Statistical analysis of the solar wind quasi-invariant using STEREO and WIND

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Abstract: The ratio of the solar wind magnetic and kinetic energy densities defines the solar wind Quasi Invariant (QI), which is the inverse of the squared Alfven Mach number: This combined solar wind parameter correlates well with the sunspot number.

This study uses solar wind data from the STEREO A, STEREO B and WIND spacecraft from 2007-2012. We statistically analyze changes of QI from the solar activity minima 2007-2009, through the rising phase of the solar activity close to the current solar wind maxima of solar cycle no. 24. Fitting the probability distributions (PDFs) of QI with log-normal and log-kappa distributions we present and discuss the PDFs with respect to #) progression of the solar cycle, #) differences between slow/fast solar wind and #) the presence of coronal mass ejections.

Researching the QI's from STEREO and WIND allows us to see in situ solar activity - of which the QI is a known index - on both sides of the Sun. This opens the perspective and is a contribution to the SUN-360: Full view of the Sun.

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What is the solar-wind Quasi-Invariant QI ?

"We define a quasi-invariant (QI) as a combination of physical parameters that has a significant higher correlation with some index than the correlations obtained by considering each component taken separately with the same index." (Osherovich et al., 2007)
Correlation coefficient between QI and sunspotnumber (yearly): cc=0.98

$$QI \equiv \frac{B^2/8\pi}{\rho v^2/2} \equiv M_A^{-2}, \tag{1}$$

- combination of the magnetic energy density with the kinetic energy density
- M_A the Alfvén Mach number (v/v_A)

(Osherovich et al., 1999.)

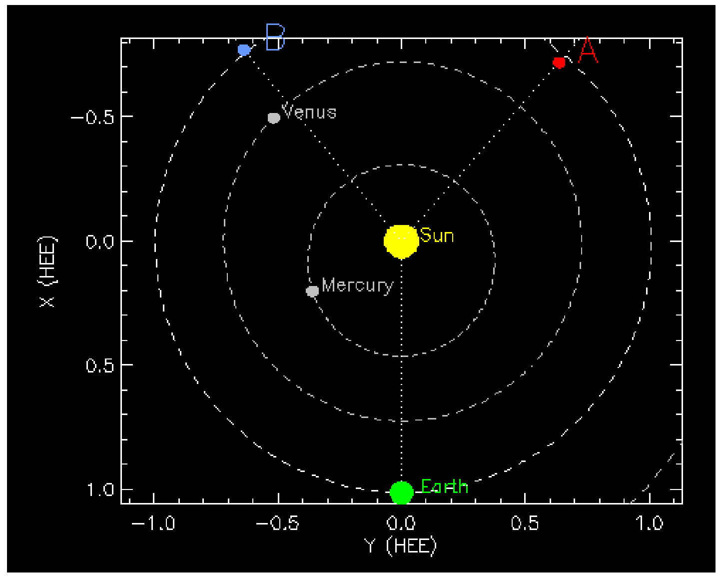


Figure above: Positions of STEREO-A and STEREO-B on June 15, 2013.

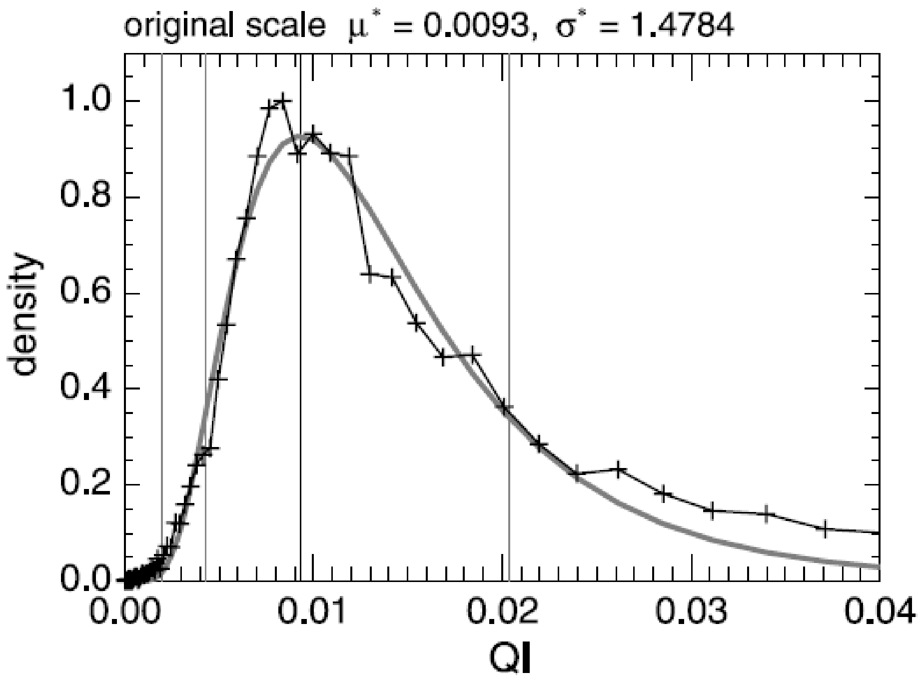
The dataset:

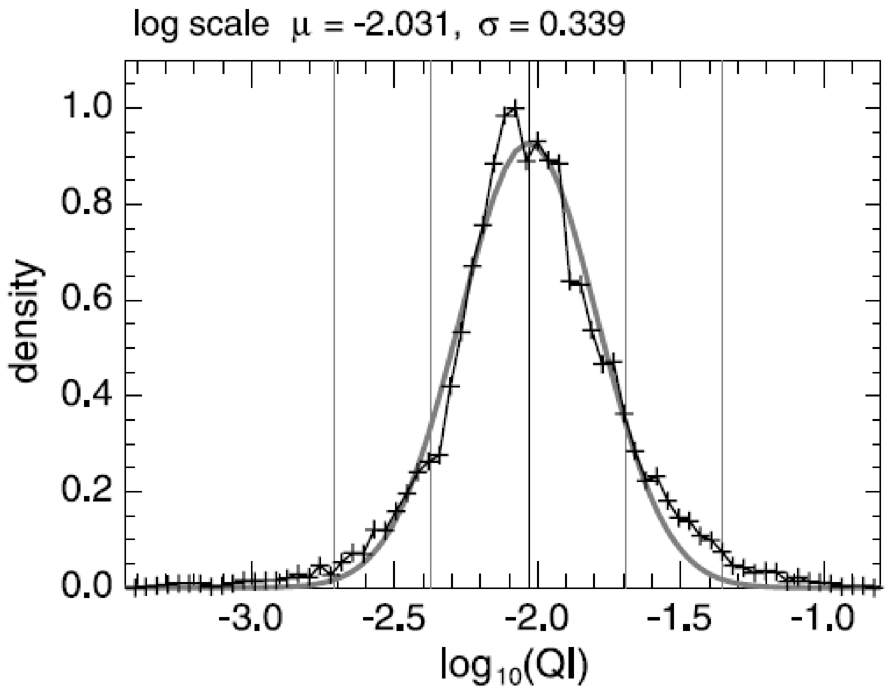
Solar wind magnetic field and plasma data from the OMNI database,
http://omniweb.gsfc.nasa.gov/

Stereo A, Stero B data is taken from Space Science Center, University of California, Los Angeles
http://www-ssc.igpp.ucla.edu/ssc/stereo/

How QI is described statistically?

For each year we determine the probability density function for QI.
A more detailed analysis distinguishes between fast and slow solar wind (separation limit 400 km/s).
Each PDF is fitted by log-normal and log-kappa distribution.





Figures left from Leitner et al., 2009a: Distribution of QI values in the year 2007 for STEREO A. To obtain the mean value μ* and standard deviation σ* the distribution is first converted into a logarithmic scale, where the distribution is fitted by a Gaussian curve (solid line) and the results are then converted back to the original scale.

$$f_g(x) = \frac{1}{\sqrt{\pi}\sigma} \exp\left[-\frac{(x-\mu)^2}{\sigma^2}\right]$$

$$f_g(x) = \frac{1}{x} \frac{1}{\sqrt{\pi}\sigma} \exp\left[-\frac{(\log(x)-\mu)^2}{\sigma^2}\right]$$

In the Cartesian system of coordinates, μ has the meaning of a scale parameter and σ represents a shape parameter. More comfortable, lognormal distributions are described in terms of the log-transformed variable, using as parameters the expected value, or mean of the distribution, and the standard deviation. Transformation to the Cartesian system gives the geometric mean μ* and the multiplivative standard deviation sigma*. Such the 1-σ interval, covering 68,8% of the varuation, is given by the interval [μ*/σ*, μ*·σ*] and the 2-σ interval, containing 95,5% of the varaiation, is given by [μ^*/σ^{*2}, $\mu^*\cdot\sigma^2$] (Leitner et al, 2009b)

How QI is described statistically: Log-kappa distribution

The cornerstone of normal and log-normal distribution is the Boltzmann-Gibbs entropy. For complex systems thes Boltzmann-Gibbs entropy was extended by Tsallis (Tsallis 1988). The Tsallis q-statistics were then linked to the family of kappa-distributions (Leubner 2002 and 2004) and a generalized nonextensive solution for the one dimensional distribution is given by Leubner and Vörös 2005 as

$$f(x) = \frac{1}{\sqrt{\kappa\pi}\sigma} \frac{\Gamma[\kappa]}{\Gamma[\kappa - 1/2]} \left(1 + \frac{1}{\kappa} \frac{(x-\mu)^2}{\sigma^2}\right)^{-\kappa}$$

where μ is the mean of the distribution, σ is the standard deviation, Γ is the Euler gamma function, and κ corresponds to the degree of deviation from the normal distribution. The quantity κ covers the range $½ < \kappa < \infty$ and for $\kappa \rightarrow \infty$ the equation equals to the normal distribition equation. In contrast to normal distributions low κ values correspond to pronaunced tails in the distribution.

In order to the the case of skewed distributions, log-kappa distribiutions are introduced, defined as:

$$f_h(x) = \frac{1}{x} \frac{1}{\sqrt{\kappa\pi}\sigma} \frac{\Gamma[\kappa]}{\Gamma[\kappa - 1/2]} \left(1 + \frac{1}{\kappa} \frac{(\log(x)-\mu)^2}{\sigma^2}\right)^{-\kappa}$$

from Leitner et al. 2009b

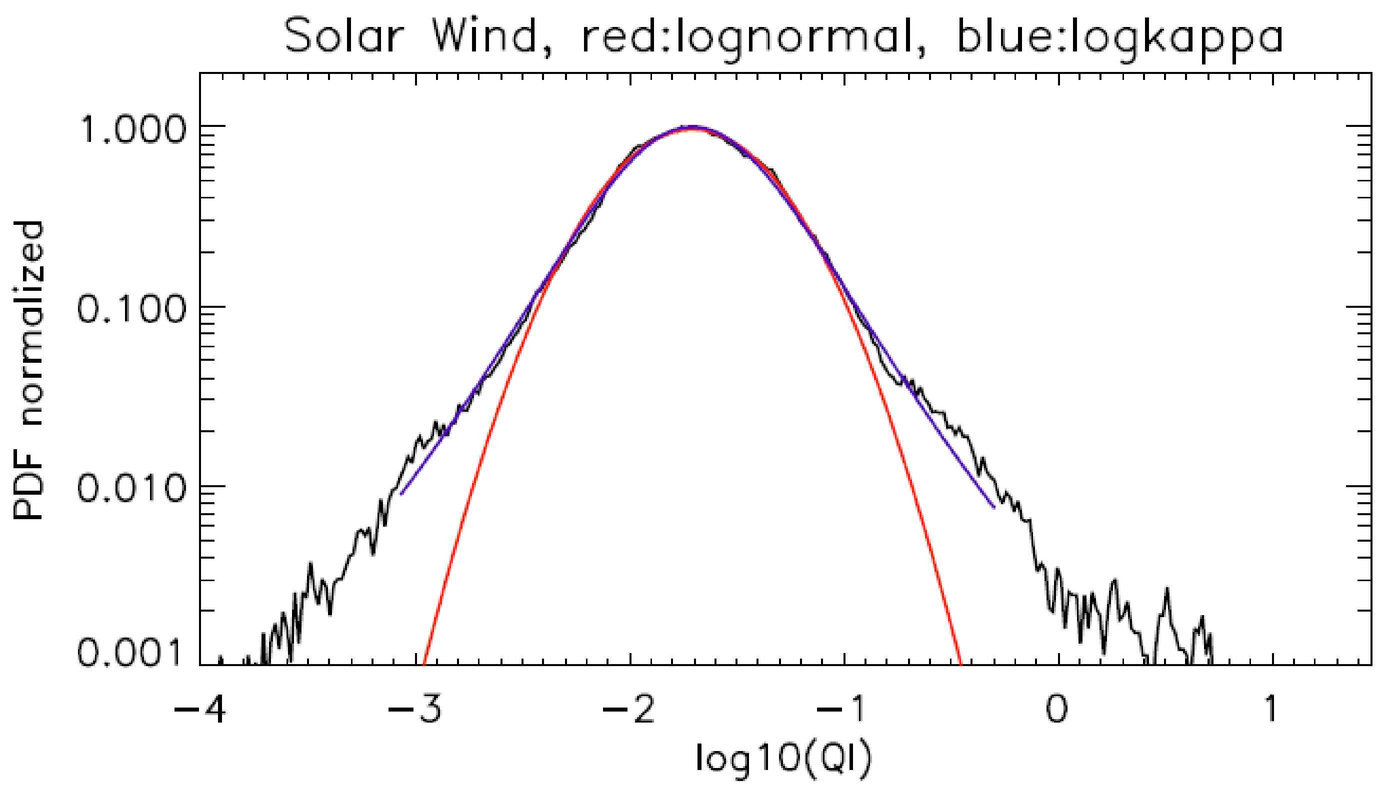


Figure abobe: Distribution of QI for the year 2012 observed by STEREO B

Log-kappa distribution:

• non Gaussian statistics
• presence of independet multiplicatice processes and nonextensice processes
• kappa distributions comprising the effects of nonlocality and long-range interactions
• multiplicative standard variation
• approbriate describtion of the PDF tails

Change of solar wind quasi-invariant in solar-cycle 23

QI is linked very closely to the activity cycle. This behaviour is shown in the plots left and below, where QI distributions for each year are compared with each other. Distributions close to the solar maximm are in red and orange colors, distributions during solar minimum are in blue colors.

Figures and captions from Leitner et al., 2011.

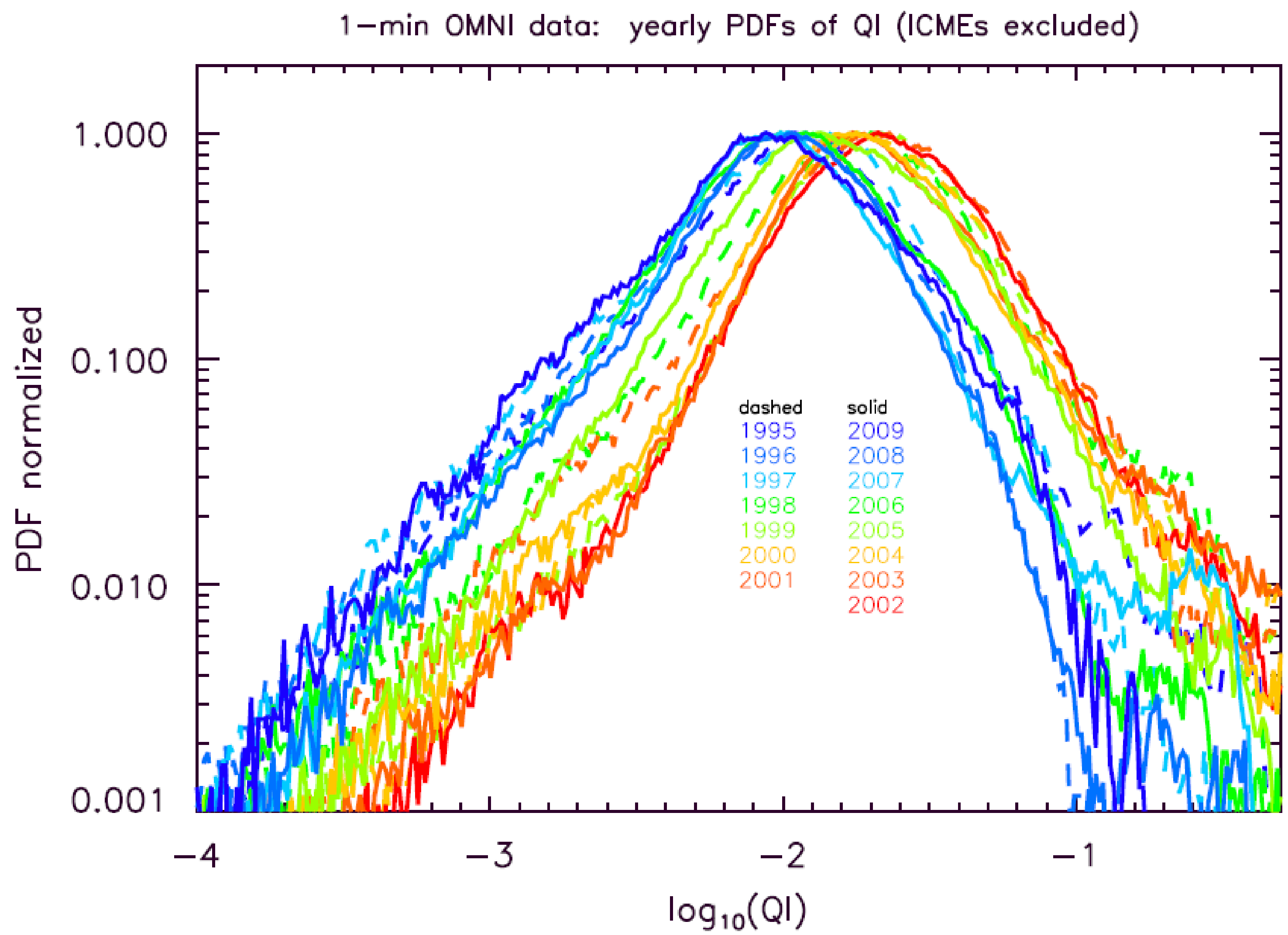


Fig. 2. Yearly PDFs for QI, where ICMEs are excluded from the data. The color coding is symmetrical to 2002, a year during solar maximum. Years during solar minimum are colored in blue, maximum years are shown by red and orange colors.

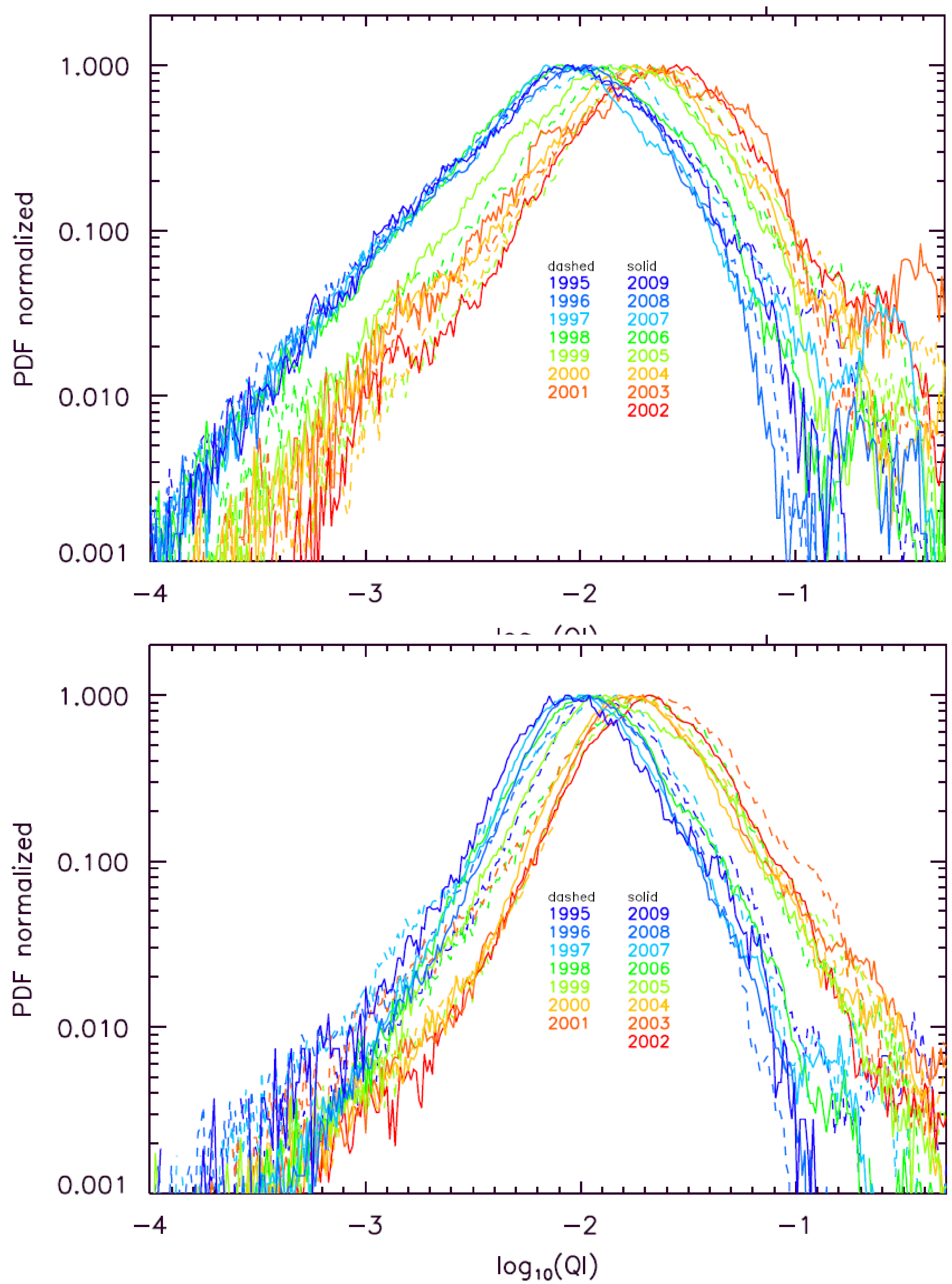


Fig. 3. The top panel gives the PDFs for the slow solar wind component, $v_p < 400\,\mathrm{km\,s^{-1}}$, and bottom panel for the fast solar wind, $v_p > 400\,\mathrm{km\,s^{-1}}$. The color coding is symmetrical to 2002, a year during solar maximum. Years during solar minimum are colored in blue, maximum years are shown by red and orange colors.

Comparision between STEREO and OMNI

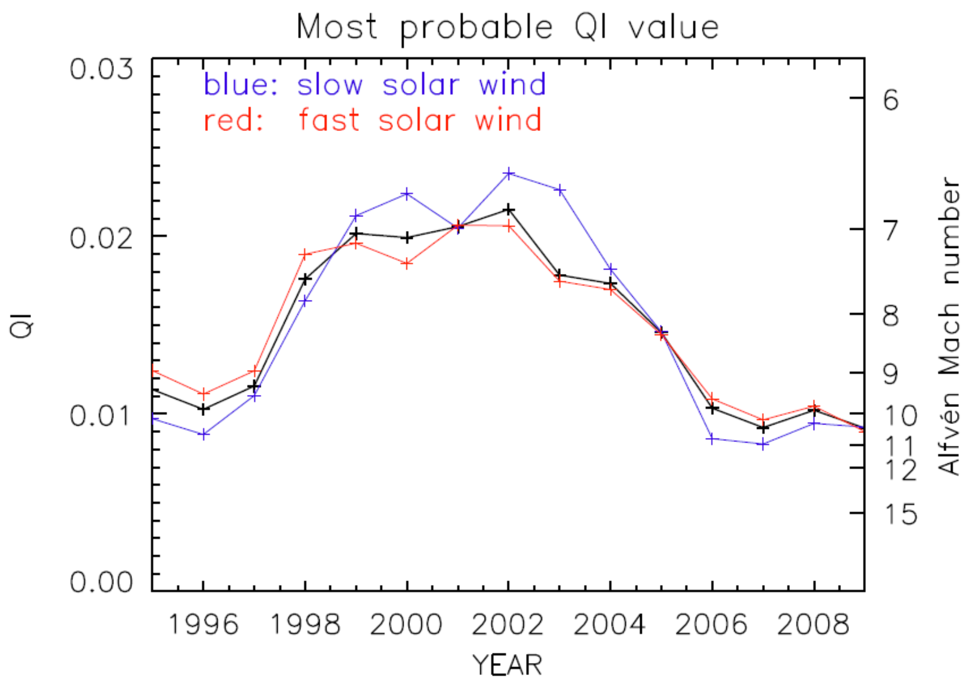
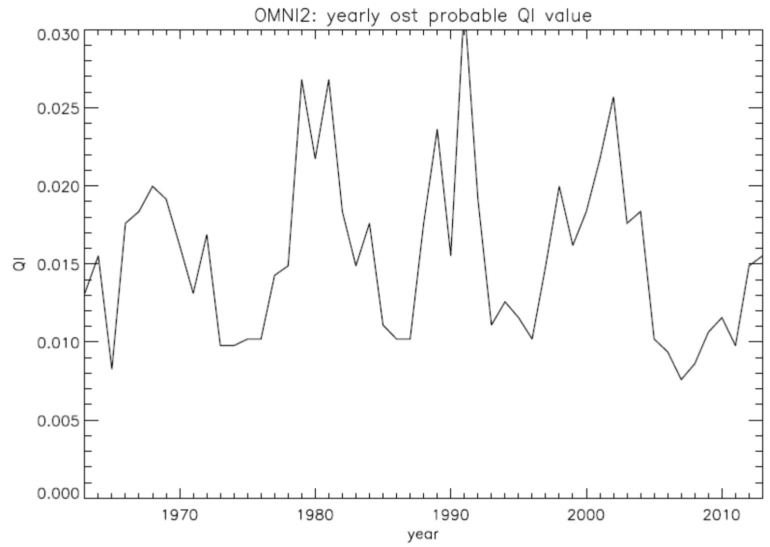
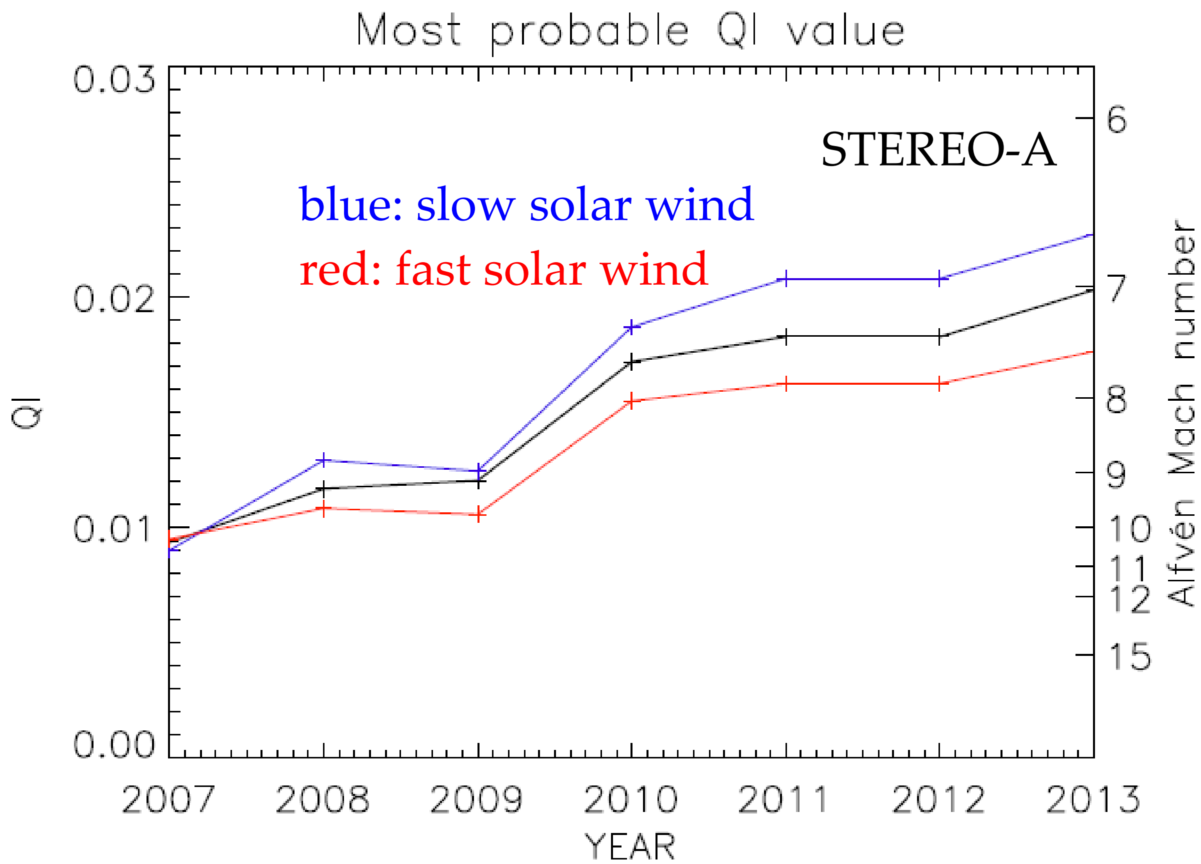
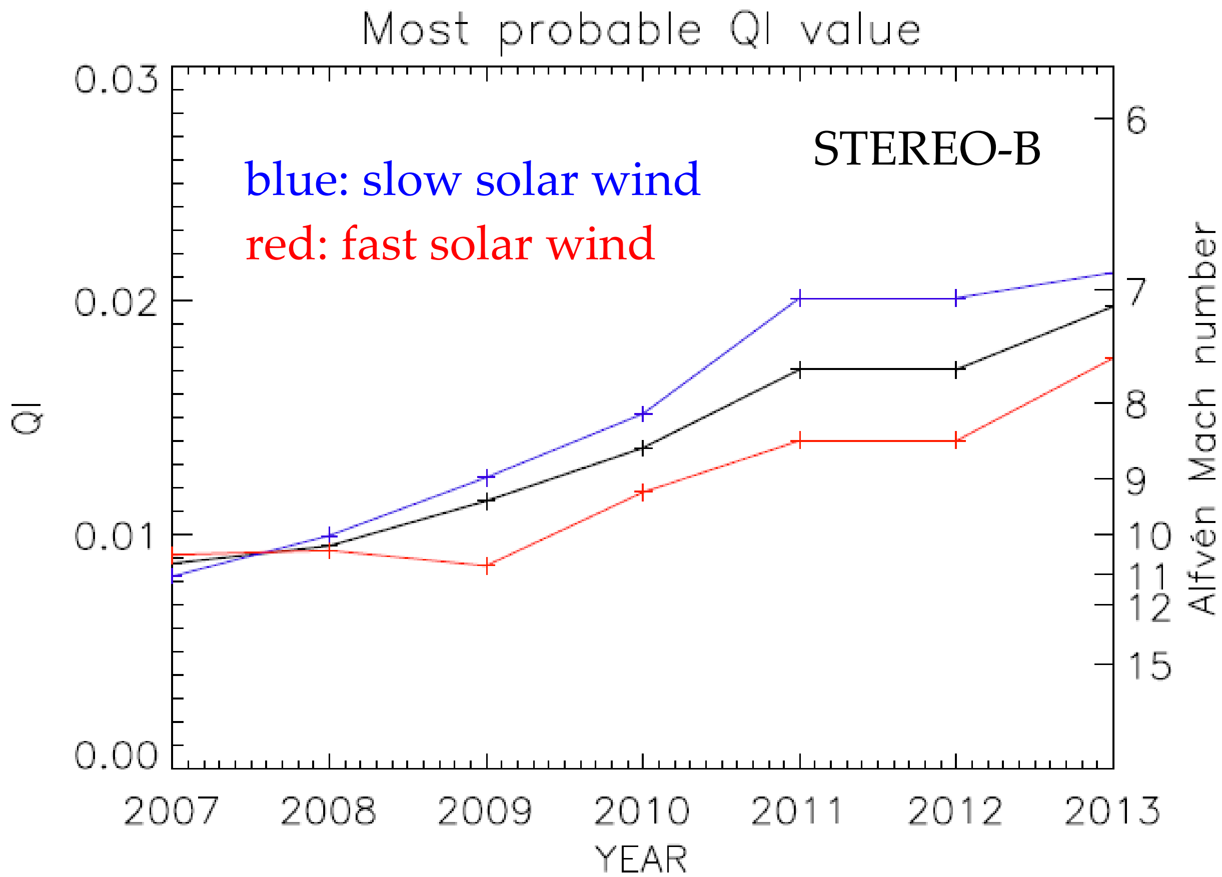


Figure left from Leitner et al., 2011. Yearly mean QI values using OMNI dataset. We distinguish between fast and slow solar winds, where we choose 400 km/s as a demarcation value between the two streams. Interplanetary coronal mass ejections (ICMEs) are excluded from the dataset. Figure right shows yearly most probable QI values (fast and slow solar wind, ICMEs) for the whole OMNI dataset.

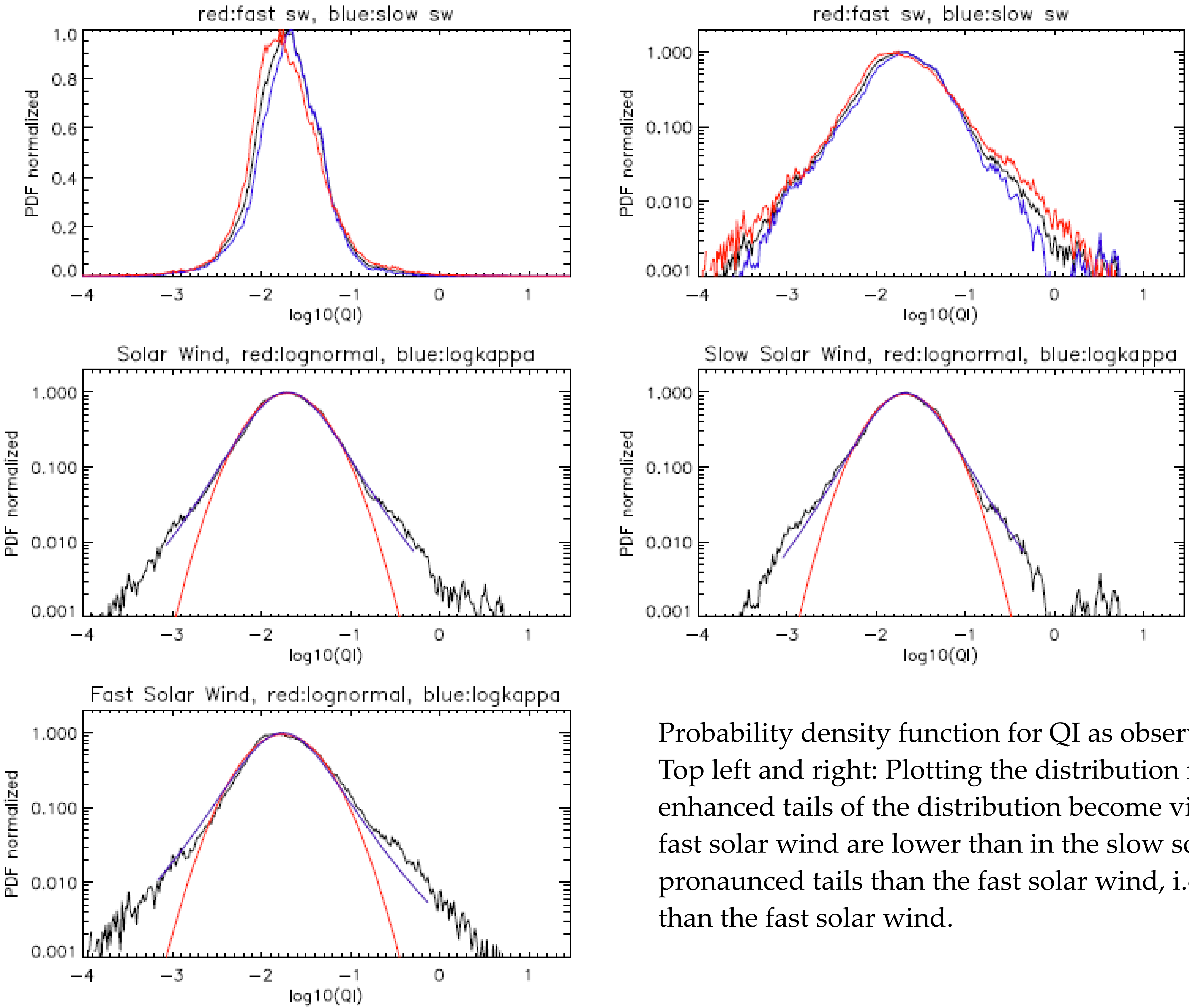






Figures above: Most probable QI values for STEREO-B and STEREO-B. Slow and fast solar wind were determined using 400 km/s as demarcation line. ICMEs are not excluded.

Probability density functions for the solar wind quasi invariant: STEREO-B 2012



Probability density function for QI as observed by STERO-B in the year 2012. Top left and right: Plotting the distribution in a log-log scale the nature of the enhanced tails of the distribution become visible. Most probable QI values in the fast solar wind are lower than in the slow solar wind. The slow solar wind has less pronaunced tails than the fast solar wind, i.e. closer to the Gaussian distribution than the fast solar wind.

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