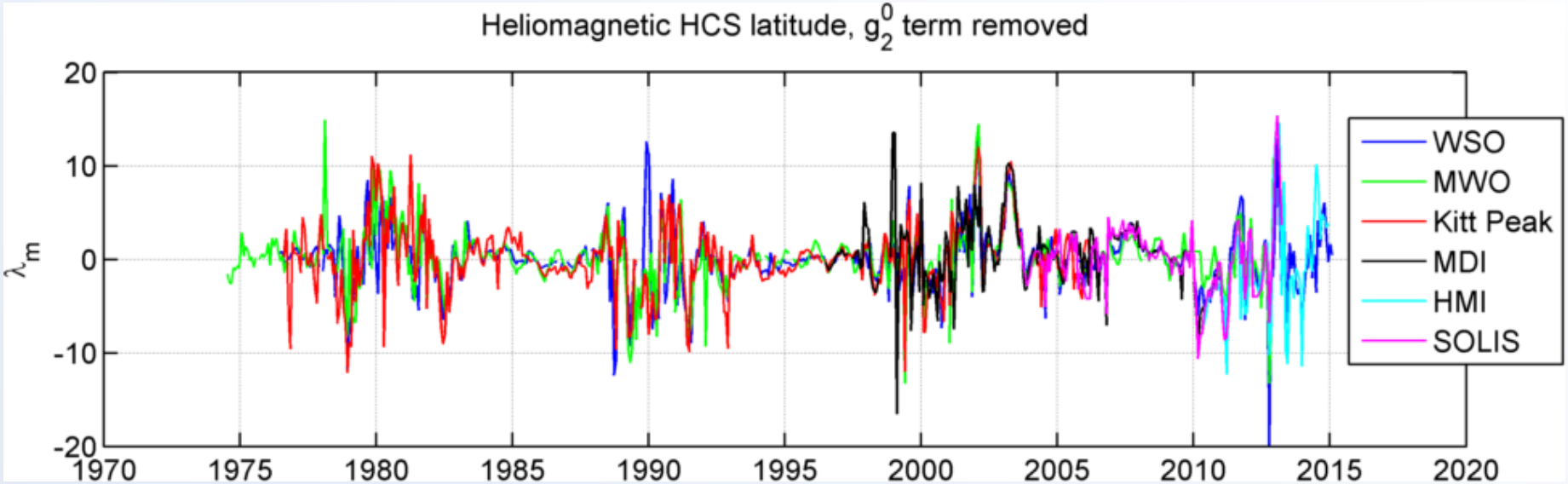
In order to have southward shifted HCS, dipole and quadruple terms must have **opposite signs**.



HCS asymmetry: Dipole and quadrupole

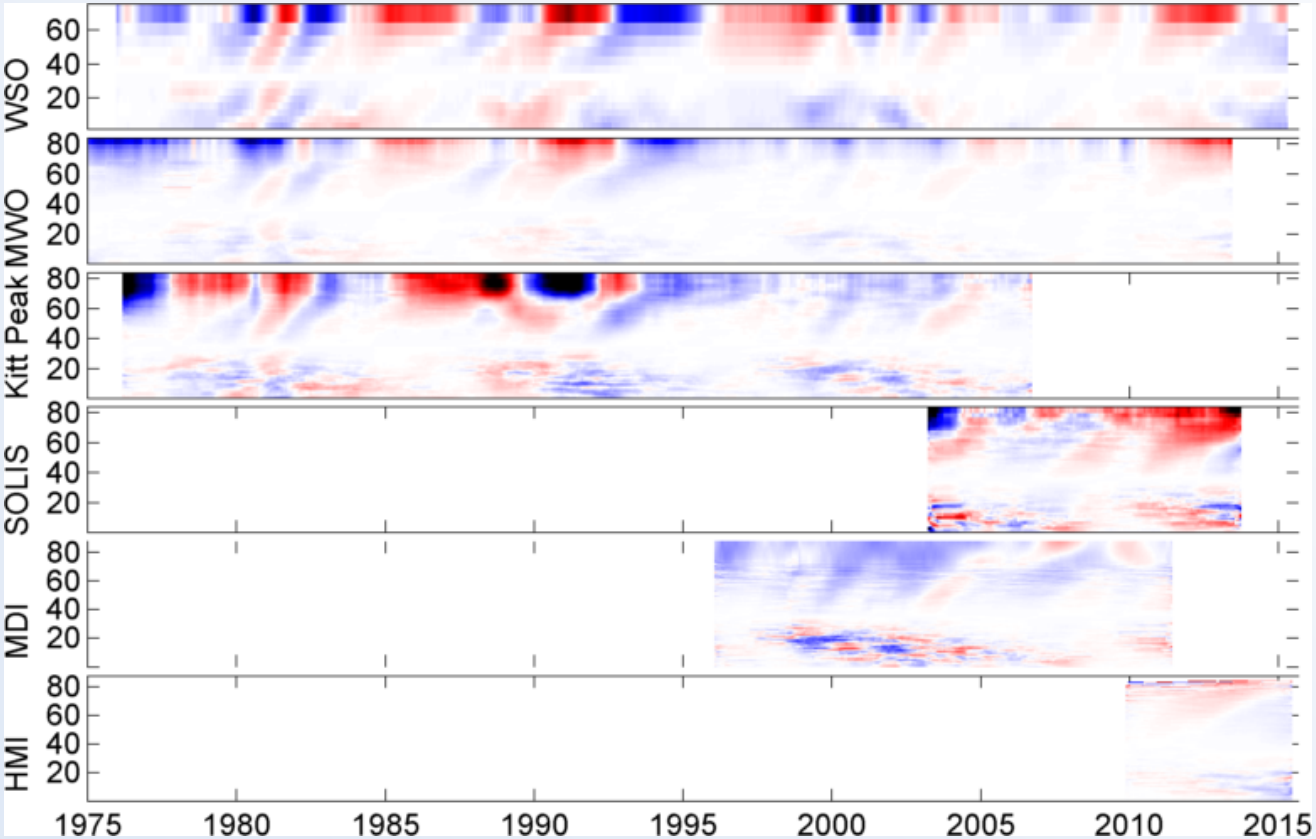


Non-quadrupole λ_m



- We calculate λ_m also for "non-quadrupole" data where g_2^0-term has been removed before calculating the PFSS coronal field.
- The southward shift of the HCS is mainly due to the quadrupole moment in the photospheric magnetic field.
- Differences between data sets as well as yearly oscillation (due to varying b_0 angle) are significantly smaller in non-quadrupole data.

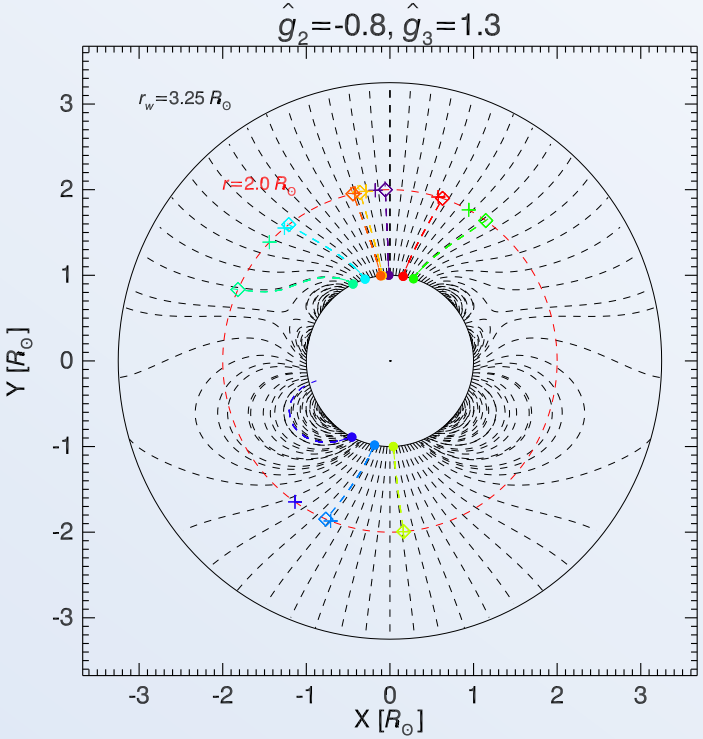
Origin of g_2^0 quadrupole

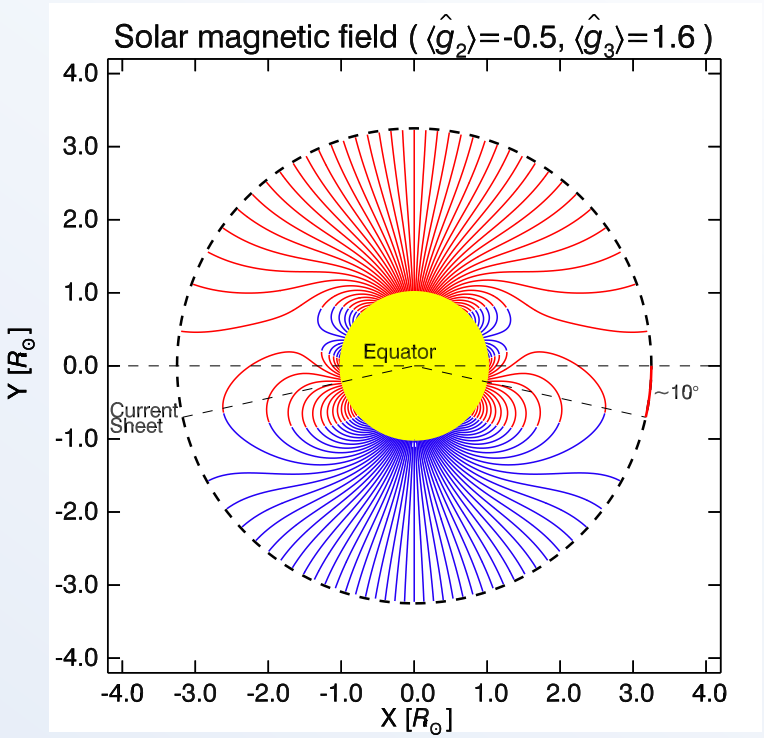


Color scale saturates at 50% of maximum value

- Latitudinal contribution to g_2^0-term, north and south summed together and smoothed over 13 rotations.
- g_2^0-term mainly relates to polar field N-S asymmetry, which arises from N-S asymmetric surges of flux drifting toward poles

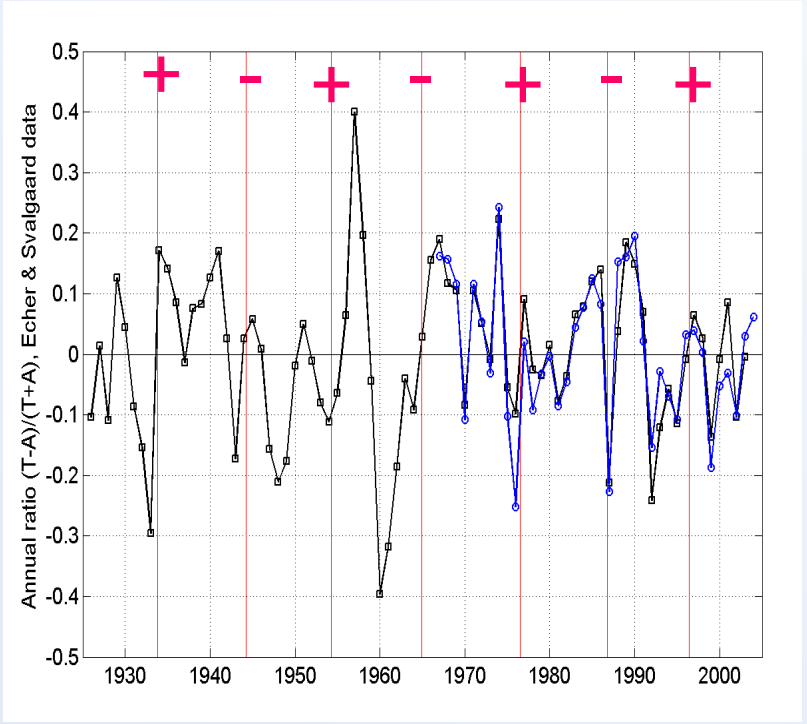
Asymmetry in polar jets

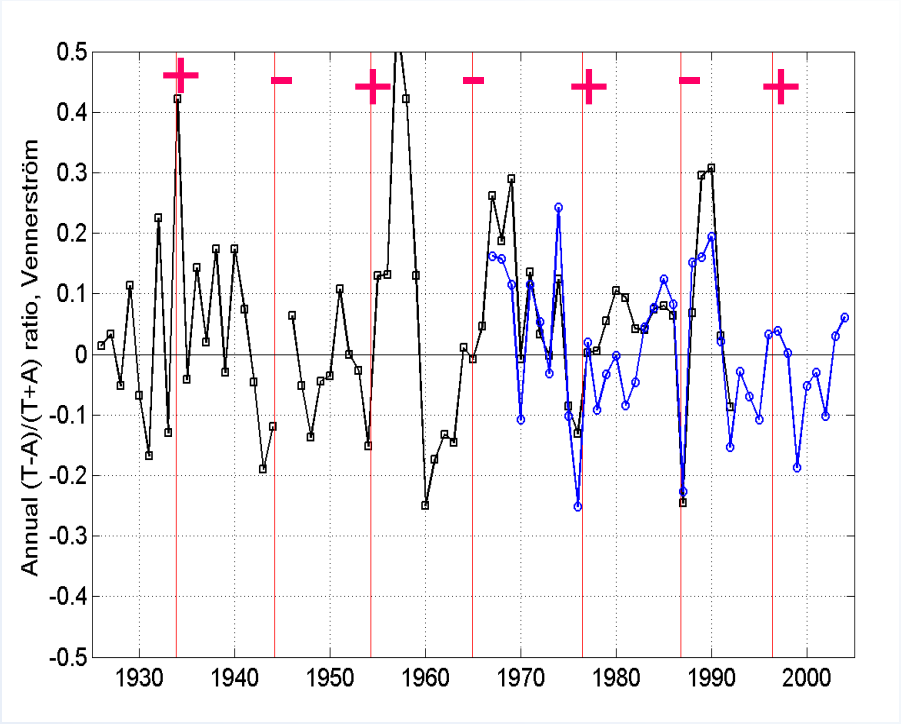




Nistico et al., 2015

Annual (T-A)/(T+A) ratio





Echer & Svalgaard data (black) follows closely the Omni (blue) data.

The mean of the annual (T-A)/(T+A) ratio = -0.004.

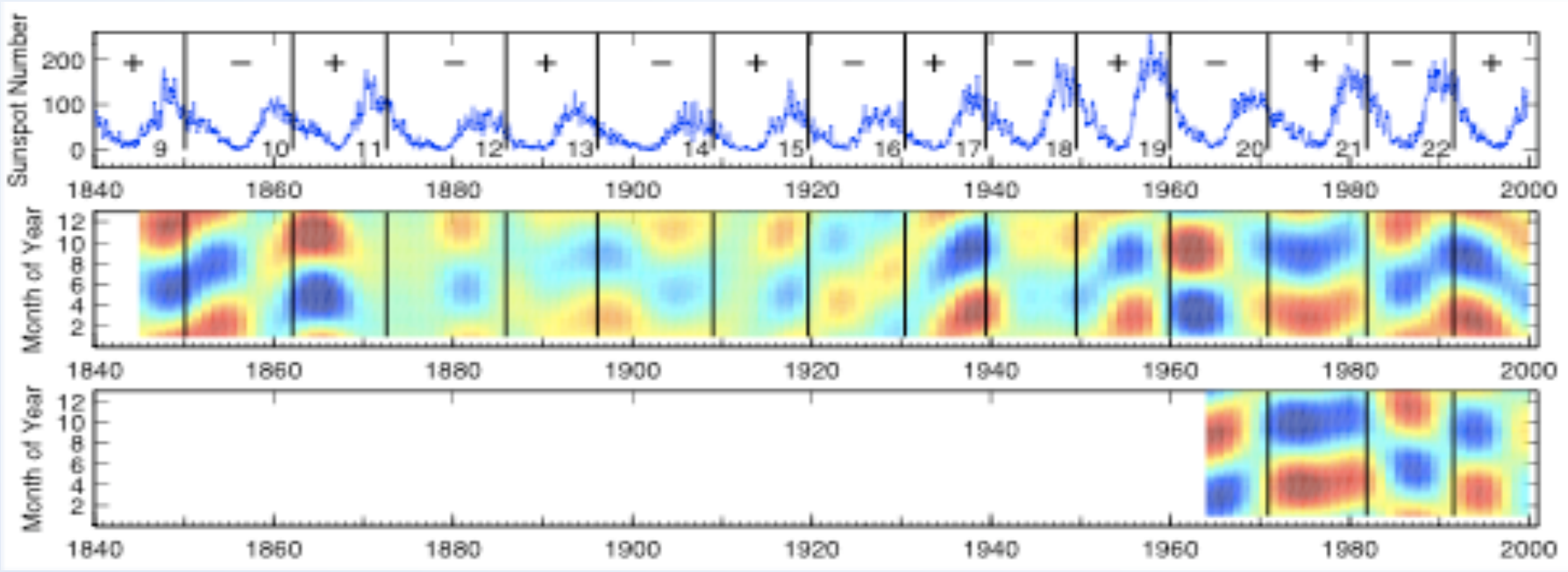
Before six of the seven last minima HCS is shifted southwards.

Vennerstrøm et al data (black) follows fairly closely the Omni (blue) data.

The mean of the annual (T-A)/(T+A) ratio = 0.04.

The overall pattern is fairly similar to that of Echer & Svalgaard.

Streamer belt NS shift: Long-term evolution



- **Is the Gleissberg cycle = one phase (half) of the N-S asymmetry cycle?**
- **Is deVries cycle = 2 Gleissberg cycles = Full N-S asymmetry cycle ?**
- **If yes, asymmetry (together with solar activity) should get smaller shortly!**

- **If HCS asymmetry follows SB asymmetry, the Ballerina was far from Bashful and rather had a permissive phase in the 19th century !**

Mursula and Zieger, GRL, 2001.

Streamer belt asymmetry vs. HCS asymmetry

- The asymmetry of the streamer belt is related to the magnetic cycle so that the SW speed distribution is shifted towards the northern magnetic hemisphere
- HCS is always shifted towards the southern heliographic hemisphere.
  - » **For positive minima HCS and streamer belt are shifted oppositely.**
  - » **For negative minima HCS and streamer belt are both shifted southards.**
- This new pattern allows for interesting new possibilities for predicting space climate (and space weather).

Conclusions

- HCS asymmetry is known to exist since 1920s (over the GMM)
- Verified with several methods and databases

Conclusions

- Streamer belt asymmetry is known since 1840s.
- HCS asymmetry and Streamer belt asymmetry do NOT show the same (at least during most those cycles studied)
- Streamer belt asymmetry shows a long-term (about 200 year) alternating pattern.

Important?

- Space Weather and Space Climate applications
  - Possibility for improved at longer lead time
- Dynamo essentially hemispherically asymmetric
  - New constraints for modeling
- Significance to solar activity: Larger (absolute) asymmetry connected with larger (absolute) activity, not smaller