

## ABSTRACT

ULYSSES spacecraft solar polar passes at solar minimum provide in situ observations of evolving MHD turbulence in the solar wind under ideal conditions of fast quiet flow. We focused on the south polar pass of 1994 and the north polar pass of 1995 which provide extended intervals of quiet, fast solar wind at a range of radial distances and latitudes.

Fully developed inertial range turbulence has a characteristic statistical similarity property of quantities that characterize the flow, such as the magnetic field components  $B_k(t)$ , so that the  $p$ th moment of fluctuations have power law dependence on scale  $\tau$  such that  $\langle |B_k(t+\tau) - B_k(t)|^p \rangle \sim \tau^{\zeta(p)}$ . We instead found a generalized similarity  $\langle |B_k(t+\tau) - B_k(t)|^p \rangle \sim g(\tau/\tau_0)^{\zeta(p)}$  consistent with Extended Self Similarity; and in particular all of these ULYSSES observations, from both polar passes, share the same single function  $g(\tau/\tau_0)$ .

If these observations are indeed characteristic of MHD turbulence evolving in situ, then this quantifies for the first time a key aspect of the universal nature of evolving MHD turbulence in a system of finite size.

Further possibilities of testing universal aspects of evolving turbulence are also in progress using data from the Hinode mission. Many 2D images of the solar corona are provided by the Solar Optical Telescope on Hinode; showing several turbulent upflows in space and time. Current work on this analysis will be discussed briefly.

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## Instrument and Data Set

- Ulysses is a joint NASA and European Space Agency mission
- Non ecliptic orbit
- South and North polar passes of about three months each
- Ulysses magnetometer provides us Magnetic Field observations along the radial, normal and transverse direction with a simple frequency of 1 minute in average
- Data intervals considered

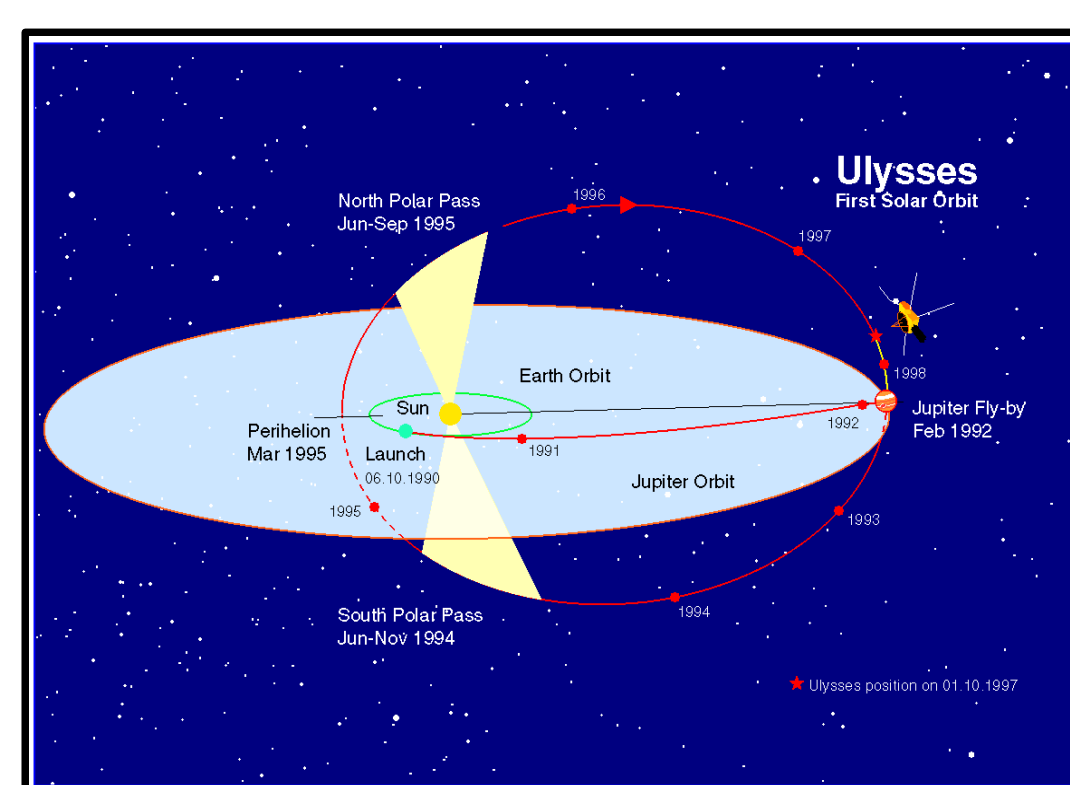


Figure 1. Ulysses spacecraft orbit.

South Polar pass of 1994, days 210–269.

North Polar pass of 1995, days 180–239.

The solar wind: an ideal laboratory to study MHD turbulent fluctuations in a high Reynolds number magnetofluid [1].

- $f^{-5/3}$  Inertial range of turbulence at small scales (high frequencies)
- $f^{-1}$  Scaling at large scales (low frequencies)

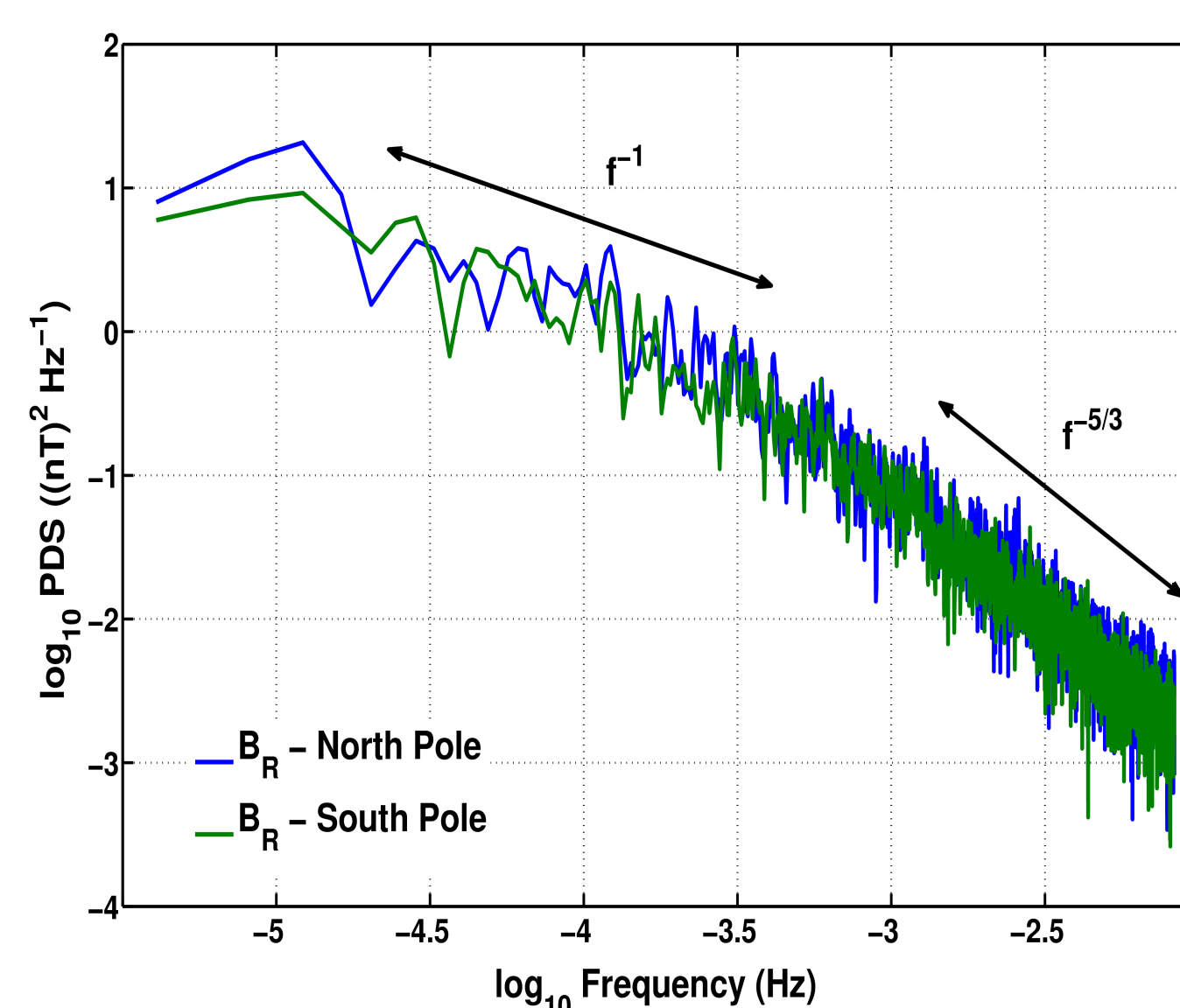


Figure 2. Log-log plots of the PSD for the radial magnetic field component,  $B_R$ , for the South 1994 and North 1995 polar passes at the heliospheric distance of 2.204 AU.

## Generalized Structure Function (GSF)

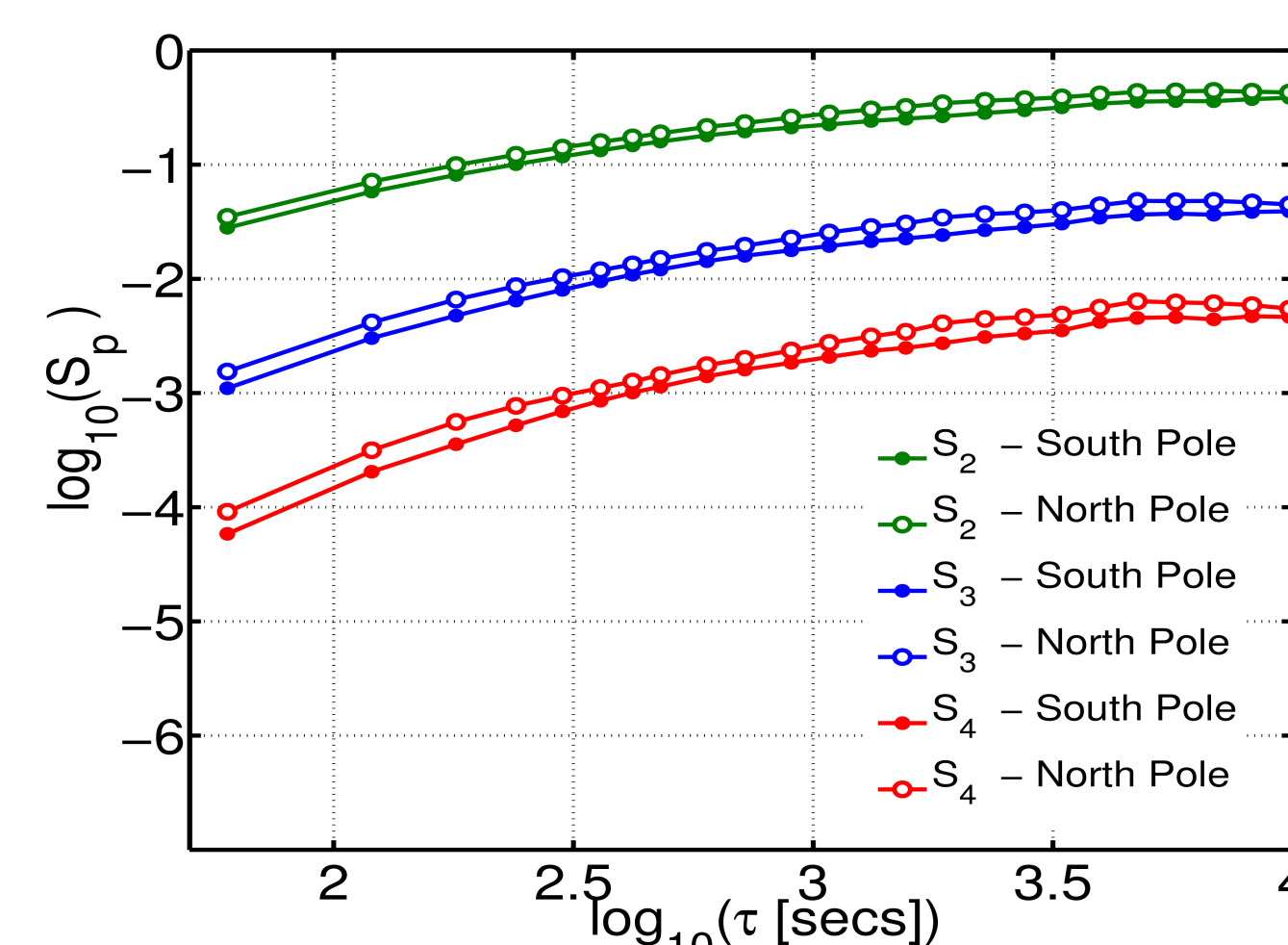
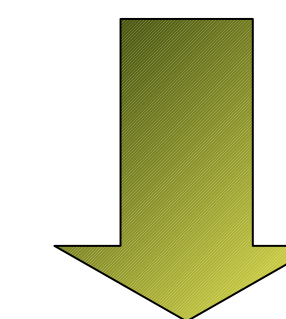


Figure 3. GSFs of  $S_p$  versus  $\tau$  on log-log axis for  $p=2, 3$  and  $4$ .  $S_p$  refers to the radial component of the magnetic field,  $B_r$ , from both the North and South polar passes analysed at the same heliocentric distance of 2.204 AU. The plots are shifted for clarity.

• The inertial range extends from  $\tau \sim 1$  min to  $\tau \sim 15$  mins

•  $S_p$  clearly curve for  $\tau < 30$  mins

• No single straight line fit over the inertial range



•  $\zeta(p)$  in non linear in  $p$  within the IR of turbulence as Kolmogorov theory predict.

• Similarity aspects persist but GSF analysis is not enough to quantifies the turbulent scaling.

## ESS analysis and UNIVERSALITY

Extended self-similarity (ESS) is defined as ratios of GSFs [2] :

$$S_p(\tau) \sim [S_q(\tau)]^{\zeta(p)/\zeta(q)}$$

A generalised form of ESS is suggested by:

$$S_p(\tau) = S_p(\tau_0) [g(\tau/\tau_0)]^{\zeta(p)} \quad [3-4]$$

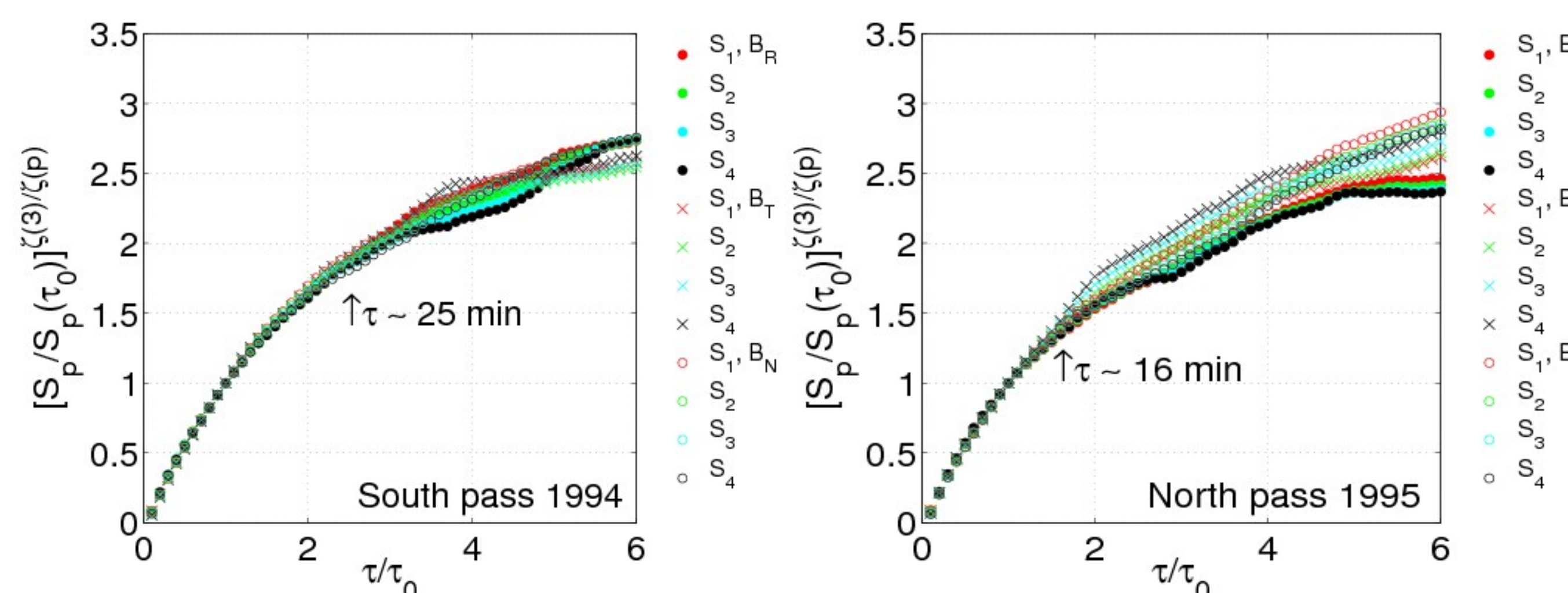


Figure 4.  $[S_p(\tau)/S_p(\tau_0)]^{\zeta(p)/\zeta(q)}$  versus  $\tau/\tau_0$ , ( $\tau_0 = 10$  mins) for  $p$  up to 4, for all field components at the same heliocentric distance for the Ulysses polar passes of interest.

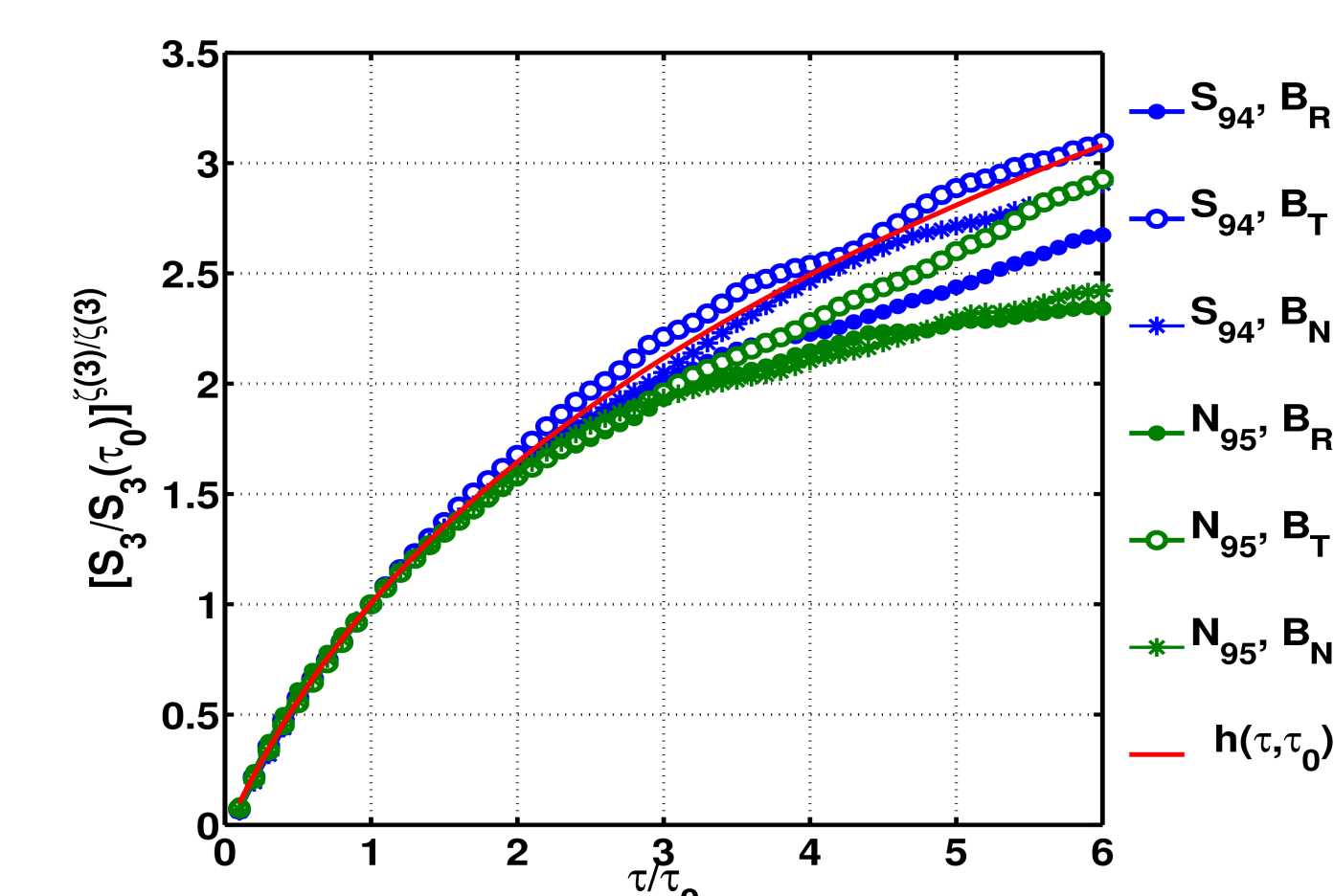


Figure 5.  $[S_3(\tau)/S_3(\tau_0)]^{\zeta(3)/\zeta(3)}$  versus  $\tau/\tau_0$  for all magnetic field components and for both polar passes considered at the same heliocentric distance .

A good fit for  $g(\tau/\tau_0)$  is of the form:

$$h(\tau, \tau_0, \tau_i) = a \cdot (\tau/\tau_i)^{b \cdot (\tau/\tau_0)}$$

where

•  $\tau_0 = 10$  minutes ( $\sim$  outer scales)

•  $\tau_i = 1$  minute ( $\sim$  inner scale)

•  $a = 0.101 \pm 0.001$

•  $b = 0.10 \pm 0.01$

## Turbulence in Solar Prominences?

Hinode, also known as Solar-B, is a Japan Aerospace Exploration Agency Solar mission with United States and United Kingdom collaboration. It has a quasi-circular sun-synchronous orbit over the day/night terminator, which allows near-continuous observation of the Sun.

• **Time interval considered:** observations from 01.00 UT to 06.00 UT on November 30, 2006 with a cadence of  $\sim 16.5$  sec on average.

• **Position on the solar disk:** North  $50^\circ$ , West  $90^\circ$ .

• **Data Set:** about 1000 2D images ( $2084 \times 1024$  pixels with a resolution of  $0.10896$  arcsec) of the solar corona in the Ca II H-line provided by the the Broadband Filter Imager (BFI) on the SOT;



Figure 6. Hinode spacecraft.

Several highly dynamic upflows appear intermittently in the data set showing relatively constant speed of  $\sim 20$  km  $s^{-1}$  and turbulent profiles [5].

**Future analysis:** quantify the scaling of turbulence performing correlation between space-time patterns . This will be done directly from the intensity information, without explicitly computing the underlying motions. Such a measure will allow us to detect similarity in the solar corona and find out possible universal aspects of turbulence.

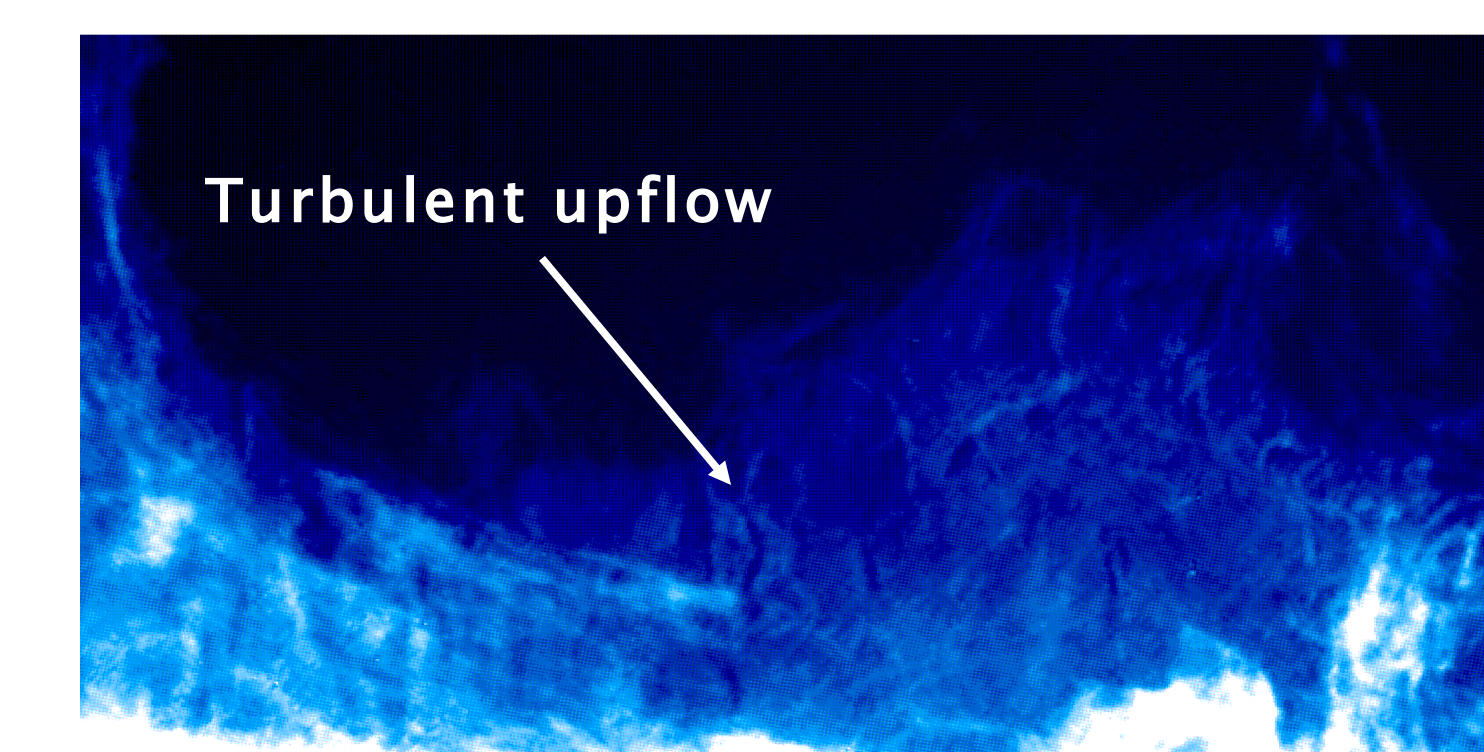


Figure 7. Image of the solar corona in the Ca II H-line on 2006 November 30, disk position N50, W90. Image has been calibrated, filtered and rotated to a horizontal position: the brightest area is the solar limb and spicules above which filamentary structures of the prominence are associated with down and up flows.

## CONCLUSIONS

• In a system of finite size, or where the turbulence is not fully evolved, universal properties of similarity, that is, power law dependence of the statistical properties of fluctuations, such as structure functions, are lost.

• Thanks to Extended Self Similarity, it is possible to recover some kind of similarity in terms of the ratios of the structure functions, showing a power law dependence on a function  $g(\tau/\tau_0)$ .

• Analysing the Ulysses dataset, we find the same function  $g(\tau/\tau_0)$  orders the statistical properties of fluctuations in all components of the magnetic field, over many intervals from north and south polar passes of 1995 and 1994 respectively.

• Future analysis on the Hinode dataset is born with the aim to perform comparative studies with other astrophysical MHD turbulent flows in systems of finite size, such as the solar corona. This would be a first step towards a formal understanding of ESS phenomenology establishing whether this generalized similarity is in fact universal.

## REFERENCES

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- [2] R. Benzi et al. Phys. Rev. E, **48**, 29 (2003)
- [3] R. M. Nicol, S. C. Chapman, R. O. Dendy, Ap. J., **679**, 862-870 (2008)
- [4] S. C. Chapman, R. M. Nicol, E. Leonardis et al. Ap. J., **695** L185-L188 (2009)
- [5] T. E. Berger et al. Ap. J., **676** L89-L92 (2008)