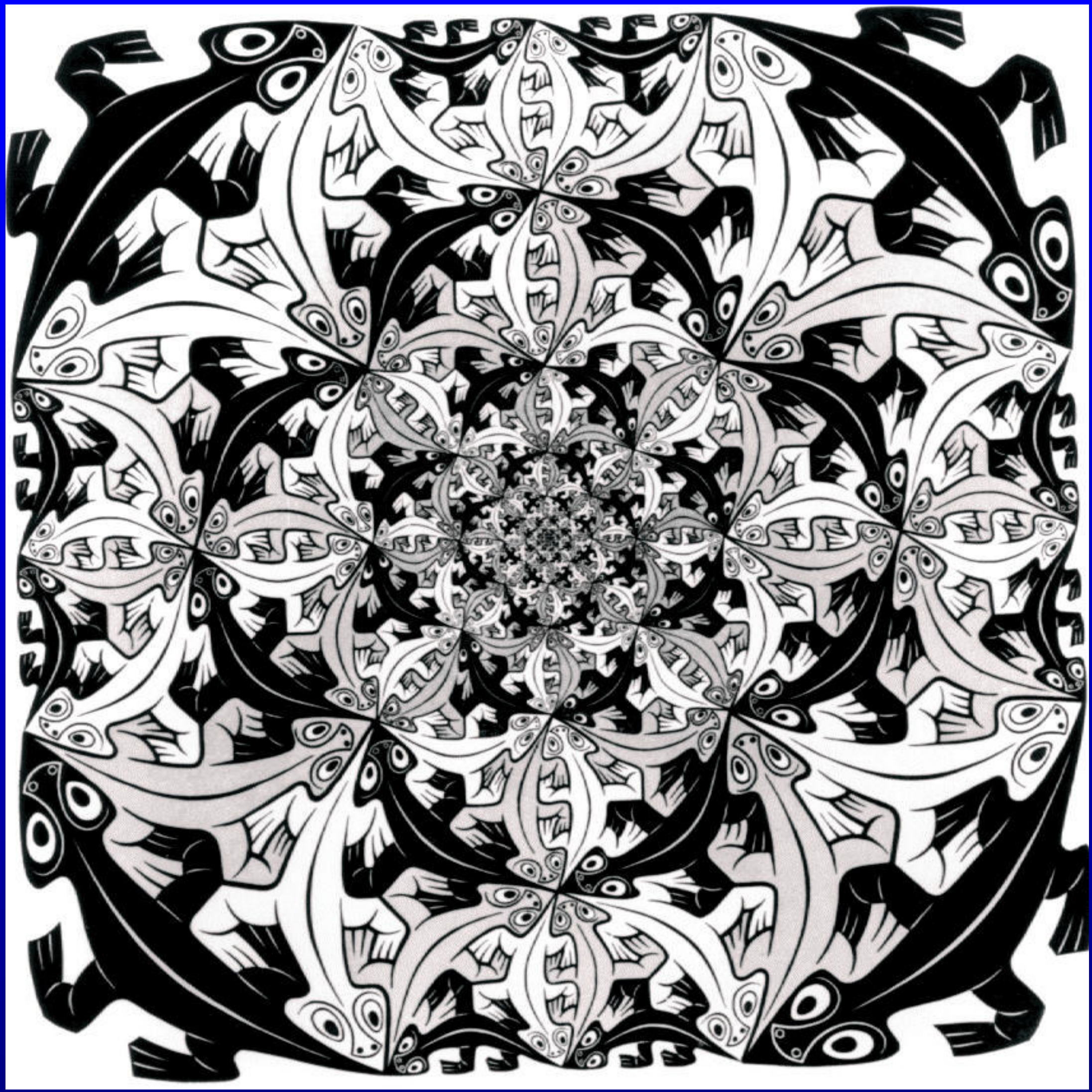
Solar cycle variability in solar wind turbulence, magnetospheric currents, and ionospheric electric fields

Murray L. Parkinson

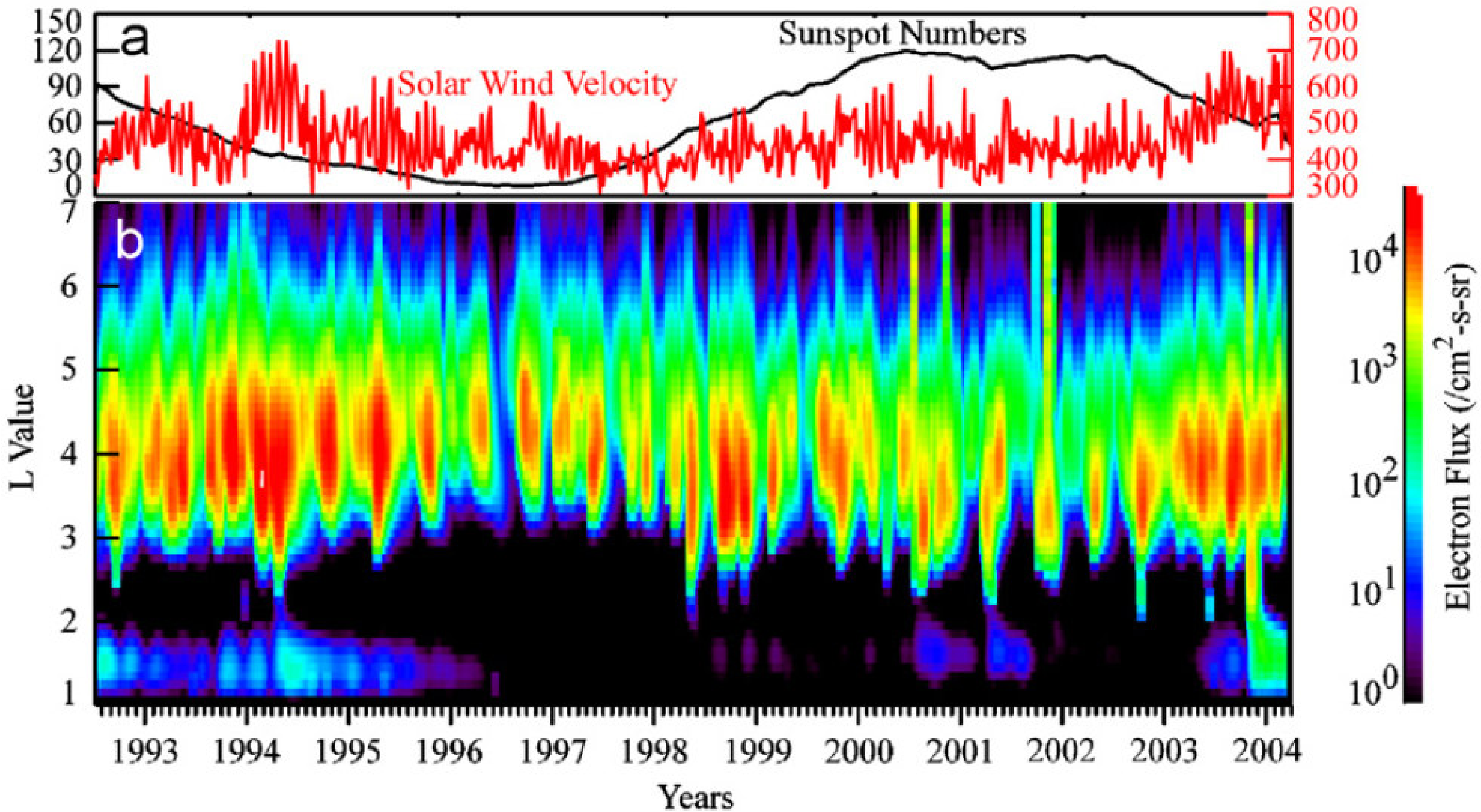
Physics Department, La Trobe University, Melbourne, Victoria, Australia



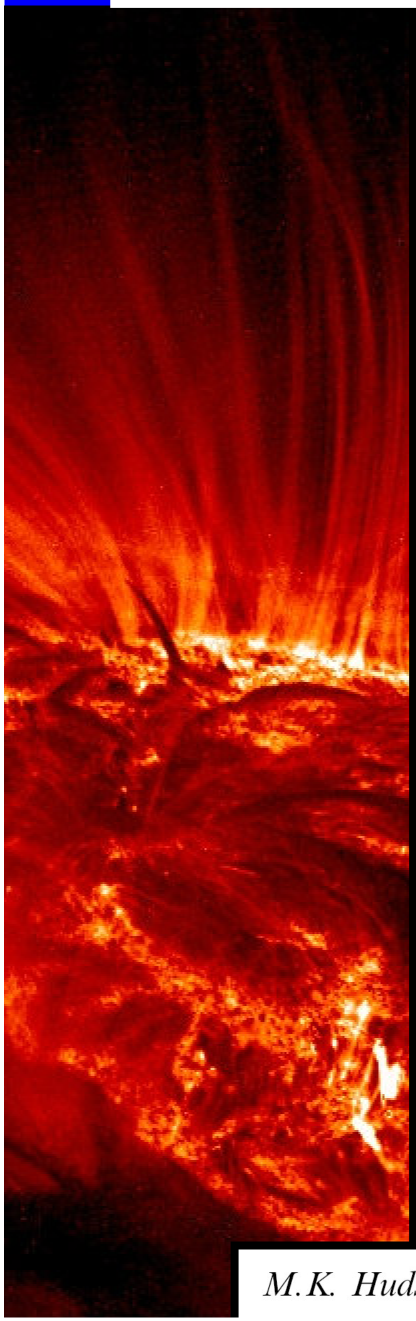
"Smaller and Smaller", **M. C. Escher, 1956**

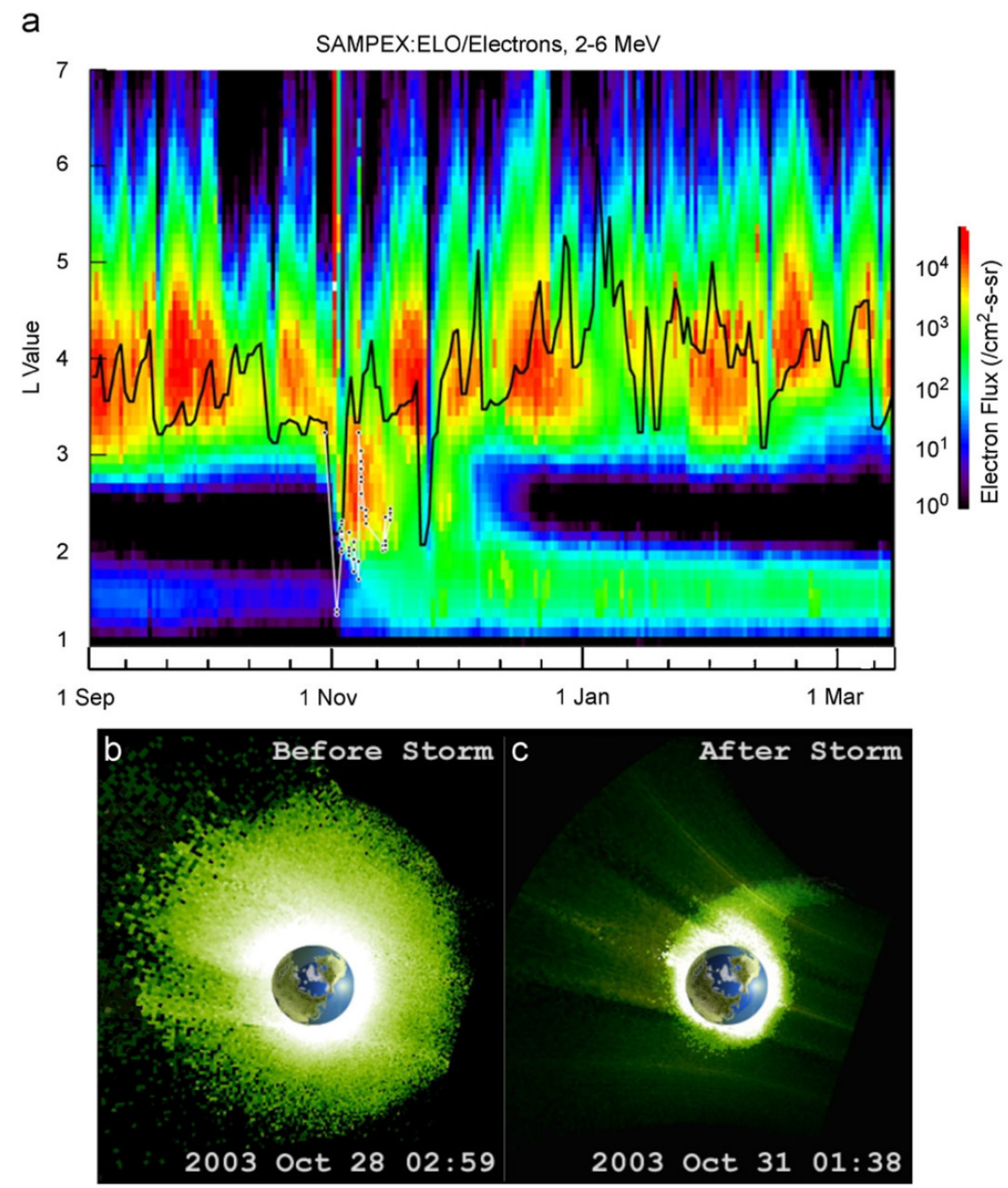
The Van Allen Radiation Belts: Recent Reviews

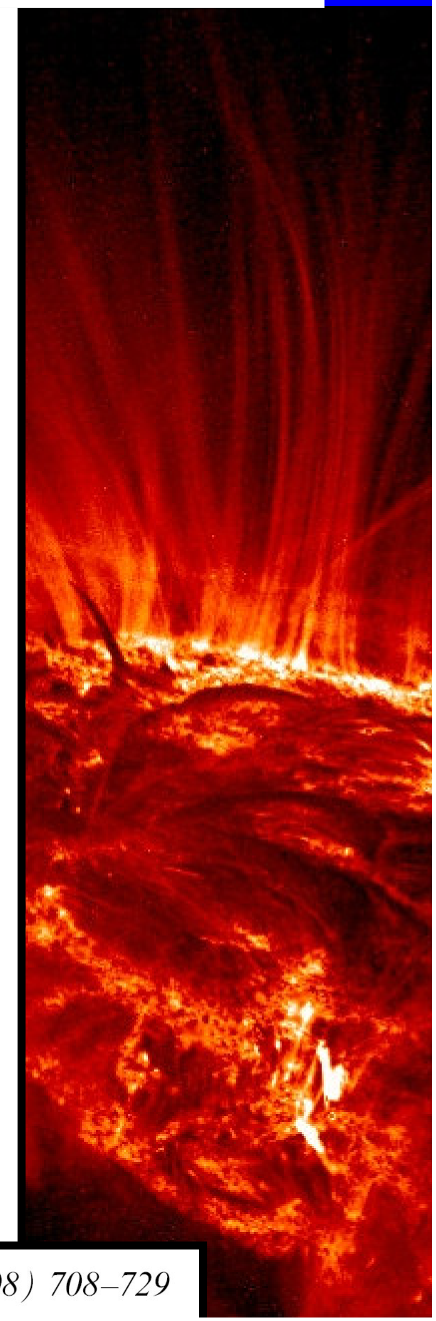
D.N. Baker, S.G. Kanekal / Journal of Atmospheric and Solar-Terrestrial Physics 70 (2008) 195–206



The Van Allen Radiation Belts: Recent Reviews







M.K. Hudson et al. / Journal of Atmospheric and Solar-Terrestrial Physics 70 (2008) 708–729

Solar wind, magnetosphere, and ionosphere data sets, 1990 to 2007

" SOLAR WIND "

- OMNI 1-min solar wind data at the Earth's bow shock nose. ACE, Wind, IMP-8, and Geotail interspersed data, 1995–2007. (Joe King & Natalia Papitashvili GSFC/SPDF). http://omniweb.gsfc.nasa.gov/html/HROdocum.html

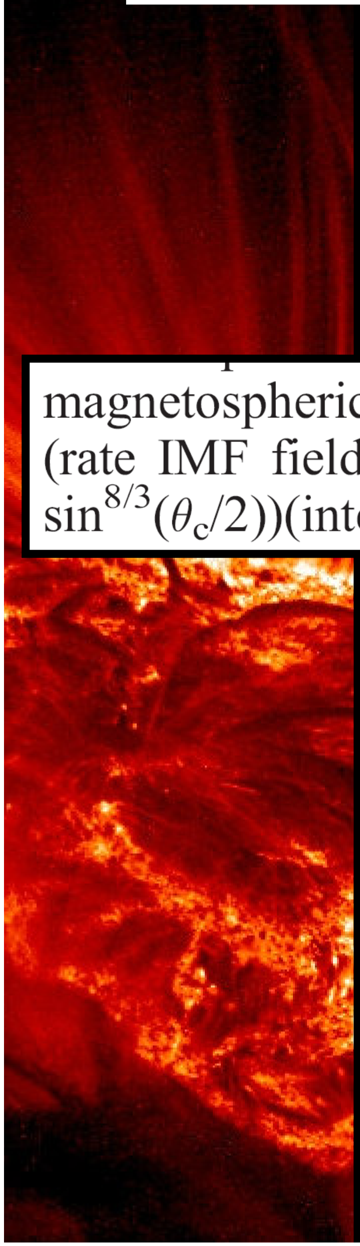
" MAGNETOSPHERE "

- Ground-based geomagnetic indices at 1-min resolution from WDC-C2 Kyoto, Japan. AL (substorms; westward electrojet; substorm current wedge, DP1 current), AU (~DP2 day & night side merging), AE (magnetospheric current activity), SYM-H (storms; equatorial ring current activity; 1-min version of Dst), 1990–2007. http://swdcwww.kugi.kyoto-u.ac.jp/index.html

" IONOSPHERE "

- Tasman International Geospace Environment Radar (TIGER) SuperDARN radar measurements of F-region meridional Doppler shift (ionospheric zonal electric field) (Dyson and Devlin, 2000). 1-min/2-min resolution. Tasmania beams 3, 4, and 5 only, 2000–2007. http://www.tiger.latrobe.edu.au/

Solar wind-magnetosphere coupling function: Newell et al. (2007)



JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, A01206, doi:10.1029/2006JA012015, 2007

A nearly universal solar wind-magnetosphere coupling function inferred from 10 magnetospheric state variables

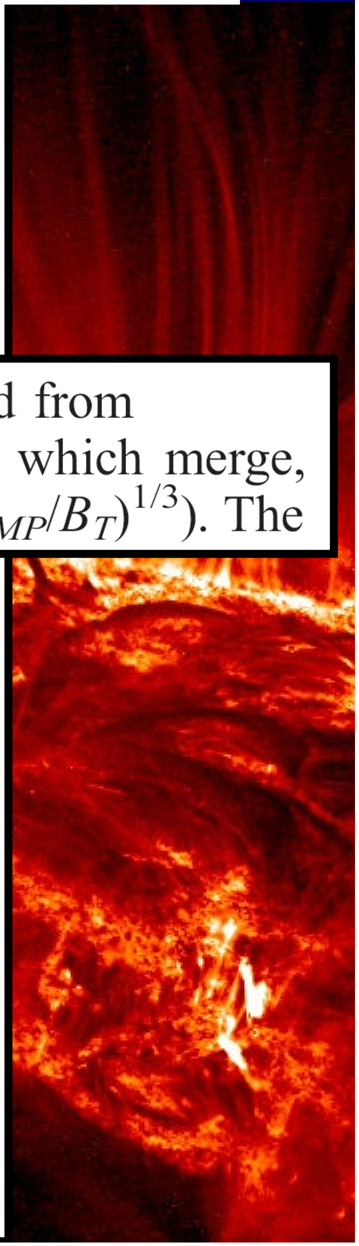
P. T. Newell,[1] T. Sotirelis,[1] K. Liou,[1] C.-I. Meng,[1] and F. J. Rich[2]

Received 10 August 2006; revised 9 October 2006; accepted 25 October 2006; published 12 January 2007.

magnetospheric activity. This is $d\Phi_{MP}/dt = v^{4/3}B_T^{2/3}\sin^{8/3}(\theta_c/2)$, calculated from (rate IMF field lines approach the magnetopause, $\sim v$)(% of IMF lines which merge, $\sin^{8/3}(\theta_c/2)$)(interplanetary field magnitude, B_T)(merging line length, $\sim(B_{MP}/B_T)^{1/3}$). The

20 candidate solar wind coupling functions. One function, representing the rate magnetic flux is opened at the magnetopause, correlated best with 9 out of 10 indices of magnetospheric activity. This is $d\Phi_{MP}/dt = v^{4/3}B_T^{2/3}\sin^{8/3}(\theta_c/2)$, calculated from (rate IMF field lines approach the magnetopause, $\sim v$)(% of IMF lines which merge, $\sin^{8/3}(\theta_c/2)$)(interplanetary field magnitude, B_T)(merging line length, $\sim(B_{MP}/B_T)^{1/3}$). The merging line length is based on flux matching between the solar wind and a dipole field and agrees with a superposed IMF on a vacuum dipole. The IMF clock angle dependence matches the merging rate reported (albeit with limited statistics) at high altitude. The nonlinearities of the magnetospheric response to B_T and v are evident when the mean values of indices are plotted, in scatterplots, and in the superior correlations from $d\Phi_{MP}/dt$. Our results show that a wide variety of magnetospheric phenomena can be predicted with reasonable accuracy ($r > 0.80$ in several cases) ab initio, that is without the time history of the target index, by a single function, estimating the dayside merging rate. Across all state variables studied (including AL, which is hard to predict, and polar cap size, which is hard to measure), $d\Phi_{MP}/dt$ accounts for about 57.2% of the variance, compared to 50.9% for E_{KL} and 48.8% for vBs. All data sets included at least thousands of points over many years, up to two solar cycles, with just two parameter fits, and the correlations are thus robust. The sole index which does not correlate best with $d\Phi_{MP}/dt$ is Dst, which correlates best ($r = 0.87$) with $p^{1/2}d\Phi_{MP}/dt$. If $d\Phi_{MP}/dt$ were credited with this success, its average score would be even higher.

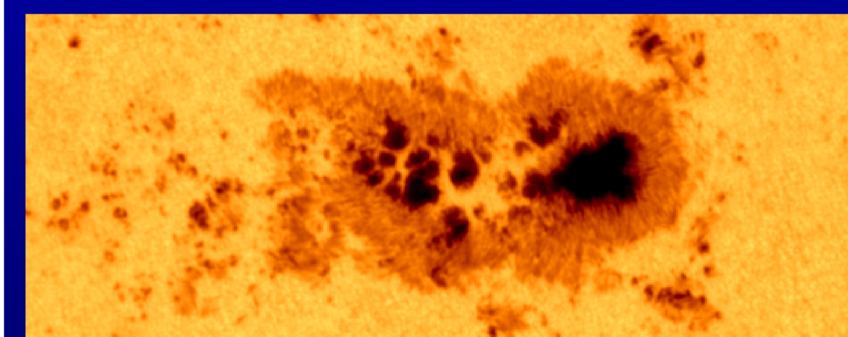
Citation: Newell, P. T., T. Sotirelis, K. Liou, C.-I. Meng, and F. J. Rich (2007), A nearly universal solar wind-magnetosphere coupling function inferred from 10 magnetospheric state variables, *J. Geophys. Res.*, *112*, A01206, doi:10.1029/2006JA012015.



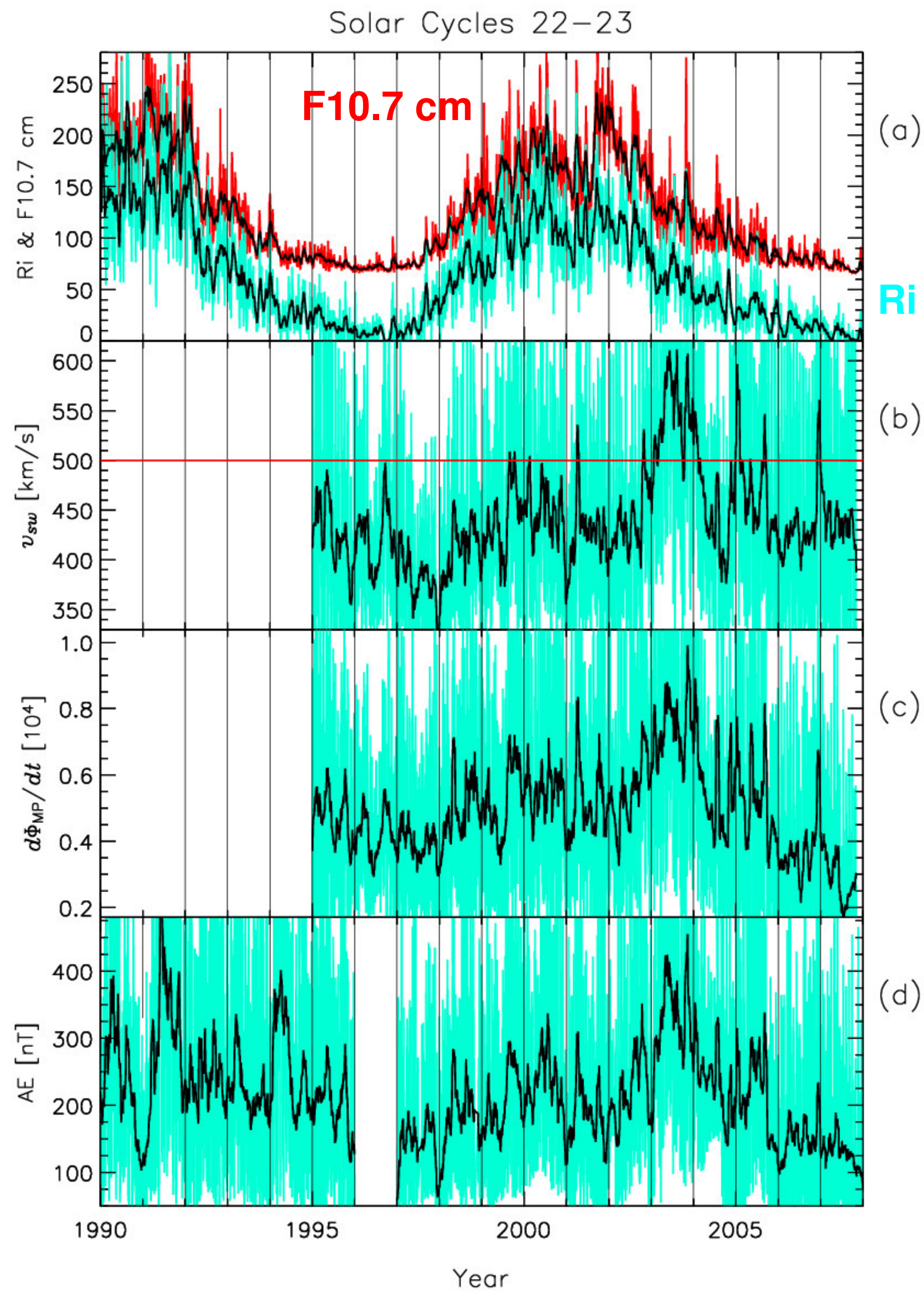
Large-Scale Solar Wind (1 AU) and Geo-magnetic Activity

Time Scales: 1-day (blue) and 27-day (black) running averages

(a) Daily sunspot number and F10.7 cm flux
(b) Solar wind speed
(c) Newell et al. (2007) coupling function
(d) AE index



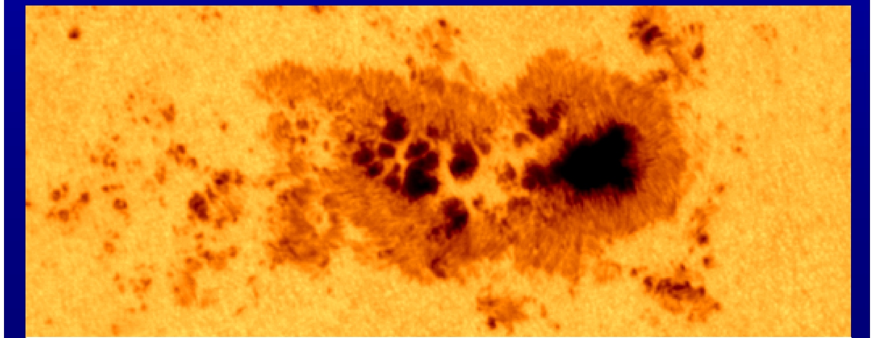
Gigantic Sunspot Group 09:36 UT, 22 September 2000 (SOHO/MDI)



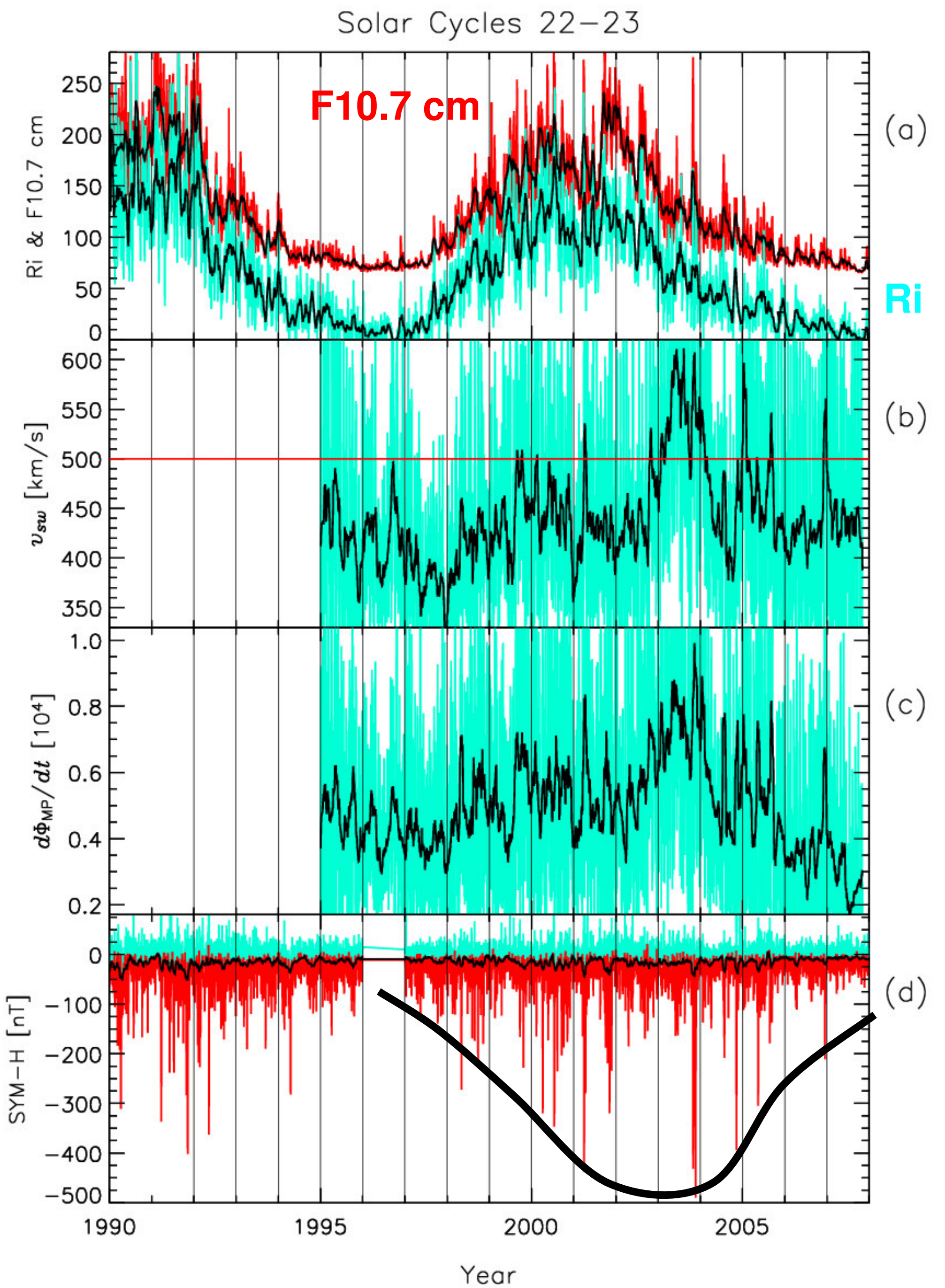
Large-Scale Solar Wind (1 AU) and Geo-magnetic Activity

Time Scales: 1-day (blue) and 27-day (black) running averages

(a) Daily sunspot number and F10.7 cm flux
(b) Solar wind speed
(c) Newell et al. (2007) coupling function
(d) SYM-H, SYM-H index

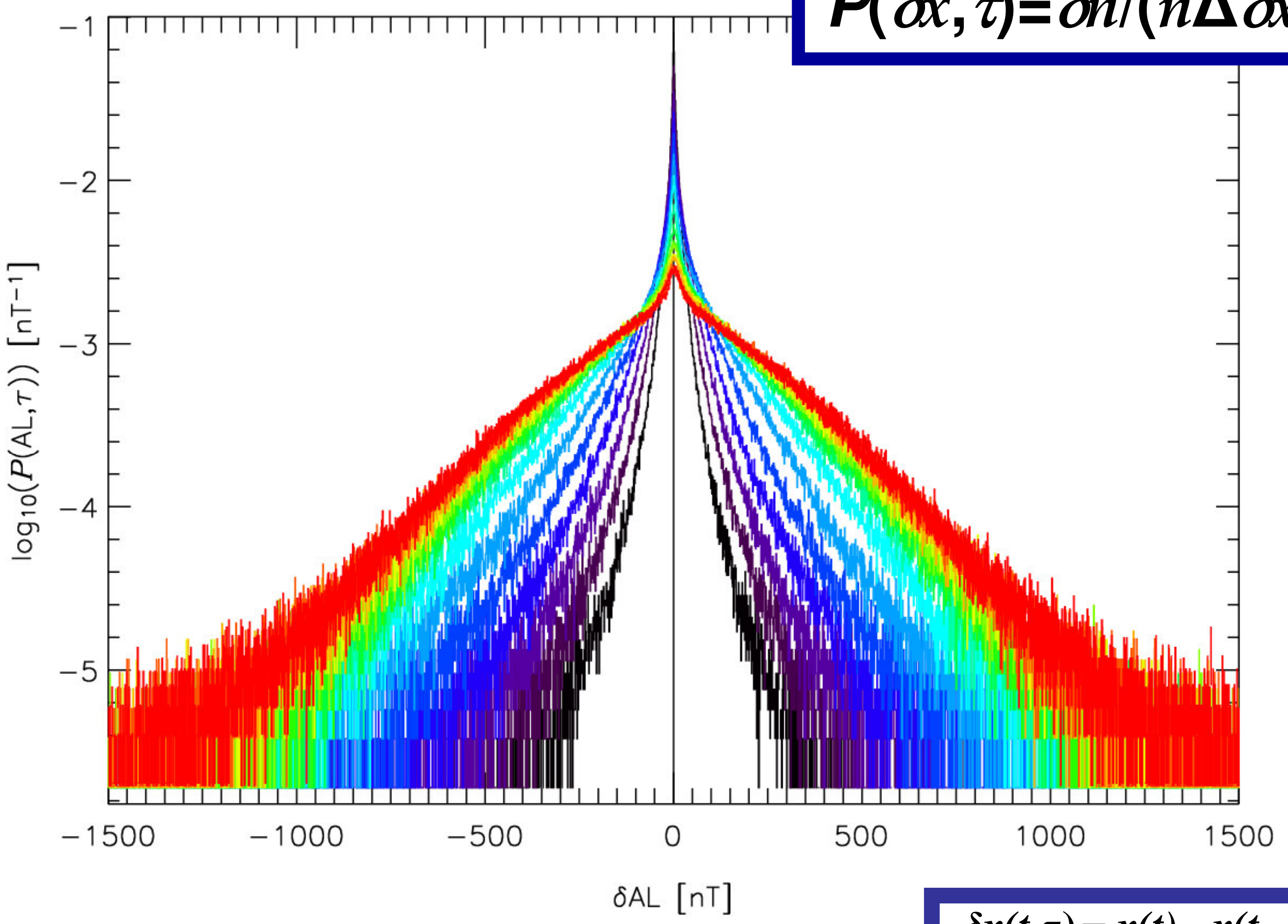


Gigantic Sunspot Group 09:36 UT, 22 September 2000 (SOHO/MDI)



Probability Density Functions of Fluctuations in the AL index for Year 2003 (WDC-C2 Kyoto Data)

$$P(\delta x,\tau)=\delta n/(n\Delta\delta x)$$



$$\delta x(t,\tau)=x(t)-x(t-\tau)$$

τ =1 min (black), 2 min, 4 min to 32,768 min (23 day) (red); 3σ Error Bars

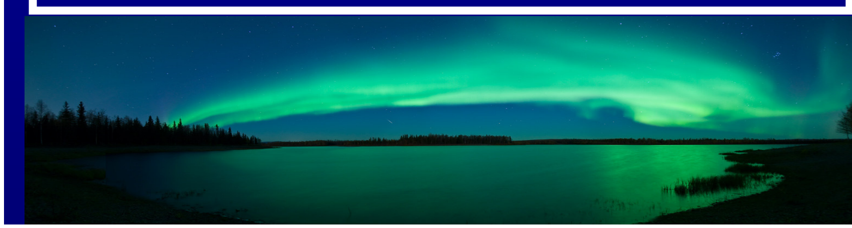
Evolution of Fluctuations in the AL index

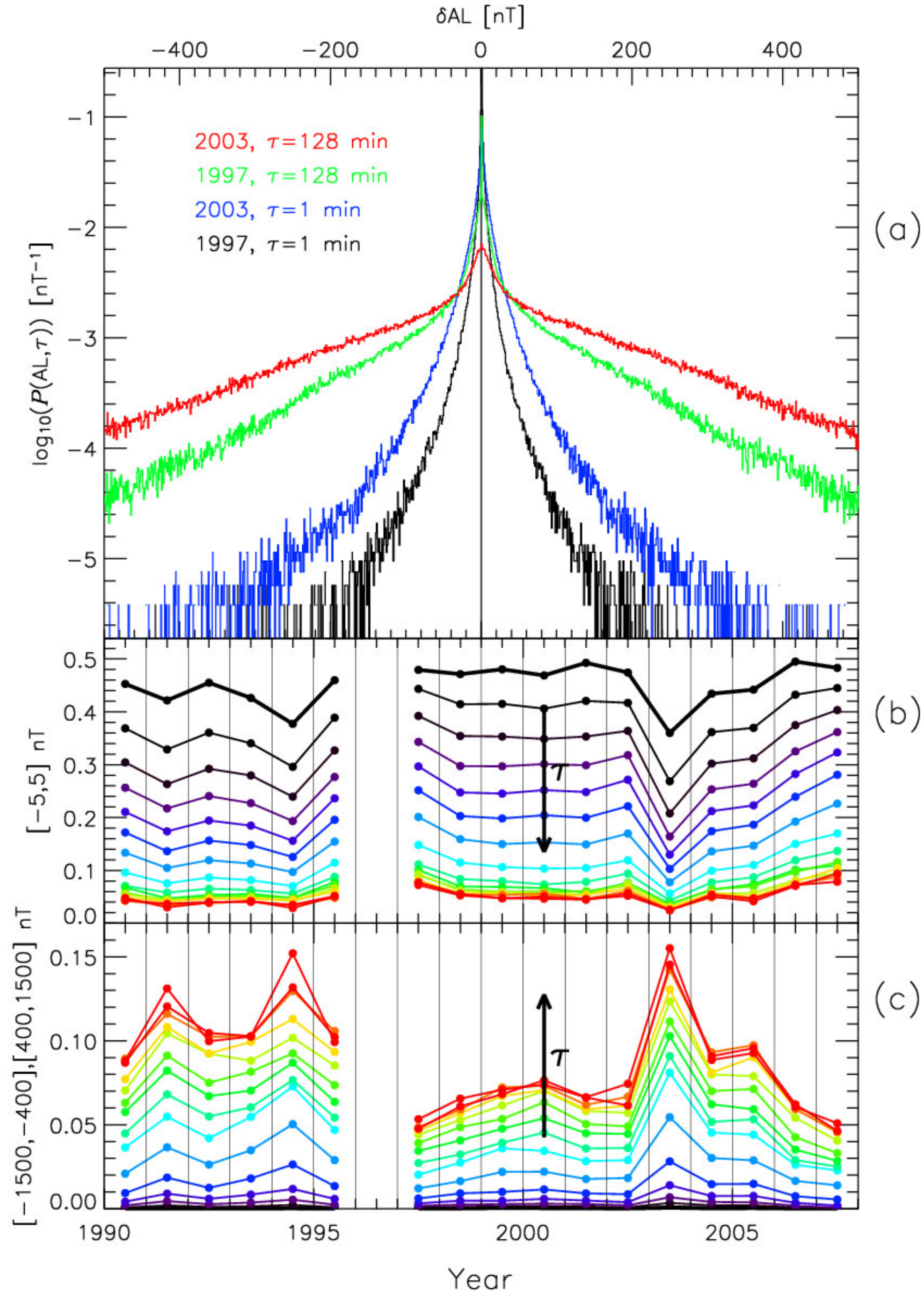
(a) Annual Probability Density Functions (PDFs) of δAL at τ = 1 min & 128 min for 1997 and 2003

(b) Evolution of Probability Density (PD) over the peaks [-5, 5] nT

(c) Evolution of PD over the wings [-1500, -400] & [400, 1500] nT

τ =1 min (black) to 32,768 min (23 day) (red)





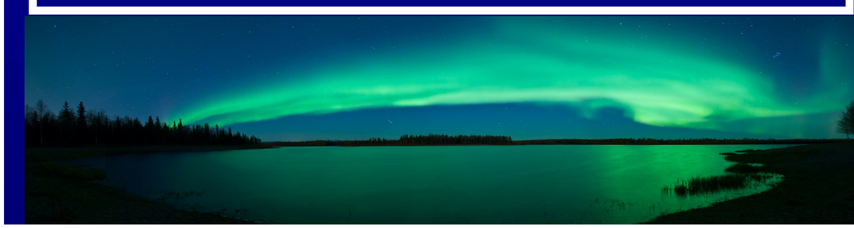
Evolution of Fluctuat-ions in the AU index

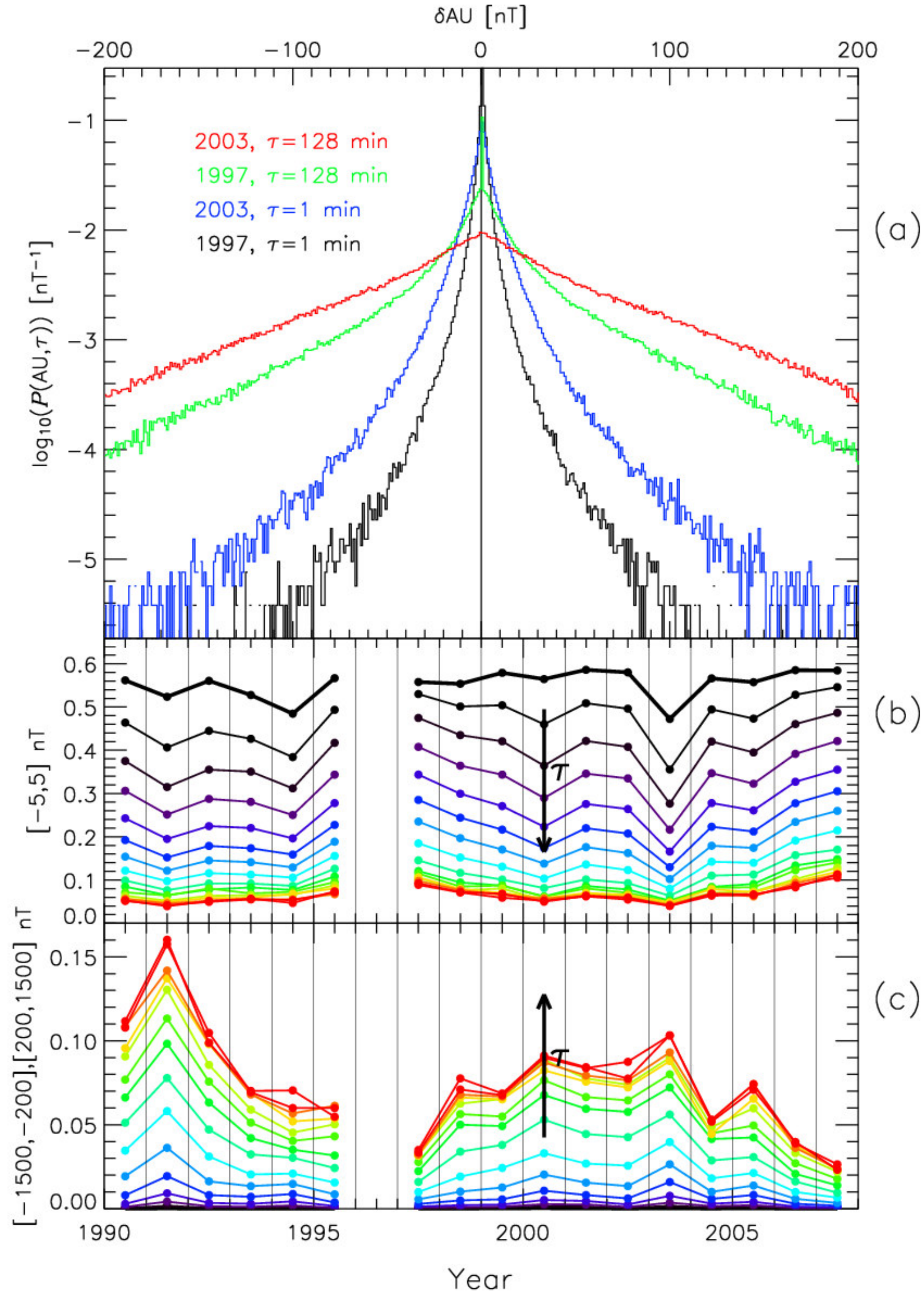
(a) Annual Probability Density Functions (PDFs) of δAU at τ = 1 min & 128 min for 1997 and 2003

(b) Evolution of Probability Density (PD) over the peaks [-5, 5] nT

(c) Evolution of PD over the wings [-1500, -200] & [200, 1500] nT

τ =1 min (black) to 32,768 min (23 day) (red)





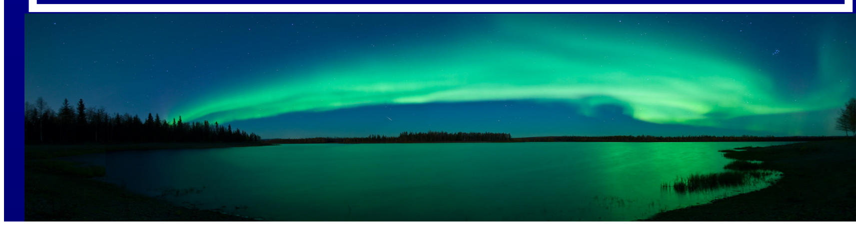
Evolution of Fluctuations in SYM-H index

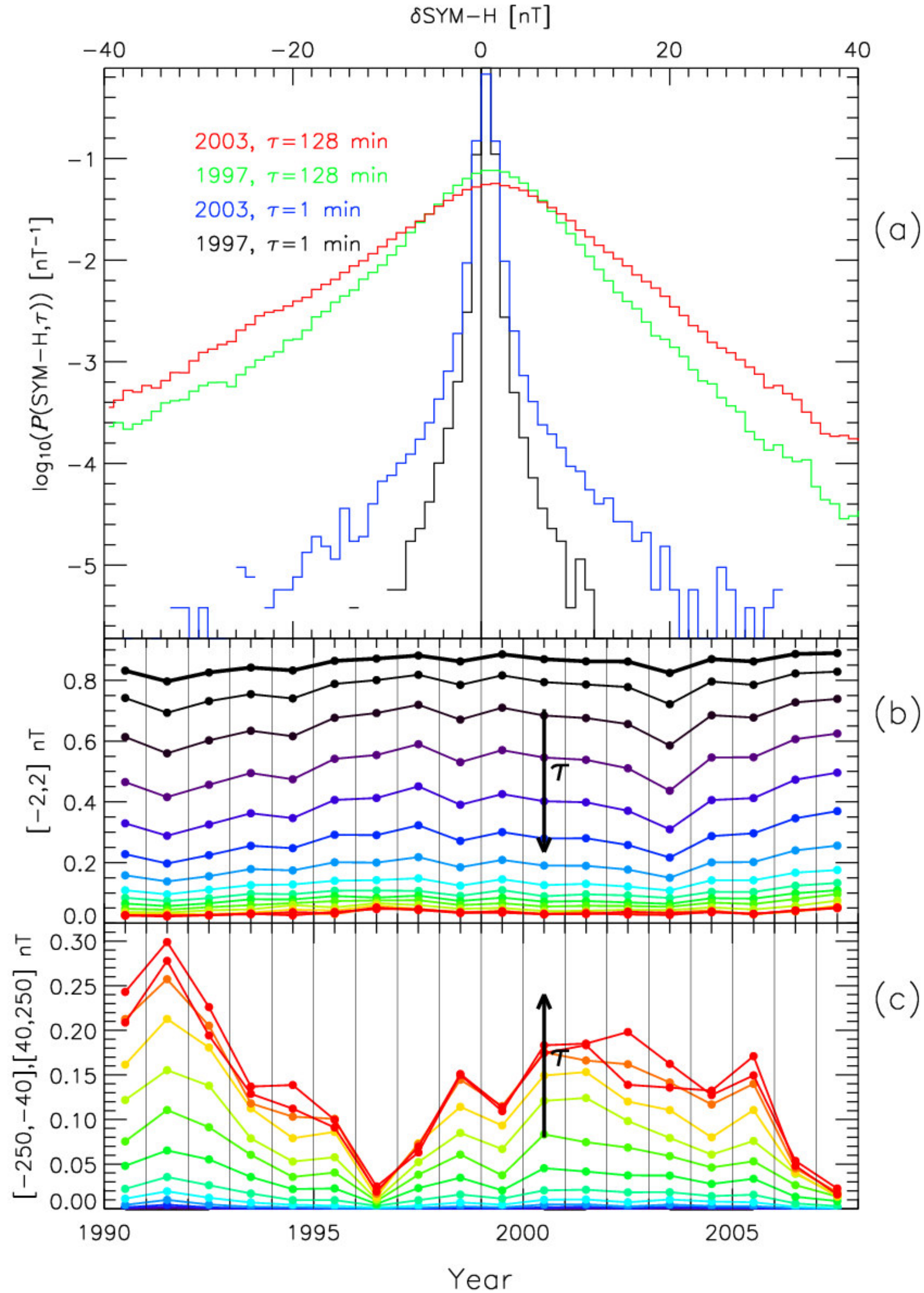
(a) Annual Probability Density Functions (PDFs) of δSYM-H at τ = 1 min & 128 min for 1997 and 2003

(b) Evolution of Probability Density (PD) over the peaks [-2, 2] nT

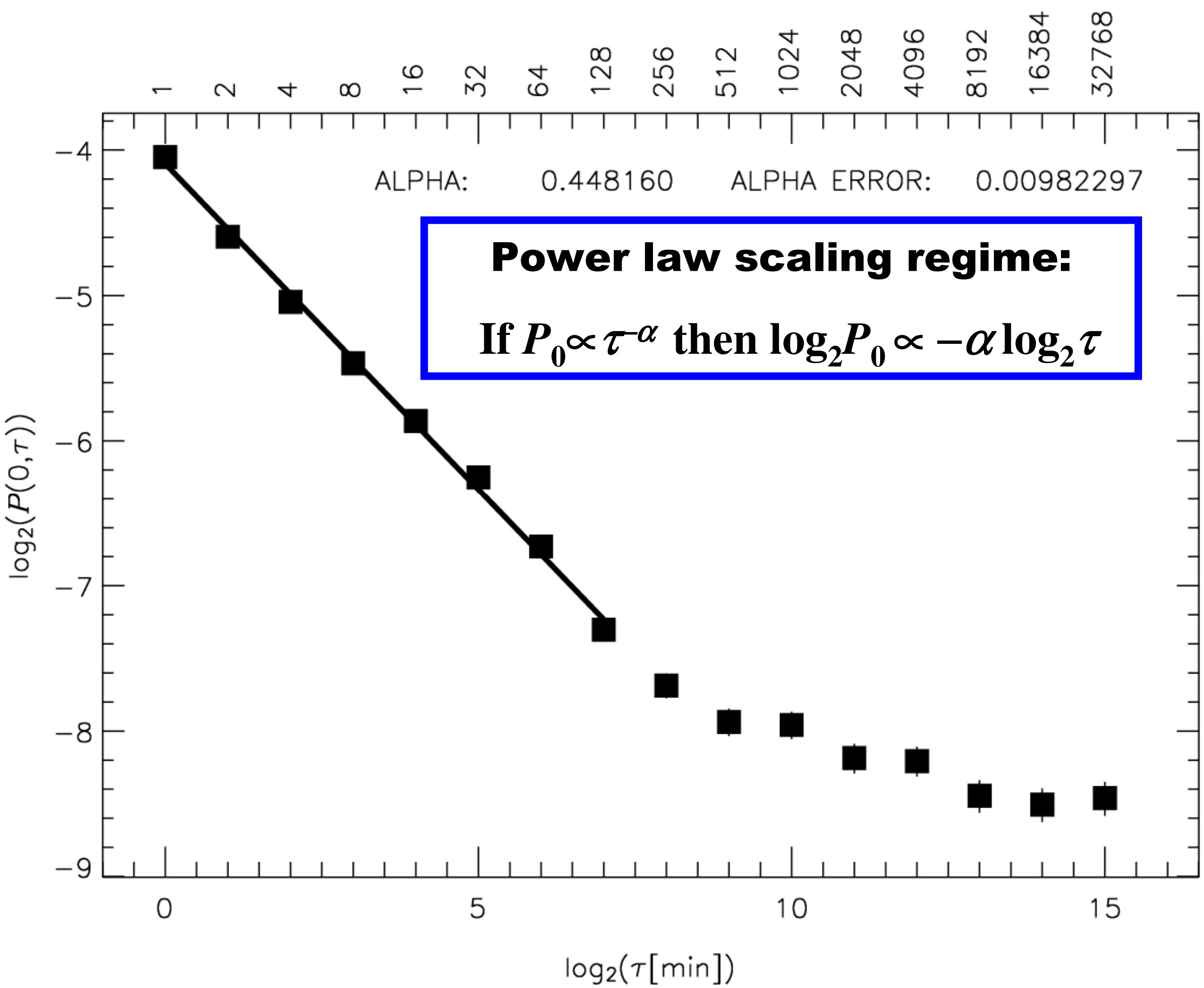
(c) Evolution of PD over the wings [-250, -40] & [40, 250] nT

τ =1 min (black) to 32,768 min (23 day) (red)



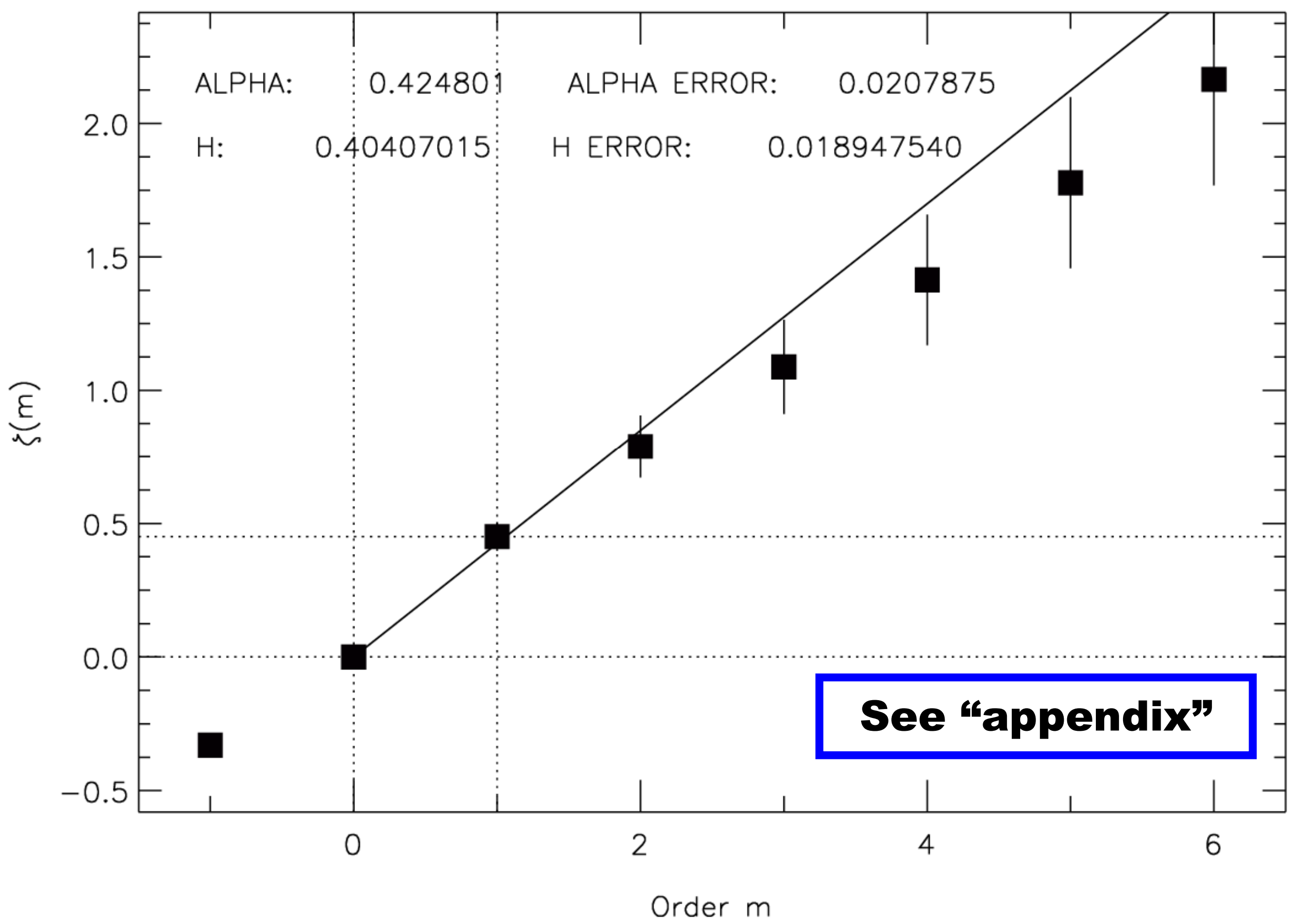


Scaling of the PDF Peaks for Fluctuations in the AL index for Year 2003 (WDC-C2 Kyoto Data)



PDF Bin Size of 1 km s^{-1}; 3σ Error Bars

GSF Analysis of Fluctuations in Solar Wind Speed for Year 2000: ζ Plot

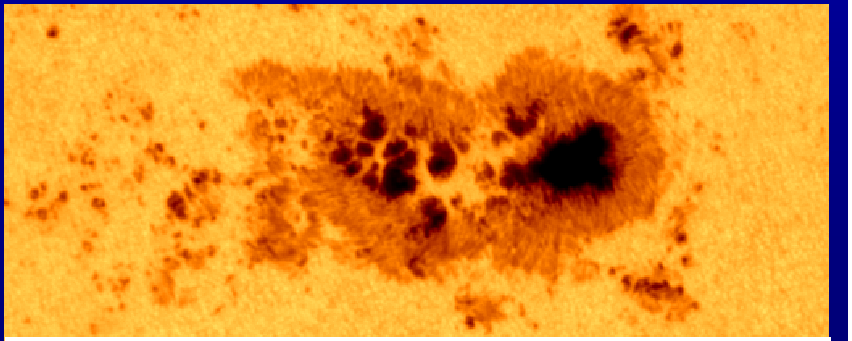


See "appendix"

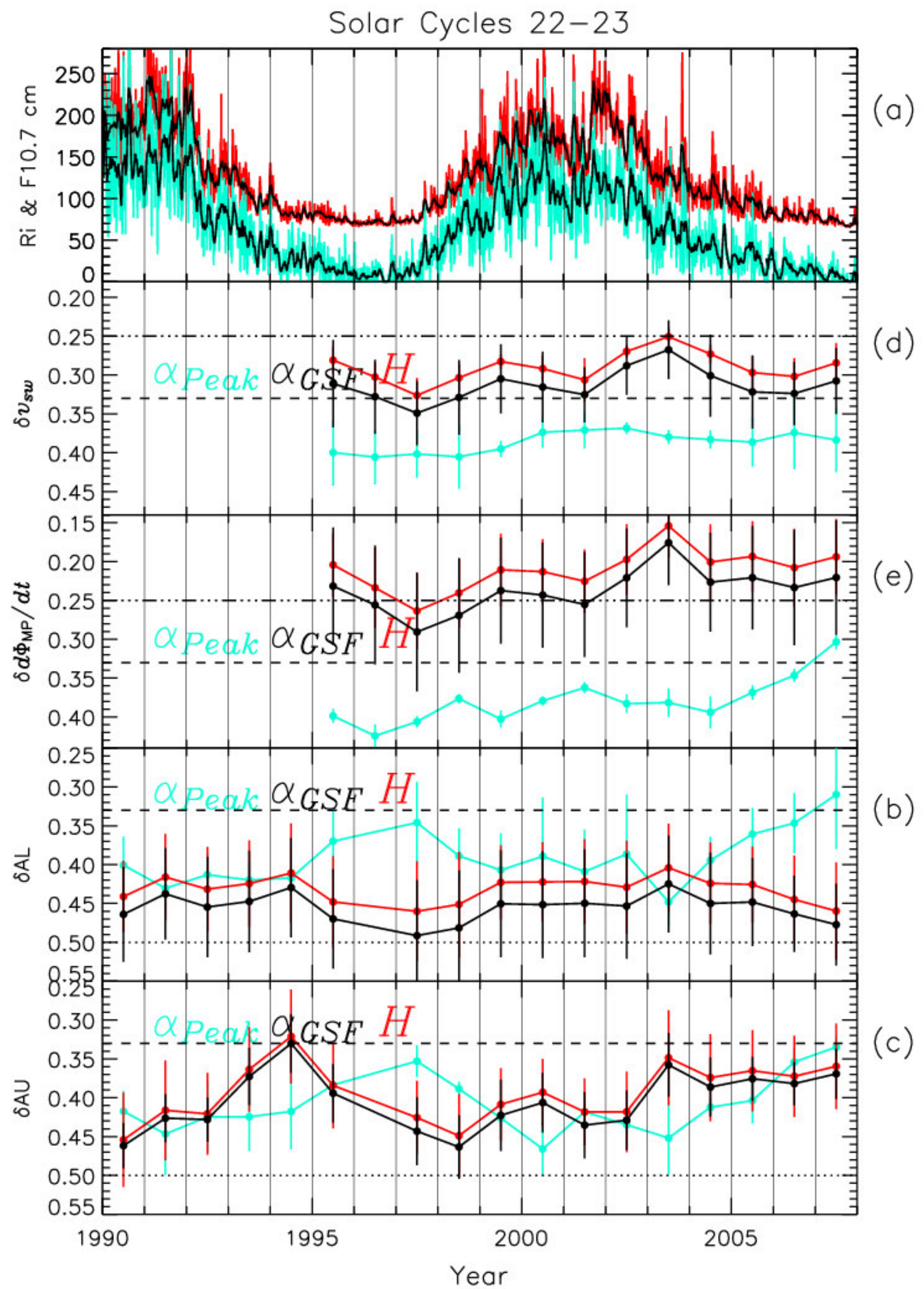
Weighted Least Squares Fits; 3σ Error Bars

Evolution of Annual Scaling Exponents for Geomagnetic Indices, 1990-2007

(a) Daily sunspot number and F10.7 cm flux
(b) Scaling exponents for fluctuations in the AL index
(c) Scaling exponents for fluctuations in the AU index
(d) Scaling exponents for fluctuations in the V_{sw}
(e) Scaling exponents for fluctuations in the $d\Phi_{MP}/dt$

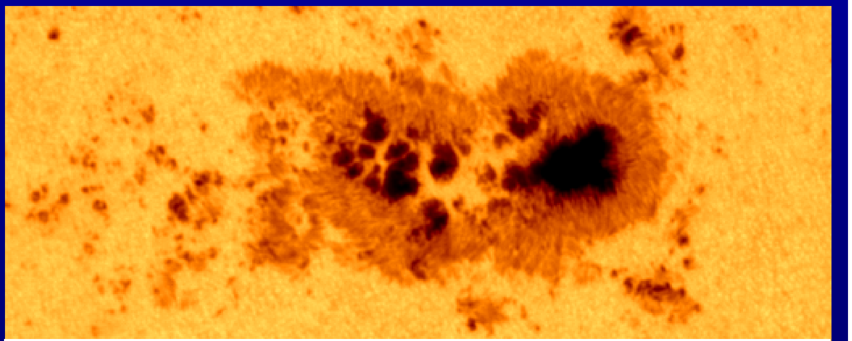


Gigantic Sunspot Group 09:36 UT, 22 September 2000 (SOHO/MDI)

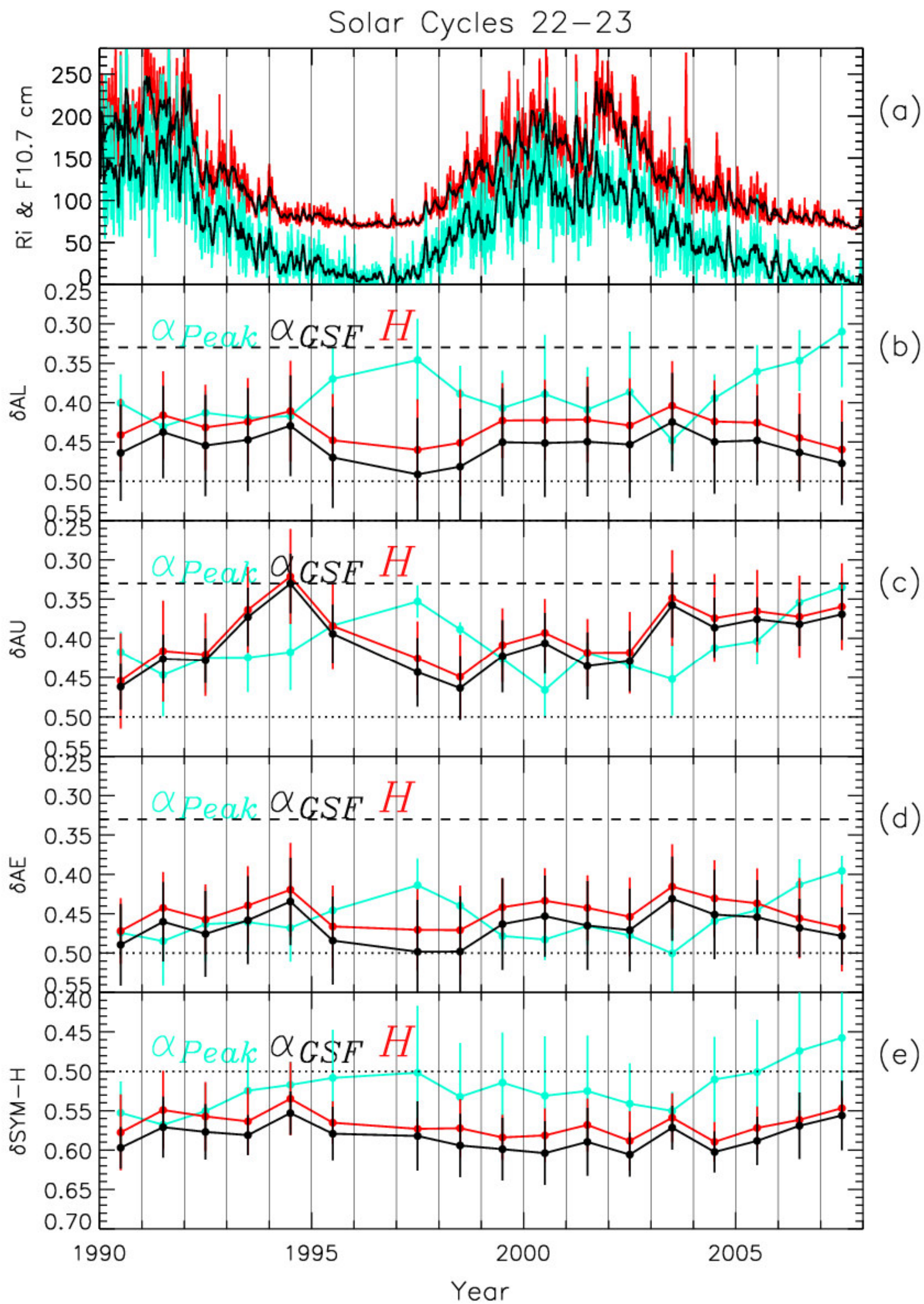


Evolution of Annual Scaling Exponents for Geomagnetic Indices, 1990-2007

(a) Daily sunspot number and F10.7 cm flux
(b) Scaling exponents for fluctuations in the AL index
(c) Scaling exponents for fluctuations in the AU index
(d) Scaling exponents for fluctuations in the AE index
(e) Scaling exponents for fluctuations in the SYM-H index



Gigantic Sunspot Group 09:36 UT, 22 September 2000 (SOHO/MDI)



Summary: Long-term variations in geomagnetic activity

- From the point of view of the Earth's magnetosphere and geomagnetic activity, "solar max" sometimes occurs during the coronal hole season of the declining phase (e.g. 2003). However, solar wind data will need to be recorded over many more solar cycles to reliably qualify the typical geo-effectiveness of different phases of the solar cycles.

- CRRES, SAMPEX and POLAR spacecraft data show that the Earth's inner radiation belt is created during the recovery phase of major geomagnetic storms associated with high speed solar wind streams. These streams are more prevalent during the declining phase of the sunspot cycle. IMAGE EUV data show the inner edge of the outer radiation belt and the co-located plasmapause move Earthward during storms.

- Long-term variations in the 27-day running average of the AE index resemble corresponding variations in the solar wind speed and the Newell et al. (2008) coupling function $d\Phi_{MP}/dt$. Major peaks in these parameters tend to occur during solar maximum years (viz. CMEs) and declining phase years (viz. high speed streams). The solar wind speed is the dominant solar wind parameter regulating geomagnetic activity.

- Although the resemblance between SYM-H (Dst) and v_{SW} and $d\Phi_{MP}/dt$ is less striking, the long-term envelop of minimum negative excursions of SYM-H does track $d\Phi_{MP}/dt$, and clearly, major storms are more likely to be associated with CMEs and high speed streams.

Summary: Long-term variations in geomagnetic activity

- The PDFs of the AE index are leptokurtic (sharply peaked) on time scales of 1 min to hours. More of this leptokurticity arises from the AL index than the AU index; the PDFs of the latter become Gaussian at shorter τ. Whilst leptokurtic at time scales of mins, the PDFs of SYM-H are distinctly Gaussian for τ~2 hours.

- The PDFs of fluctuations in AL, AU, and AE were used to track the shift in probability density between large and small values from one year to the next. The observed changes were coherent across a broad range of time scales from mins to days, suggesting an evolution of multi-scale dynamics with the changing solar wind conditions.

- As measured by fluctuations in AE, the years 1991 (solar max) and 1994 (declining phase) were the most disturbed during solar cycle 22. The years 1996-1997 (late solar min) was the quietest and the year 2003 (declining phase) the most disturbed during solar cycle 23. There was a relatively weak local maximum during 2001 (solar max).

- The behaviour in AE was largely determined by the behaviour in AL. In contrast, the AU probability density was dominated by large fluctuations during 1991 (solar max). There was a weaker secondary peak during 2003 (declining phase).

- For SYM-H (storms), the multi-scale evolution had more in common with corresponding variations in AU than AL. The variations in AU and SYM-H were also similar to variations in IMF B^2 and v_{SW} (Parkinson et al., 2007).

- Are the preceding results consistent with the notion that AU is more closely driven by the solar wind, whereas AL (substorms) and SYM-H are more self-organised?

Summary: Long-term variations in geomagnetic activity

- Structure function analysis revealed quasi-linear (power law) scaling regimes from τ ~2 mins to ~2 hours for all parameters (to a greater or lesser extent). The scaling exponents α for fluctuations in v_{SW} had a local maximum of α =0.35 for 1997 and a local minimum of α =0.27 for 2003. Similarly, for fluctuations in $d\Phi_{MP}/dt$ there was a maximum of α =0.28 for 1997 and a minimum of α =0.18 for 2003.

- The scaling exponent for fluctuations in AL had a local maximum of α =0.49 for 1997 and local minima of α =0.43 for 1994 and α =0.42 for 2003. For fluctuations in AU, there were local maxima of α =0.46 for 1990 and 2003 and a strong local minimum of 0.33 for 1994 and a secondary minimum of 0.36 for 2003.

- For fluctuations in AE, the local maxima were α =0.49 for 1990 and α =0.50 for 1998, and the local minima were α =0.43 for 1994 and 2003. For SYM-H, the local maxima was α =0.61 for 2002 but indistinct, and the local minima were α =0.56 for 1994 and α =0.57 for 2003. The one sigma errors were typically ±0.02 for all parameters.

- In general, fluctuations in the AL index exhibited stronger multi-fractal behaviour than fluctuations in the AU index. Parkinson (2006) reported stronger multi-fractal scaling of electric field fluctuations in the substorm-affected (~AL) nightside ionosphere than the dayside ionosphere.

- Although the variations in the scaling exponents are complicated and difficult to explain, the similarities and differences point towards the importance of coronal hole seasons in the declining phase of solar activity in producing changes in the multi-scale dynamics of both the solar wind at 1 AU and the Earth's magnetosphere.