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High-Latitude Polar Ionoasphere: Turbulence and Plasma Inhomogeneity

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IAASARS

Aim

To discuss the impact of *turbulence* and its link with the formation of ionospheric plasma inhomogeneities in the polar ionosphere during magnetic storm.

Outline

- *Introduction to turbulence*
- *Turbulence in the polar ionosphere*
- *The St. Patrick' storm: ionospheric observations*
- *Discussion & Conclusion*

Introduction to turbulence

The word turbulence comes from Latin "turba", which was used to indicate a disordered motion of large groups of people

Leonardo Da Vinci was the first to use this term to address the irregular motions of fluids.

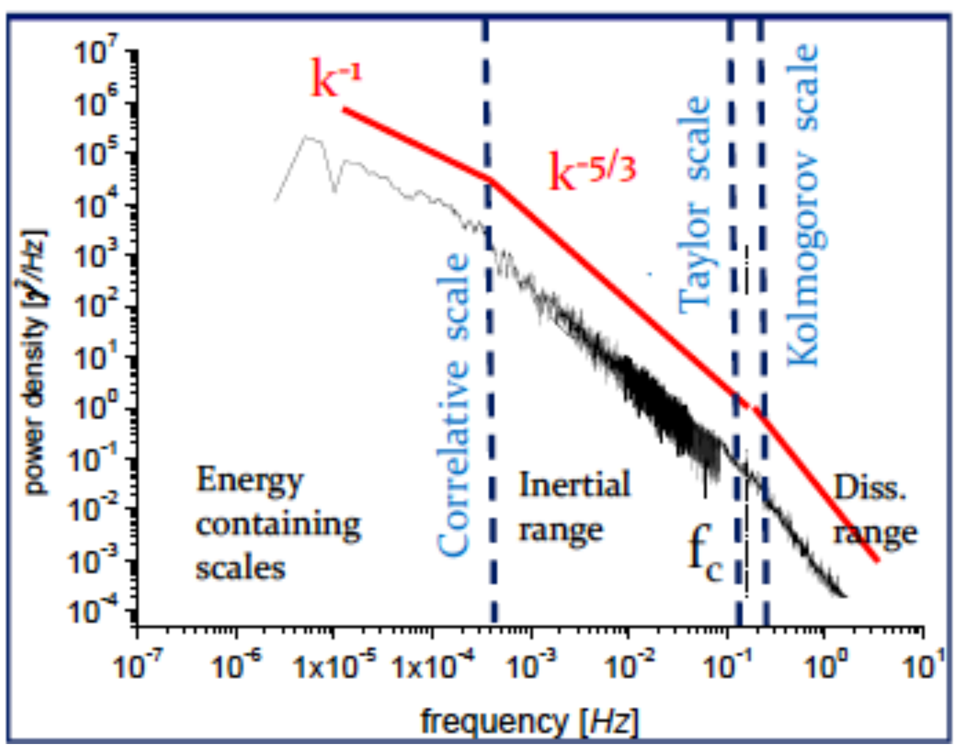
Credit: Treccani

Introduction to turbulence

Nowadays, "as a state of a physical system with many interacting degrees of freedom deviated far from equilibrium. This state is irregular both in time and in space and is accompanied by dissipation" (G. Falkovich, 2008).

Turbulence is the result of *nonlinear interaction between motions of different spatial and temporal scales,* where the dissipation is generally negligible, and it occurs when the *externally excited motion scale substantially deviates from the dissipation ones.*

from Bruno & Carbone, 2013



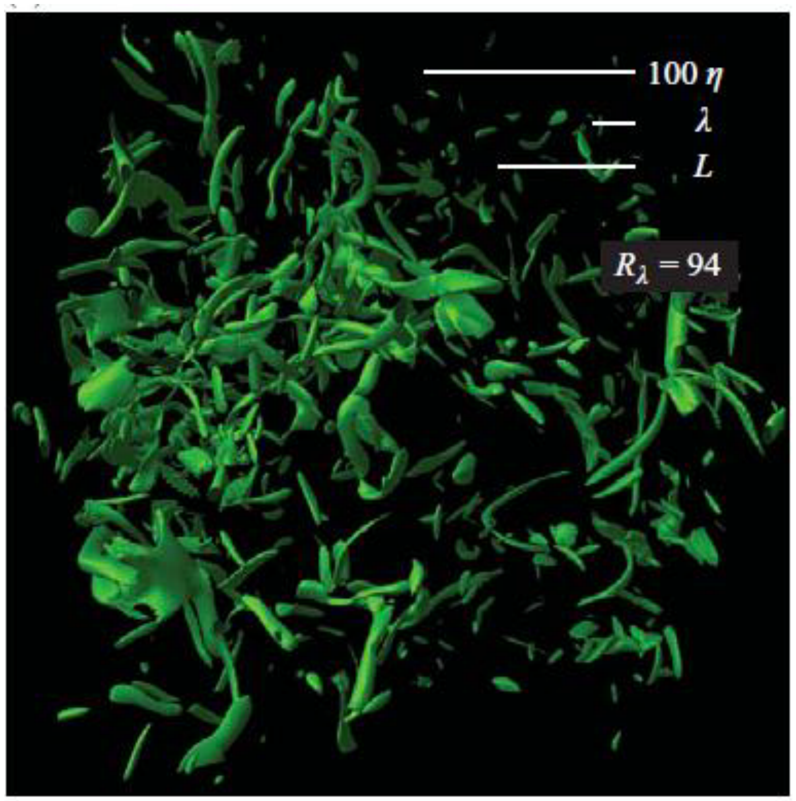
Turbulence is *ubiquitous in astrophysical and space media.*

For instance, *solar wind, the interplanetary medium and magnetotail CPS* are *turbulent plasma regions* [extensively investigated (see e.g. *Bruno and Carbone,* 2015)].

Introduction to turbulence

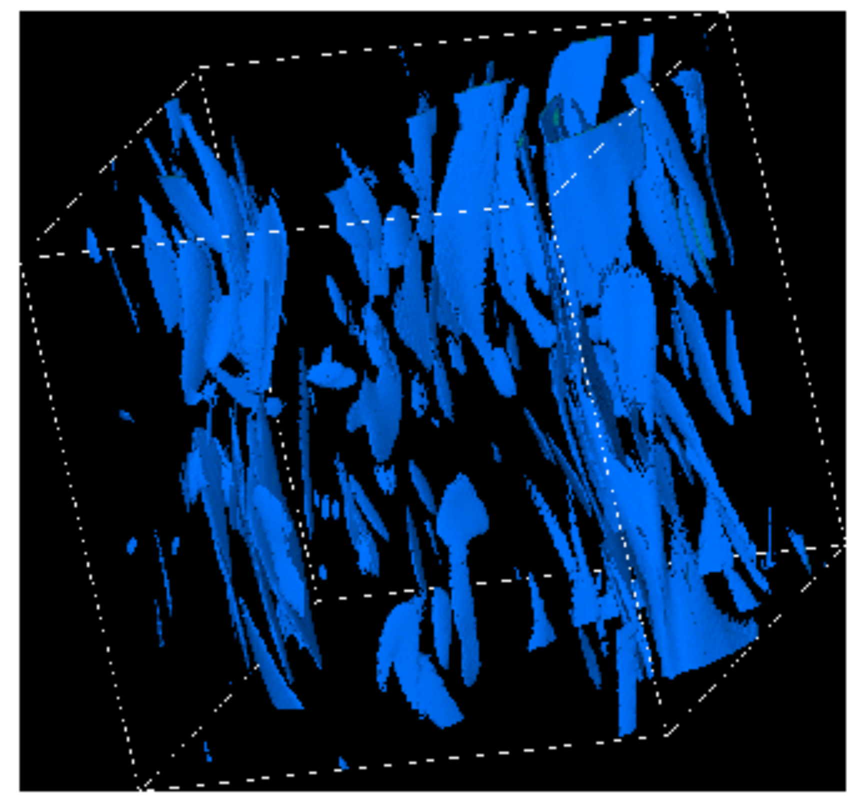
Turbulence plays a crucial role in *fluids, plasmas and transport processes*, and is responsible for the generation of *multiscale coherent structures.*

B = 0 ⇒ filaments



from Ishihara et al., 2007

B ≠ 0 ⇒ ribbons



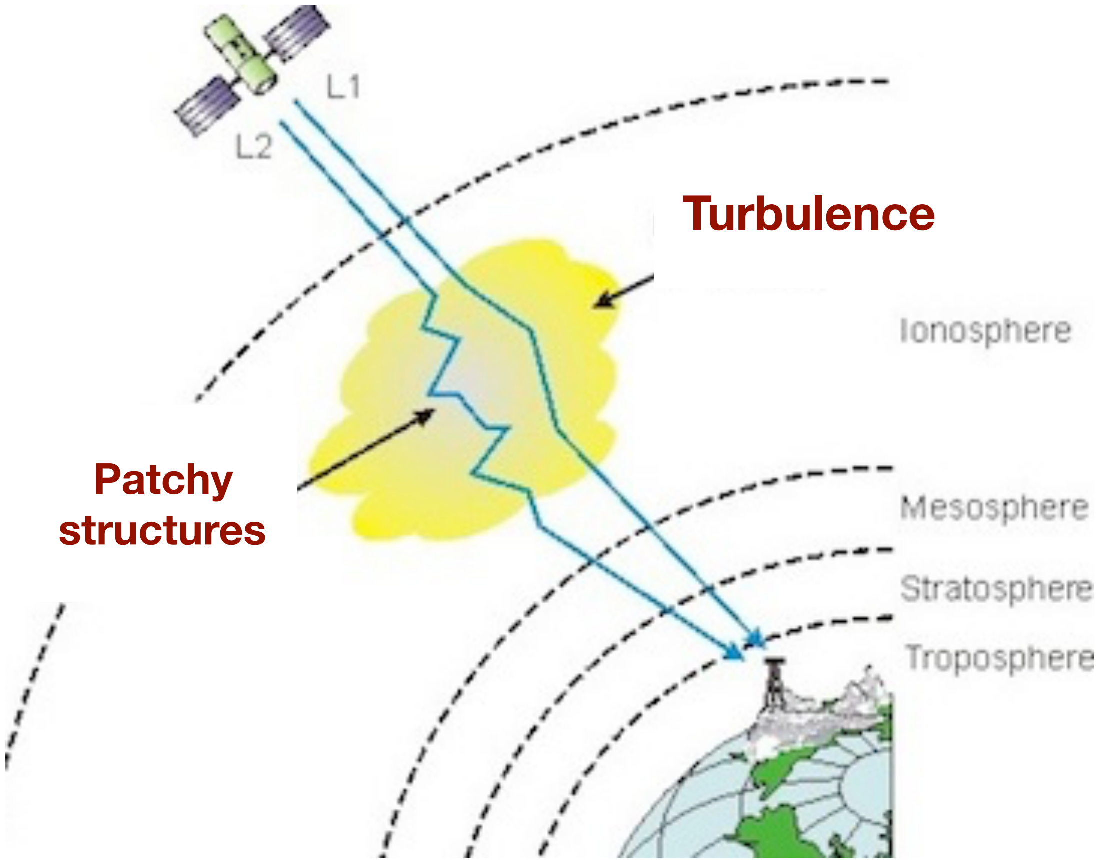
from Biskamp & Nuller, 2000

The dynamics of *coherent turbulent structures* is at basis of several processes in space plasmas, involving *plasma acceleration, heating, and inhomogeneity.*

Turbulence in the polar ionosphere

In the framework of ionospheric plasmas the study of turbulence might play a special role to understand several processes as the ionospheric heating and the formation of magnetic and plasma structures that can affect the medium homogeneity generating patchy structures.

Credit: adapted from web

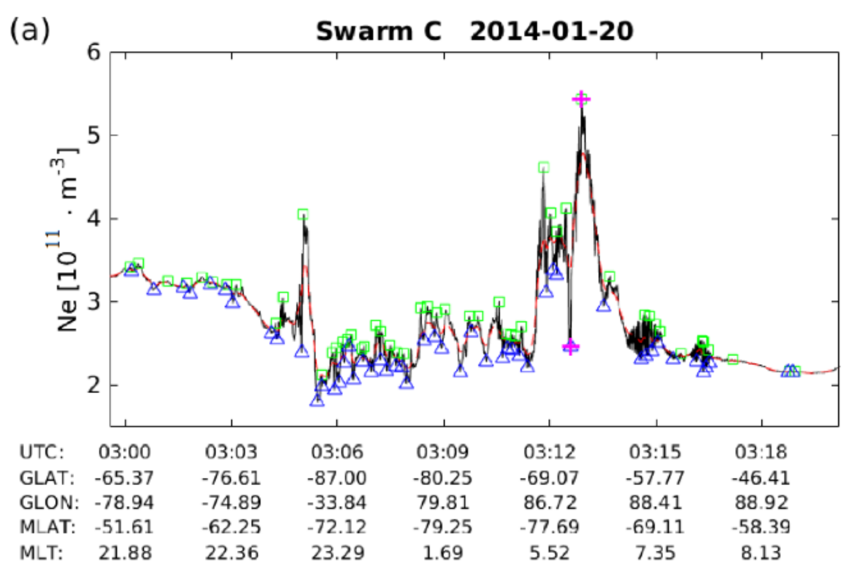


These *coherent patchy structures* generated by the turbulence can, indeed, have an important effect in *telecommunication*, in *Global Positioning System* (GPS), *Geographic Information System* (GIS), and *Global Navigation Satellite System* (GNSS) to list just few examples of technologies.

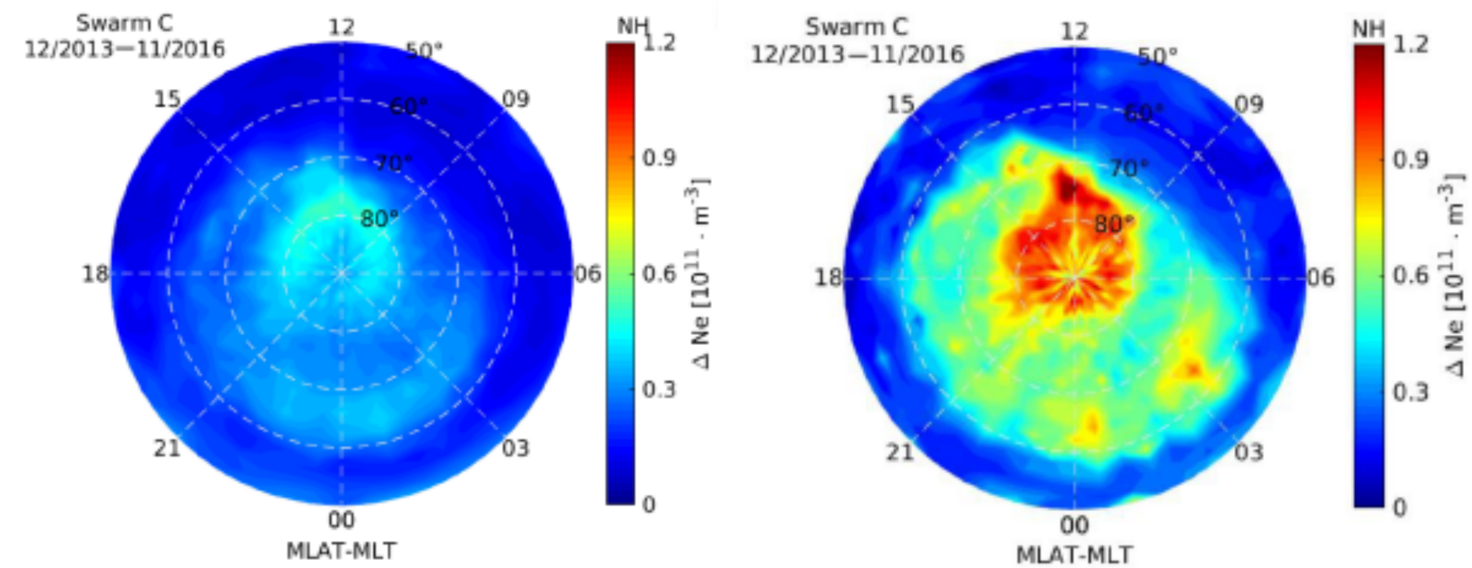
Turbulence in the polar ionosphere

Indeed, turbulence is a valid physical mechanisms to understand the *formation of structures and irregularities over a wide range of scales* in the high-latitude ionosphere is crucial due to the role that these play in *radio-propagation and positioning systems (GPS)*.

Plasma density Ne



Plasma density gradient ΔNe



No GPS signal loss | *GPS signal loss*

from Xiong et al., Ann. Geophys., 36, 679, 2018

Bulk plasma processes, such as plasma instability-induced turbulence, can be sources for formation of *multiscale structures and irregularities*.

Turbulence in the polar ionosphere

Electric field fluctuations - SIERRA Auroral oval observations (700 km)

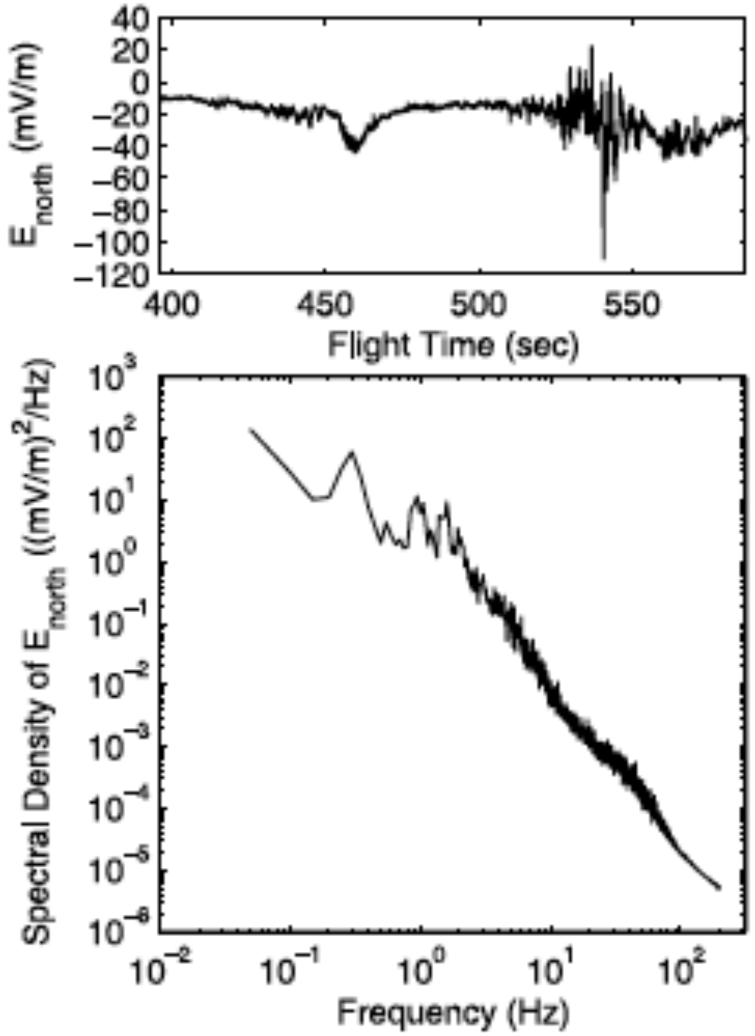


Figure 1. Top: Plot of electric field component E_{north} versus the flight time of SIERRA for the duration when the rocket was above 700 km altitude. Bottom: Average spectral density of E_{north} over the duration.

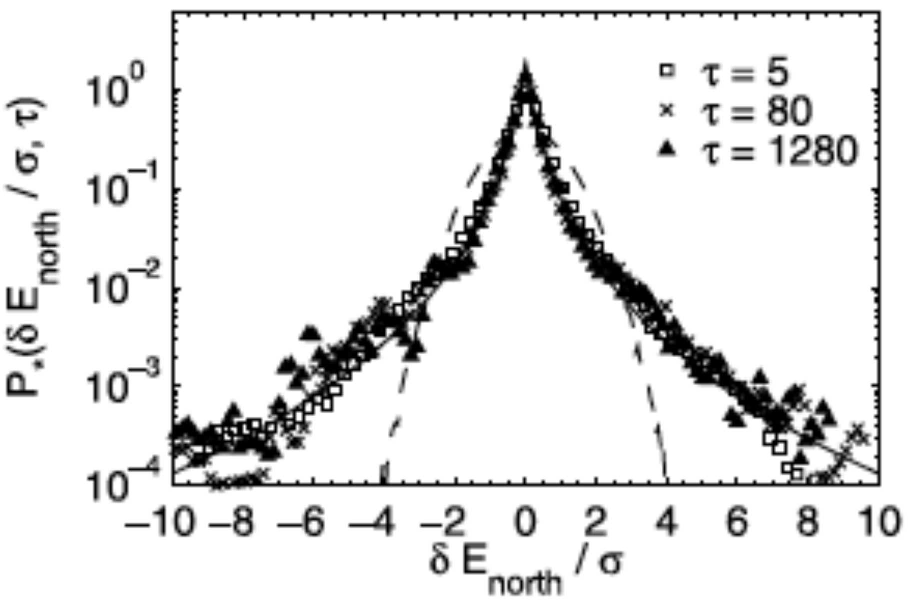
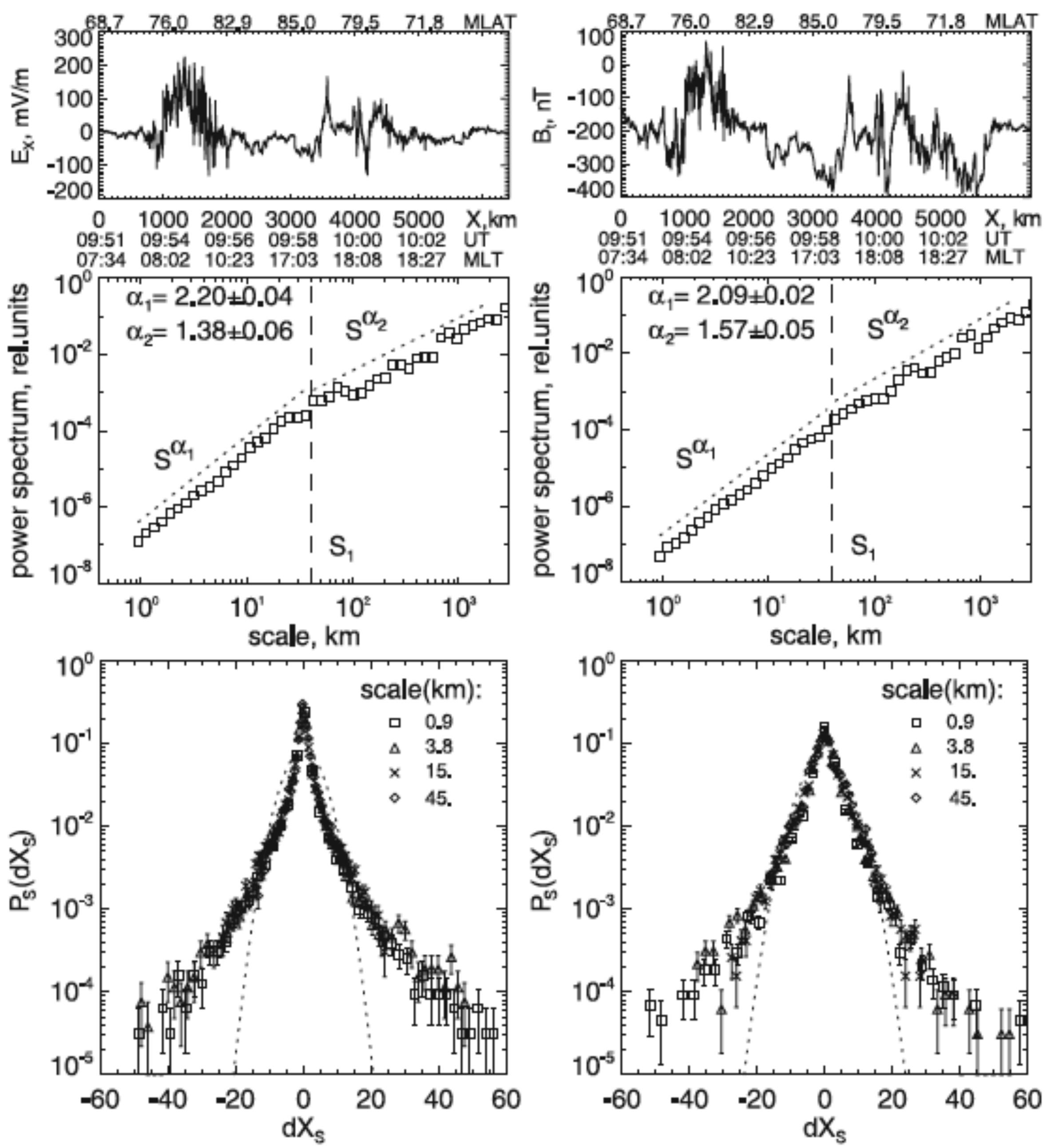


Figure 2. Normalized PDF $P_*(\delta E_{\rm north}/\sigma, \tau)$ at $\tau = 5$, 80 and 1280 ms. The solid line corresponds to the normalized Castaing distribution with $\lambda = 1.02$. The results of the analyses for Gaussian fluctuations (dashed) are shown for comparison.

from Tam et al., GRL, 2005

Turbulence in the polar ionosphere

Magnetic/electric field fluctuations - Polar Ionosphere DE2 (300/1000 km)



Relationship between the high-latitude electric and magnetic turbulence and the Birkeland field-aligned currents

I. V. Golovchanskaya,[1] A. A. Ostapenko,[1] and B. V. Kozelov[1]

Received 7 May 2006; revised 15 September 2006; accepted 26 September 2006; published 1 December 2006.

[1] We demonstrate the turbulent properties of the high-latitude electric and magnetic fluctuations, observed by the low-altitude polar-orbiting Dynamic Explorer 2 (DE2) satellite, by means of spectrum analysis and examination of the probability density function (PDF) of the fluctuations. To gain insight into the origin of the underlying turbulence, we calculate turbulent field patterns from DE2 observations under different IMF conditions and compare them with the associated patterns of the Birkeland field-aligned currents (FACs). A clear similarity of these two groups of distributions suggests a close, perhaps cause and effect relationship between the large-scale FACs and turbulent fields. This finding gives more evidence for the association of the turbulence under study and discrete auroral features, which are known to arise in the regions of strong background FACs.

from Golochanskaya et al., JGR, 2006

Turbulence in the polar ionosphere

Density fluctuations - ICI 2 sounding rocket (~ 330 km)

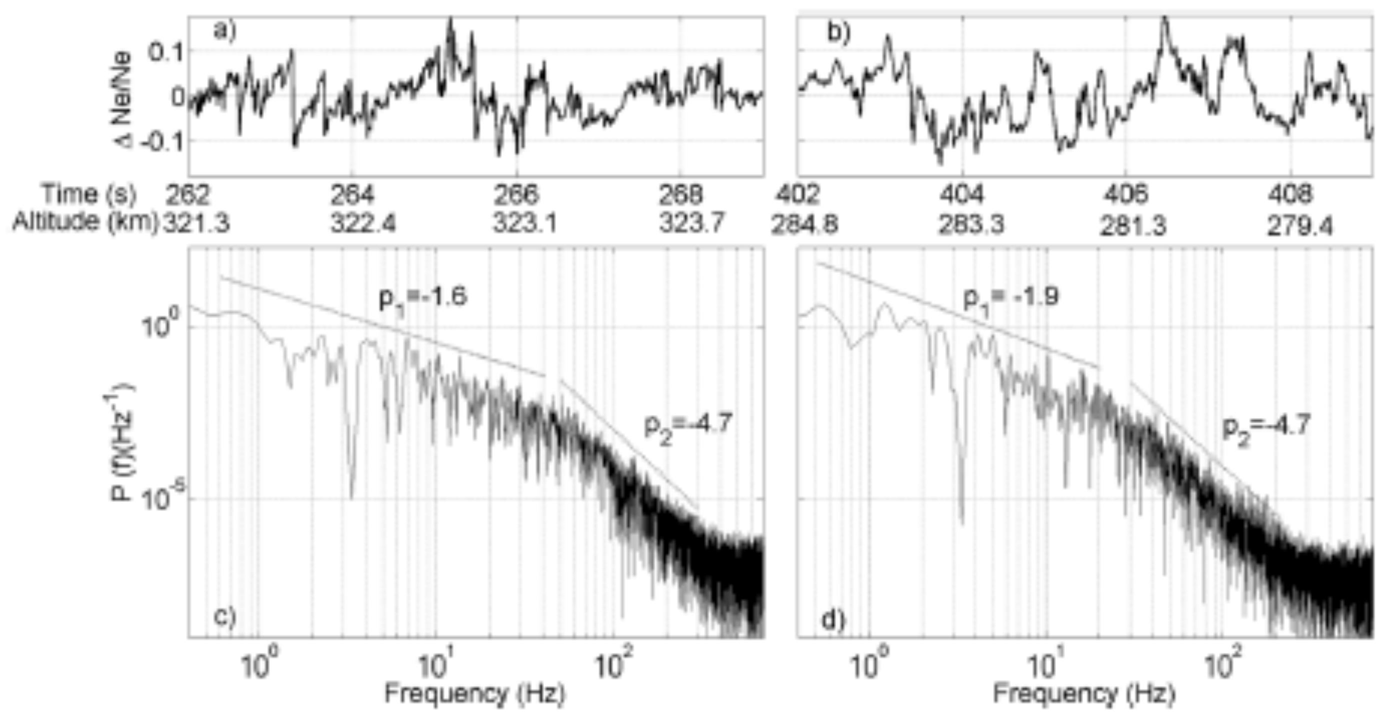


Figure 3. Case A: (a) Fluctuations of the electron density data between t_{of} = 262 s and t_{of} = 269 s. (c) Power spectrum of $\Delta Ne/Ne$ between t_{of} = 262 s and t_{of} = 269 s. Case B: (b) Fluctuations of the data between t_{of} = 402 s and t_{of} = 409 s. (d) Power spectrum of $\Delta Ne/Ne$ between t_{of} = 402 s and t_{of} = 409 s.

from Spicher et al., JGR, 2015

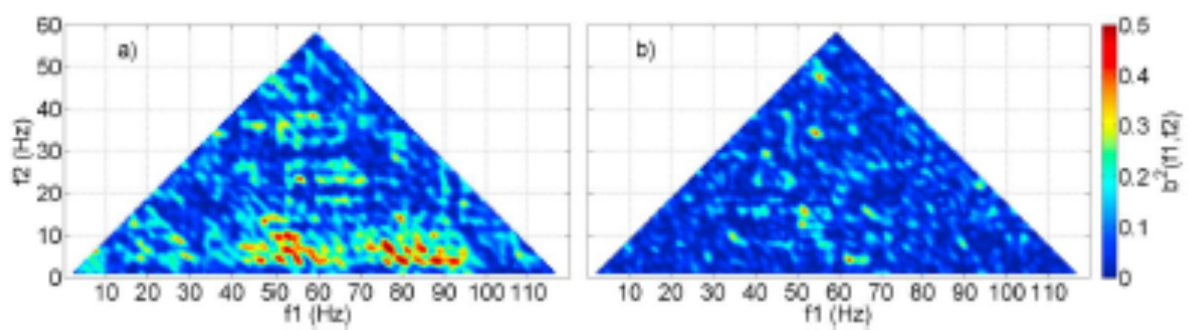
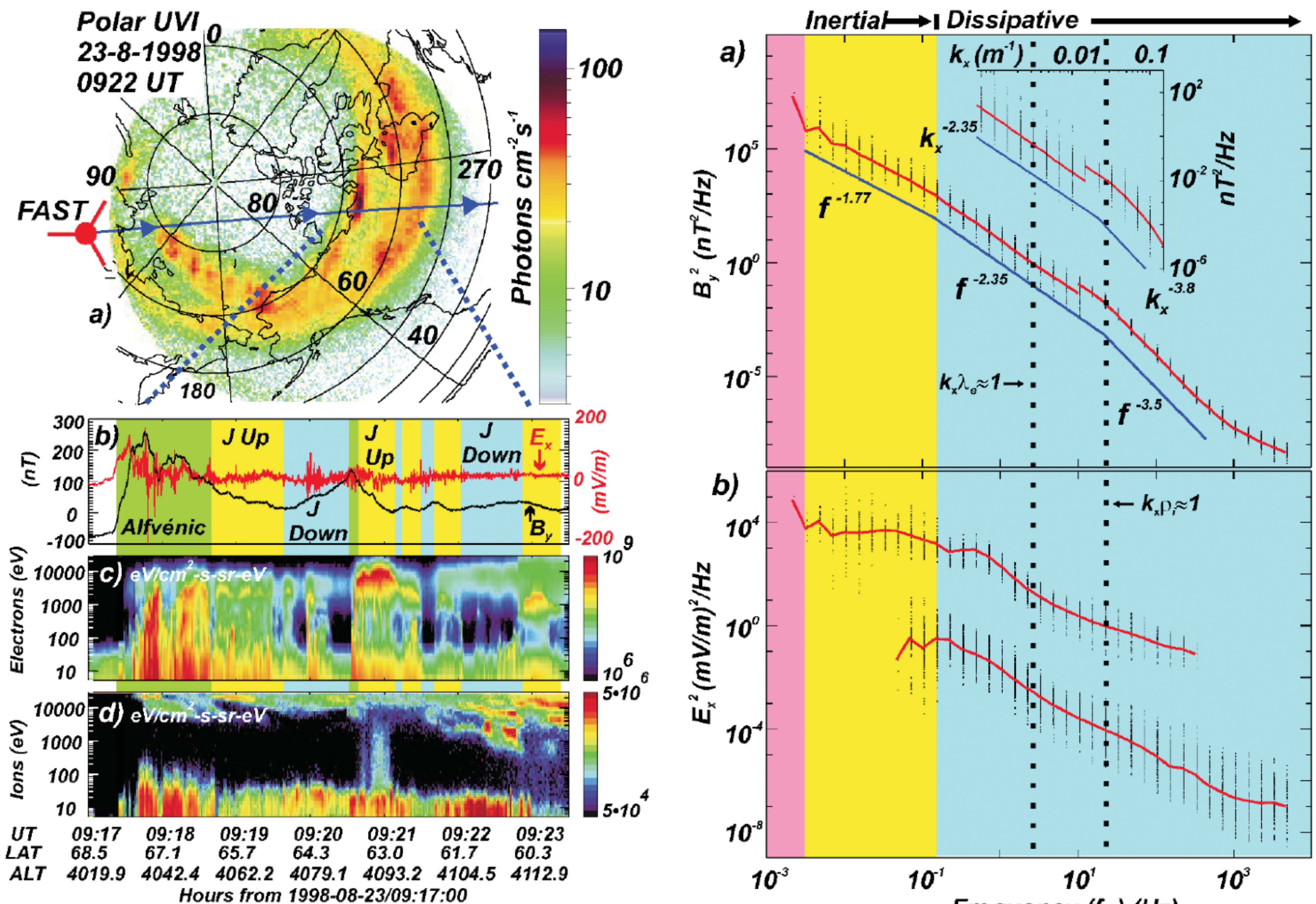


Figure 4. Fourier bicoherence of the density fluctuations observed for (a) Case A and (b) Case B.

Turbulence in the polar ionosphere

Turbulent Alfvénic fluctuations in the Auroral Oval



from Chaston et al., PRL, 2008

Turbulence in the polar ionosphere

A way to get *information* on plasma turbulence features is the *analysis of the scaling features of the fluctuations* of fields and plasma quantities.

This approach is, for instance, capable of *providing information on the patchy and intermittent character* of fluctuations, which is inherently connected to the nonlinear features of the dynamics of the system under study.

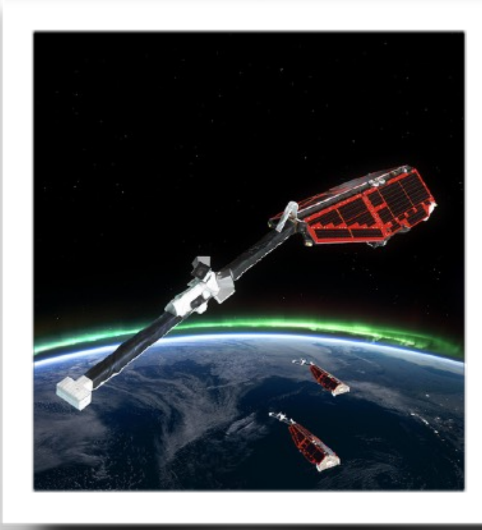
In the framework of magnetosphere-ionosphere coupling a relevant issue is to understand the relationship among *scaling features of turbulent fluctuations*, *plasma transport* and the *system dynamics* in response to solar wind changes.

In what follows, we will show *some recent results* on electron density scaling features and their relationships with plasma inhomogeneities in the polar ionosphere, *using Swarm observations* during the St. Patrick' storm.

The St. Patrick' storm

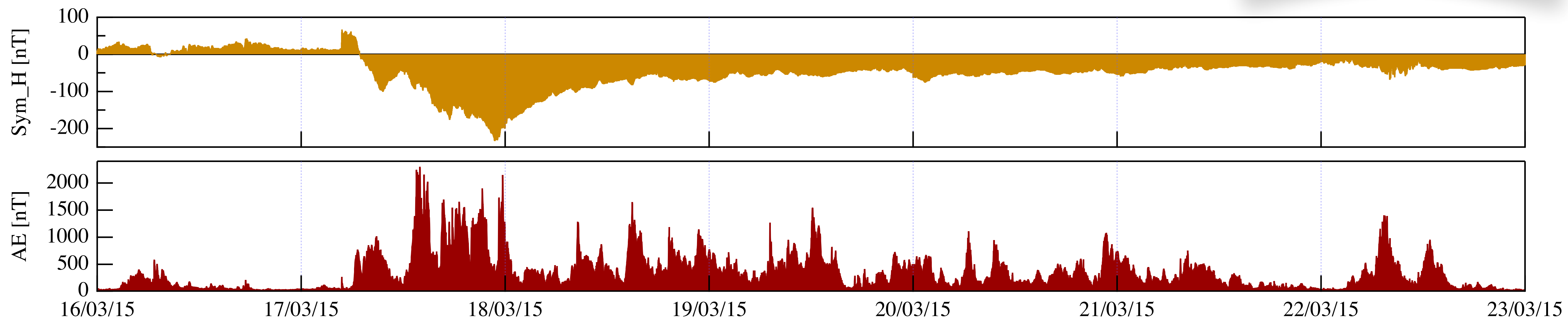
We consider *magnetic field and electron density data* recorded onboard of *ESA-Swarm A satellite from 16 to 22 March 2015.*

Typical data resolution is 1 Hz (50 Hz/magnetic field 2 Hz e^- density).



The Rate Of change of Density Index (RODI) has been evaluated using the method described by Jin et al. (JGR 2019).

RODI quantifies the electron density inhomogeneity.



The St. Patrick' storm

To study the nature of the turbulent fluctuations we have investigated the local scaling features of the *q*[th]*-order structure function* (400 s moving window),

$$S_q(\tau) = \langle | \ x(t+\tau) - x(t) \ |^q \rangle_T$$

that for scale-invariant signals is expected to scale as,

$$S_q(\tau) \sim \tau^{\gamma(q)}$$

In particular we concentrate our attention to the *2*[nd] *order structure function*, because the value of $\gamma(2)$ permits to infer the spectral properties of the analyzed signal.

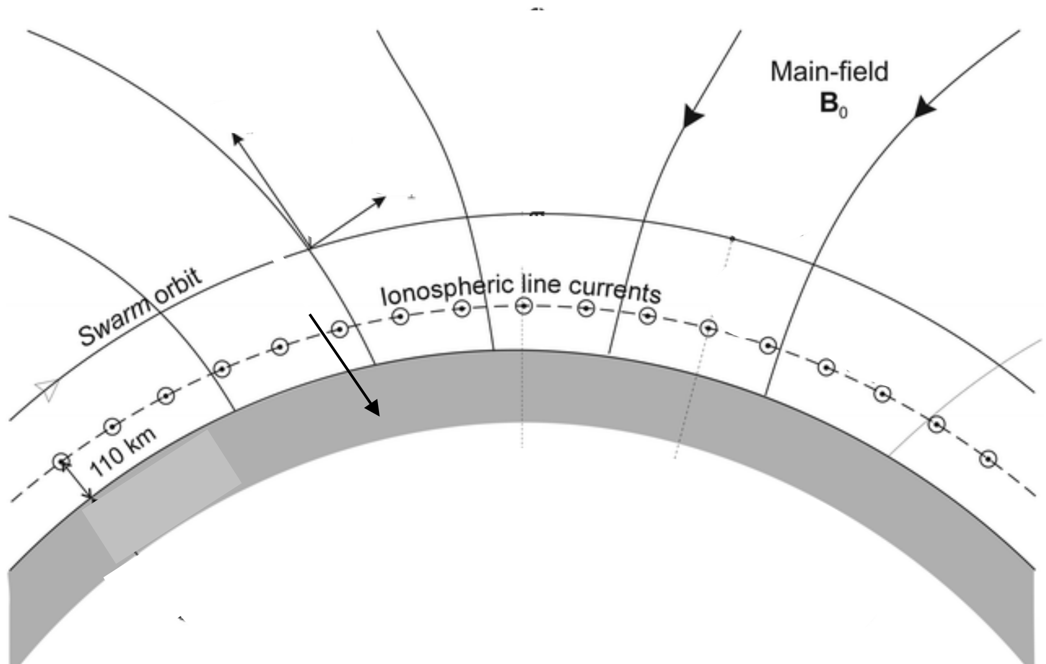
Indeed, according to *Wiener-Khinchin theorem*, the Fourier power spectral density (PSD) exponent β of a signal is related to $\gamma(2)$ according to the following relation:

$$PSD(f) \sim f^{-\beta} \quad \rightarrow \quad \beta = \gamma(2) + 1$$

The St. Patrick' storm

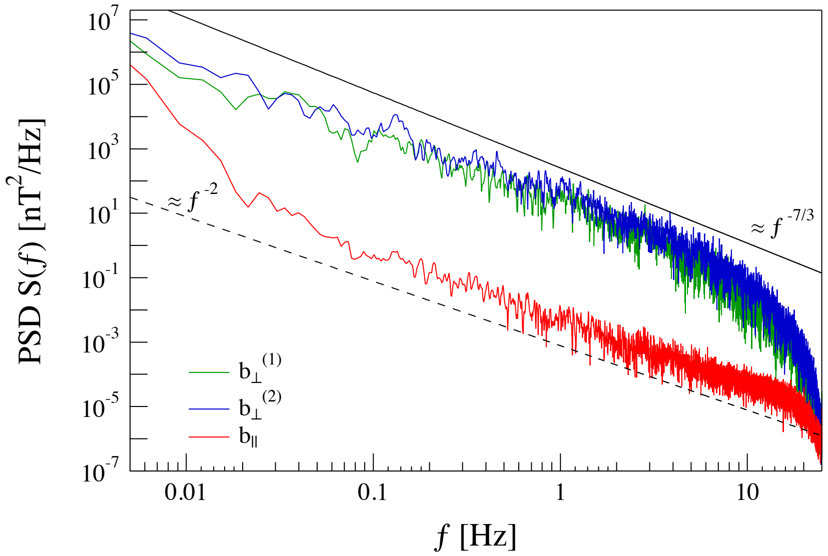
Furthermore, due to the strong magnetic field and the *low-beta plasma* condition, we expect that *fluctuations are strongly anisotropic*.

Thus, we remove the main geomagnetic field using *CHAOS 6 model* (Finlay et al., 2016) to better quantify the fluctuations and adopt a local reference system.



adapted from Drost Aakjær et al., EPS, 2016

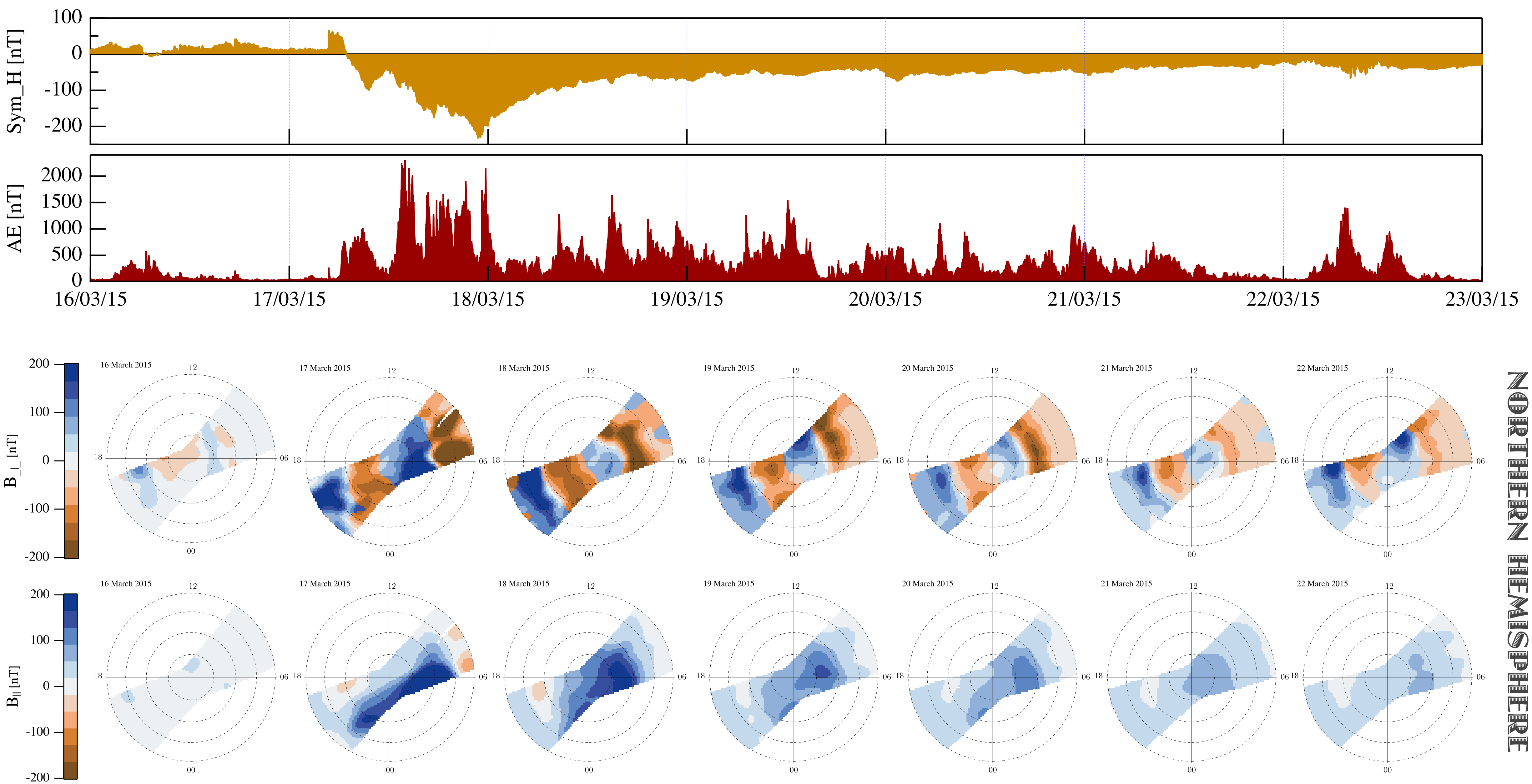
$$B_{||} = \frac{1}{B_0}\mathbf{B}_{ext} \cdot \mathbf{B}_0 \qquad \mathbf{B}_\perp = \mathbf{B}_{ext} - B_{||}\frac{\mathbf{B}_0}{B_0}$$



$$R(f) = \frac{S_\perp^{(1)}(f) + S_\perp^{(2)}(f)}{2S_{||}(f)} \longrightarrow \langle \log R \rangle \sim 4.8(4.9)$$

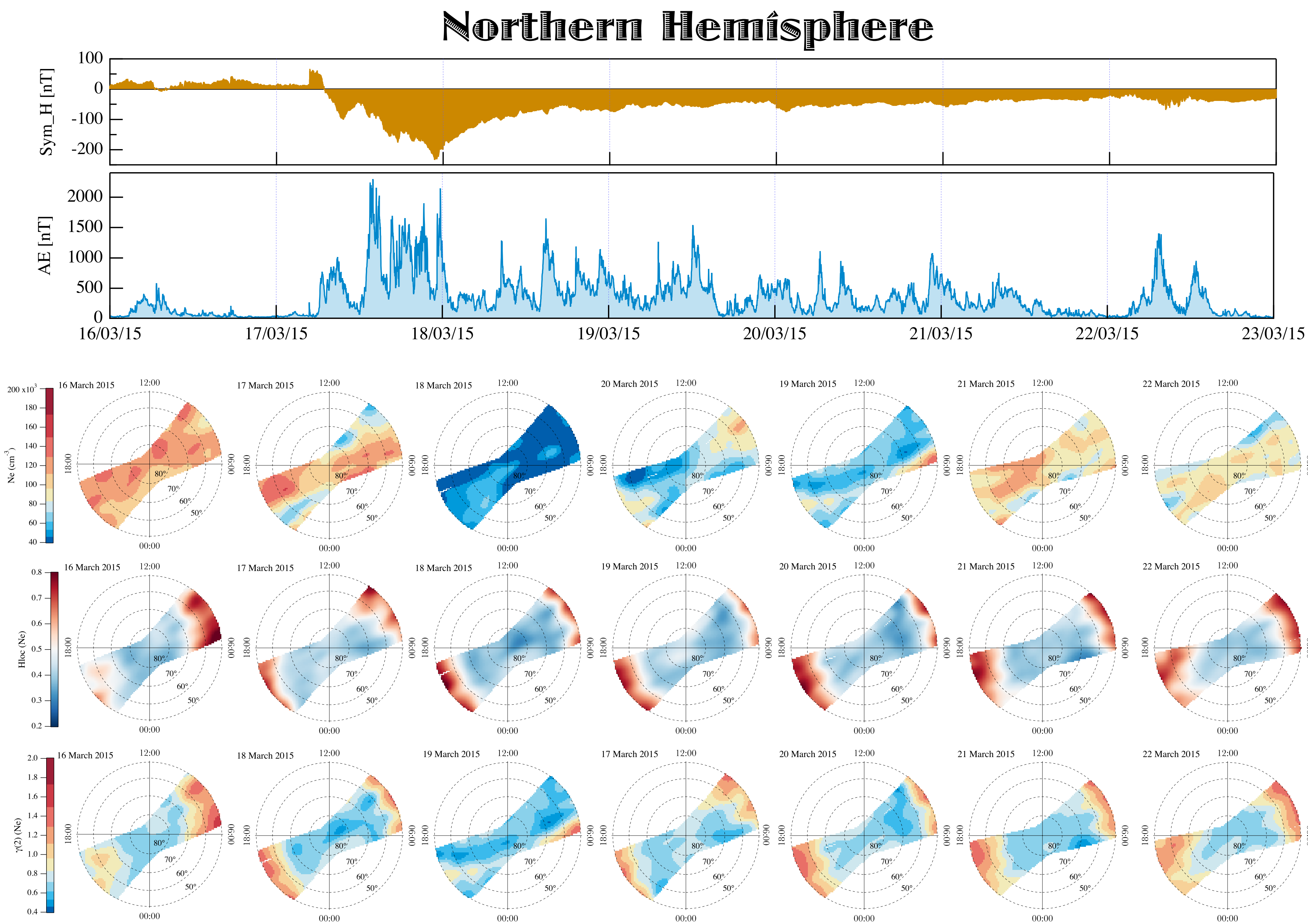
The St. Patrick' storm

Magnetic field components



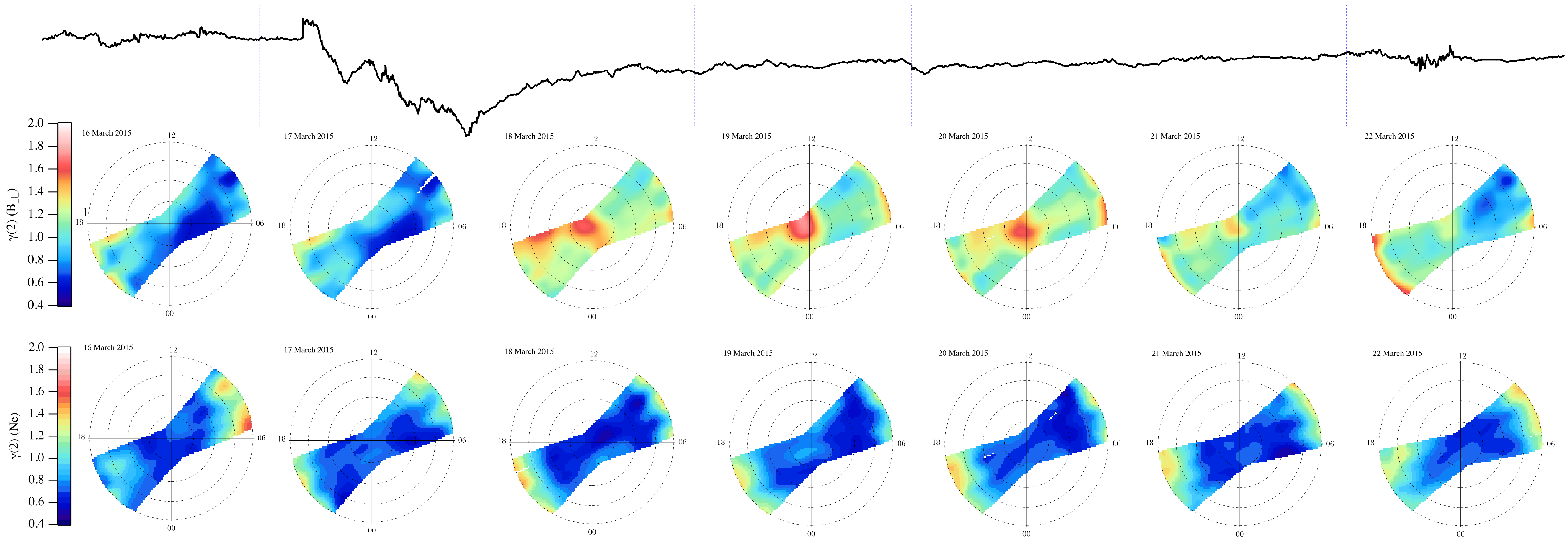
The St. Patrick' storm

Electron Density



The St. Patrick' storm

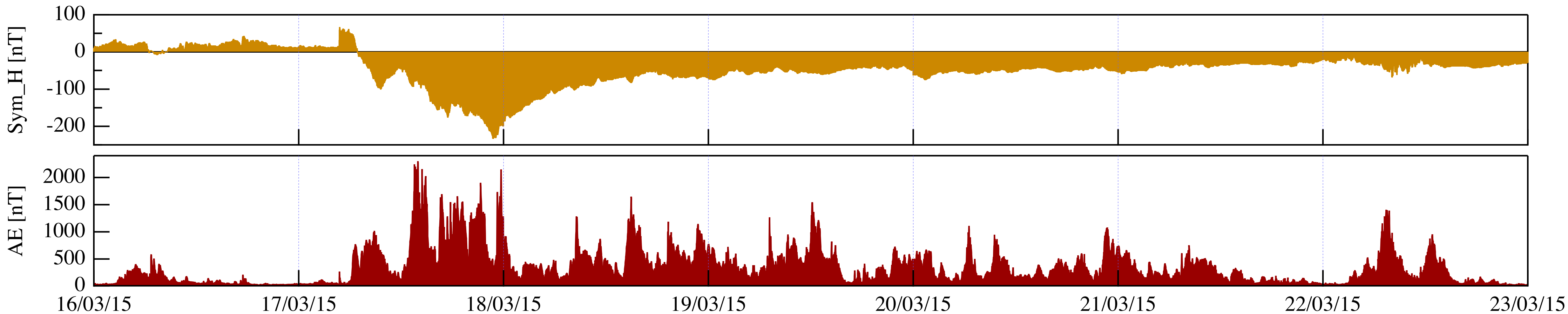
Evolution of 2nd order scaling exponent of magnetic field and electron density

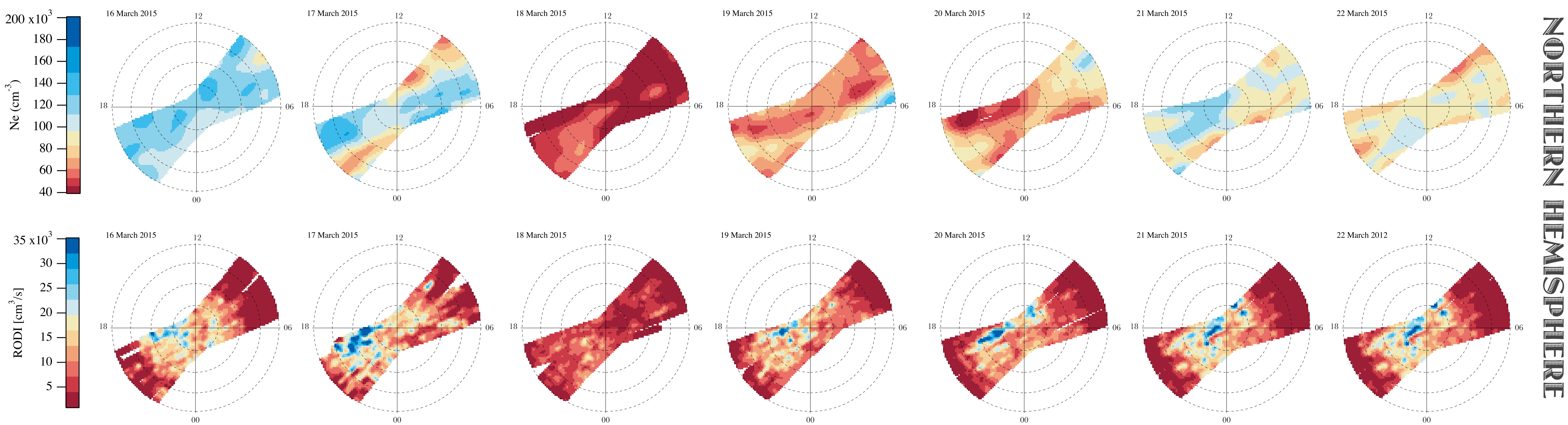


The spectral scaling exponents of the magnetic field and electron density fluctuations change during the development of the geomagnetic storm and depend on the latitude and MLT. The electron density is characterized by values of the spectral density exponents lower than those associated with the magnetic field fluctuations.

The St. Patrick' storm

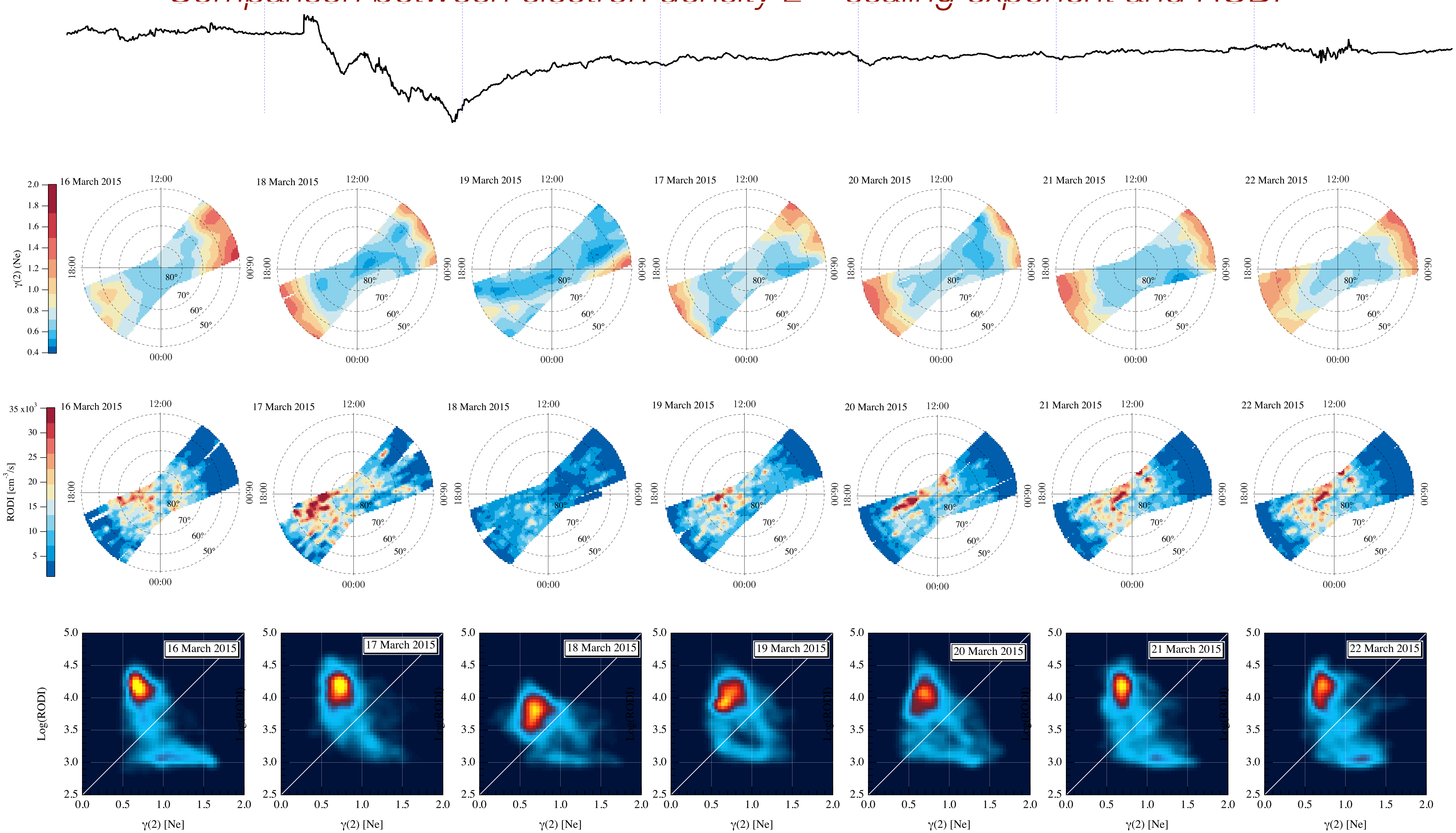
Comparison between electron density patterns and RODI





The St. Patrick' storm

Comparison between electron density 2nd-scaling exponent and RODI



The St. Patrick' storm

The *2nd-order scaling exponents* of magnetic field and electron density change during the development of the geomagnetic storm and depend on the latitude and MLT.

High values of RODI, which indicates plasma structuring, *are correlated to an anti-persistent character* of the electron density fluctuations and *values of the spectral exponent around 1.66*.

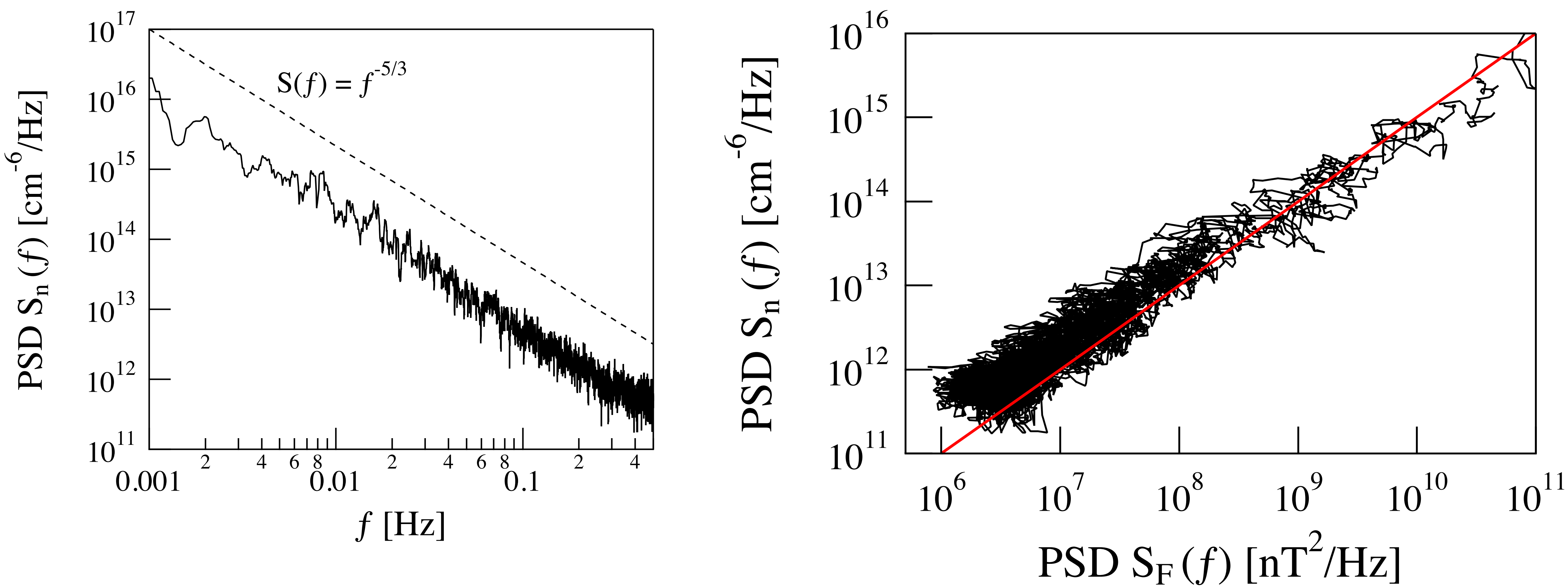
These features remain throughout the storm and may be a *signature of the role that turbulence might play in generating multi scale plasma structures.*

The *electron density* shows *spectral (scaling) exponents lower* than those associated with the *magnetic field fluctuations*.

Passive scalar nature of electron density.

The St. Patrick' storm

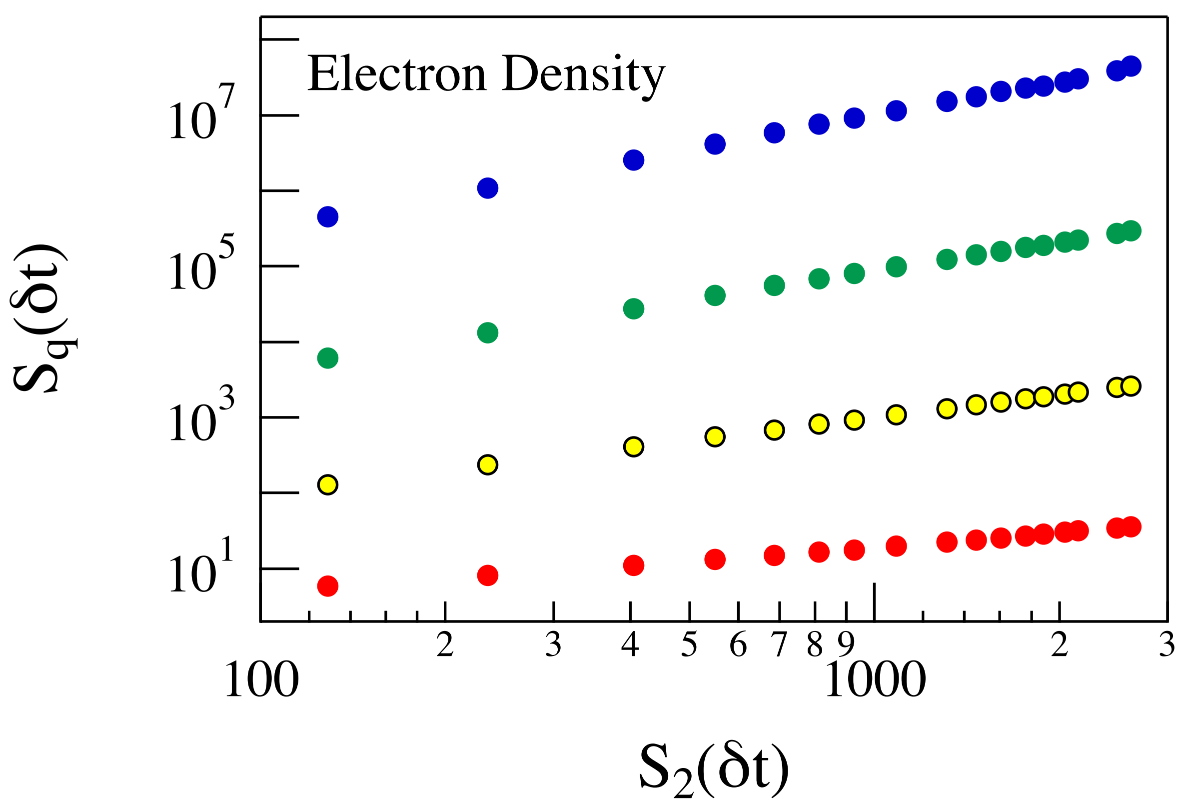
To check the hypothesis of a *passive scalar nature* of electron density fluctuations we investigate the global spectral and scaling features for the day 17th March limiting our analysis to the a magnetic latitude between *60° < Lat < 80°* in the northern hemisphere.

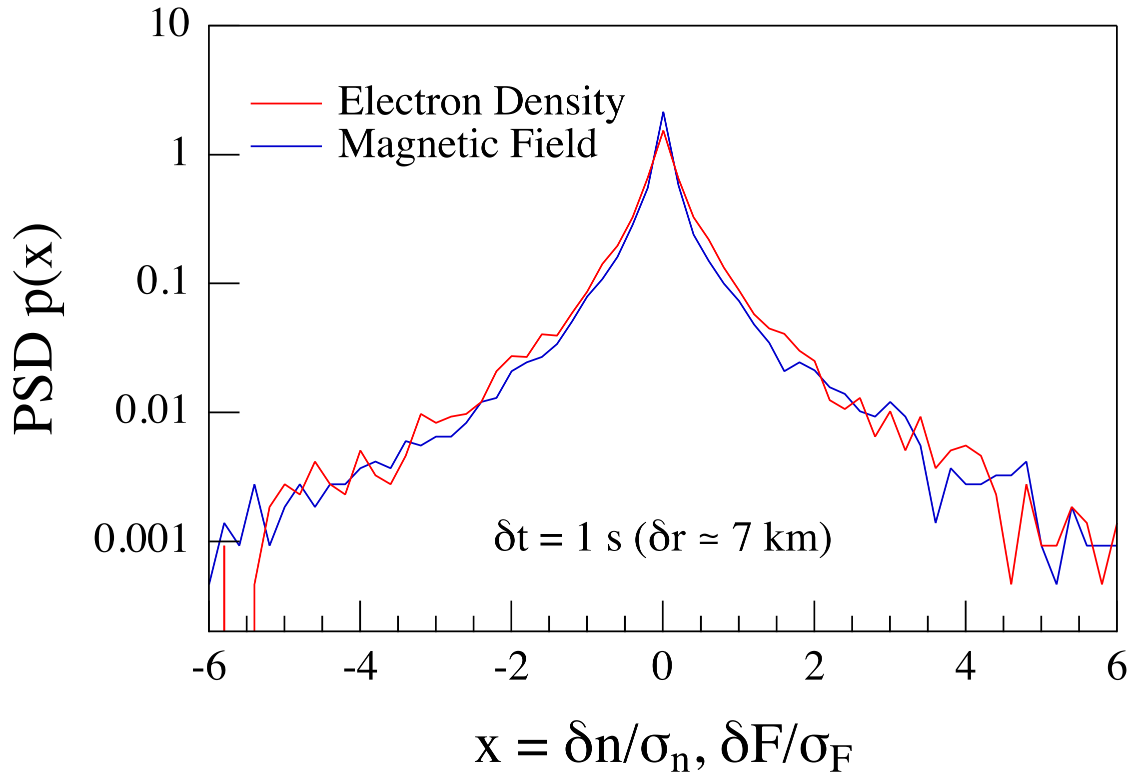


The St. Patrick' storm

Extended self-similarity (Benzi et al.) and PDF of the electron density and magnetic field increments.

$$S_q(r) = (S_2(r))^{q/2} \quad (KOC - theory)$$



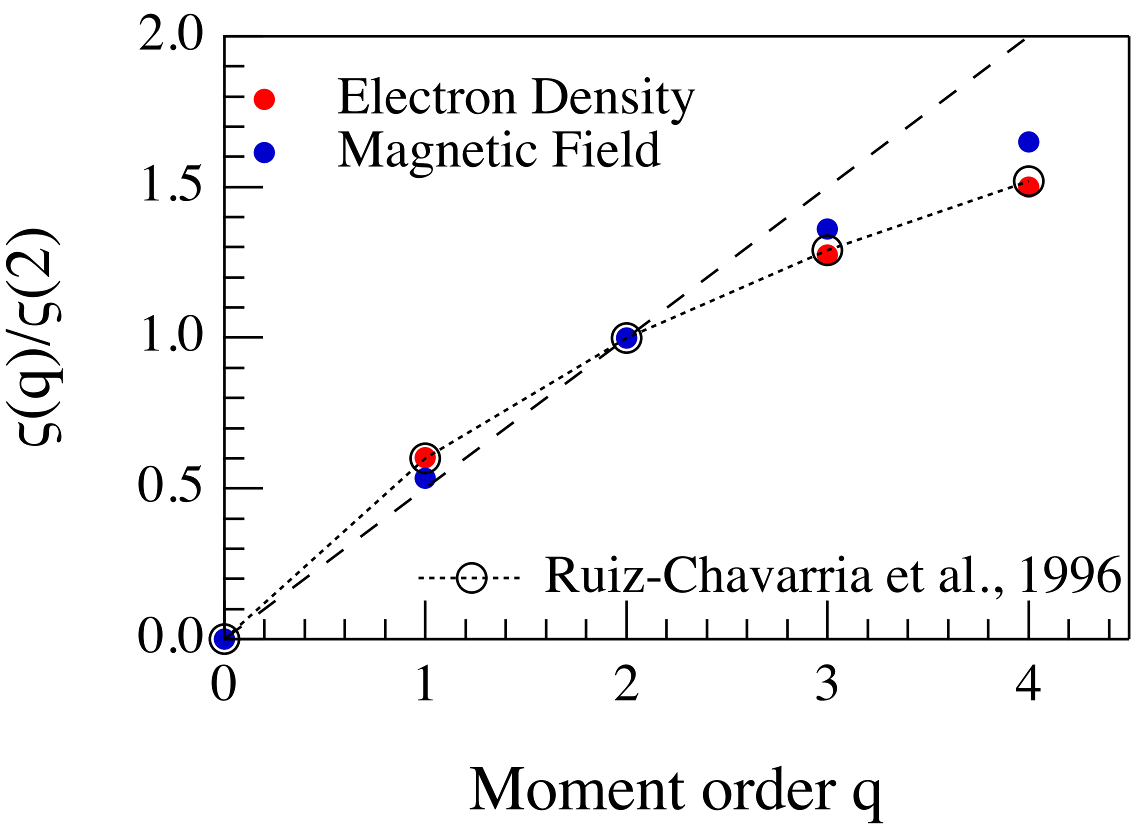


$$\delta t \in [1, 100]s$$

The St. Patrick’ storm

Extended self-similarity (Benzi et al.) and PDF of the electron density and magnetic field increments.

$$S_q(\delta t) = (S_2(\delta t))^{\xi(q)} \qquad mono - fractal \ \rightarrow \ \xi(q) = \zeta(q)/\zeta(2) = q/2$$



q	$\xi(q)$ This work	$\xi(q)$ Ruiz-Chavarria et al.
1	0.601 ± 0.008	0.60 ± 0.01
2	1	1
3	1.275 ± 0.007	1.29 ± 0.02
4	1.500 ± 0.010	1.53 ± 0.03

To our knowledge, this is the first evidence for a passive scalar nature of electron density in ionospheric high latitude regions.

Discussion & Conclusions

Summarizing the results of our analysis we have found that:

- magnetic field fluctuations are strongly anisotropic;
- electron density and magnetic field are characterized by spectral properties, which depend on the polar ionospheric regions and change during the storm phases;
- the anti-persistent character of the electron density fluctuations, showing a spectral exponent near 1.7, agrees with RODI increase. This could be a signature of the role that turbulence might play in generating multi scale plasma structures.
- a very striking evidence for the occurrence of turbulence and intermittency in electron density fluctuations in the high latitude regions;
- the observed intermittency has the same universality class of a passive scalar quantity in fluid turbulence (Ruiz-Chavarria et al., 1996).

$$\partial_t n_e + (\mathbf{v} \cdot \nabla) n_e = \chi \nabla^2 n_e + f(\mathbf{r}, t)$$

Discussion & Conclusions

The observed *turbulence is mainly 2D*, which is in agreement with the fact that for *low-β plasmas* fluctuations are essentially confined to a *plane perpendicular to the mean field*, since field lines resist to bending in the parallel direction.

In this regime the *turbulence* may be governed by the *slow coalescence of magnetic eddies* and the *spectrum can steepen* from $k^{-3/2}$ to $k^{-5/2}$ (Biskamp and Schwarz, 2001).

$$\mathbf{B} = (\delta B_x, \delta B_y, B_0)$$

$$\mathbf{J} \times \mathbf{B} = 0$$

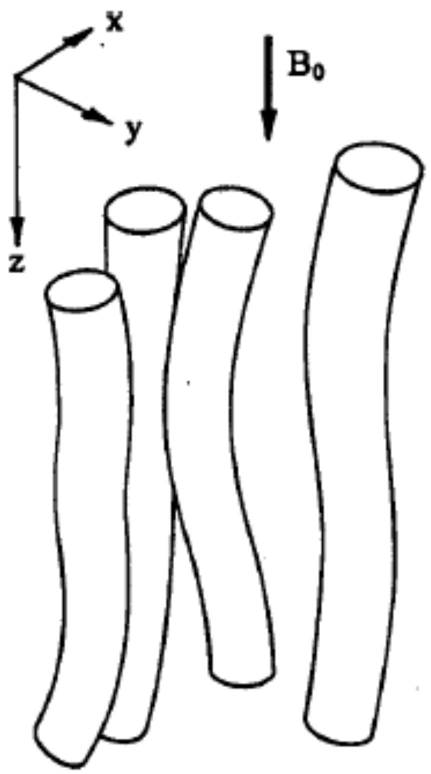
$$\nabla \cdot \mathbf{J} = 0$$

$$\mathbf{B} \cdot \nabla J_z = 0$$

$$\nabla \cdot \mathbf{B} = 0$$

$$B_0 \frac{\partial J_z}{\partial z} = -\left(\delta B_x \frac{\partial}{\partial x} + \delta B_y \frac{\partial}{\partial y}\right) J_z + \ldots$$

$$(\delta B_x, \delta B_y) = \left(\frac{\partial \psi}{\partial y}, -\frac{\partial \psi}{\partial x}\right)$$



from Chang et al., PP, 2004

Discussion & Conclusions

The turbulent (spectral exponent near 1.7) and intermittent nature of electron density could be the origin for the formation of multiscale patchy structures responsible for the occurrence of ionospheric scintillations and radio propagation anomalies

The passive nature of these electron density fluctuations greatly supports the hypothesis that fluid and/or magneto-hydrodynamic turbulence has to be considered as the most promising phenomena generating ionospheric plasma anomalies and that such process is inherently a multiscale phenomenon.

The emergence of turbulence, intermittency and passive scalar features in the ionospheric density fluctuations is very important in the framework of Space Weather related studies.

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Acknowledgements

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