Magnetic flux density in the heliosphere

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Introduction

One of the key parameters to characterize the solar cycle is the magnetic field of the corona.

Definition: Open magnetic flux of the Sun is the number of field lines crossing the source surface of the solar wind.

If the field lines originate close to the Sun and continues to the outer heliosphere, then the number of field lines crossing through any closed surface around the Sun, i.e., the magnetic flux must be the same.

If the sign of the crossings (inward or outward magnetic polarity) is considered, then the flux is zero.

Open flux: we **discard the polarity,** it is customary to use abs(B_R) .

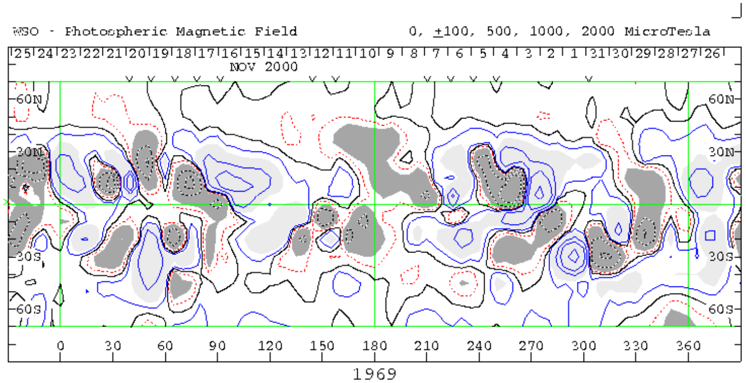
If the solar wind flow is radial, then the quantity $B_R R^2$ should conserve (magnetic flux density, normalized to 1 AU), provided that the magnetic field is frozen into the solar wind.

In principle, B_R can be a function of heliographic location (longitude and latitude) and time (solar cycle phase).

Two ways to determine the open magnetic flux:

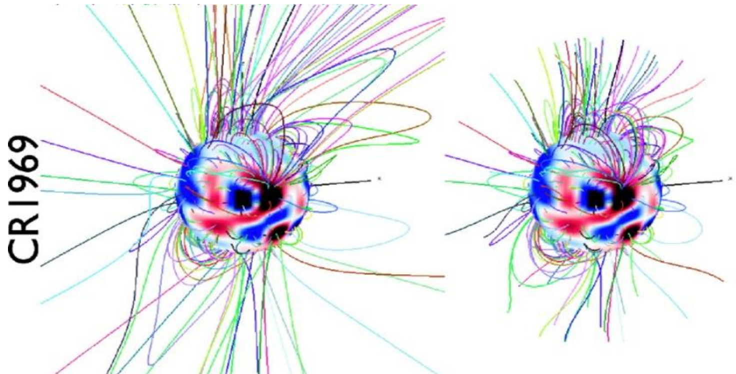
- **Photospheric** measurements + model calculations
- **Interplanetary** measurements

Open Magnetic flux from photospheric observations



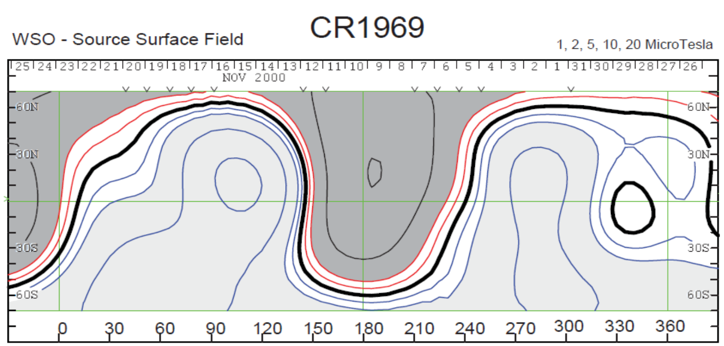
Wilcox Solar Observatory

Photospheric measurements
Problem: saturation at high heliographic latitude



Riley et al., ApJ, **653**, 1510-1516, 2006

Modeling (PFSS, MHD)



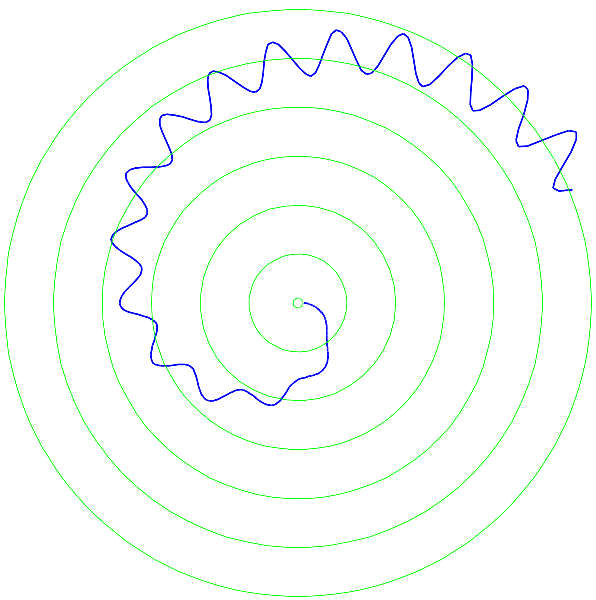
Source surface: magnetic field at 2-3 RS

Open magnetic flux from interplanetary observations

Interplanetary magnetic field measurements provide vantage point (calibration) of source surface field.

Magnetic flux frozen to the plasma + radial propagation of solar wind: $B_R\ R^2$ constant

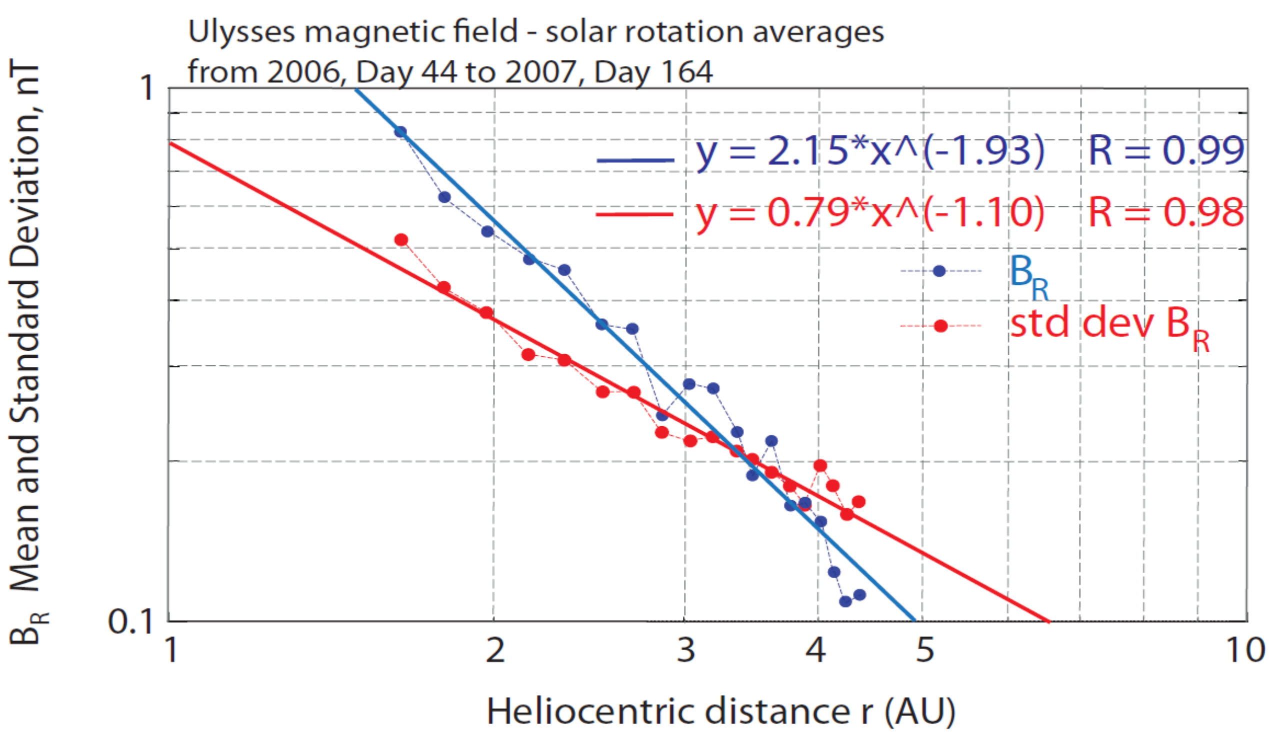
But! Abs(B_R) R^2 is not constant. The reason is: fluctuations of the magnetic field.



Affect of fluctuations: false opposite magnetic sectors, overestimation of the open flux, in particular at

- Larger Parker angle
- Larger fluctuations of the field

Fluctuations increase with radial distance ("flux excess" problem)



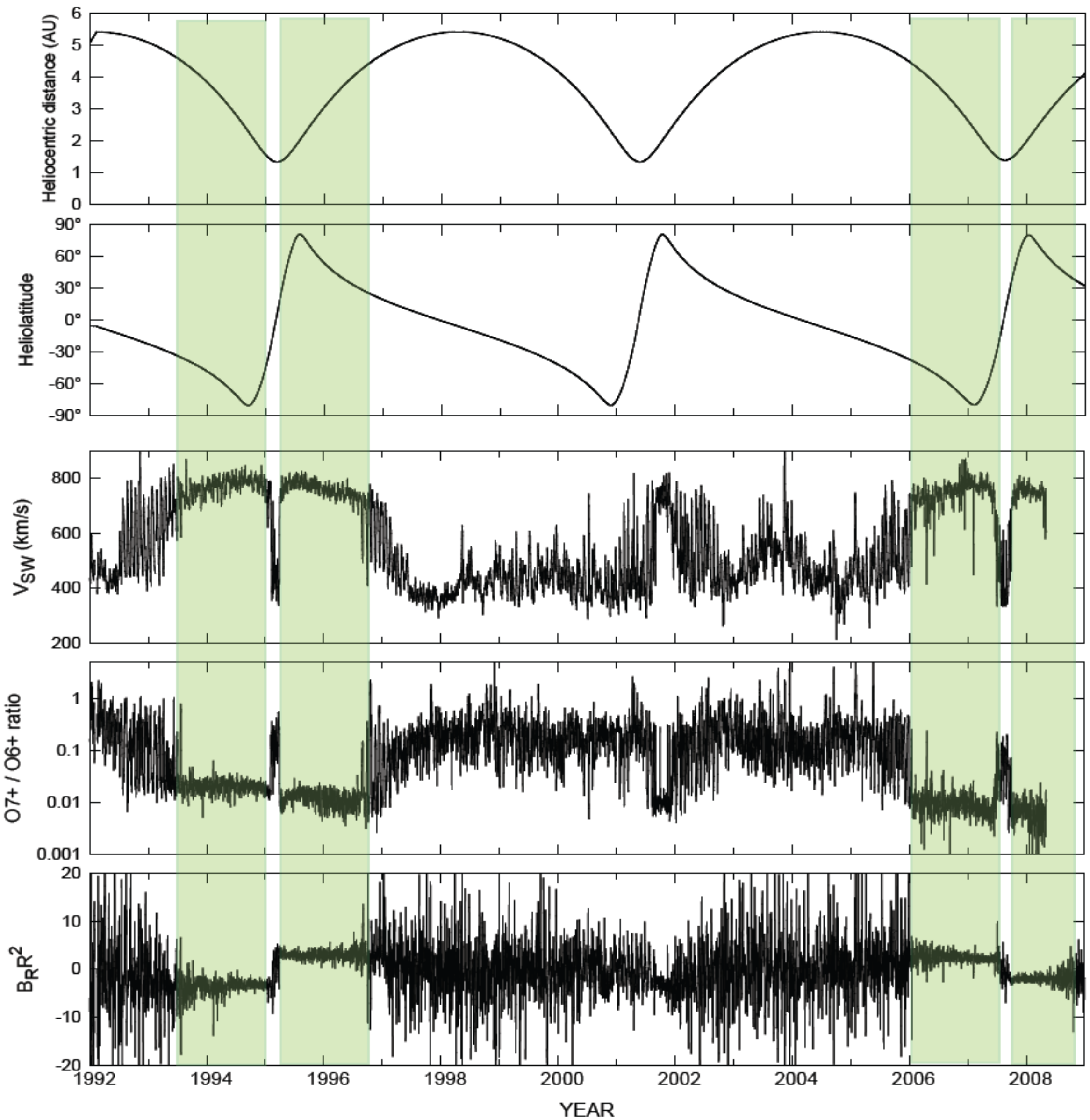
The radial component B_R of the magnetic field decreases as ~ R^{-2} with heliocentric distance

The standard deviation of the fluctuations of R_B decreases as ~ R^{-1} with heliocentric distance

From Smith, JGR, 2011

From Smith, E.J., 2011, JGR, 116, A12101, doi:10.1029/2011JA016521

Level of magnetic field fluctuations is different for the slow and fast wind



Heliocentric distance

Heliolatitude

Solar wind speed
(km/s)

Oxygen freezing in
temperature ~
O^{7+} / O^{6+} ratio

Radial component of the HMF
normalised to 1 AU
$B_R \cdot R^2$ (nT . AU^2)

Distributions of the radial magnetic component

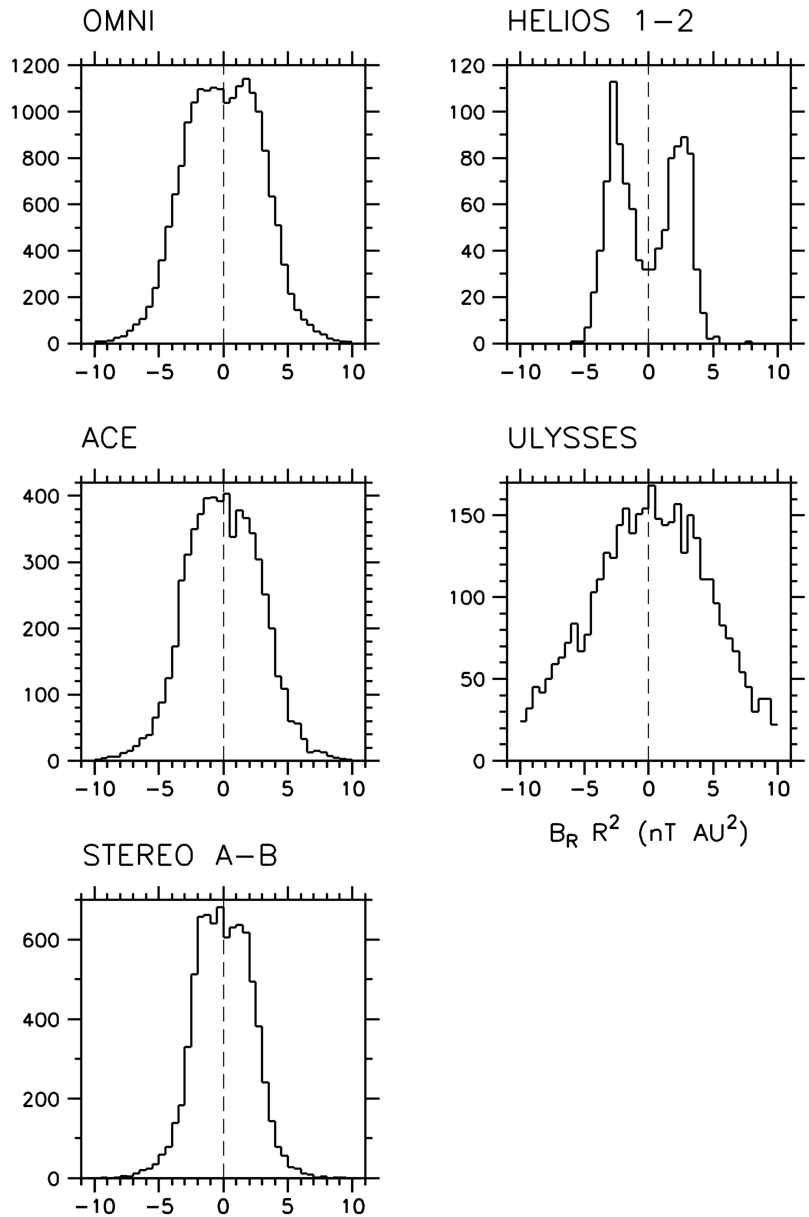
1 AU

0.3 - 0.5 AU

1 AU

3 – 4.5 AU
Slow wind

1 AU

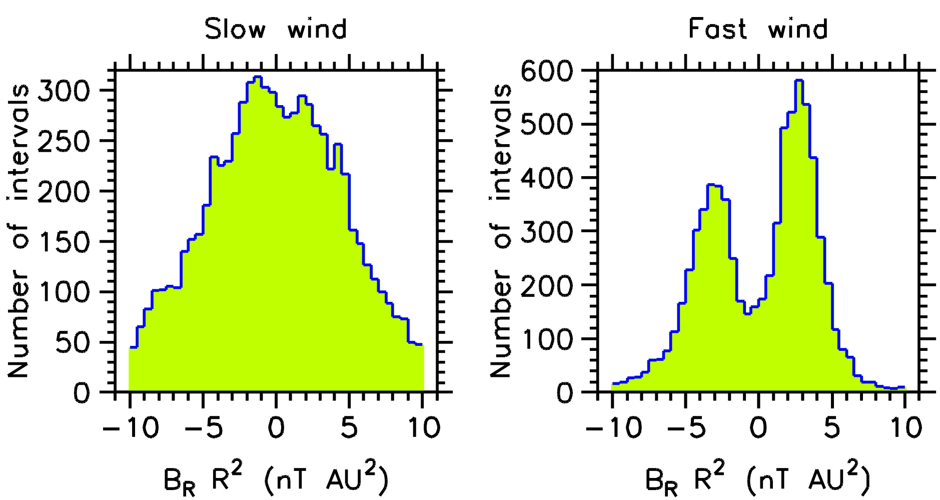


Distribution of the open flux

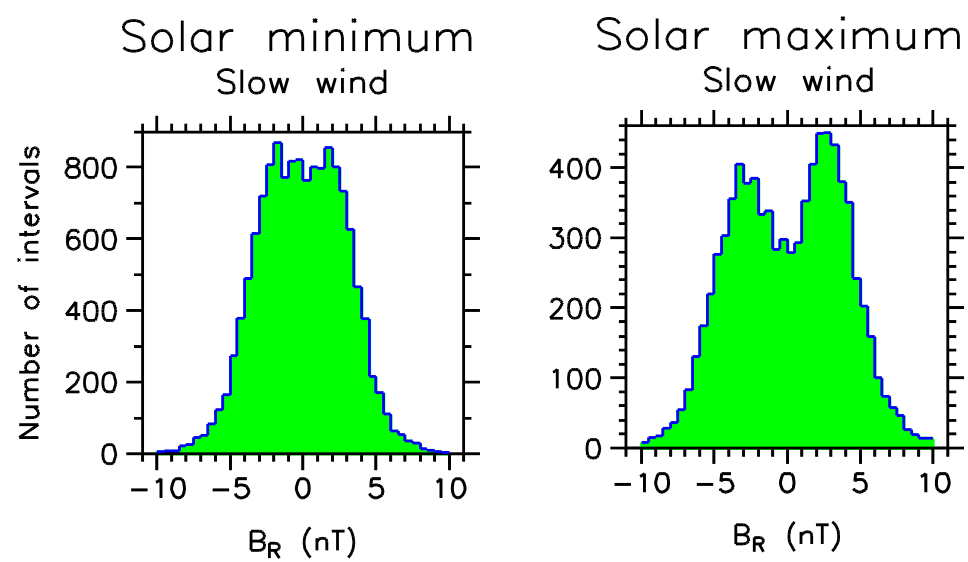
Distribution of the open magnetic flux density, $B_R\ R^2$ is a complex function of heliospheric location, solar wind velocity and phase of solar cycle

Two-humped distributions (negative and positive magnetic polarities), or one-humped distributions?

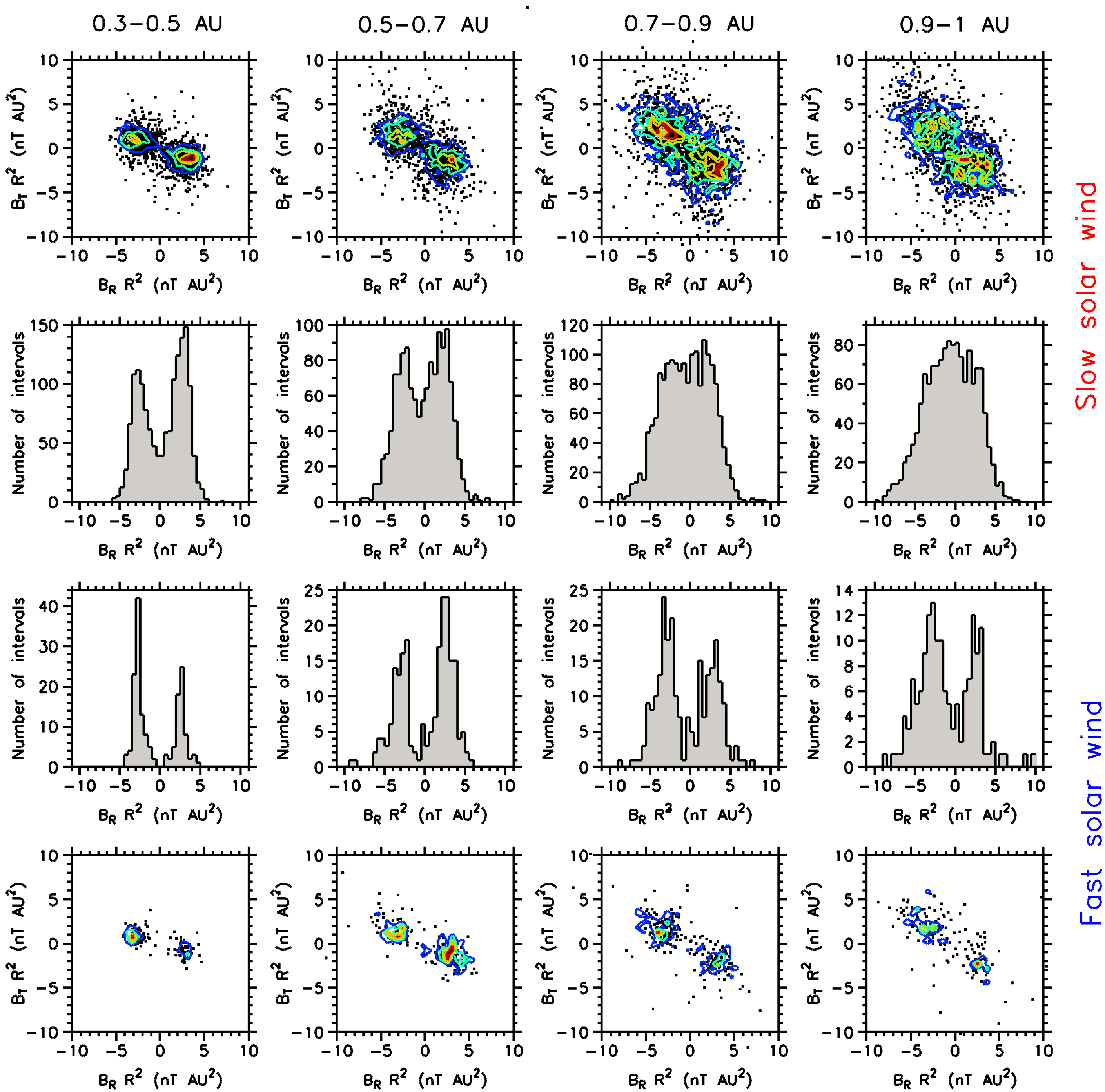
Solar origin, or evolution in solar wind?



Different open flux distribution in the slow and fast solar wind (Ulysses)



Different open flux distribution during solar minimum and maximum (OMNI)



Helios 1-2

Two-humped B_R distributions close to Sun

Two-humped 2D distributions everywhere

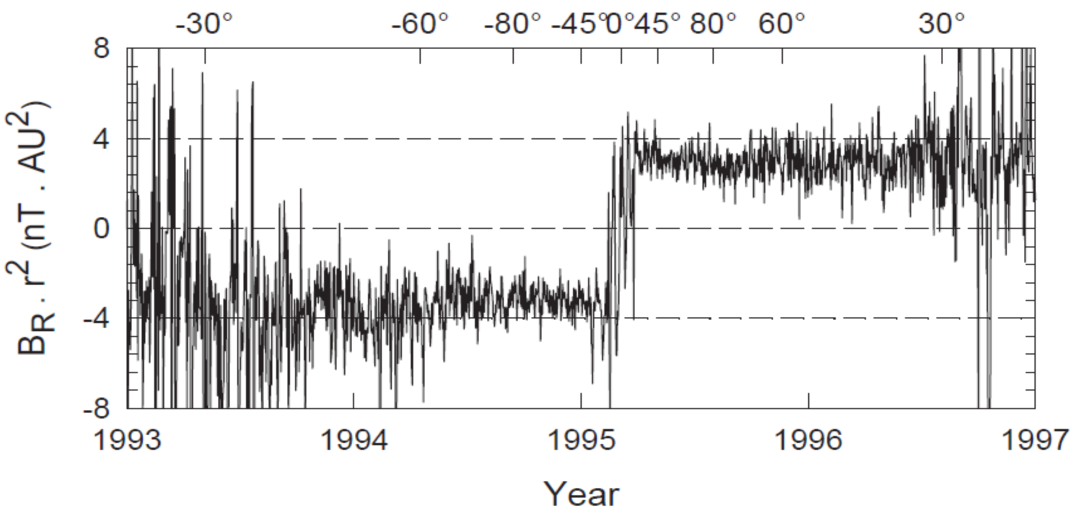
Projection of 2D distribution to horizontal line: positive and negative polarities overlap at larger distances from the Sun, because

- Fluctuations increase
- Parker angle increases

Erdős and Balogh, ApJ, 753, 130 (2012)

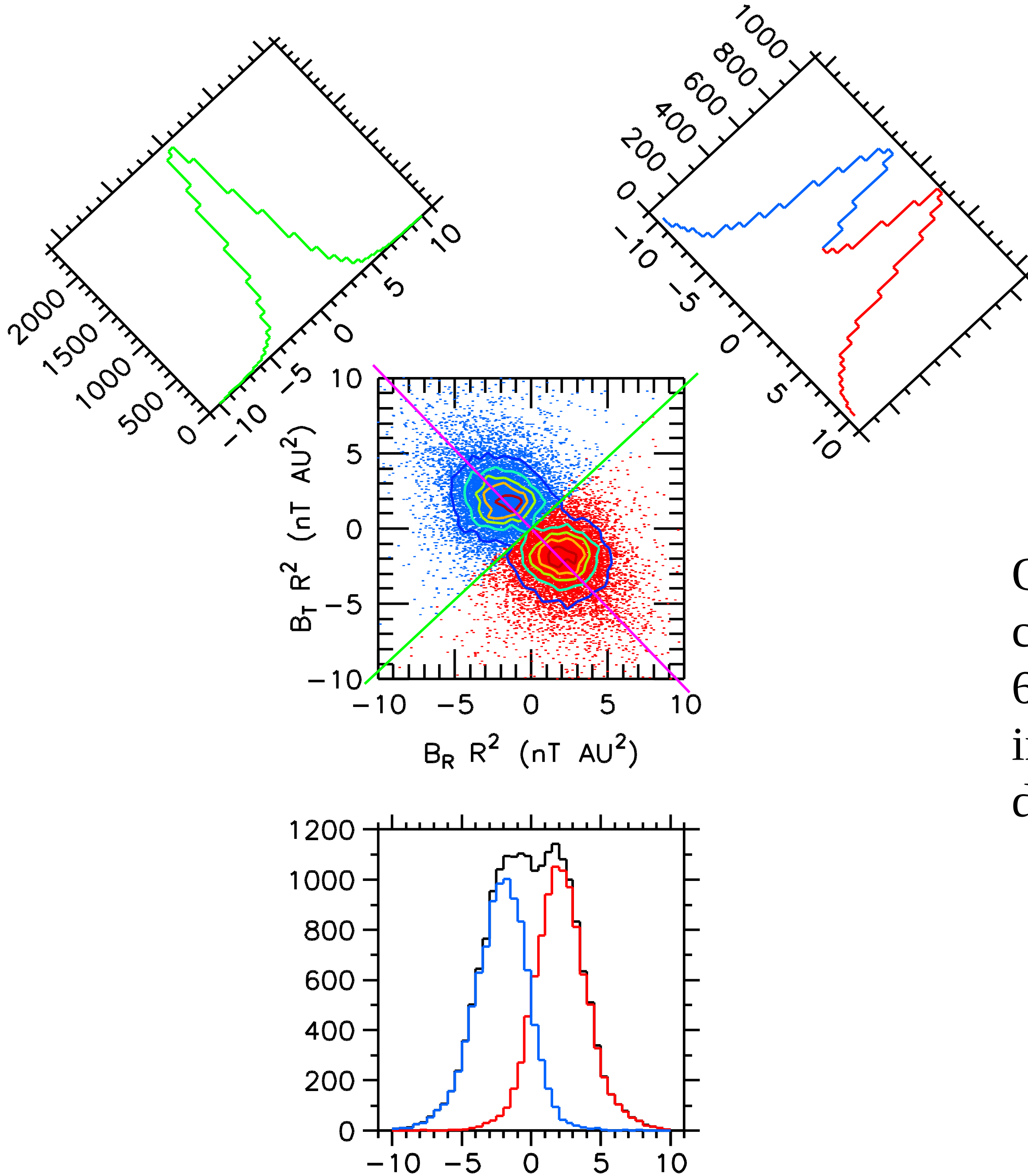
Bad news: need to make corrections for the fluctuations.

Good news: the magnetic flux density is independent of heliospheric latitude and longitude. This means that even a single point interplanetary measurement gives a good estimation for the open magnetic flux.



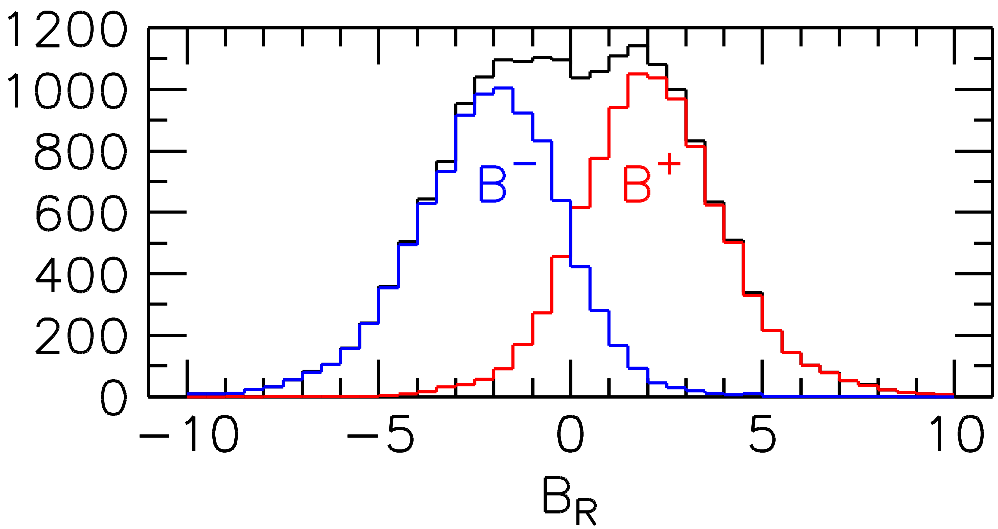
The radial component of the heliospheric magnetic field (when normalised to 1 AU) was observed to be constant as a function of heliolatitude in the fast solar wind

(Smith & Balogh, GRL, 1995)

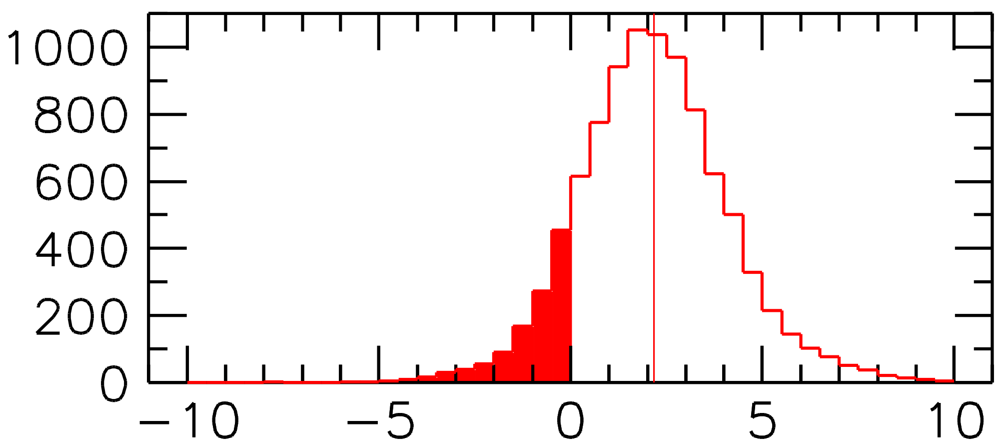


OMNI magnetic field vectors,
covering 4 decades.
6 hours averages
in slow solar wind,
during sunspot minimum.

Correction for fluctuations: sector sensitive averaging

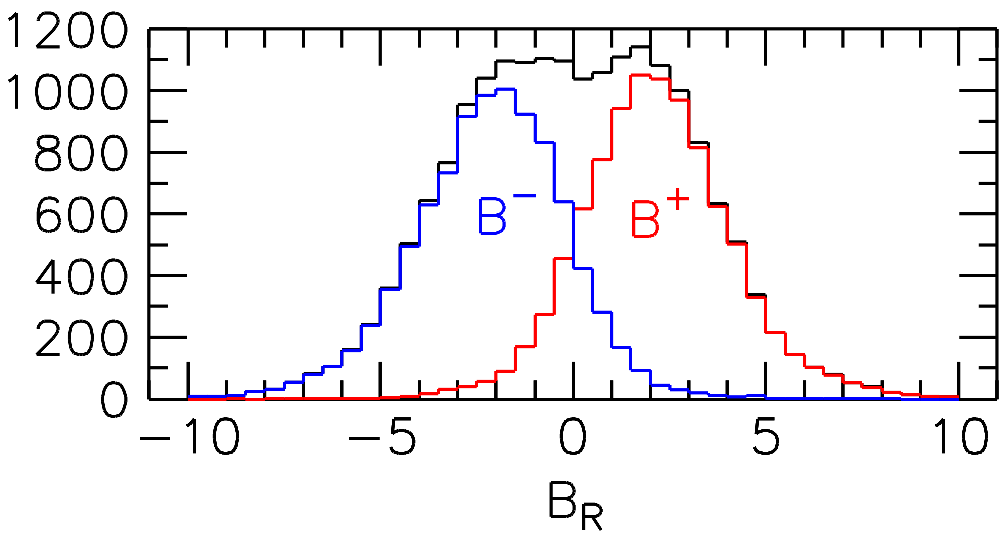


Decomposition of the B_R distribution into positive and negative polarities

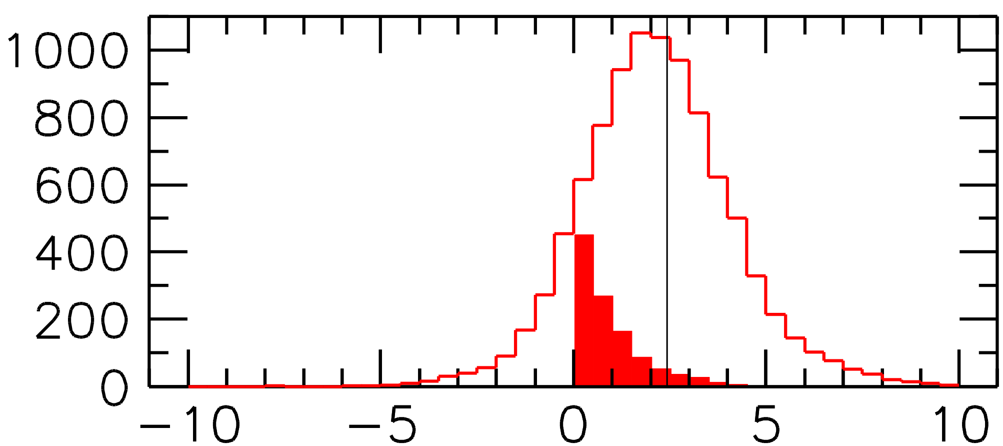


Averaging of B^+

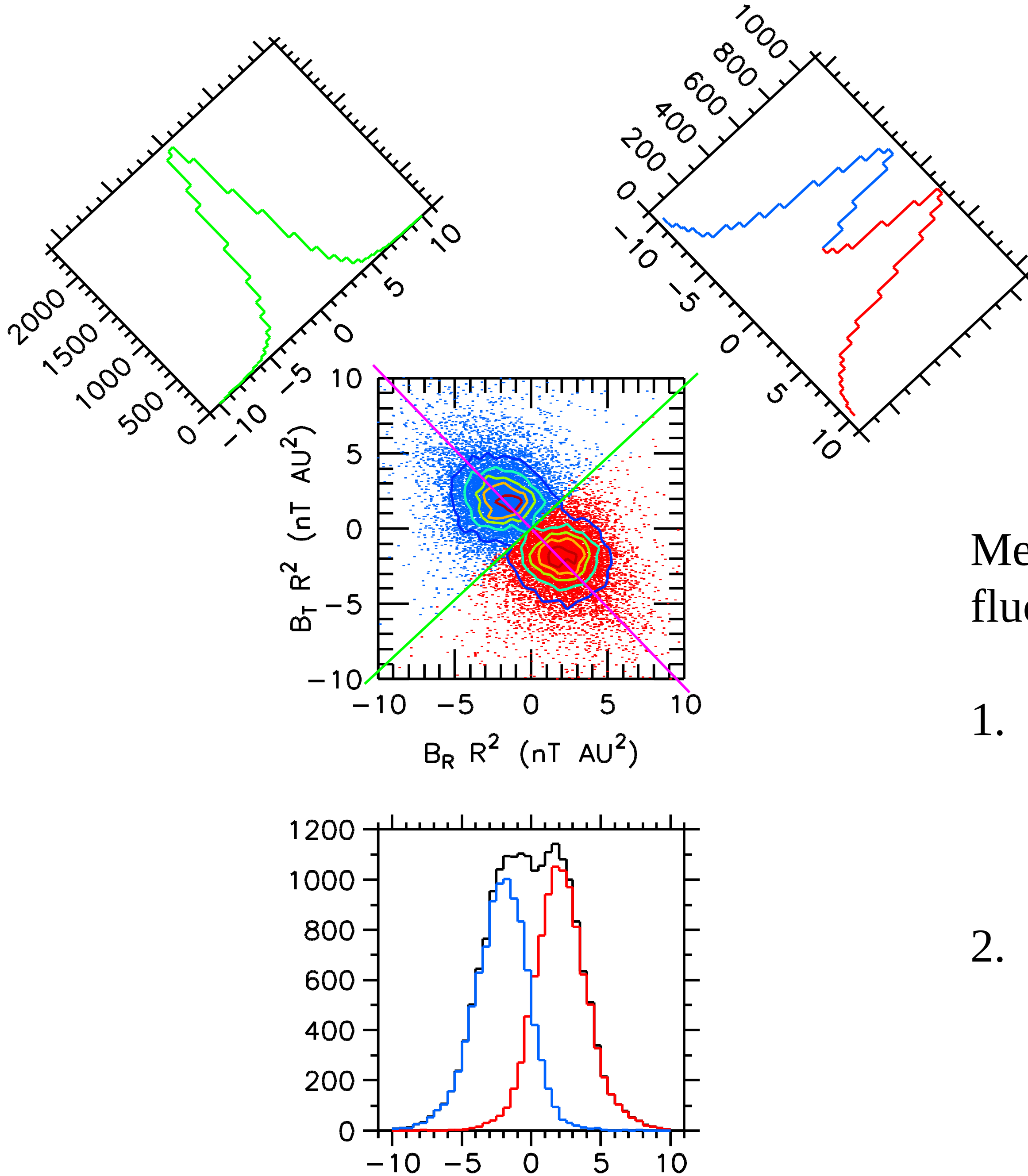
Correction for fluctuations: sector sensitive averaging



Decomposition of the B_R distribution into positive and negative polarities



Averaging of abs(B^+)

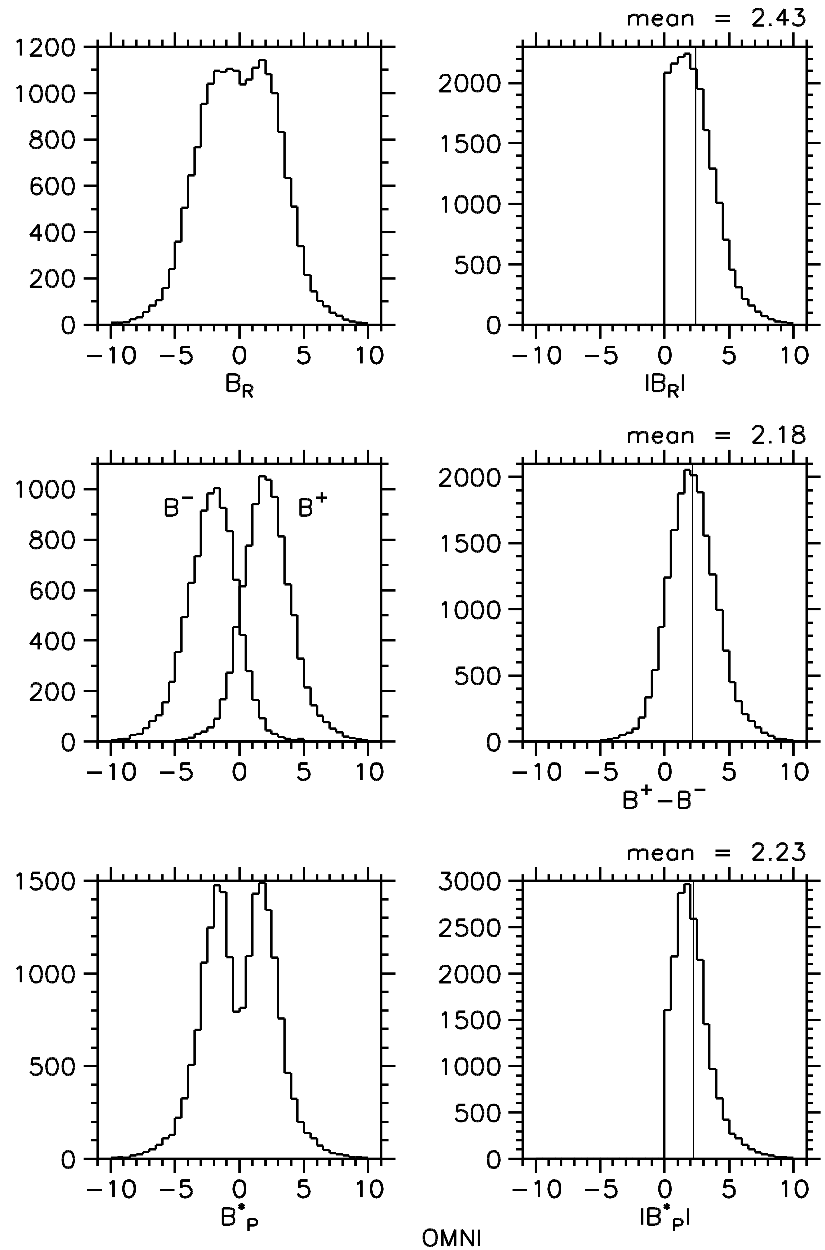


Methods for corrections of fluctuations:

1. Sector sensitive averaging
   Not <abs(B_R)> , but
   <$B^+ – B^-$>

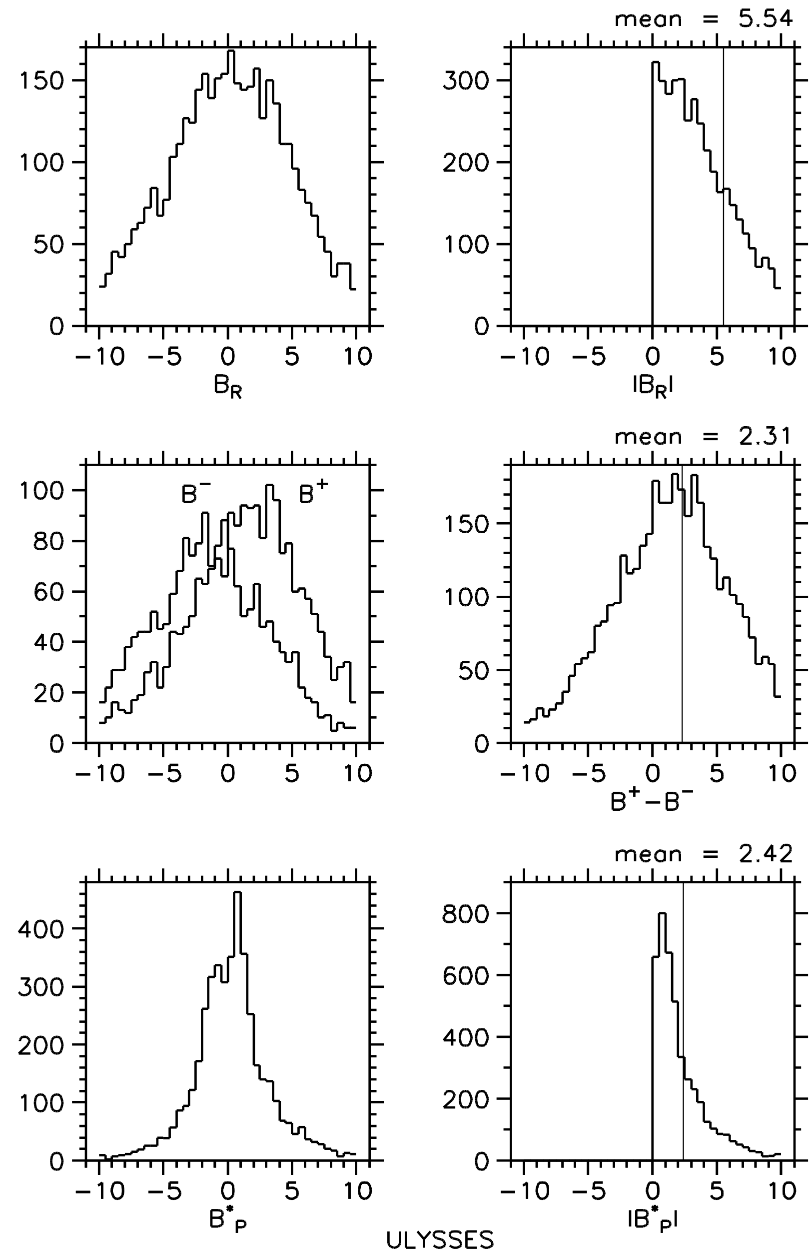
2. Neglecting fluctuations perpendicular to the Parker line

R = 1 AU



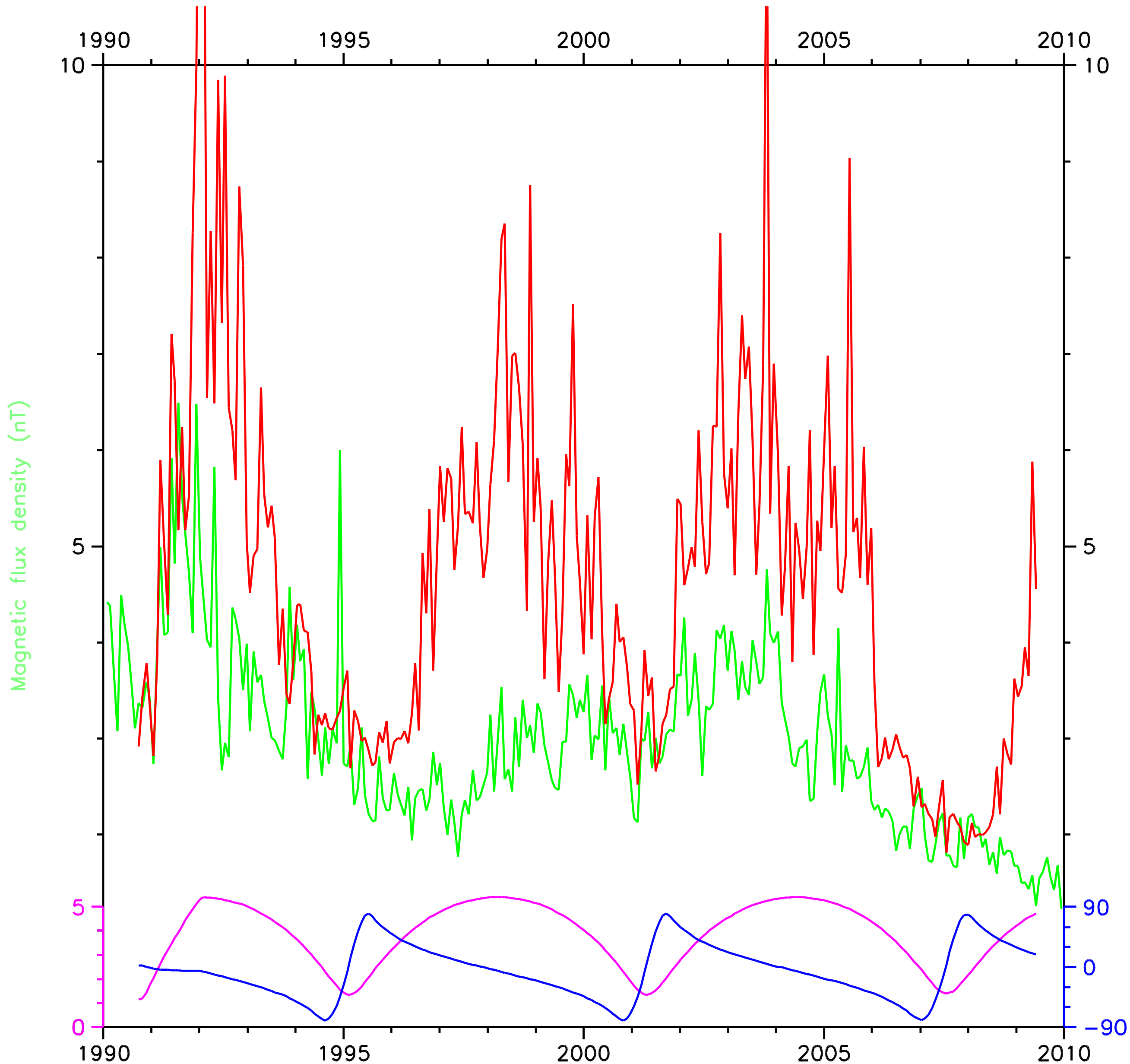
mean = 2.43
mean = 2.18
mean = 2.23
B_R
$|B_R|$
B^-
B^+
$B^+ - B^-$
B^*_P
$|B^*_P|$
OMNI

R = 3 – 4.5 AU



mean = 5.54
mean = 2.31
mean = 2.42
B_R
$|B_R|$
B^-
B^+
$B^+ - B^-$
B^*_P
$|B^*_P|$
ULYSSES

Ulysses/OMNI comparison, **uncorrected** flux



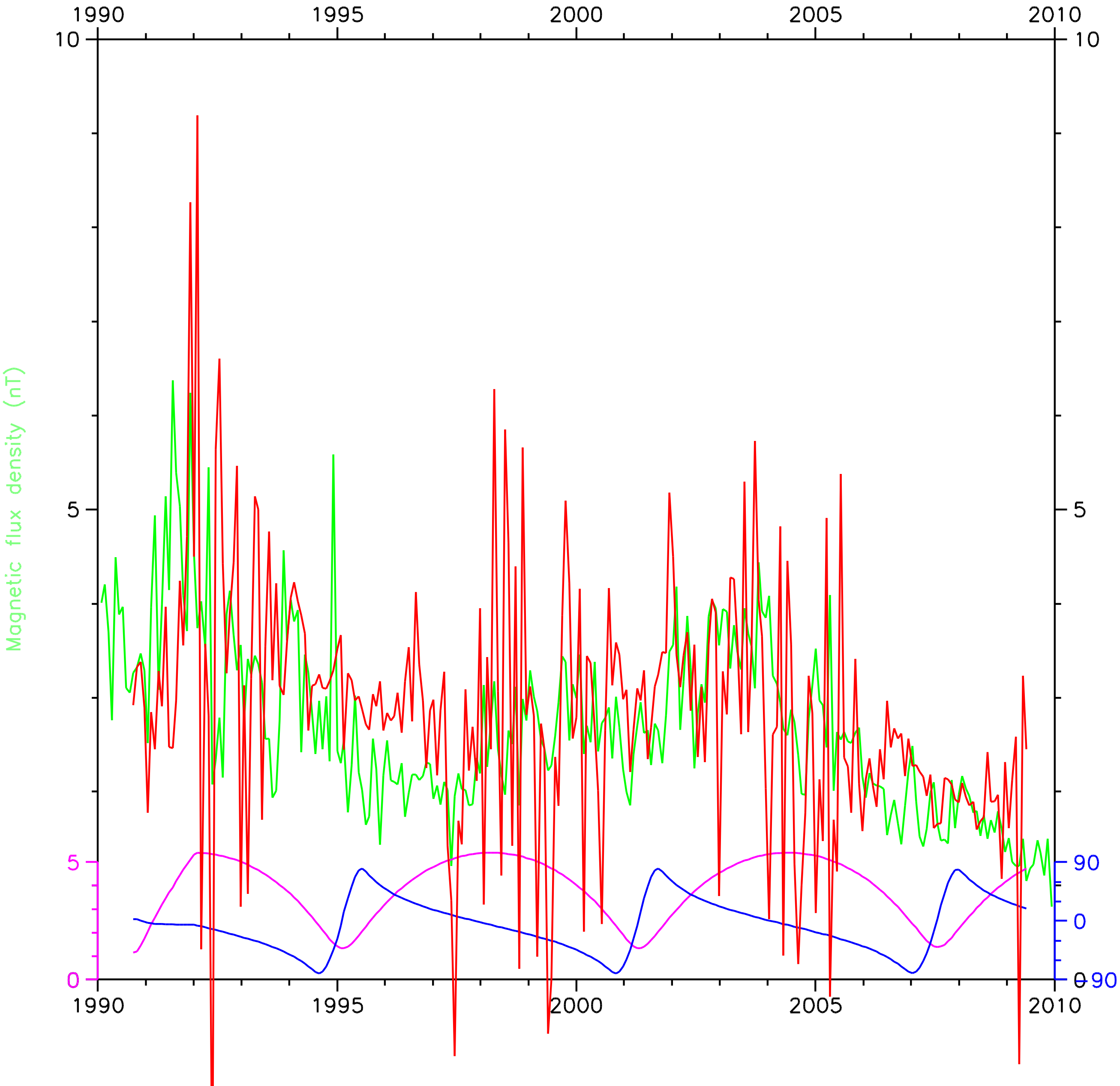
OMNI magnetic flux density (green)

Ulysses magnetic flux density (red)

Ulysses magnetic flux is far exceeding the OMNI data at aphelion of Ulysses

Heliospheric range and latitude of Ulysses

Ulysses/OMNI comparison, **sector-corrected** flux



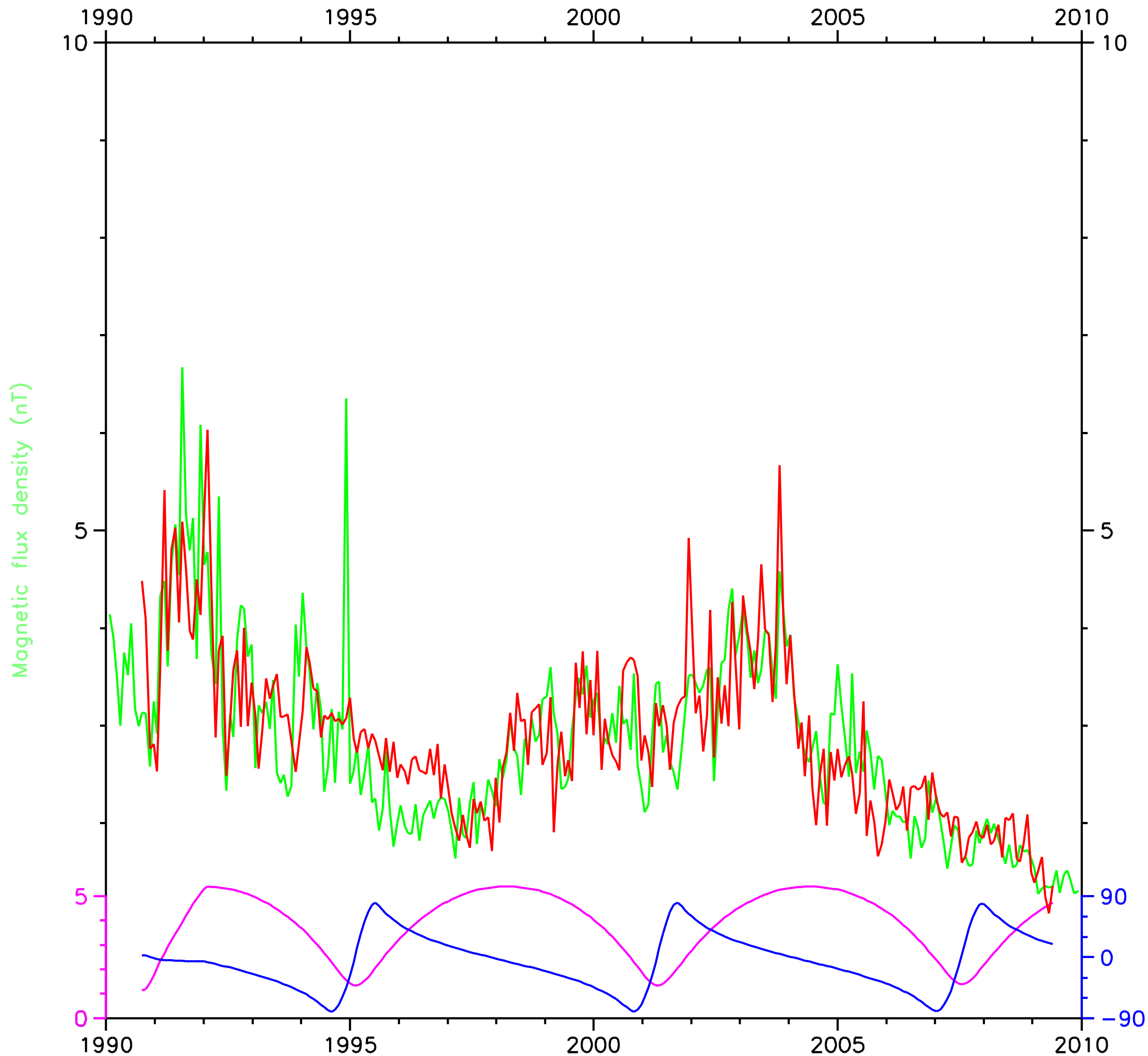
OMNI magnetic flux density (green)

Ulysses magnetic flux density (red)

Ulysses magnetic flux is close to OMNI data but large fluctuations

Heliospheric range and latitude of Ulysses

Ulysses/OMNI comparison, **corrected** flux



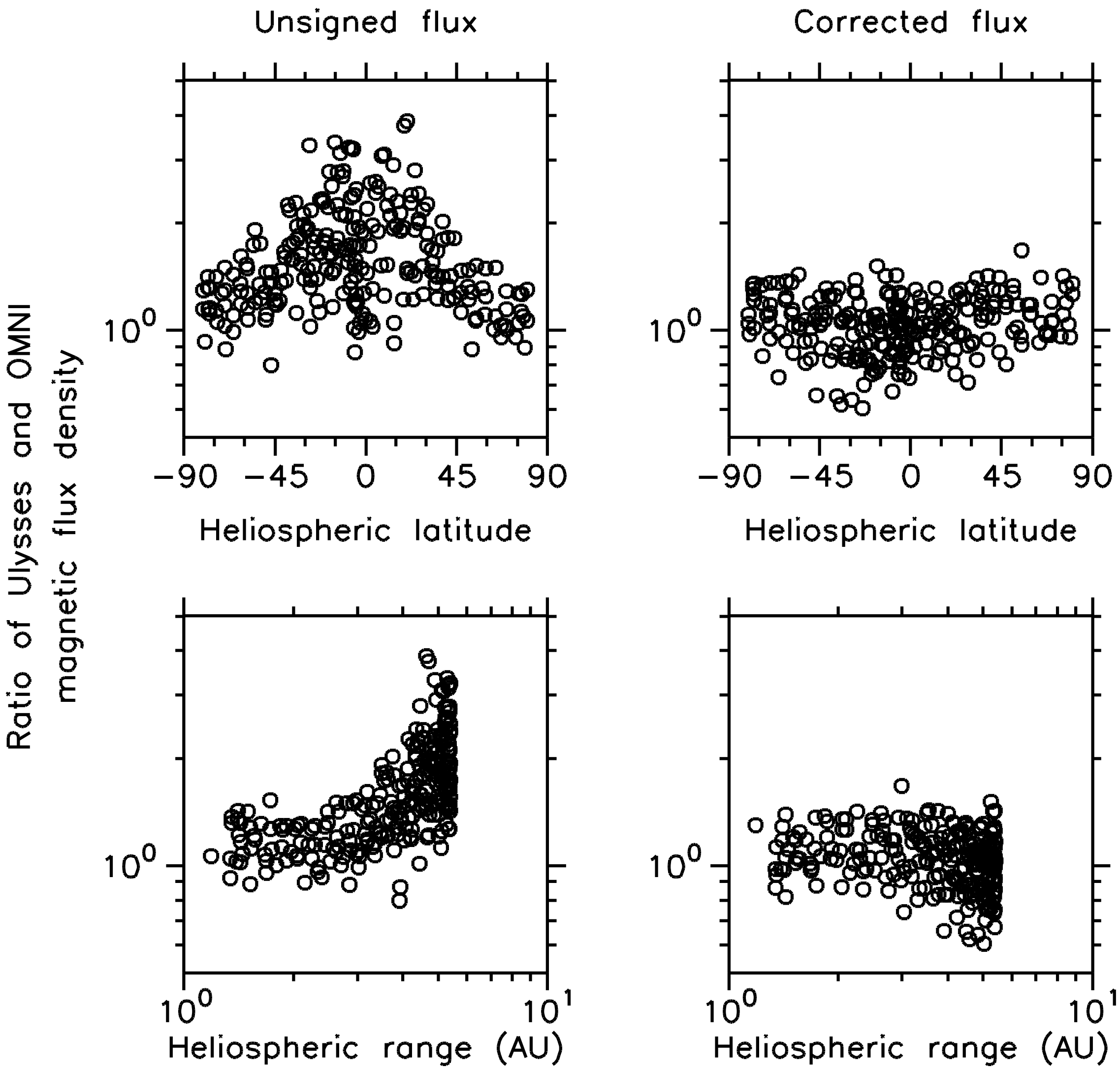
OMNI magnetic flux density (green)

Ulysses magnetic flux density (red)

The discrepancy between OMNI and Ulysses magnetic fluxes disappeared when correction is made for fluctuations.

Heliospheric range and latitude of Ulysses

Comparison of Ulysses and OMNI magnetic flux



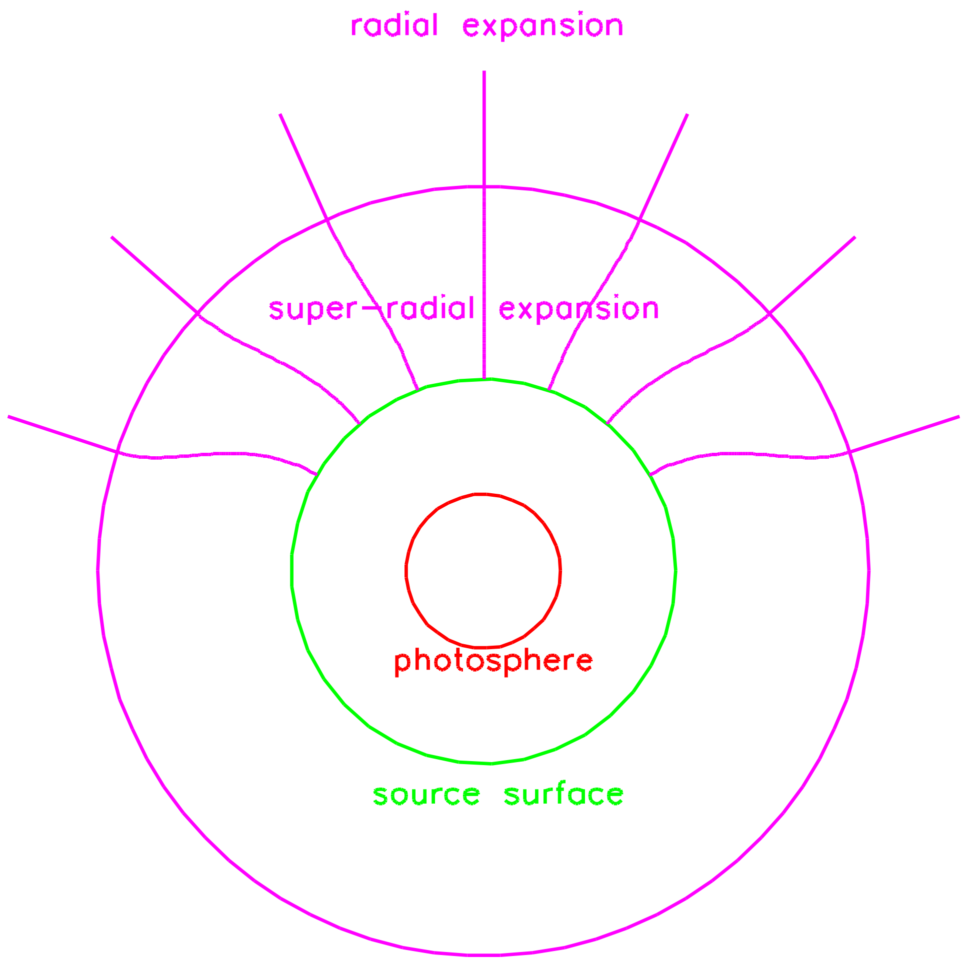
Latitudinal dependence

Radial dependence
(no excess flux)

uncorrected

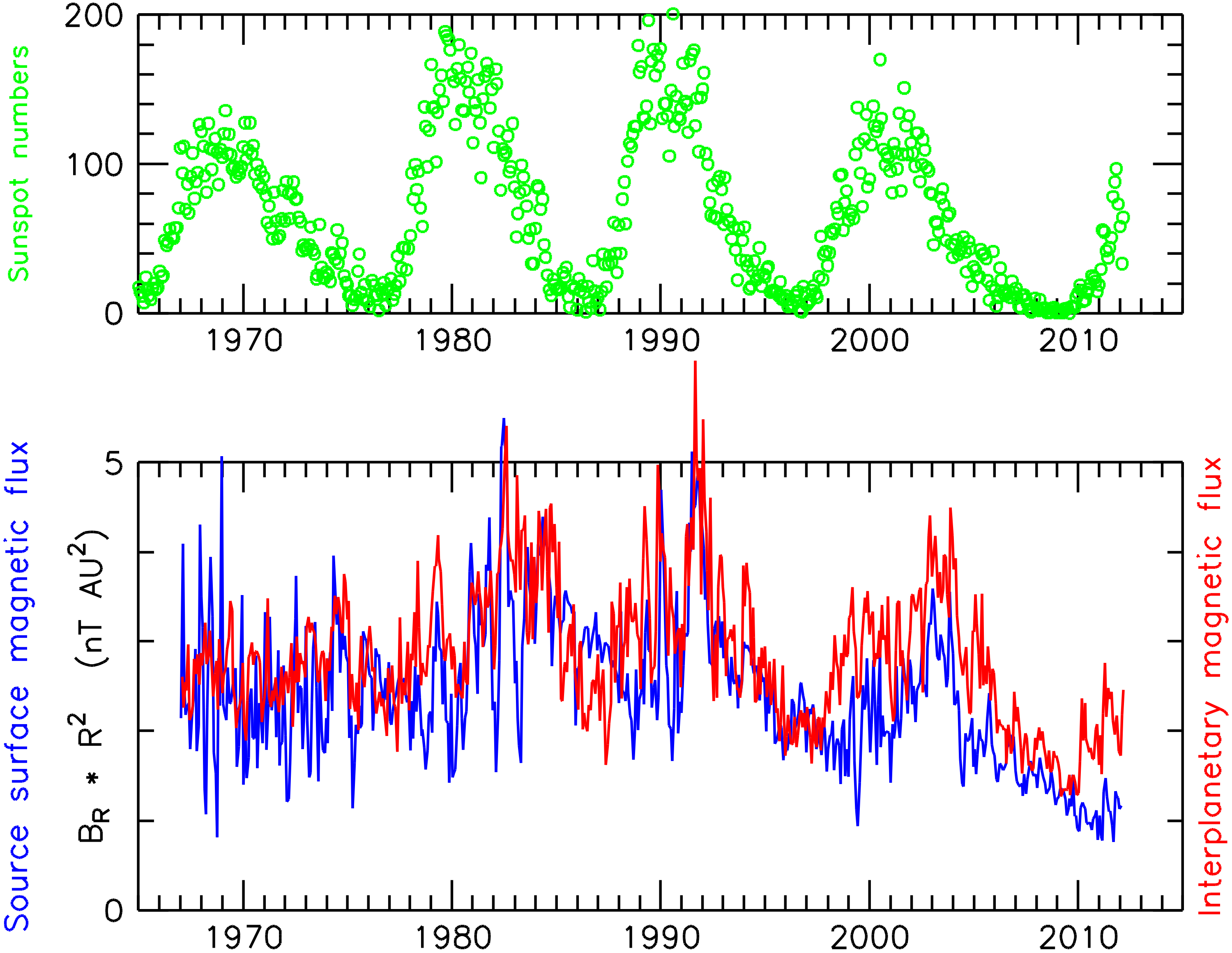
corrected

Explanation of latitudinal independence of the flux



Inside a sphere with a radius of about 10 R_S the magnetic field pressure is larger than that of the plasma. If the magnetic field is larger in a place of the source surface (for instance, at the poles), then the larger magnetic pressure diverts the flow from the radial expansion until equilibrium is reached *(Smith, 2008).*

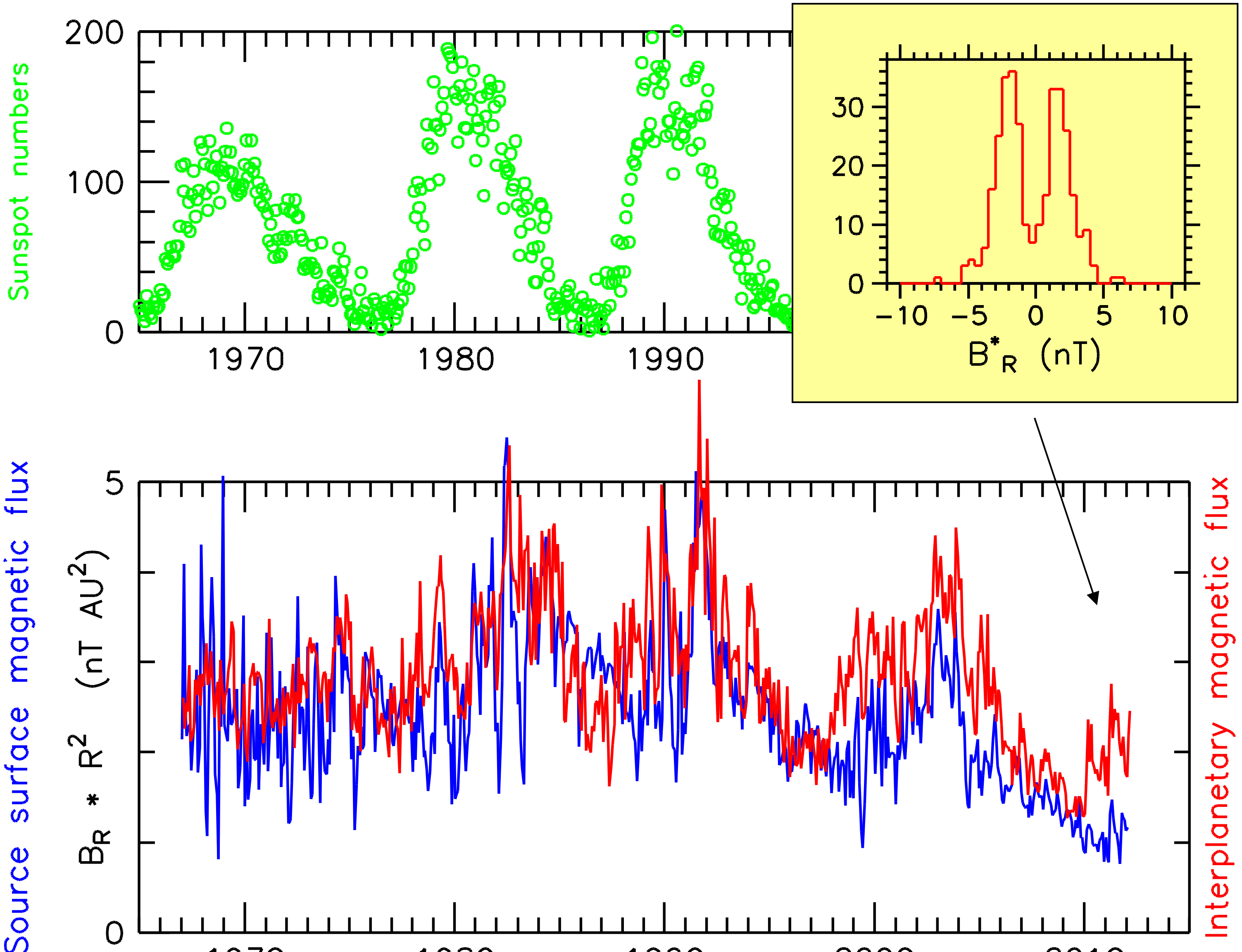
Source surface and heliospheric magnetic flux



Good agreement between solar and heliospheric magnetic flux, except rasing phase of solar cycle

Source surface magnetic field: courtesy of Yi-Ming Wang

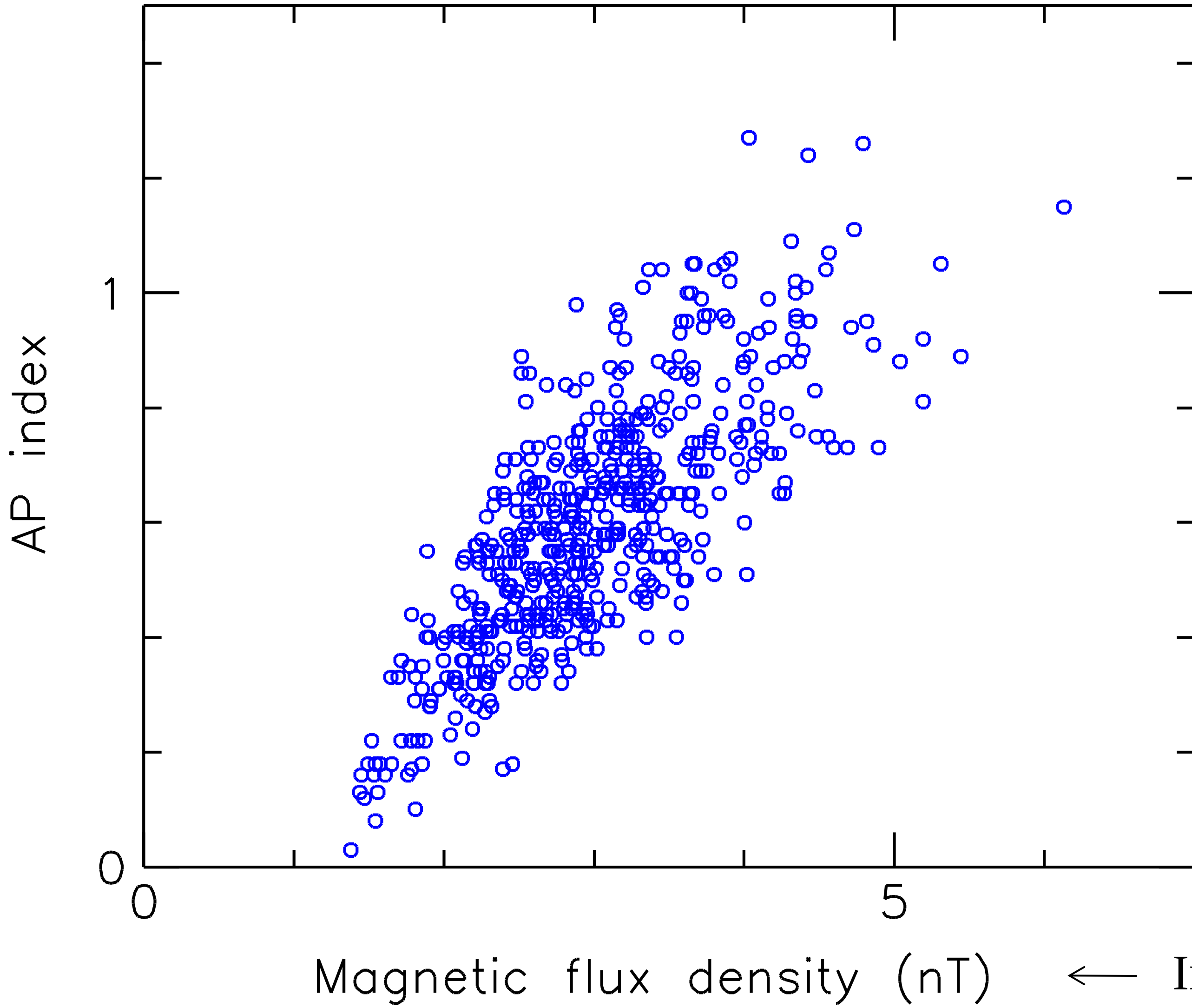
Source surface and heliospheric magnetic flux



Good agreement between solar and heliospheric magnetic flux, except rasing phase of solar cycle

Source surface magnetic field: courtesy of Yi-Ming Wang

Geo-effectivity



← Interplanetary data (OMNI)

Conclusions

The distribution of the open magnetic flux density, $B_R R^2$ depends in a complex way on the heliospheric location, type of solar wind (slow or fast) and solar activity.

Variations in $B_R R^2$ are largely caused by fluctuations of the magnetic field around the average Parker field lines.

The effects of the fluctuations can be reduced (2 methods were presented)

Results show that there is no flux excess in the outer heliosphere

The magnetic flux is uniformly distributed in the heliosphere (no latitudinal dependence)

Good agreement between heliospheric and source surface magnetic fluxes, except during the rising phase of solar cycles

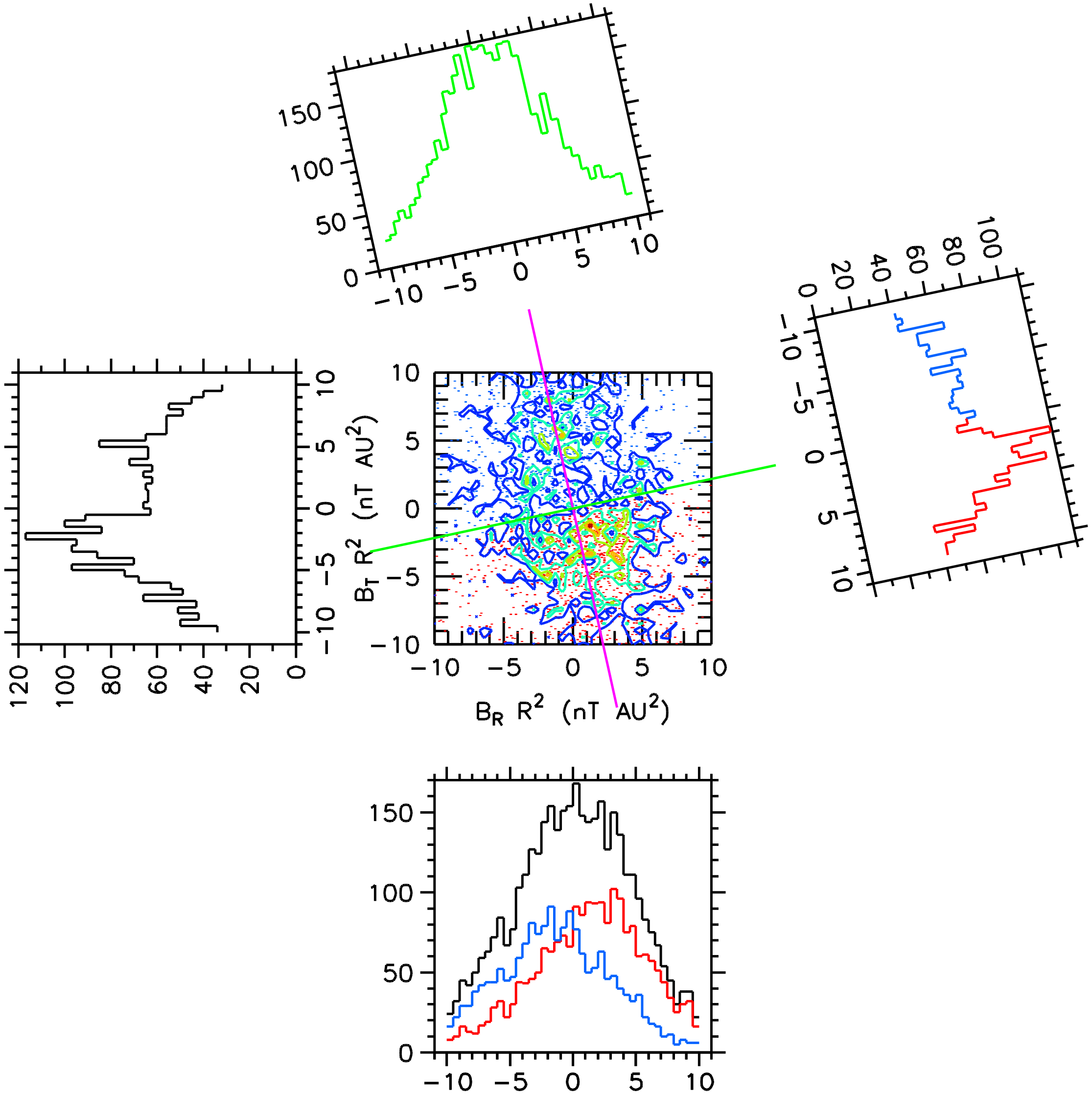
Questions

Why the interplanetary flux is higher than the source surface open flux during the rising phase of the solar cycle, in particular in the present cycle?

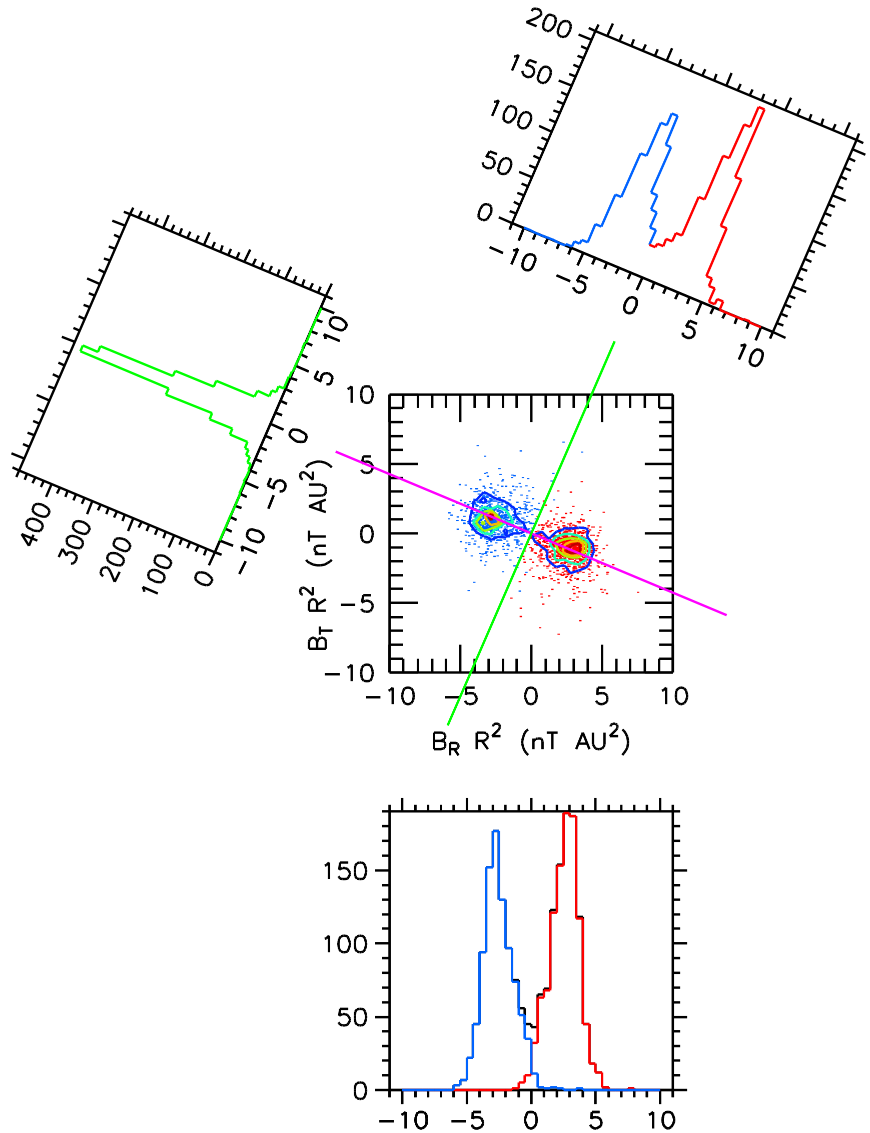
What is the open flux at CME activities?

Is there any latitudinal dependence of the open flux? (a related question is the north-south displacement of the heliospheric current sheet)

Is there any longitudinal dependence of the open flux? (preferential longitudes)



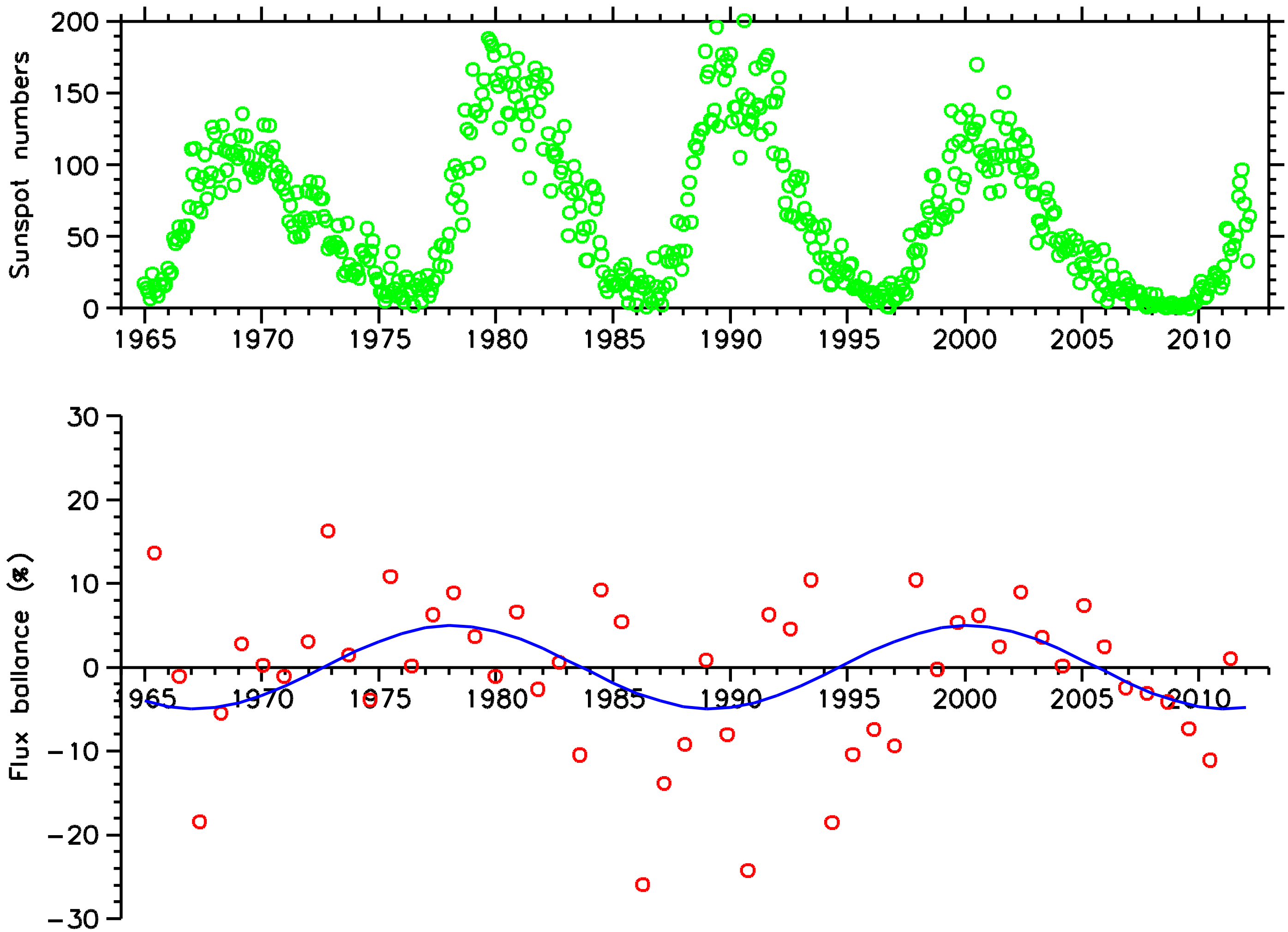
$B_T R^2$ (nT AU^2)
$B_R R^2$ (nT AU^2)



$B_T\ R^2$ (nT AU^2)
$B_R\ R^2$ (nT AU^2)

North-South (a)symmetry

(Mursula and Kalevi, 2004)



Difference between the magnetic flux averages in positive and negative sectors:

$$\frac{\langle B_R^+ \rangle + \langle B_R^- \rangle}{\langle B_R \rangle}$$

22 year wave fit results in an amplitude of 5%, corresponding to 1.5° offset of current sheet.

Not convincing result, large errors.