

# Variability in the Solar Wind Parameters Over A Solar Cycle, And Their Ground Signatures

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**Abstract.** We have examined the burst lifetime distribution functions of various solar wind parameters for 1998 and 2003 and compared them with the same for contemporaneous *SYM-H*. The analysis yields clear power-law exponents of the lifetime probability distributions. The power laws are consistently observed for different activity thresholds showing that these features are robust and repeatable, although scaling can vary depending on solar cycle.

**Keywords:** Burst lifetime, solar wind, magnetosphere, fractal.

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## INTRODUCTION

Magnetospheric indices such as *AE* (auroral electrojet) are helpful tools to elucidate statistical and other properties of the solar wind-magnetosphere interaction [Uritsky and Pudovkin, 1998; Consolini and De Michelis, 1998; Freeman et al., 2000; Uritsky et al., 2001b]. Freeman et al. [2000] examined the *AE* indices to test for evidence that the magnetosphere is a self-organized critical (SOC) system. Since a component of the *AE* indices is strongly related to the solar wind driving function  $VB_s$  [Bargatze et al., 1985], where  $V$  is the solar wind speed and  $B_s$  is the rectified southward interplanetary magnetic field (IMF) component, they considered the possibility that the solar wind, rather than the magnetosphere, was the source of the scale-free properties. They found that the scale-free properties of the index closely followed the behavior in the solar wind, namely the  $\varepsilon$ -parameter, related to solar wind power, and defined in detail in the next section. This showed that the scale-free properties of *AE* might originate in the solar wind. Uritsky et al. [2001b] established that the activity bursts in *AE* and solar wind fluctuations have different dynamical critical scaling features and therefore asserted that the solar wind cannot be responsible for the critical behavior of the magnetosphere on timescales shorter than 3.5 hours.

Because they are constructed from multiple magnetometer stations spanning  $360^\circ$  in longitude, *AE* indices can be considered global geomagnetic activity

indicators. However, they represent rather localized effects in that all the component stations are in or near the auroral oval. The ionospheric current systems whose magnetic perturbations they measure are almost exclusively at high-latitudes, so *AE* indices provide limited information about the behavior at low- and mid-latitudes, regions that map to the ring current, near-earth plasma sheet and other neighborhoods in the magnetosphere with relatively dense plasma. Another index provides information related to those regions; *SYM-H* is a global geomagnetic index which uses data from different low- and mid-latitude ground-based magnetometer stations spanning the longitudes across the globe and thus is not strongly influenced by auroral current systems. It measures the horizontal magnetic field fluctuation near the geomagnetic equator and differs from the better known *DST* index primarily by its cadence of one-minute rather than one hour, and by slightly different convolution of the station data; the two indices are interchangeable in an operational sense [Wanliss and Showalter, 2006]. In this paper we therefore consider *SYM-H* equivalent to *DST*.

Space storm studies frequently utilize *DST* (*SYM-H*) because it, at least in part, reflects variations in the intensity of the symmetric part of the ring current that circles Earth at altitudes ranging from about 3 to 8 Earth radii ( $R_E$ ). Magnetic perturbations from the ring current reduce the strength of the magnetic field at the Earth's surface and *SYM-H* is usually thought of as a proxy measure of the strength of a space storm

[Dessler and Parker, 1959; Schopke, 1966]. Scale-free fractal and multifractal properties of *SYM-H* have recently been elucidated [Wanliss, 2004, 2005; Wanliss et al., 2005]. Wanliss and Weygand [2007] examined the scale-free burst lifetime distributions of *SYM-H* and compare them to the distributions from contemporaneous solar wind observations. They found evidence that statistics of low-latitude magnetospheric fluctuations are relatively independent of solar wind fluctuation statistics. In this paper we examine the burst lifetime distributions of a greater number of solar wind variables, and compare these to the ground based *SYM-H*.

## BURST LIFETIME DISTRIBUTIONS

In a physical system the time interval between two “events” is called a waiting-time, for instance, the time between avalanches. Various definitions could be used, for example the time interval between event triggering [Wheatland, 2000], the time interval between maxima in intensity [Choe et al., 2002], the time interval from the end of a burst and the start of the next one [Sánchez et al., 2002], or the time interval when intensity fluctuations are above a given intensity [Freeman et al., 2000]. We will label these respectively as the waiting-times, the interpeak, quiet, and burst lifetimes. If there is a lack of a characteristic time scale the probability densities vary with power law relations

$$P(\tau) \sim \tau^{-\gamma}$$

where  $\gamma$  is the scaling constant, and  $\tau$  is the time length during which fluctuations follow one of the above time scale definitions. In this paper we consider the *burst lifetimes* with constant thresholds as defined by Freeman et al. [2000]. A constant threshold may be used since if the system producing the signal is in a SOC state the gradient of the power-law *portion* of the burst lifetime distribution will be independent of the threshold level [Paczuski et al., 2005]. To properly evaluate the scaling exponent we must adopt an apt condition for the size  $\Delta_i$  of the *i*th bin. Since we expect the burst lifetime distribution to be an inverse power law, bins of equal size will result in those corresponding to large times to collect only a small amount of data, resulting in an unbalanced weight and unreliable calculation of the power law exponent. For this reason  $P(\tau)$  was calculated by adopting bin sizes that are equal in logarithm space. That is,  $\ln(\tau_i) - \ln(\tau_{i-1})$  is constant, where  $\tau_i$  and  $\tau_{i-1}$  are the centers of consecutive bins. The size of the *i*th bin,  $\Delta_i = \tau_i - \tau_{i-1}$ ,

will compensate for the decrease in the density of the data. The probability density for each bin is given by

$$P(\tau_i) = n_i / N\Delta_i$$

where  $n_i$  is the number of data points in the *i*th bin, and  $N$  is the total number of lifetimes computed from the original signal  $X(t)$ .

In this paper  $X(t) = \{SYM-H, SYM-H^*, VB_s, \varepsilon, B, \rho\}$ , where  $VB_s$  is defined above and

$$\varepsilon = 2 \times 10^7 \cdot VB^2 \sin^4(\theta/2),$$

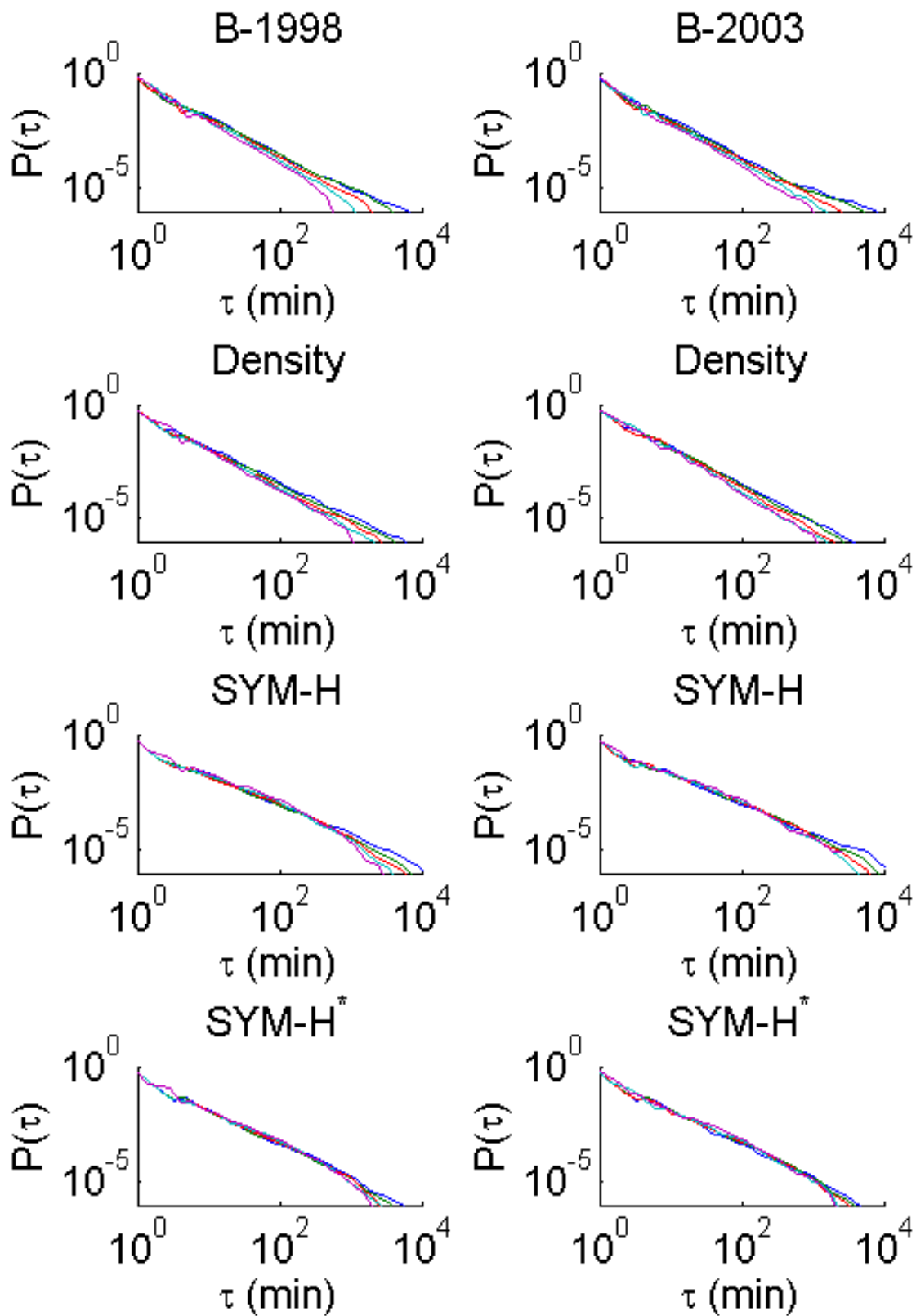
$$B^2 = B_x^2 + B_y^2 + B_z^2,$$

$$\theta = \tan^{-1}(B_y / B_z),$$

with IMF components  $B_x$ ,  $B_y$ , and  $B_z$  in GSM coordinates;  $\varepsilon$  is expressed in Watts when  $V$  is in km/s and  $B$  is in nanoTesla, and plasma density  $\rho$  is in  $m^{-3}$ . Solar wind data were interpolated with 1 minute cadence for comparison with *SYM-H*. A relatively complete record of the solar wind data is available from 1995 onwards. The solar wind records are constructed from available satellite data from solar wind monitors. The key parameter database from the GEOTAIL, WIND, and ACE spacecraft was used to construct this time series on a month-by-month basis. The key parameter database for the above satellites was consulted, and when there was more than one satellite sampling the solar wind, data from the satellite was selected that had the fewest gaps. Here we analyze data for solar minimum (1998) and maximum (2003) The *SYM-H* records are from the World Data Center, Japan.

For each dataset a set of thresholds was compiled that corresponded to the 10, 25, 50, 75, and 90 percentiles of the cumulative probability distribution of the respective series. As with Freeman et al. [2000] and Wanliss and Weygand [2007], these thresholds were set to test the original assumption that the power law slopes are threshold independent. The shape of the distributions for  $VB_s$ , and  $\varepsilon$ , were essentially the same as found by Wanliss and Weygand [2007]. However the slopes are different. Figure 1 shows the associated distributions for total magnetic field  $B$ , density, *SYM-H*, and the pressure corrected  $SYM-H^* = SYM-H - b(P_{dyn})^{1/2} + c$ , where  $b = 7.26 \text{ nT}/(\text{nPa})^{1/2}$  and  $c = 11 \text{ nT}$ . The latter correction takes into account effects of the magnetopause currents.

The *SYM-H* burst lifetimes have a power law region that extends to greater than three orders of magnitude, from the smallest timescales to above 1000 minutes, for all percentiles. The power law begins to



**FIGURE 1.** Waiting time distributions, from top to bottom of total magnetic field  $B$ , number density,  $SYM-H$ , and  $SYM-H^*$ . The left column shows results for solar minimum (1998), and the right column for solar maximum (2003). The percentiles are color coded.

break at large lifetimes, suggestive of an exponential roll off.

We fitted the distribution function with a model comprising the product of an inverse power law with an exponential cutoff, viz.

$$P(\tau) = \frac{A}{\tau^\gamma} \exp\left(\frac{-\tau}{T_c}\right).$$

All fitting of the data to models is achieved via a robust Levenberg-Marquardt algorithm [Press *et al.*, 1992].

## DISCUSSION AND CONCLUSIONS

Table 1 summarizes the slopes obtained from the waiting time distributions. The power law exponents for solar wind parameters are essentially similar. Although there is a slight decrease in values from solar minimum to maximum, except for density, results are statistically similar within the error limits. This does not suggest that amplitudes are the same during different solar phases - they are not - but that the statistical fluctuations are similar in scale throughout the cycle. For the *SYM-H* case results are quite different. *SYM-H\** is similar to the solar wind results, except during solar maximum.

**TABLE 1.** Scaling exponents obtained from the 50<sup>th</sup> percentile waiting time distributions.

Parameter	1998	2003
$VB_s$	1.63±0.07	1.56±0.06
$\epsilon$	1.75±0.07	1.65±0.07
B	1.73±0.07	1.65±0.07
Density	1.65±0.06	1.73±0.07
<i>SYM-H</i>	1.39±0.06	1.31±0.05
<i>SYM-H*</i>	1.70±0.06	1.52±0.06

Our major conclusion is that during solar maximum it appears that the scaling properties of low-latitude magnetosphere, whose output is recorded by *SYM-H*, is not purely a direct response to the scale-free properties of the solar wind but is due to inherent properties of the inner magnetosphere. The result, for *SYM-H* are the same as for the work by Wanliss and Weygand [2007], which used three years data around the same solar minimum and maximum. However, the results from the solar wind are considerably different.

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