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Equatorial plasma bubbles and turbulence: magnetic field and electron density scaling properties

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We all have the opportunity to directly observe **turbulence** phenomena

Photo by Stephen Hocking on Unsplash

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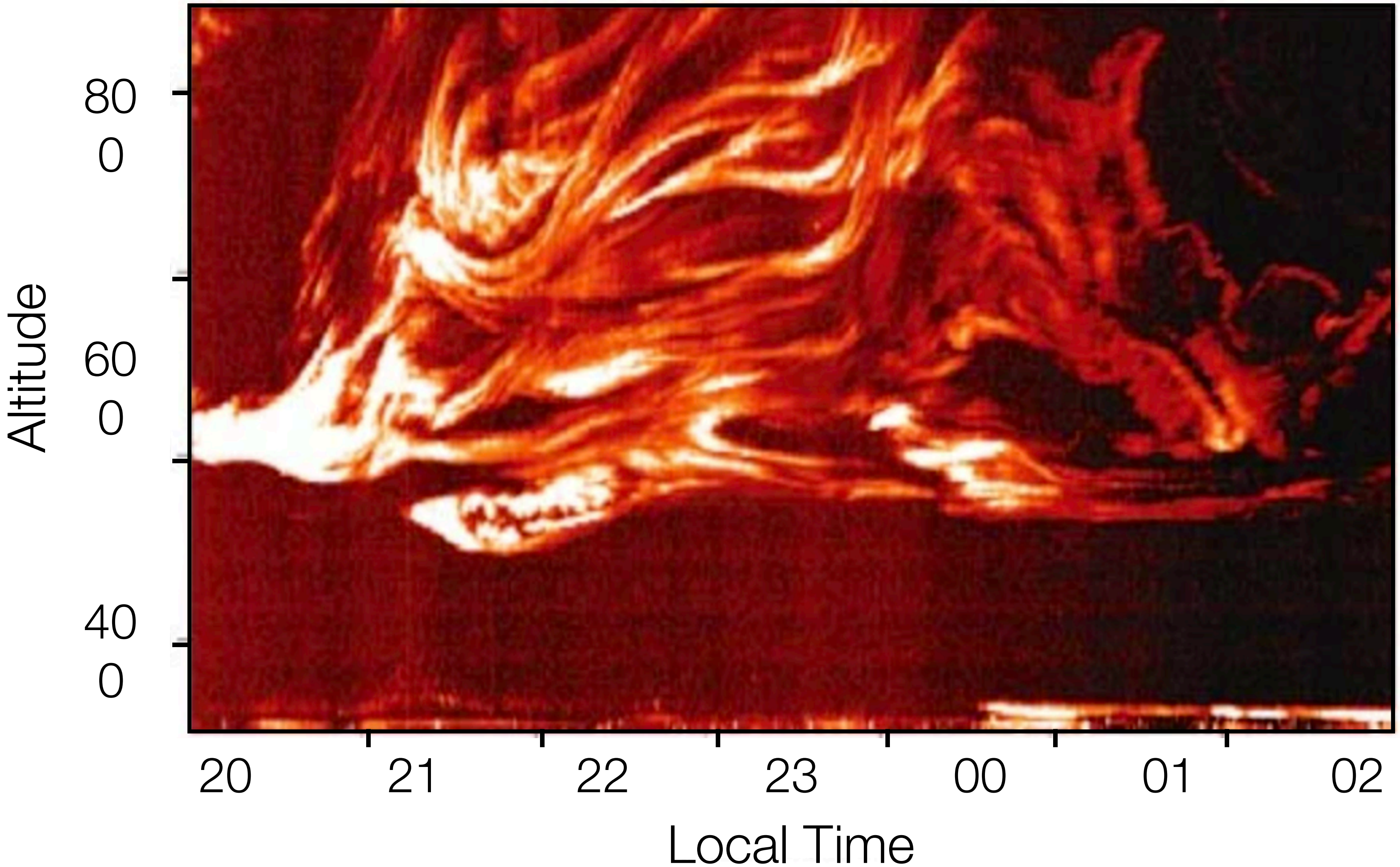
Turbulent processes also exist in the **ionospheric environment**



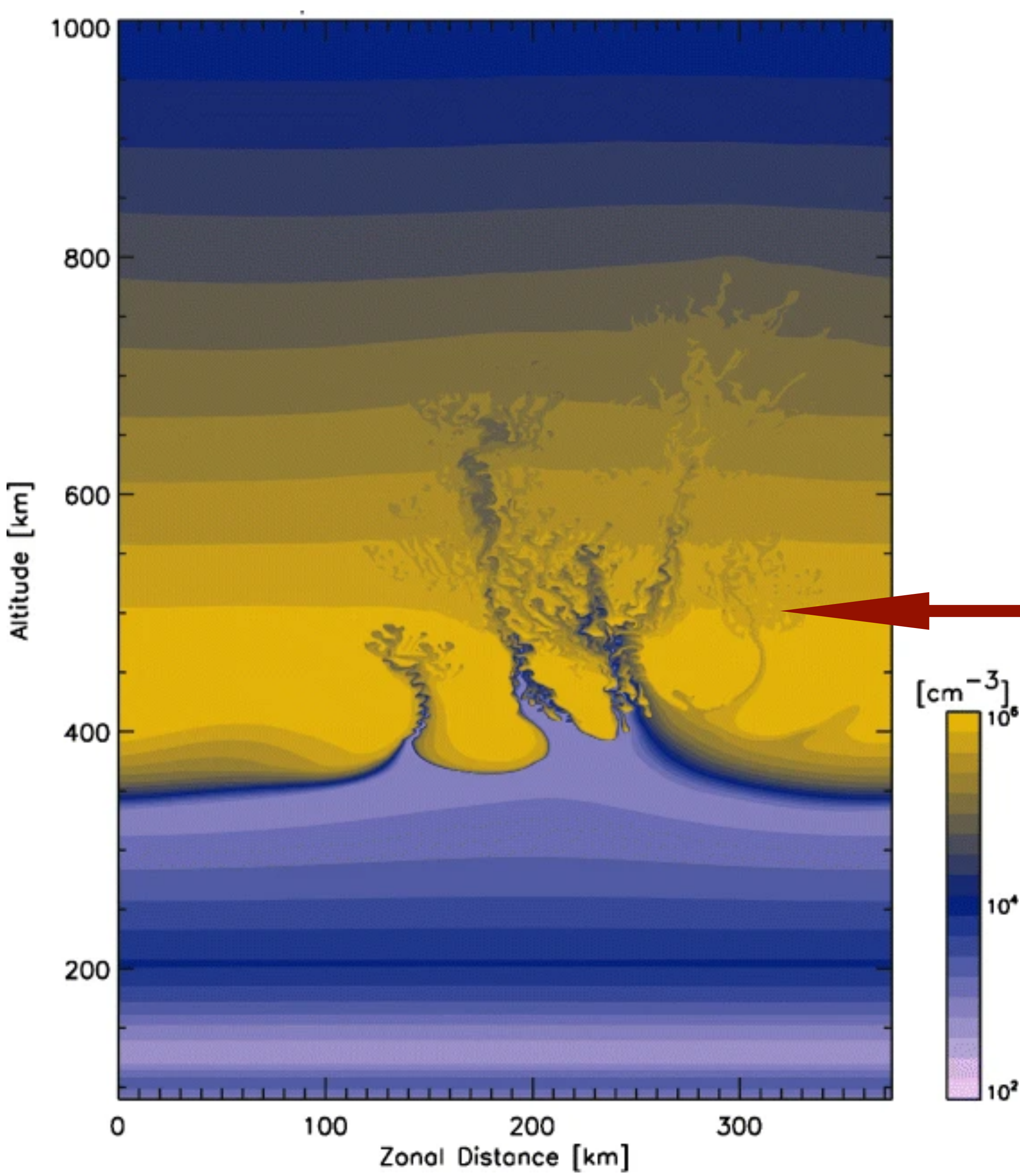
Ionospheric plasma is frequently turbulent, and this turbulence regime plays an important role in the formation and dynamics of ionospheric irregularities.

This figure appeared on the cover of *Space Weather quarterly* digest (Vol. 3, Spring 2006).

Energy spectra of **equatorial plasma bubbles** follow a power-law scaling, indicating a turbulent nature

Plasma Bubbles are plumes of low density plasma that rise up from the bottomside of the F layer towards the exosphere.

They can be observed in the equatorial and low-latitude regions during post-sunset hours



Here, the result of a numerical simulation that shows spatial evolution of EPBs.

This figure clearly shows the non-linear evolution of the irregularity into the ionosphere, which supports its turbulent nature.

Yokoyama, T. *Prog Earth Planet Sci* **4**, 37 (2017).

How can we **learn more about the physical properties** of plasma bubbles?

DATA: Swarm satellites can help us accomplish our goal

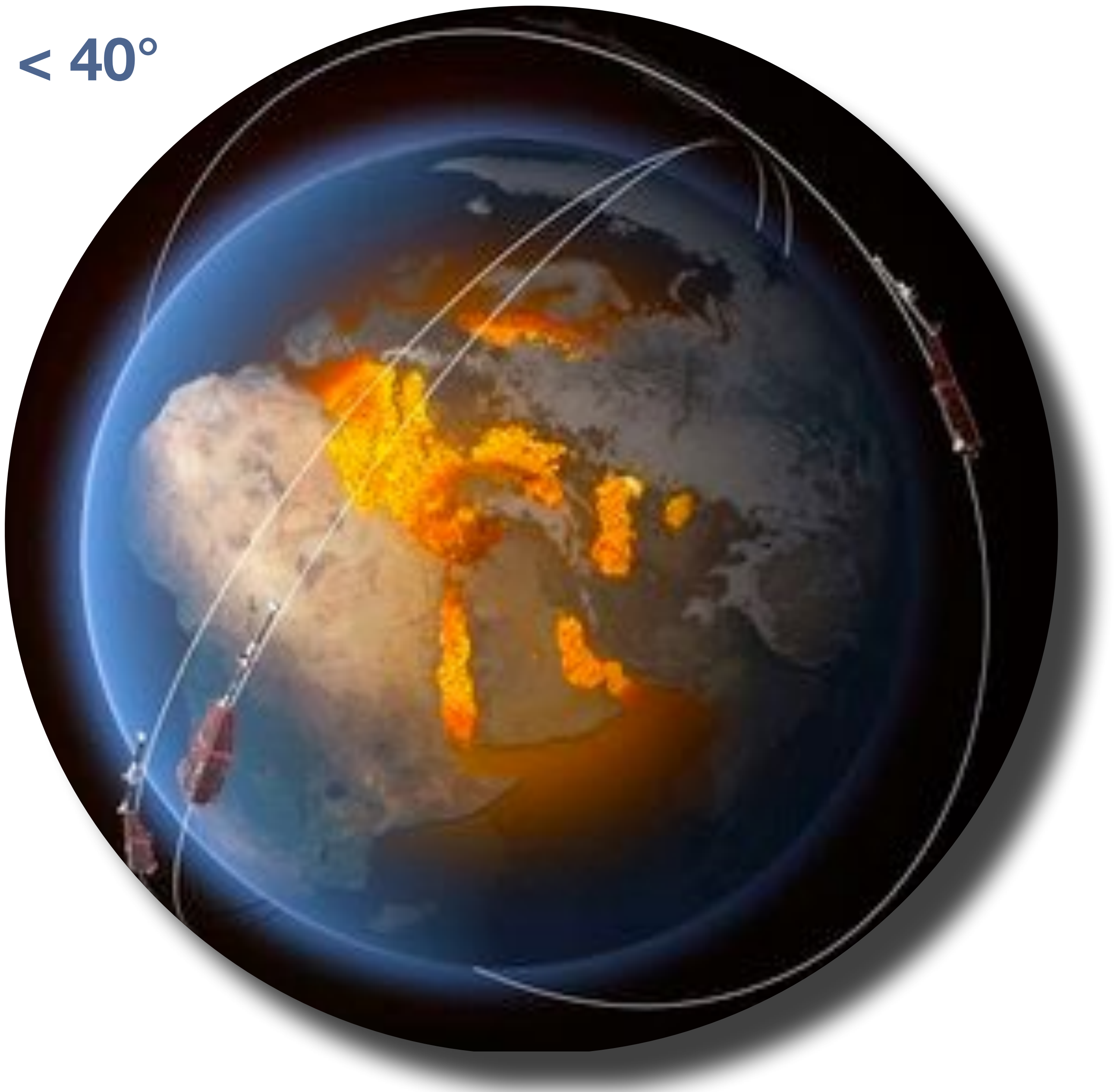
1 April 2014 - 31 January 2016 (High solar activity)

Kp<3 (low/moderate geomagnetic activity)

18:00-24:00 LT

|Lat| < 40°

Swarm A



★1Hz **Electron density** time series

★1 Hz **Magnetic field strength** time series.To highlight the magnetic signatures associated with plasma bubbles, we remove from the magnetic field measurements the contribution due to the magnetic field of internal origin, as modeled by CHAOS-6.

★Swarm Level-2 Ionospheric Bubble Index (**IBI**) product.

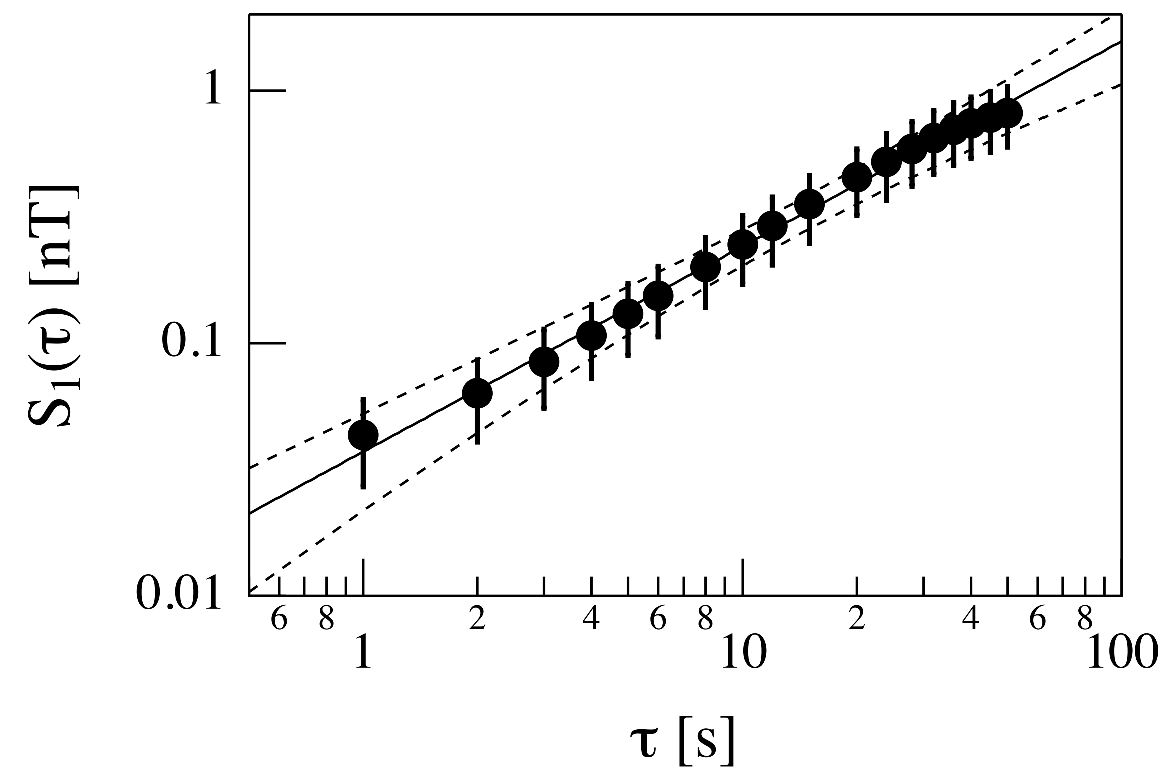
The signal's turbulent nature can be studied thanks to the structure functions

We consider **qth-order structure function** $S_q(\tau)$, which for a signal $N_e(t)$ defined over an interval T is given by

$$S_q(\tau) =< |N_e(t+\tau) - N_e(t)|^q >_T$$

when we deal with a scale-invariant signal the $S_q(\tau)$ exhibits a power law behavior:

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



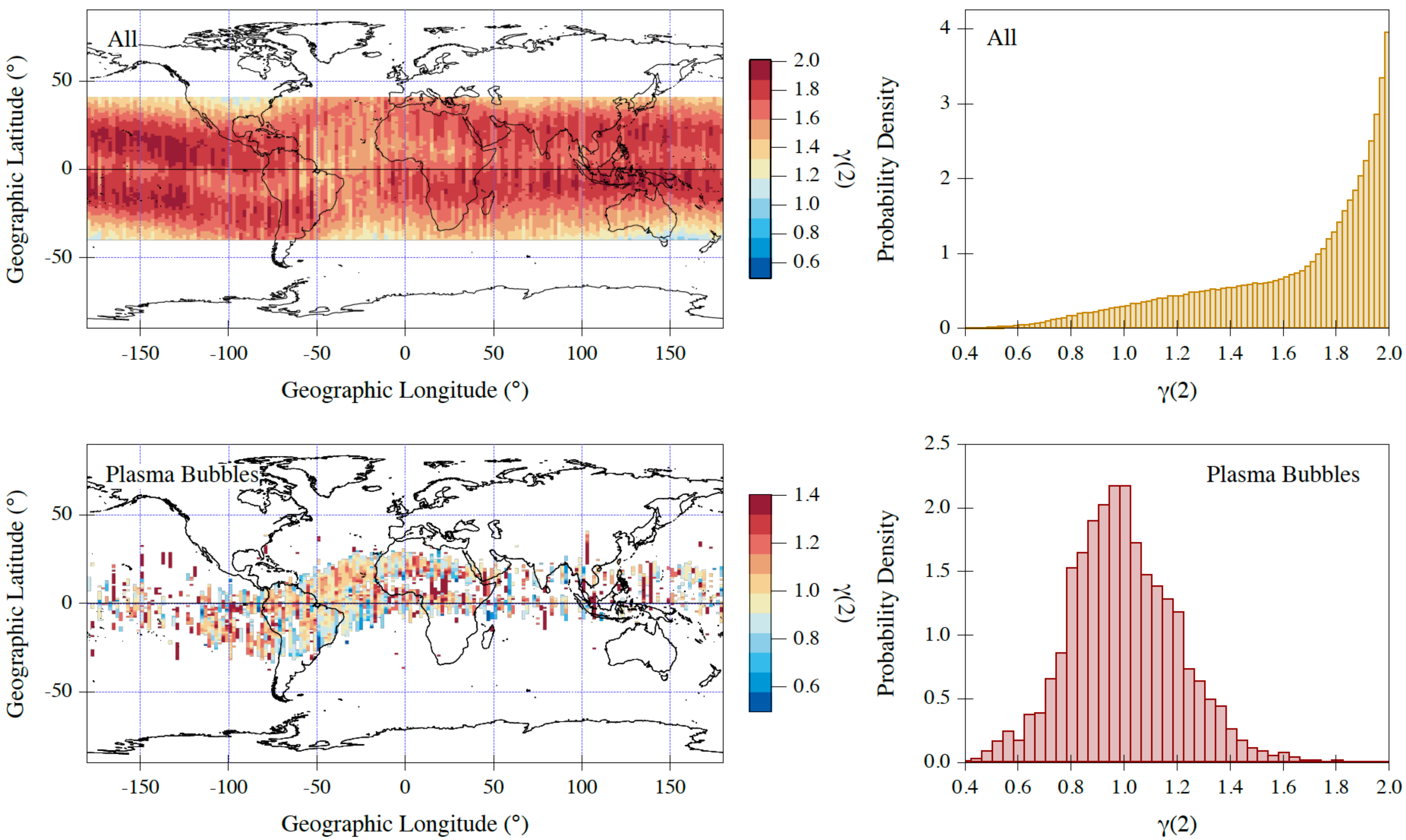
We have estimated:

$\gamma(1)$ first-order scaling exponent, known as Hurst exponent

$\gamma(2)$ second-order scaling exponent, which provides the **Fourier power spectral density exponent** β through Wiener-Khinchin theorem ($\beta = \gamma(2) + 1$)

Results: **Turbulent Character of plasma bubbles**

$$S_2(\tau) = < |N_e(t+\tau) - N_e(t)|^2 >_T \sim \tau^{\gamma(2)}$$



Plasma bubbles exhibit scaling properties, which are completely different from the surrounding environment.

In the case of magnetohydrodynamic turbulence,
the observed spectral features could be the result of a 2D intermittent turbulence due to the formation of coherent structures.

From De Michelis et al., Remote Sensing, 13, 759, 2021

Is it possible to study the **dynamics of plasma bubbles** using **magnetic field scaling properties**?

$$\Delta B \approx -\frac{\mu_0 k_B}{B}\Delta[N_e(T_e + T_i)]$$

Assumptions:

- Plasma is in a steady-state configuration
- Gravity can be neglected
- Field line geometry is linear

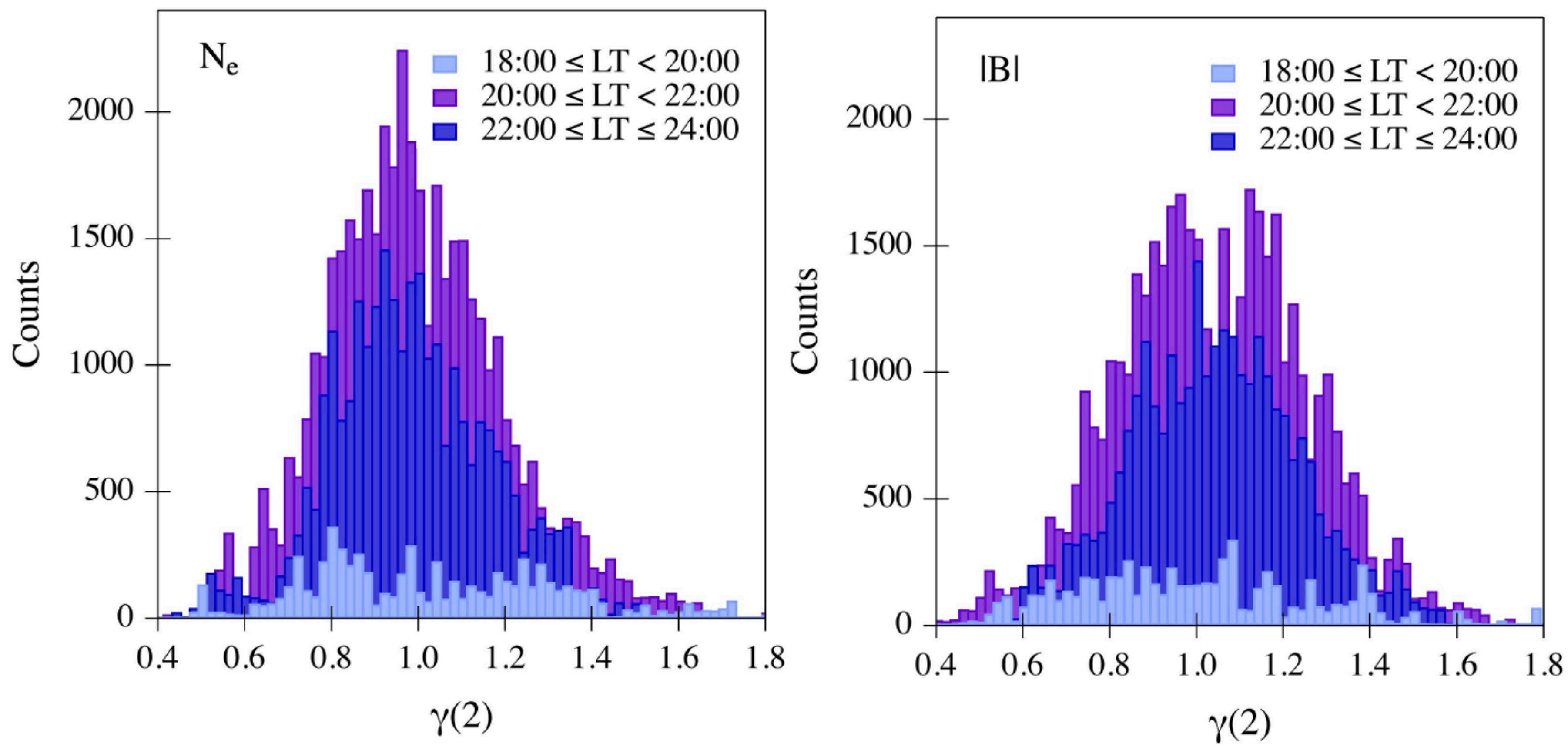
Many important features of EPB have been obtained indirectly from the analysis of their magnetic signatures (for example, the dependence on latitude, longitude, solar and geomagnetic activity have been obtained by using magnetic field data recorded by LEO satellites.

However, the study of the dynamical features of these plasma density irregularities by using only the magnetic field might not be correct being necessary to assume that the scaling properties of the electron density and magnetic field fluctuations are equal.

$$\Delta B \approx C_0\, \Delta N_e \sim \tau^{\gamma(1)} \quad \Longrightarrow \quad \langle |\Delta B|^q \rangle \approx \langle |\Delta N_e|^q \rangle \sim \tau^{\gamma(q)}$$

Is it possible to study the **dynamics of plasma bubbles** using **magnetic field scaling properties**?

$$\Delta B \sim -\frac{\mu_0 k_B}{B}\Delta[N_e(T_e + T_i)]$$



Histograms of $\gamma(2)$ associate with Ne and |B| inside plasma bubbles over three different time intervals is shown here. The distributions differ, particularly in the time interval 20-22 LT, where we see a bimodal distribution in the case of the magnetic field.

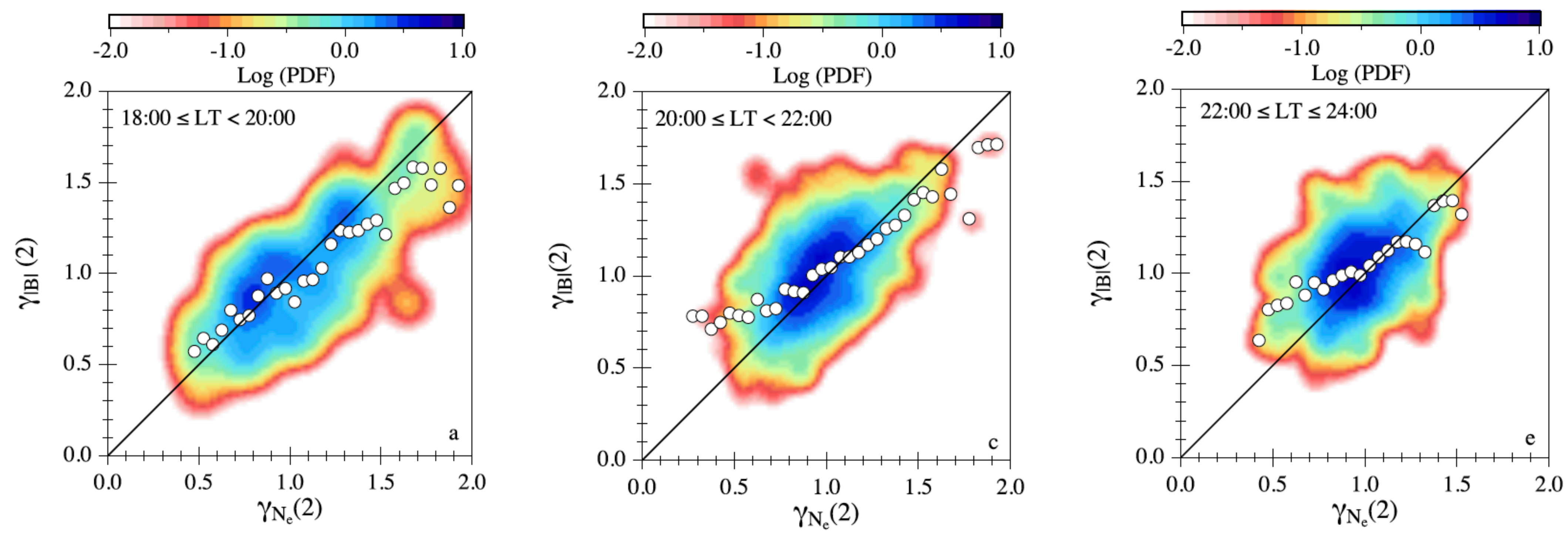
From De Michelis et al., Remote Sensing, 14, 918, 2022

Results: Magnetic field and electron density scaling properties

Our findings suggest that a more complex relation may exist between the spectral features of the electron density and magnetic field in the plasma irregularities, which depends on the local time. The discrepancies depend on the evolution of plasma bubbles with local time and on its turbulent nature.

In the early stage of plasma bubble formation, the instability growth is still quasi-linear, we find a quasi-linear relationship in average between the scaling properties of electron density and those of magnetic field. Conversely, when these structures develop, the evolution of turbulent fluctuations can strongly affect also other physical quantities such as the plasma temperature fluctuations which could modify the spectral features. This means that the assumption of negligible temperature fluctuations could no longer be valid for hours approaching midnight. In other words, the electron temperature fluctuations could play an important role when turbulence is fully developed.

From De Michelis et al., Remote Sensing, 14, 918, 2022



The joint probability distributions of $\gamma(2)$ values relative to Ne and |B| along with the mean values of $\gamma_{|B|}(2)$ exponent (white circles) for fixed $\gamma_{N_e}(2)$ at the three different selected two-hour time intervals.

Papers summarized in the presentation

Open Access | Article

Ionospheric Turbulence and the Equatorial Plasma Density Irregularities: Scaling Features and RODI

by Paola De Michelis [1,*], Giuseppe Consolini [2], Roberta Tozzi [1], Alessio Pignalberi [1], Michael Pezzopane [1], Igino Coco [1], Fabio Giannattasio [1] and Maria Federica Marcucci [2]

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Magnetic Field and Electron Density Scaling Properties in the Equatorial Plasma Bubbles

by Paola De Michelis [1,*], Giuseppe Consolini [2], Tommaso Alberti [2], Roberta Tozzi [1], Fabio Giannattasio [1], Igino Coco [1], Michael Pezzopane [1] and Alessio Pignalberi [1]

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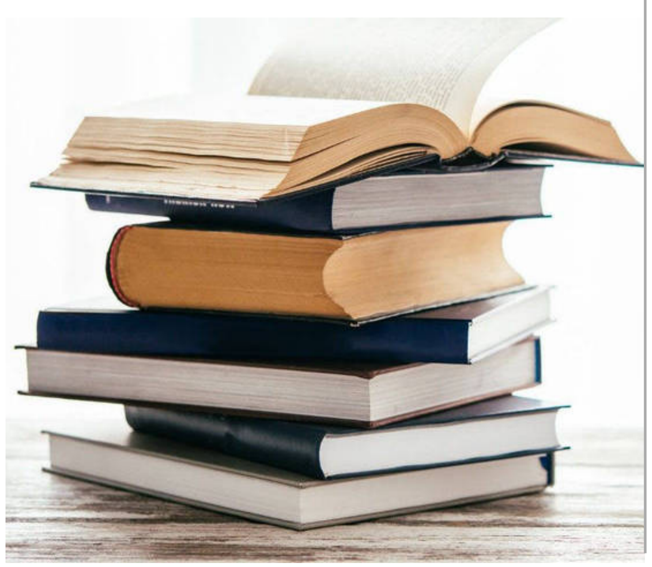

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