Long-Term Datasets for the Understanding of Solar and Stellar Magnetic Cycles
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A study on the variations in long-range dependence of solar energetic particles during different solar cycles

Vipindas V., Sumesh Gopinath and Girish T. E.

Department of Physics, University College, Thiruvananthapuram - 695034, Kerala, India
emails: vpndasv@gmail.com, sumeshgopinath@gmail.com, tegirish5@yahoo.com

Abstract. Solar Energetic Particles (SEPs) are high-energy particles ejected by the Sun which consist of protons, electrons and heavy ions having energies in the range of a few tens of keVs to several GeVs. The statistical features of the solar energetic particles (SEPs) during different periods of solar cycles are highly variable. In the present study we try to quantify the long-range dependence (or long-memory) of the solar energetic particles during different periods of solar cycle (SC) 23 and 24. For stochastic processes, long-range dependence or self-similarity is usually quantified by the Hurst exponent. We compare the Hurst exponent of SEP proton fluxes having energies (>1MeV to >100 MeV) for different periods, which include both solar maximum and minimum years, in order to find whether SC-dependent self-similarity exist for SEP flux.

Keywords. Solar energetic particles, solar proton flux

1. Introduction

Solar energetic particles are high-energy particles that originate either from a solar flare site or by shock waves associated with coronal mass ejections (CMEs)(Kahler and Vourlidas 2014). They are of particular importance because they can endanger life in outer/near-Earth space. SEPs can be accelerated to energies of several tens of MeV within 5-10 solar radii and can reach Earth in a few hours. This makes prediction of SEP events quite challenging. The effect of high-energy particle flux is having severe implications for the lifetime of the satellites as well as the performance of instruments onboard spacecraft (Ryan *et al.* 2000, Vipindas *et al.* 2016).

2. Data and Method

For the present analysis, 5-minute GOES-10 solar particle (proton) fluxes having energies (>1MeV to >100 MeV for the years 2000, 2001, 2007 and 2008 have been taken from GOES Space Environment Monitor archive of World Data Center for Solar and Terrestrial Physics, Boulder, operated by NOAA/NCEI.

Detrended fluctuation analysis (DFA) could accurately estimate Hurst exponent in the presence of (extrinsic) non-stationaries while eliminating spurious detection of long-range dependence (Bryce & Sprague 2012). In the present work we use novel robust detrended fluctuation analysis (r-DFA) for the computation of the scaling (Hurst) exponent at 95% confidence limits. The method generally calculates the slope of the root mean square of the average fluctuation function versus the scale (segment length/box size) for different polynomial orders in a robust way. For details of r-DFA, the readers are directed to the article of Habib *et al.* (2017). For the present analysis, we take first order r-DFA for all SEP data during solar maximum and minimum years.

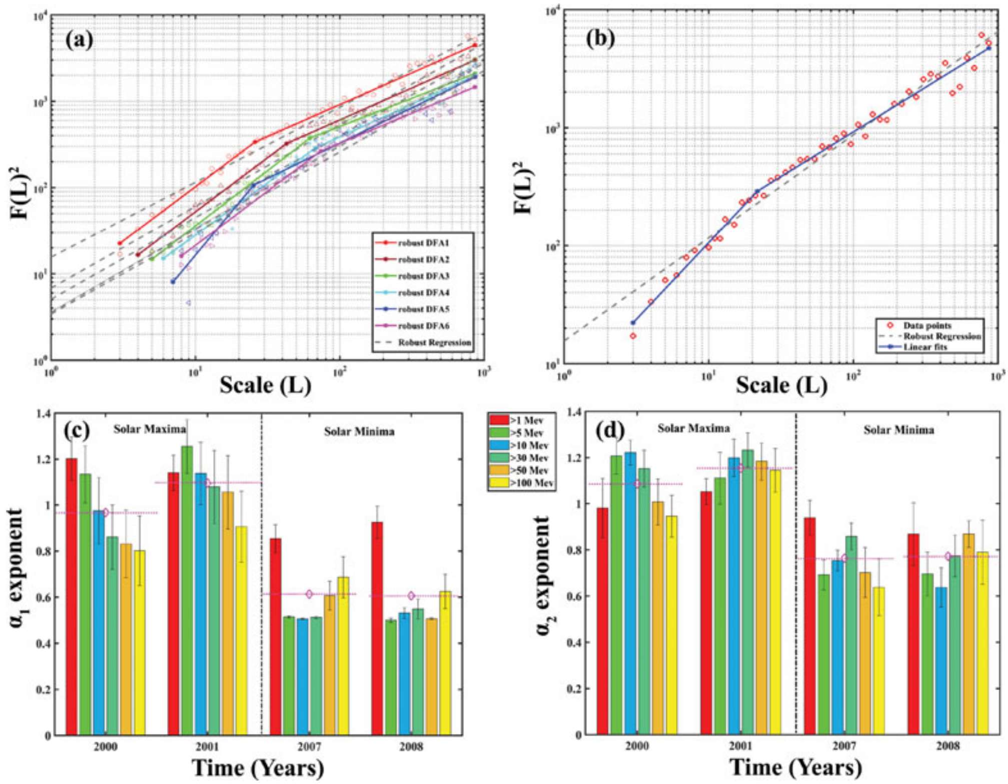

Figure 1. (a) The r-DFA of SEP Proton flux >1 MeV for the month of January, 2000 (b) First order r-DFA for the same data (c) The bar plot showing the α_1 exponent & (d) The bar plot showing the α_2 exponent. The horizontal dots show the average over all fluxes for an year. The vertical dashes are partitioning the bargraph into solar maximum & minimum periods.

3. Results and Conclusion

The figure 1(a) shows the r-DFA of SEP Proton flux >1 MeV for the month of January, 2000. The crossovers are evident between scales 20-80 which shows the fractal behavior of SEPs. Figure 1(b) shows first order r-DFA for the same data. Although not shown, higher DFA orders also yield similar results. From Figs. 1(c) & 1(d) it is clearly evident that the average values of α exponents during solar maximum are higher than that during solar minimum for all energy ranges of SEPs. This in turn shows that there exists a higher persistency or self-similarity during solar maximum while persistency reduces during solar minimum for all energy ranges of SEPs. It is also clear that SEP flux at different energy levels show dissimilar persistency values. The new r-DFA technique can be considered as a promising technique for the analysis of solar energetic particle flux.

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