Dependence of Intermittency of Fast and Slow Solar Wind from the Radial Distance, Heliospheric Latitude, and Solar Cycle

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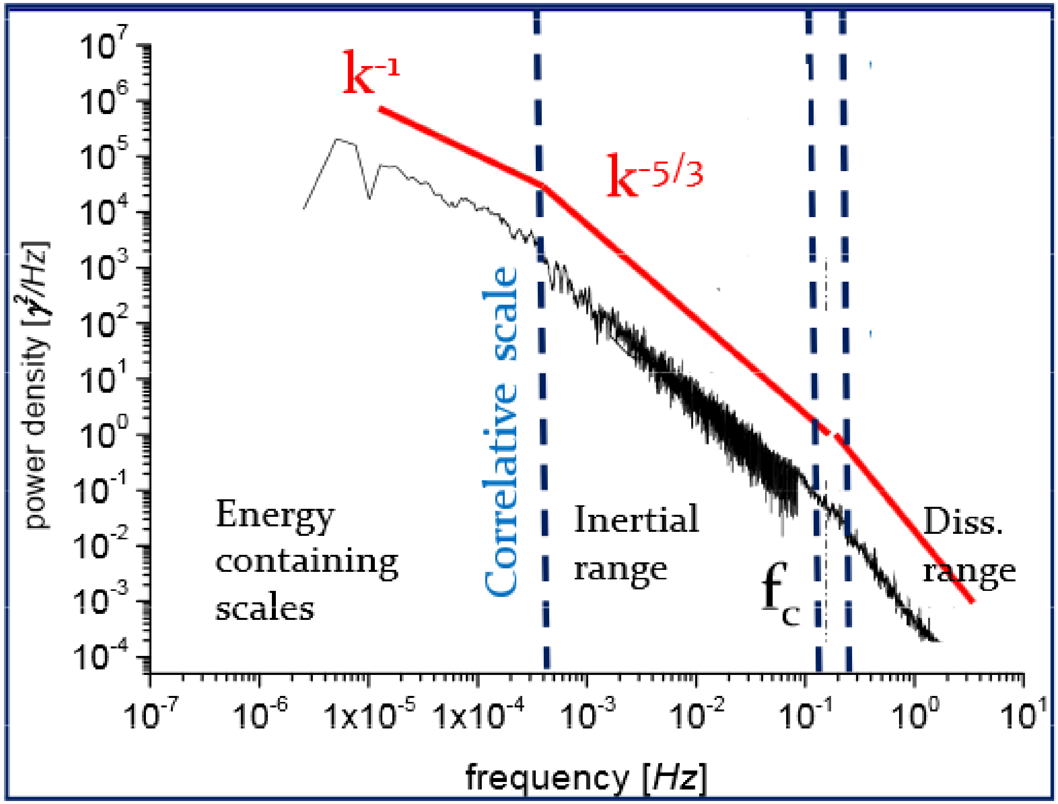
Turbulence in the solar wind



The spectral properties of magnetic field and plasma velocity fluctuations show power law behavior

Typical interplanetary magnetic field power spectrum at 1 AU (Bruno and Carbone, 2013]

Intermittency-the property of the plasma structures carying the turbulent fluctuations to break down heterogeneously at smaller and smaller scales, i.e. they become scattered in time and/or space

Intermittency in the Heliosphere

In the ecliptic:

- fast solar wind is generally less intermittent than slow wind both for wind speed and magnetic field components [*Marsch and Liu* 1993; *Bruno et al.,* 2003].
- the intermittency of the fast wind increases with the increase of the distance (0.3-0.9 AU) from the Sun [*Bruno et al.,* 2003].

Beyond the ecliptic plane:

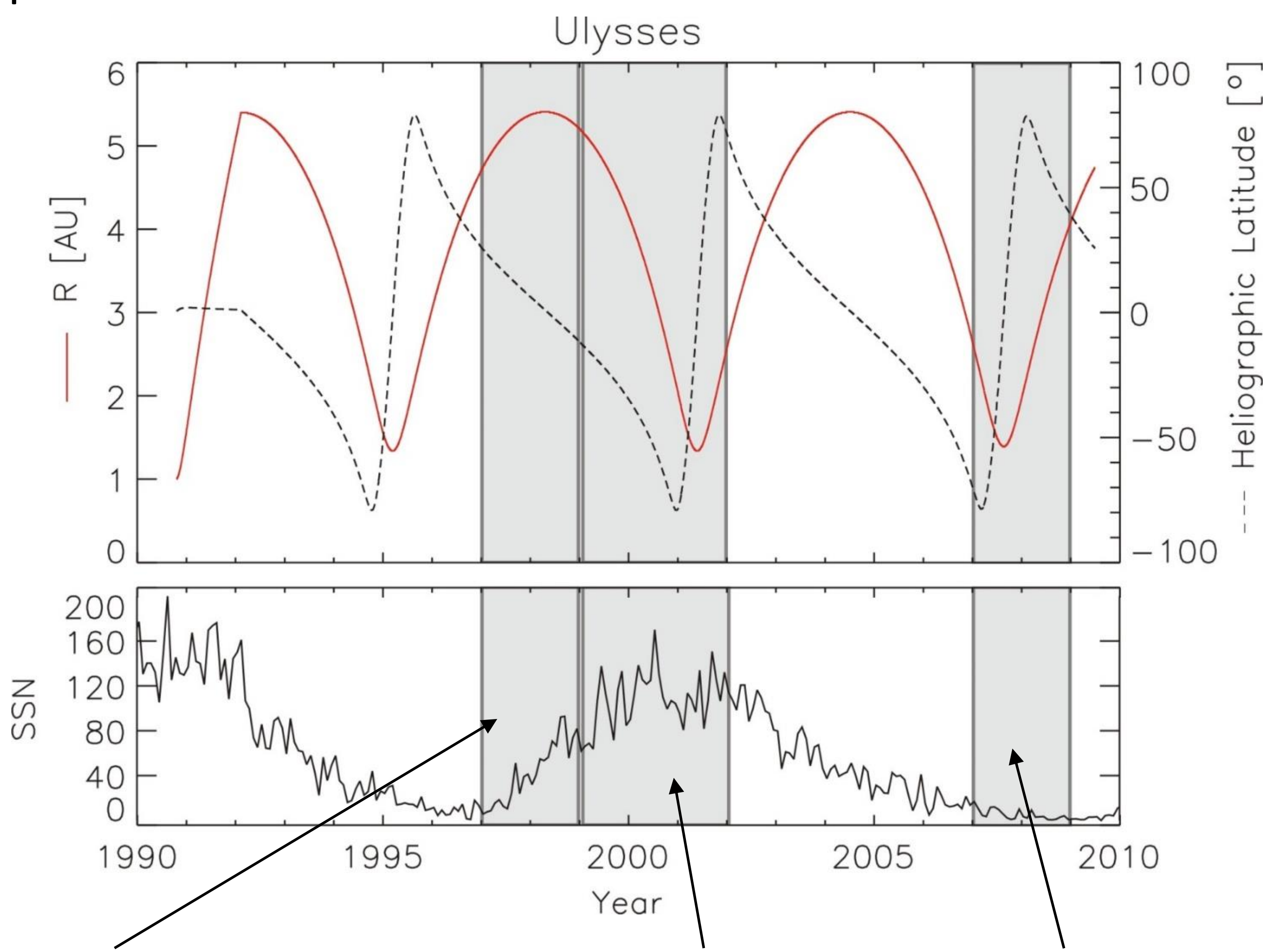
- magnetic field components measured by Ulysses present a high level of intermittency throughout minimum (1994-1996) and maximum (2000-2001) [*Pagel and Balogh*, 2002].
- slow wind has a lower level of intermittency compared with the fast flow
- [*Pagel and Balogh*, 2002] .
- in the polar coronal fast wind at solar minimum between 1994 and 1996 that intermittency increases with increasing the radial distance from the Sun [*Pagel and Balogh*, 2003]
- slow wind measured at $R = 5.1 - 5.4$ AU, $L < 20^{\circ}$, during 1992-1997 is more intermittent than fast wind and slow wind does not present radial evolution. [*Yordanova et al.*, 2009].

Ulysses Mission

1990-2009

Radial distance: 1.4 - 5.4 AU

Heliographic latitude: -82°- +82°



D5MINSW : 1997, 1998 **D1MAXSW :** 1999, 2000, 2001 **D3MINSW :** 2007 and 2008

Idea of Ulysses Data Selection

D1MAXSW : 1999, 2000, 2001
D3MINSW : 2007 and 2008
D5MINSW : 1997, 1998.

CME list (1992-2008)

The Ulysses CME list (1992-2008) prepared by Gosling and D. Reisenfeld.
http://swoops.lanl.gov/cme_list.html

Ulysses shock list (1996 – 2002)

Ulysses shock list prepared by J. Gosling and R. Forsyth (only for years 1996-2002)
http://www.sp.ph.ic.ac.uk/Ulysses/shocklist.txt

STORM

Data without CMEs and interplanetary shocks

Radial Velocity v_R

Oxygen Ion Ratio O^{7+}/O^{6+}

Magnetic Compressibility*

Proton Temperature T_p

Proton Density n_p

Fast Solar Wind (FW)

$v_R > t_V$

$O^{7+}/O^{6+} < t_{O7+/O6+}$

Compressibility $< t_{Compr}$

$T_p > t_{Tp}$

$n_p < t_n$

Slow Solar Wind (SW)

$v_R < t_V$

$O^{7+}/O^{6+} > t_{O7+/O6+}$

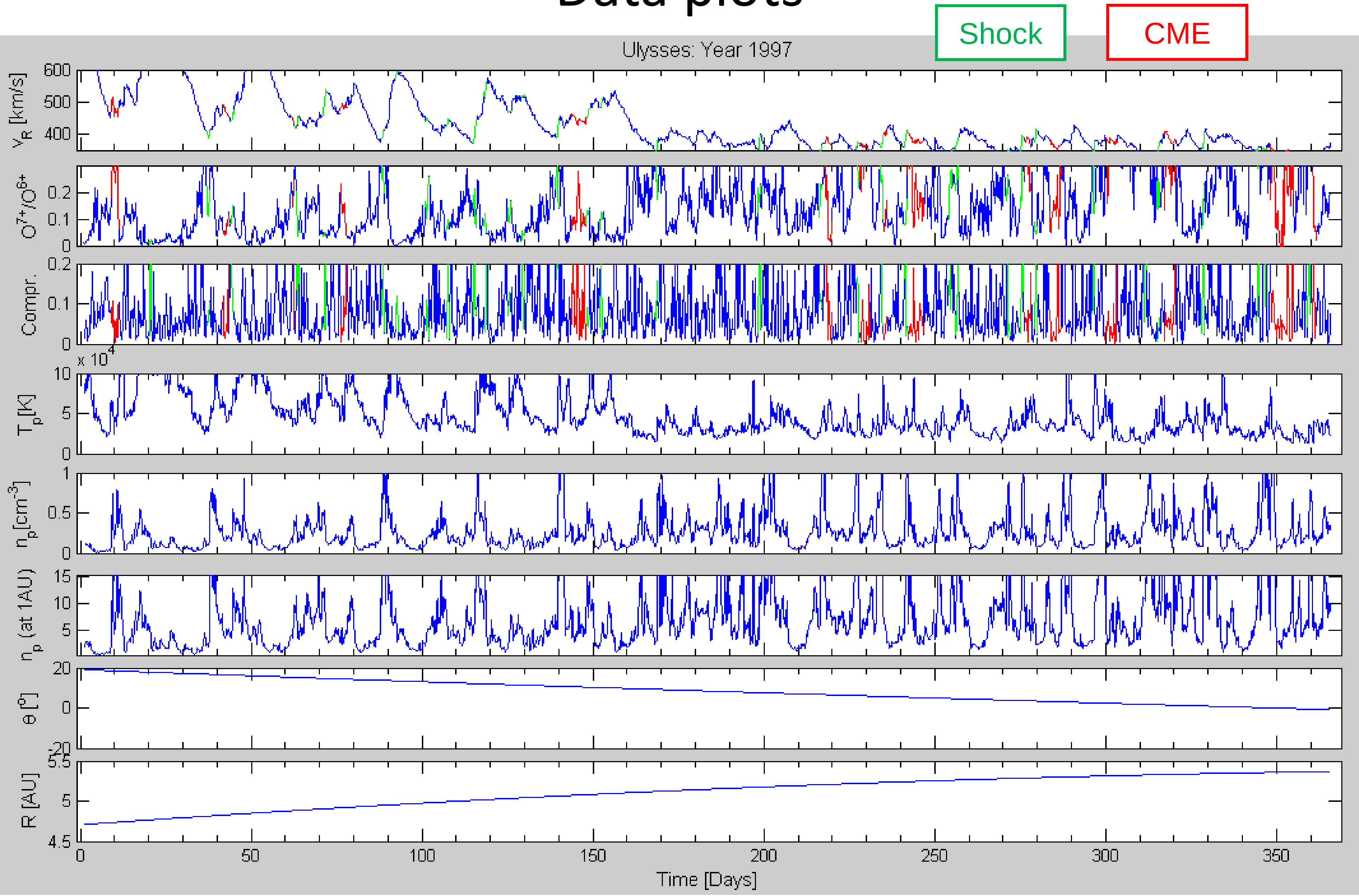
Compressibility $> t_{Compr}$

$T_p < t_{Tp}$

$n_p > t_n$

$$\text{*Compr}=\frac{\langle|B|^2\rangle-\langle|B|\rangle^2}{(\langle|B_R|^2\rangle-\langle|B_R|\rangle^2)+(\langle|B_T|^2\rangle-\langle|B_T|\rangle^2)+(\langle|B_N|^2\rangle-\langle|B_N|\rangle^2)}$$

Data plots



6-hour averages have been prepared for the data survey

Thresholds

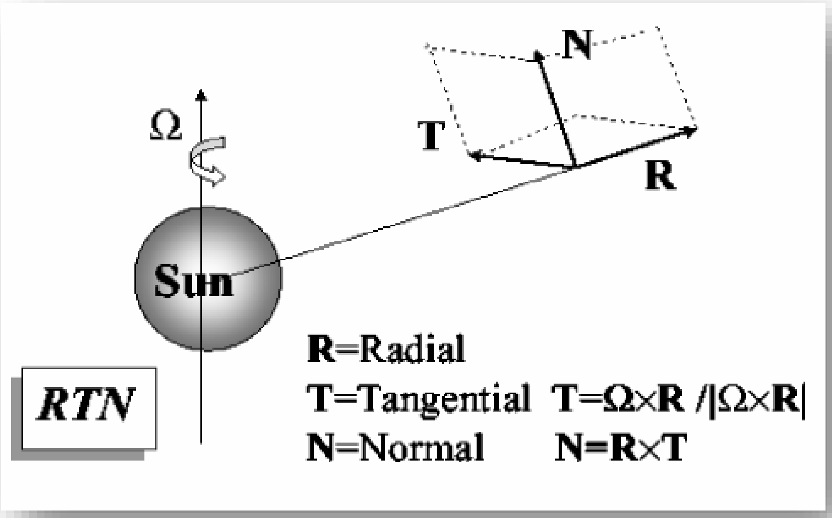
Table: The threshold values for the five solar wind parameters used during data selection

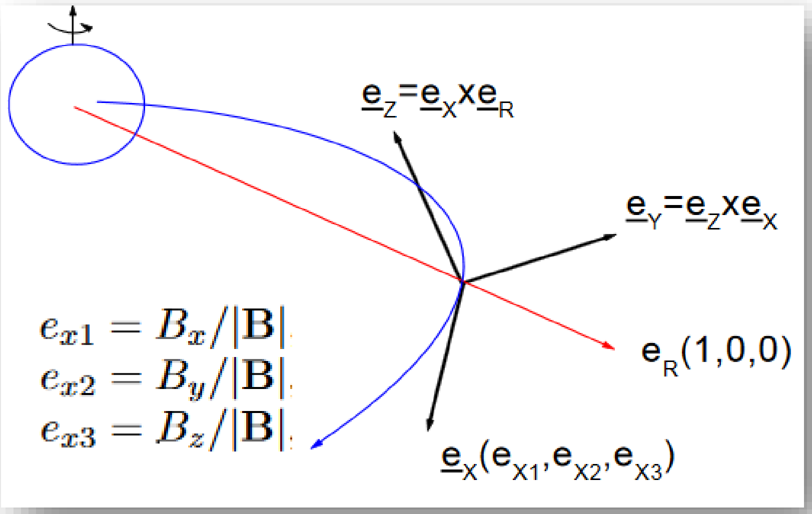
Threshold	Solar Minimum		Solar Maximum			Solar Minimum	
	1997	1998	1999	2000	2001	2007	2008
	4.7-5.4 AU	5.2-5.4 AU	4.2-5.2 AU	2.0-4.2 AU	1.3-2.6 AU	1.4-2.6 AU	2.0-4.1 AU
t_V [km/s]	500	450	450	450	500	500	500
$t_{O7+/O6+}$	0.1	0.1	0.1	0.1	0.1	0.05	0.05
$t_{Compr.}$	0.1	0.1	0.1	0.1	0.1	0.1	0.1
t_{Tp} [K]	$5*10^4$(d<160) $4*10^4$(d>160)	$4*10^4$	$5*10^4$	$5*10^4$	$1*10^5$	$8*10^4$	$8*10^4$
t_n [cm^{-3}]	0.2	0.2	0.2	0.4 (d<200) 1.2 (d>200)	1.5	1.5	0.7 (d <200) 0.3 (d>200)
t_n [cm^{-3}] (at 1 AU)	5.2	5.7	4.5	4.9 (d<200) 7.5 (d>200)	5.7	6.0	5.1 (d<200) 4.2 (d>200)

d- denotes the day of the year

Data base

126 time series (17400 h)
88 cases - Fast solar wind 38 cases - Slow solar wind
Instrument: VHM-FGM
All all components : RTN , Mean Field Ref. Sys.
0.5-1 Hz





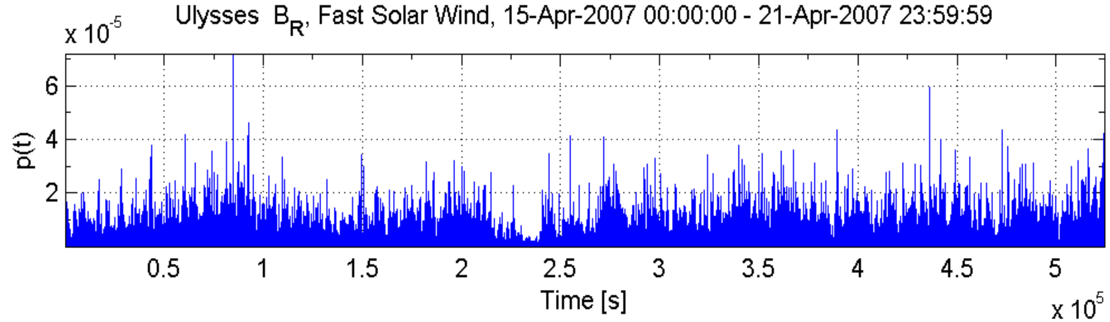
[*Bruno and Carbone*, 2013]

Multifractal analysis

1) Measure

$$\varepsilon(x_i, l) \equiv |B(x_i + l) - B(x_i)|$$

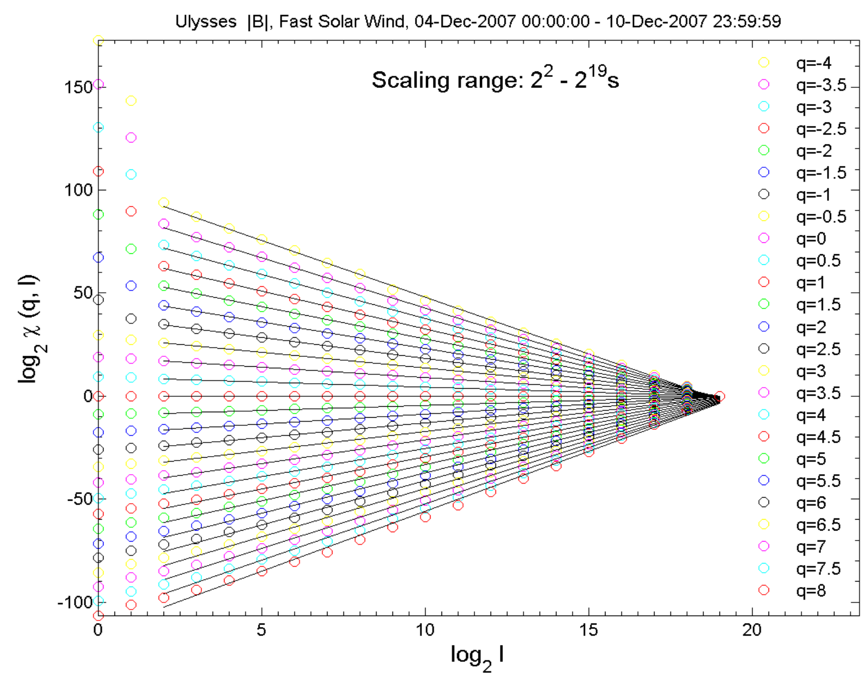
$$p(x_i, l) \equiv \frac{\varepsilon(x_i,l)}{\sum_{i=1}^{N} \varepsilon(x_i,l)} = p_i(l)$$



2) Partition Function

$$\chi(q, l) = \sum_{i=1}^{N(l)} (p_i(l))^q$$

$$\chi(q, l) \propto l^{\tau(q)}$$



Saucier and Muller, Phys. A, (1999)

The scaling of the partition function $\chi(q, l)$ in dependence on scale l.

Multifractal Spectrum

3) Legendre Transform

$$\alpha(q) = \frac{d}{dq}[\tau(q)] = \tau'(q)$$

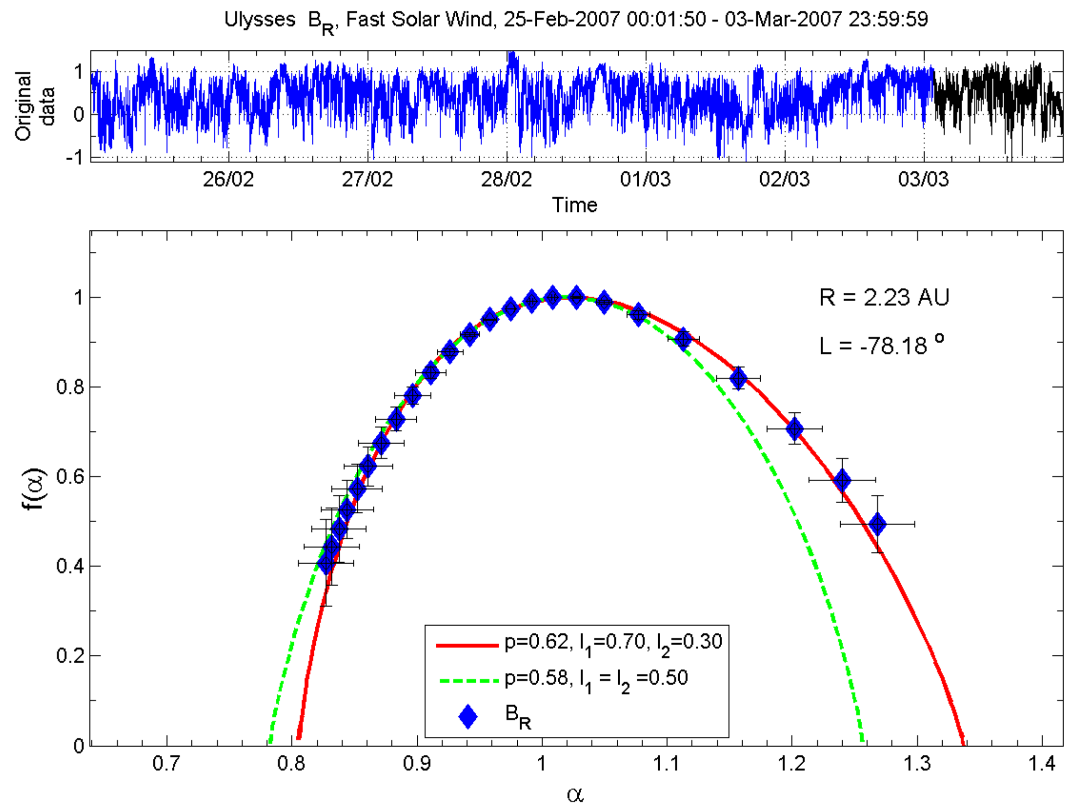
$$f(\alpha(q)) = q\alpha(q) - \tau(q)$$

4) Fit Model

2-scale model
[*Macek and Szczepaniak*, 2008]

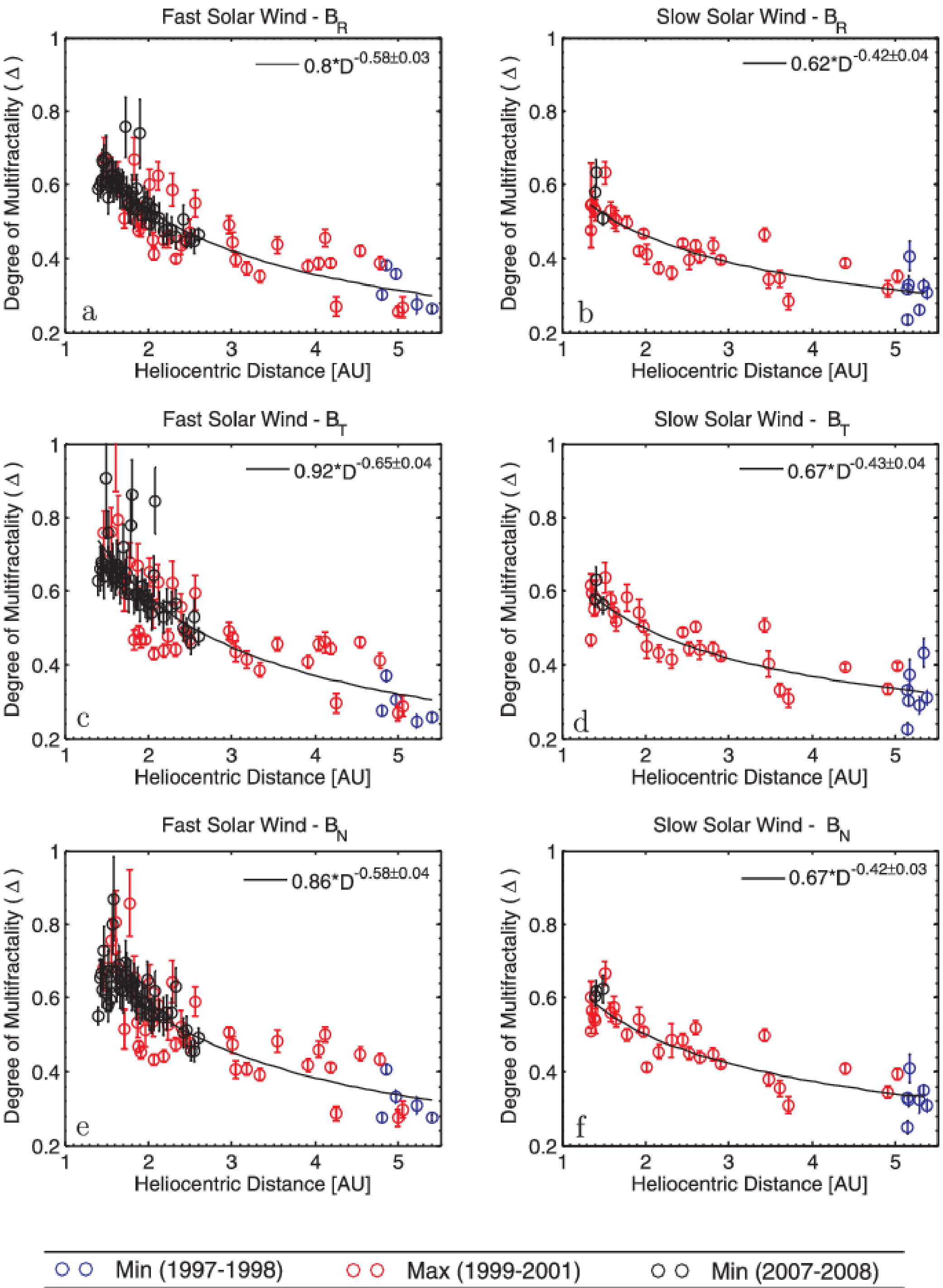
P-model
[*Meneveau and Sreenivasan*, 1987]

5) Degree of multifractality



Δ

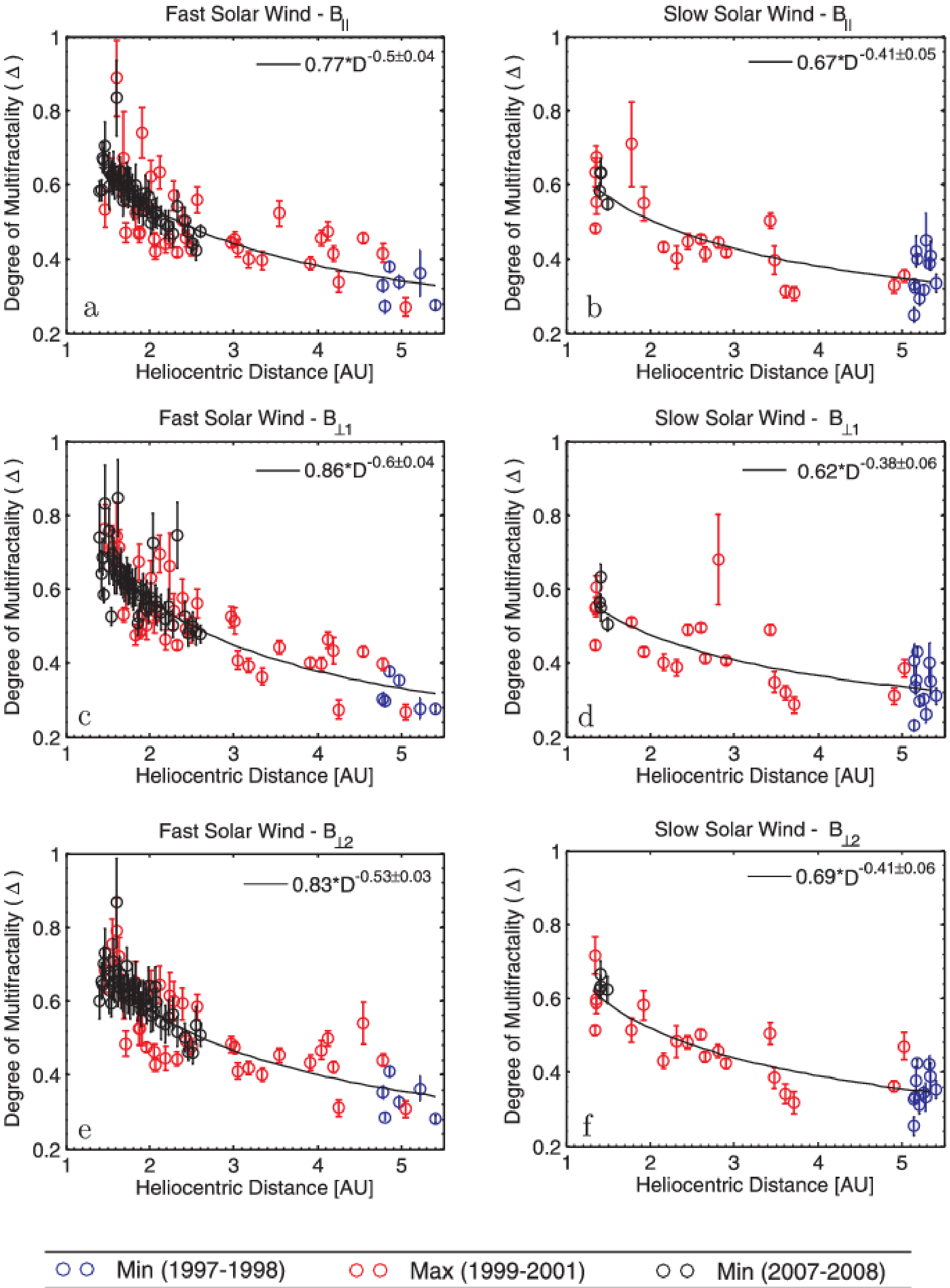
Degree of multifractality=level of intermittency



Radial evolution of multifractality (intermittency)

750 multifractal spectra

Wawrzaszek, A., M. Echim, R. Bruno, *The Astrophysical Journal*, 876: 153, doi: 10.3847/1538-4357/ab1750.



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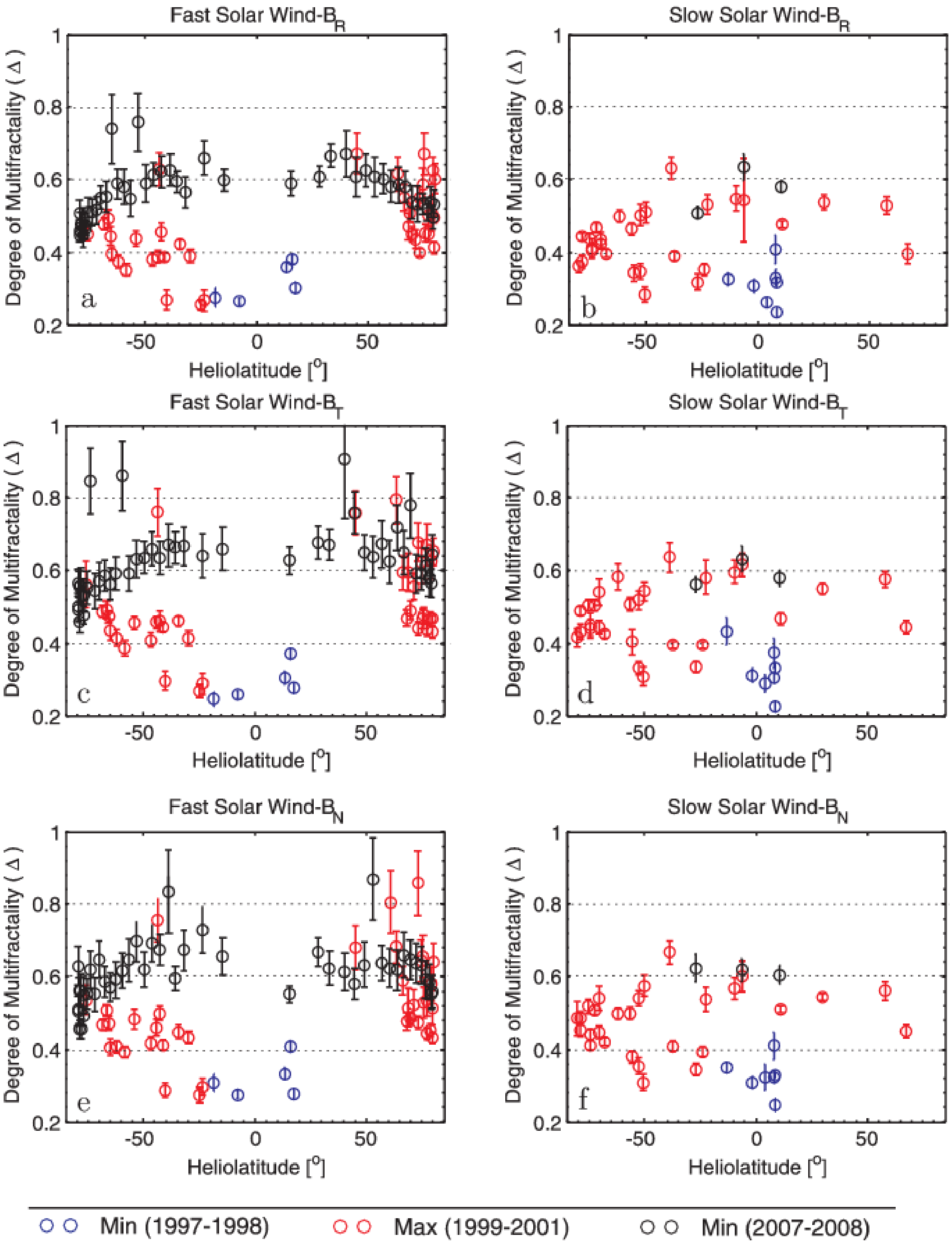
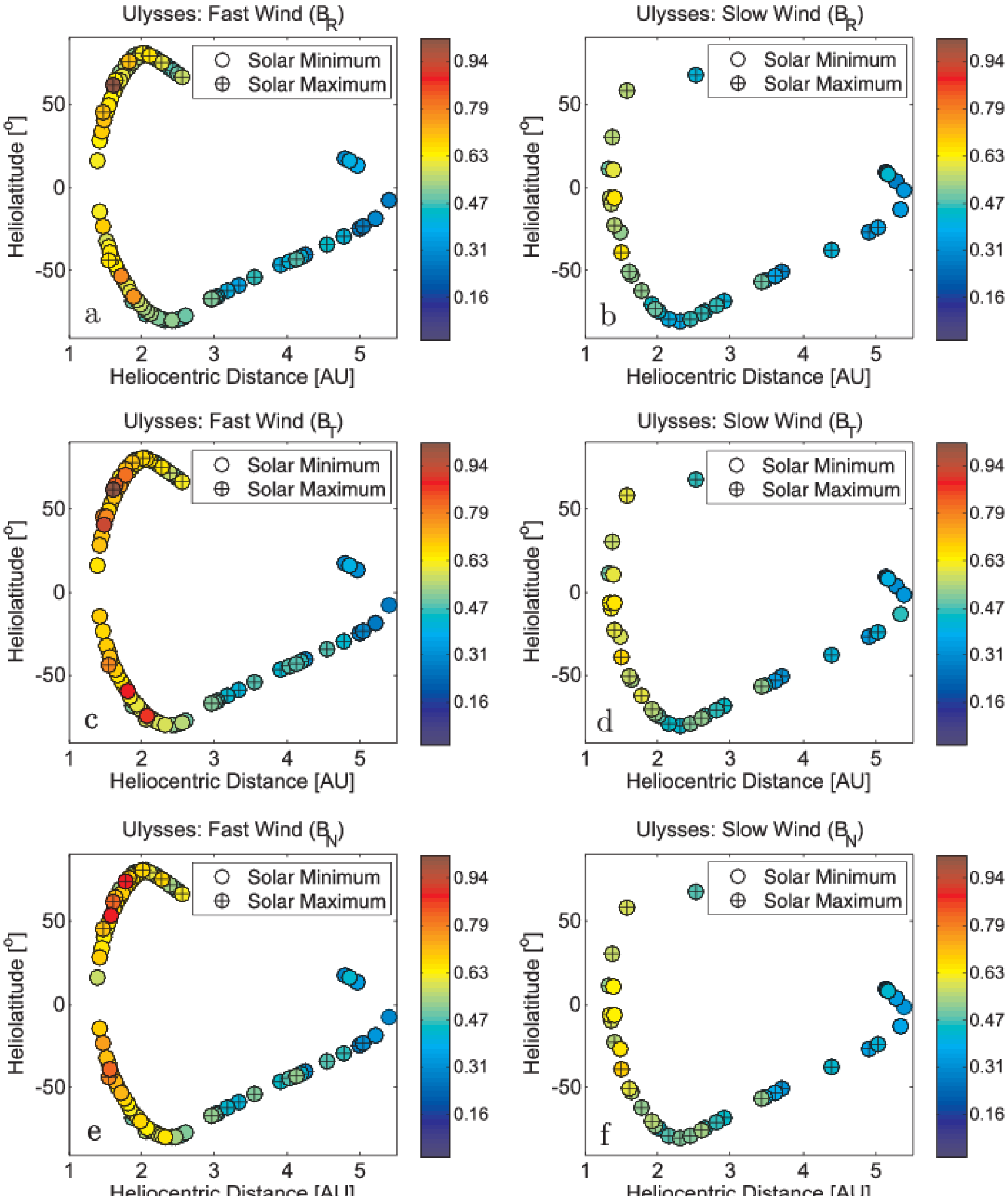


Latitudinal evolution of multifractality (intermittency)

The decrease of intermittency as the latitude increases with the smallest values at solar poles.

Wawrzaszek, A., M. Echim, R. Bruno, *The Astrophysical Journal*, 876: 153, doi: 10.3847/1538-4357/ab1750.

Maps of multifractality



Degree of multifractality as function of both heliocentric distance and heliographic latitude

Wawrzaszek, A., M. Echim, R. Bruno, *The Astrophysical Journal*, 876: 153, doi: 10.3847/1538-4357/ab1750.

Conclusions

Distance

- Analysis showed a slow decrease of degree of multifractality as a measure of intermittency with distance (behavior is observed in all magnetic field components, regardless of the reference system (RTN or MF))

Latitude

- Analysis of intermittency over a large range of heliographic latitudes revealed a latitude dependence and confirmed similar intermittent properties of the fast solar wind turbulence observed in the two hemispheres;

Solar cycle

- Analysis of data from the **solar minimum (1997–1998)** showed that intermittency is stronger for slow solar wind than for the fast wind.
- The slow solar wind from **solar maximum (1999–2001)** and from the **solar minimum (2007-2008)** revealed in many cases a smaller level of intermittency than for the fast solar wind.


Thank you for your attention
Credits: NASA

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SOLAR WIND HEAVY IONS OVER SOLAR CYCLE 23: *ACE*/SWICS MEASUREMENTS

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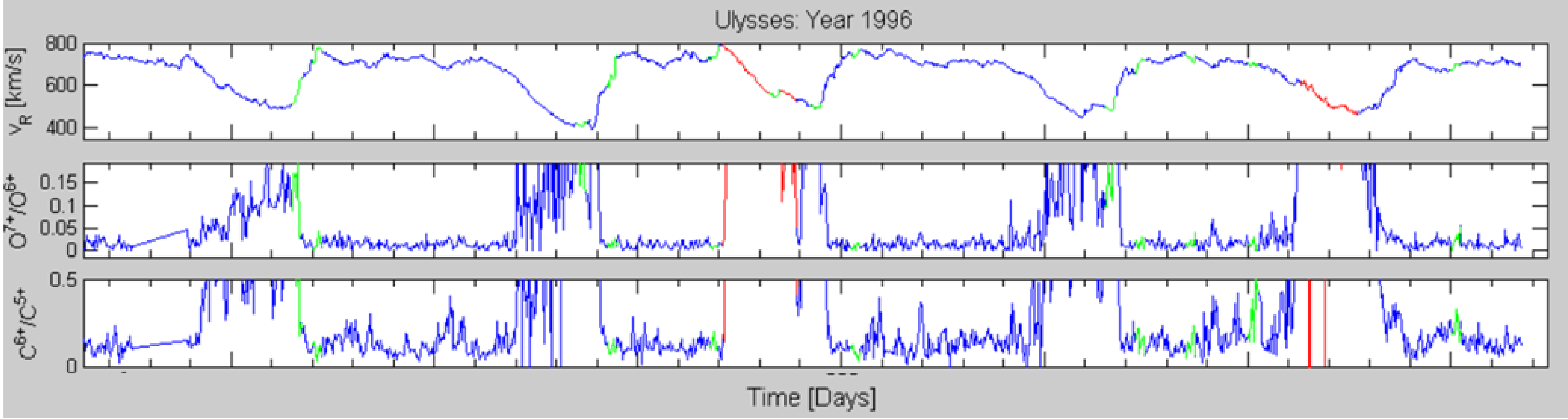
The charge states of O^{7+}/O^{6+} and C^{6+}/C^{5+} have long been used to differentiate source regions of the solar wind in the innermost solar corona (e.g., Zurbuchen et al. 2002; Zhao et al. 2009). Recently, Landi et al. (2012a) showed that C^{6+}/C^{4+} was actually a more sensitive indicator of electron temperatures in the corona and therefore an even better indicator of solar wind type and region of origin. Contrary to the charge state ratios of O and C, the average charge state of Fe (Q_{Fe}) has been shown to be a sensitive tracer of electron temperatures at larger heights, up to 4 Rs, so that it can be used as a measure of the evolutionary properties in the far corona (e.g., Lepri et al. 2001; Lepri & Zurbuchen 2004; Gruesbeck et al. 2011).



Intermittency beyond the ecliptic

Authors	Data	Method	Conclusions
Pagel and Balogh [JGR, 2003]	20 second averaged MF (Br, Bt, Bn) Min (1994 -1996) Fast solar wind 1.4 -4.1 au **28 cases**	Castaing distribution Range of considered scales 40-200 s	in the polar coronal fast intermittency increases with increasing the radial distance from the Sun transverse magnetic field components are significantly more non-Gaussian than radial
Yordanova et al. [JGR, 2009]	20 second averaged MF (Br, Bt, Bn) Min (1992-1997) Pure fast wind Fast stream Pure slow Slow stream **21 cases**	Spectral analysis Flatness factor	slow wind measured at $R = 5.1 - 5.4$ AU, $L < 20^{\circ}$ is more intermittent than fast wind slow wind does not present radial evolution Only pure fast wind presents radial dependence

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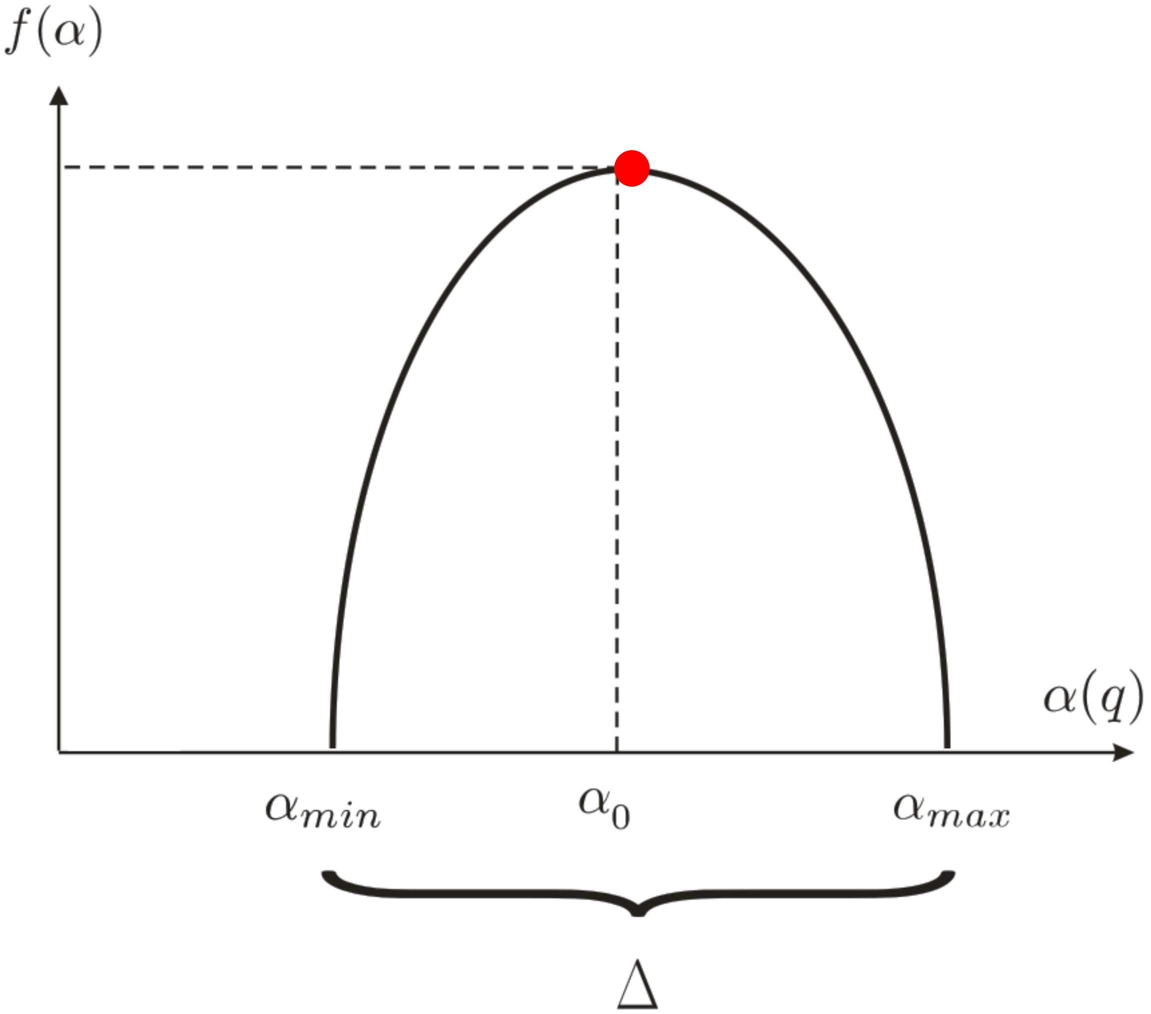
Multifractal Spectrum

Multifractal analysis is high-order method used to reveal intermittent nature of various characteristics of turbulence



Multifractal

Monofractal

α –singularity strength

$f(\alpha)$ –the fractal dimension of the subsets with local scaling indices α

Degree of Multifractality

$$\Delta \equiv \alpha_{\max} - \alpha_{\min}$$