Probing astrophysical turbulence via international collaboration

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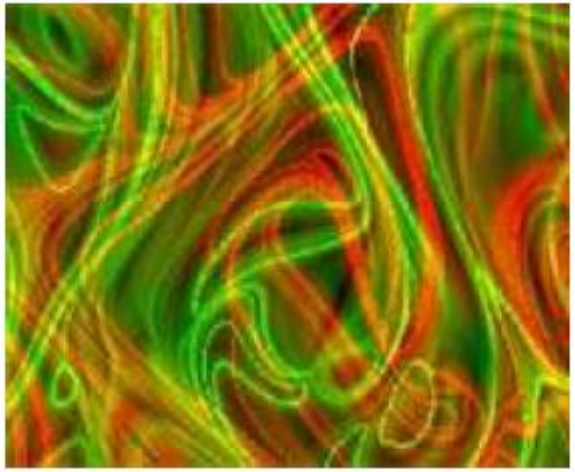

Pesquisadores brasileiros identificam as estruturas coerentes que formam o "esqueleto" dos fluxos turbulentos. Artigos foram publicados no *Astrophysical Journal Letters* (*Foto: Chian/Rempel*)

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Especiais

Esqueleto da turbulência

04/07/2011

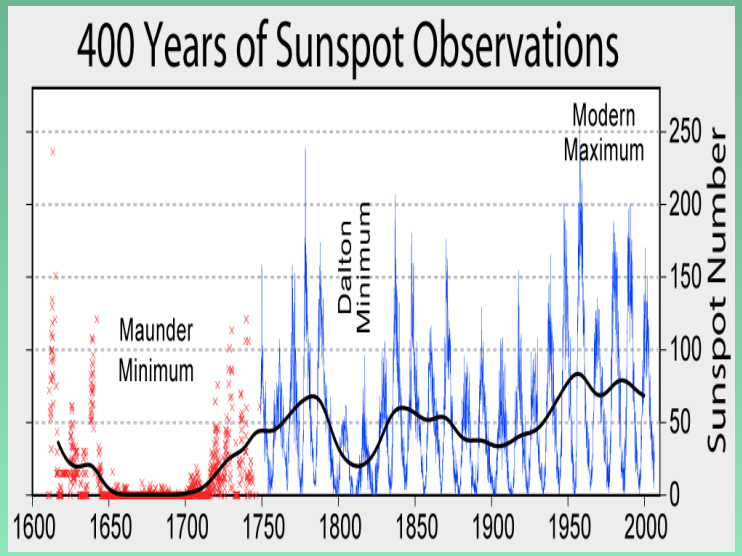
Por Fábio de Castro

Agência FAPESP – Dois estudos liderados por pesquisadores brasileiros e publicados na revista *Astrophysical Journal Letters* identificaram as estruturas coerentes que formam o "esqueleto" da turbulência.

Embora a turbulência seja um fenômeno que se caracteriza pela movimentação caótica das partículas de um fluido, existem técnicas capazes de identificar estruturas coerentes, permitindo a previsão desses movimentos.

Intermittent turbulence

Sunspot cycles: intermittency



X-ray solar image: turbulence

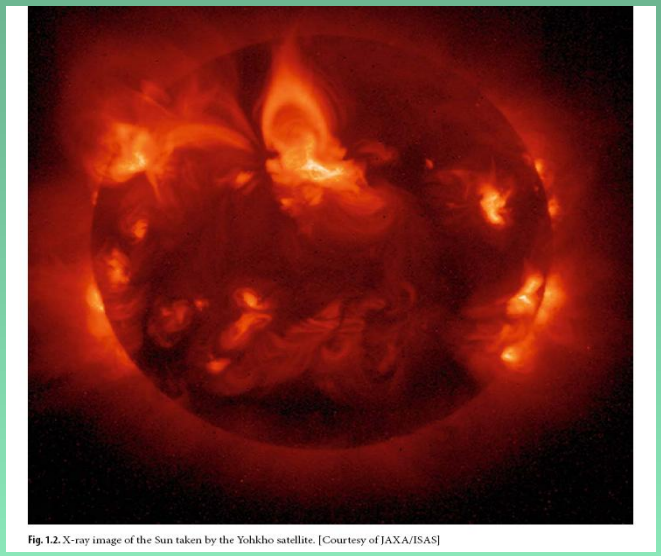


Fig. 1.2. X-ray image of the Sun taken by the Yohkho satellite. [Courtesy of JAXA/ISAS]

- Time series displays random regime switching between laminar periods of small-amplitude fluctuations and bursty periods of large-amplitude fluctuations
- Probability distribution function (PDF) displays a non-Gaussian shape (fat-tails and sharp peak) due to an excess of large- and small-amplitude fluctuations at small scales
- Power spectrum displays a power-law behavior indicative of multiscale interactions in energy cascade
- Image displays localized regions of clustering related to coherent structures

***Ref**: Bohr et al. (1998): Dynamical systems approach to turbulence (Cambridge U. Press)*
Brandenburg & Spiegel, AN (2008): Butterfly diagram => On-off intermittent solar dynamo

Outline

- **Observation of turbulence in the solar wind**
- **Simulation of turbulence in a stellar dynamo**
- **Theory of turbulence in fluids & plasmas**

Observation of turbulence in the solar wind

Coronal mass ejection

The Astrophysical Journal Letters, 733:L34 (5pp), 2011 June 1 doi:10.1088/2041-8205/733/2/L34

DETECTION OF CURRENT SHEETS AND MAGNETIC RECONNECTIONS AT THE TURBULENT LEADING EDGE OF AN INTERPLANETARY CORONAL MASS EJECTION

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ABSTRACT

The relation between current sheets, turbulence, and magnetic reconnections at the leading edge of an interplanetary coronal mass ejection detected by four *Cluster* spacecraft on 2005 January 21 is studied. We report the observational evidence of two magnetically reconnected current sheets in the vicinity of a front magnetic cloud boundary layer with the following characteristics: (1) a Kolmogorov power spectrum in the inertial subrange of the magnetic turbulence, (2) the scaling exponent of structure functions of magnetic fluctuations exhibiting multi-fractal scaling predicted by the She–Leveque magnetohydrodynamic model, and (3) bifurcated current sheets with the current density computed by both single-spacecraft and multi-spacecraft techniques.

Key words: magnetic reconnection – plasmas – shock waves – solar wind – Sun: coronal mass ejections (CMEs) – turbulence

Current sheets & Kolmogorov magnetic turbulence at the leading edge of the interplanetary coronal mass ejection of 21 January 2005: Cluster mission

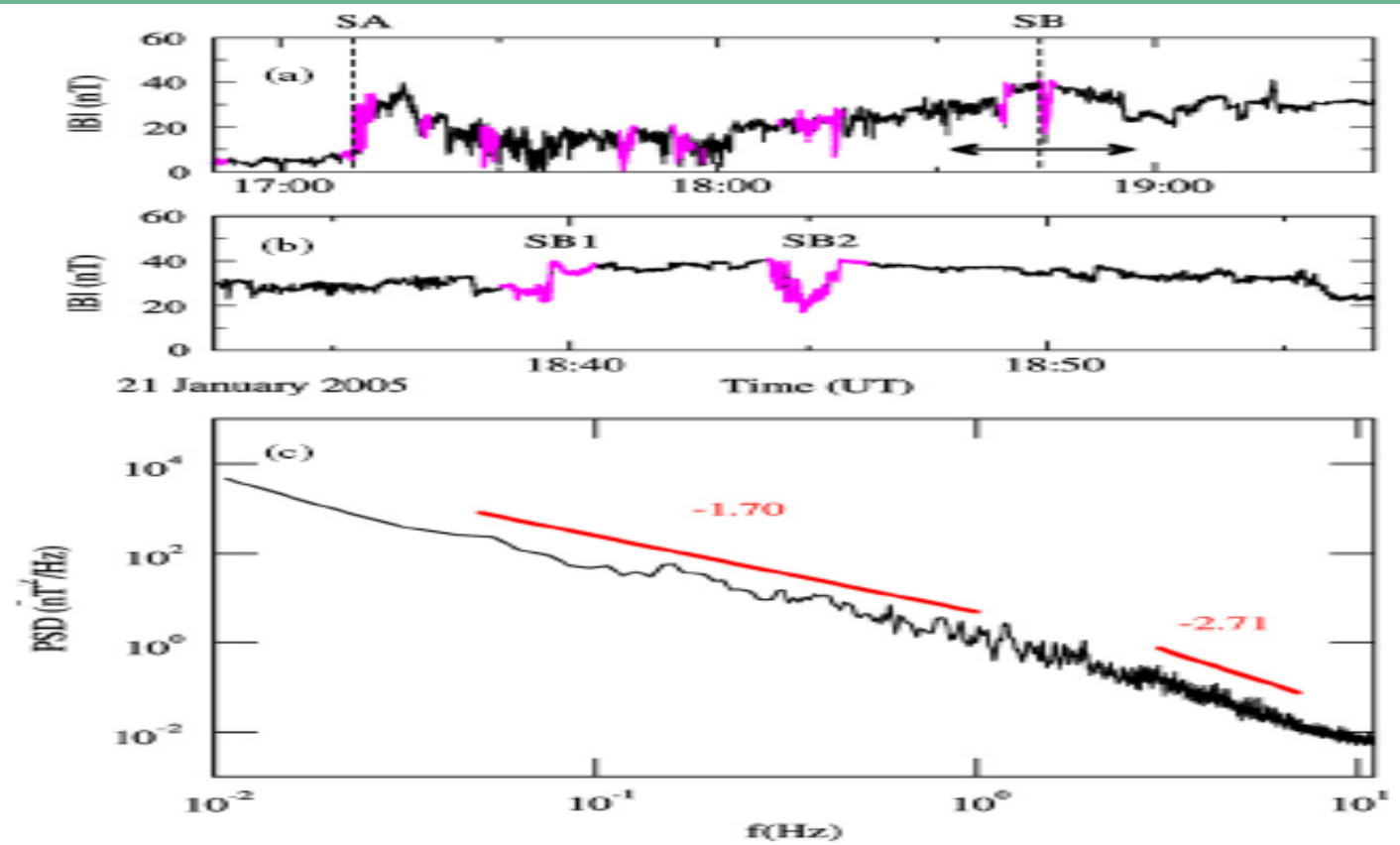

Figure 1. Detection of current sheets and magnetic turbulence by *Cluster-1* at the ICME shock of 2005 January 21. (a) Time series of $|\mathbf{B}|$ (nT) superposed by current sheets detected by the Li (2008) method, for the critical angle $\theta = 60^\circ$ and the timescale $T = 120$ s. Magenta dots indicate the points that belong to a current sheet. SA denotes the primary shock arrival. SB1 and SB2 denote the two current sheets associated with the leading edge (SB) of the ICME ejecta. (b) An enlargement of the time interval marked by a bar in (a). (c) Power spectral density, PSD ($nT^2\ Hz^{-1}$), of $|\mathbf{B}|$ for the time interval of (b); straight lines indicate the inertial and dissipative subranges. The spectral indices are calculated by a linear regression of the log–log PSD data.

Turbulence: intermittent, non-Gaussian & multifractal

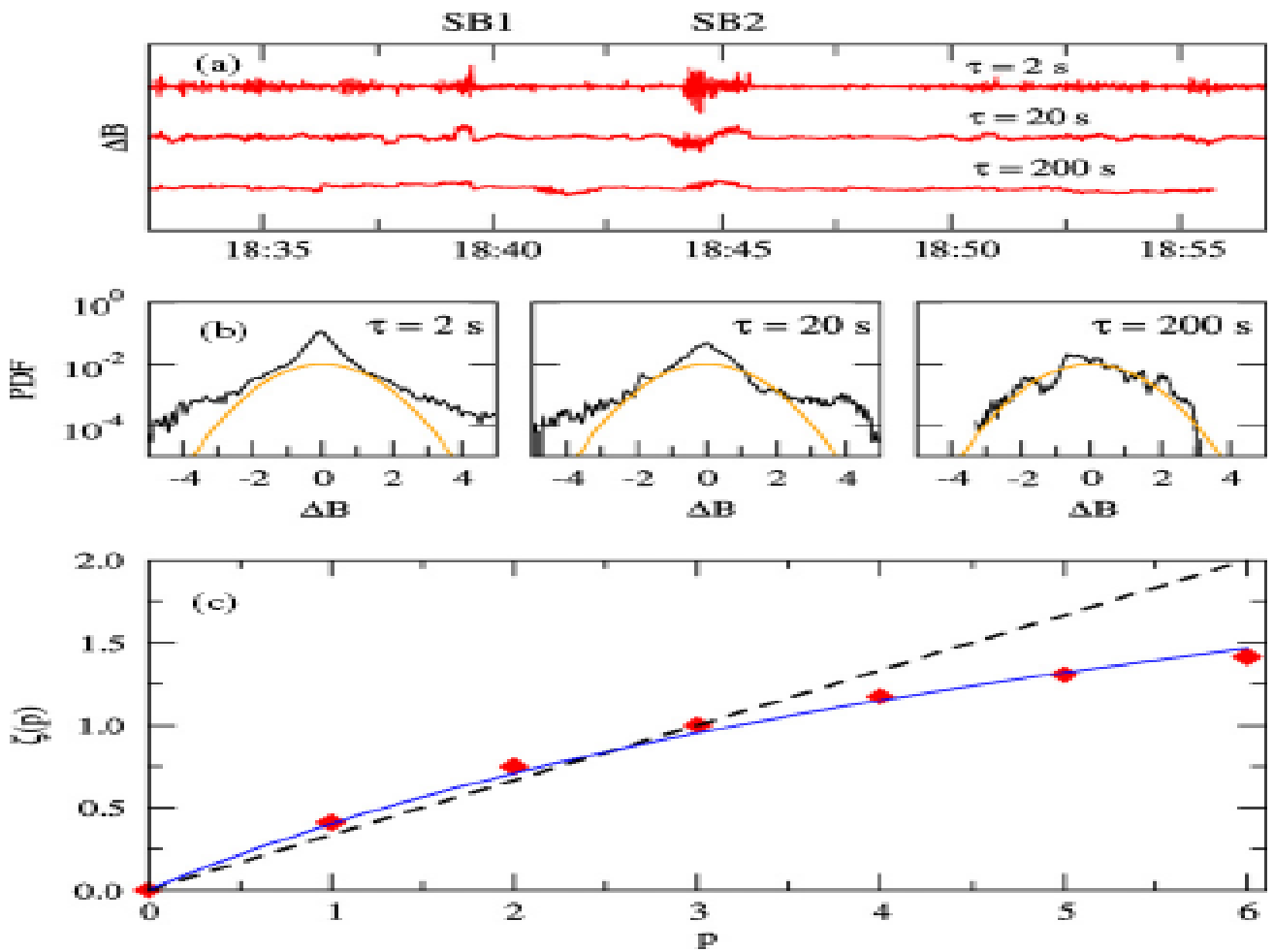

Figure 2. Scale dependence for three different timescales ($\tau = 2$ s, 20 s, and 200 s) of Figure 1(b). (a) The normalized magnetic-field two-point differences ΔB. (b) The probability density function (PDF) of ΔB, superposed by a Gaussian PDF (orange line). (c) Scaling exponent ζ of the pth-order structure function for observed values (red diamonds), superposed by the K41 self-similar scaling (black dashed line), and the multi-fractal prediction of the She–Leveque MHD model (blue curve).

Magnetic reconnection: current sheets & jets

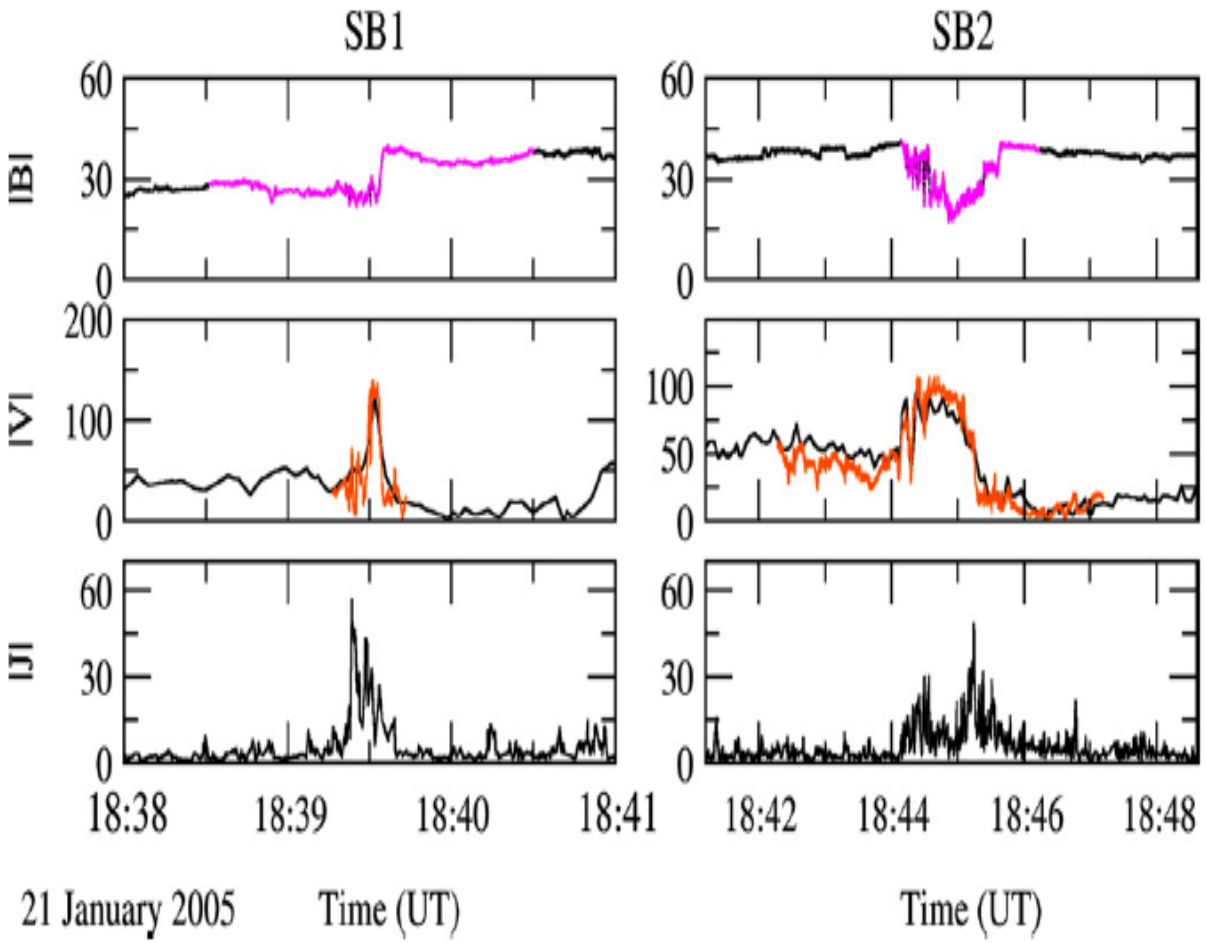

Figure 3. Detection of magnetic reconnections at the leading edge of ICME associated with the current sheets SB1 and SB2 (magenta). |**B**| (nT) is the modulus of magnetic field (enlargement of Figure 1(b)); |**V**| (km s^{-1}) is the modulus of the observed plasma velocity (black) and the plasma velocity (orange) predicted by the magnetic reconnection theory of Sonnerup et al. (1981); |**J**| (nA m^{-2}) is the modulus of current density computed by the multi-spacecraft curlometer technique of Dunlop et al. (2002).

Simulation of turbulence in a stellar dynamo

THE ASTROPHYSICAL JOURNAL LETTERS, 735:L9 (7pp), 2011 July 1 doi:10.1088/2041-8205/735/1/L9

LAGRANGIAN COHERENT STRUCTURES IN NONLINEAR DYNAMOS

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ABSTRACT

Turbulence and chaos play a fundamental role in stellar convective zones through the transport of particles, energy, and momentum, and in fast dynamos, through the stretching, twisting, and folding of magnetic flux tubes. A particularly revealing way to describe turbulent motions is through the analysis of Lagrangian coherent structures (LCSs), which are material lines or surfaces that act as transport barriers in the fluid. We report the detection of LCSs in helical MHD dynamo simulations with scale separation. In an Arnold–Beltrami–Childress flow, two dynamo regimes, a propagating coherent mean-field regime and an intermittent regime, are identified as the magnetic diffusivity is varied. The sharp contrast between the chaotic tangle of attracting and repelling LCSs in both regimes permits a unique analysis of the impact of the magnetic field on the velocity field. In a second example, LCSs reveal the link between the level of chaotic mixing of the velocity field and the saturation of a large-scale dynamo when the magnetic field exceeds the equipartition value.

Key words: chaos – dynamo – magnetohydrodynamics (MHD)

Traveling-wave dynamo *Intermittent dynamo*

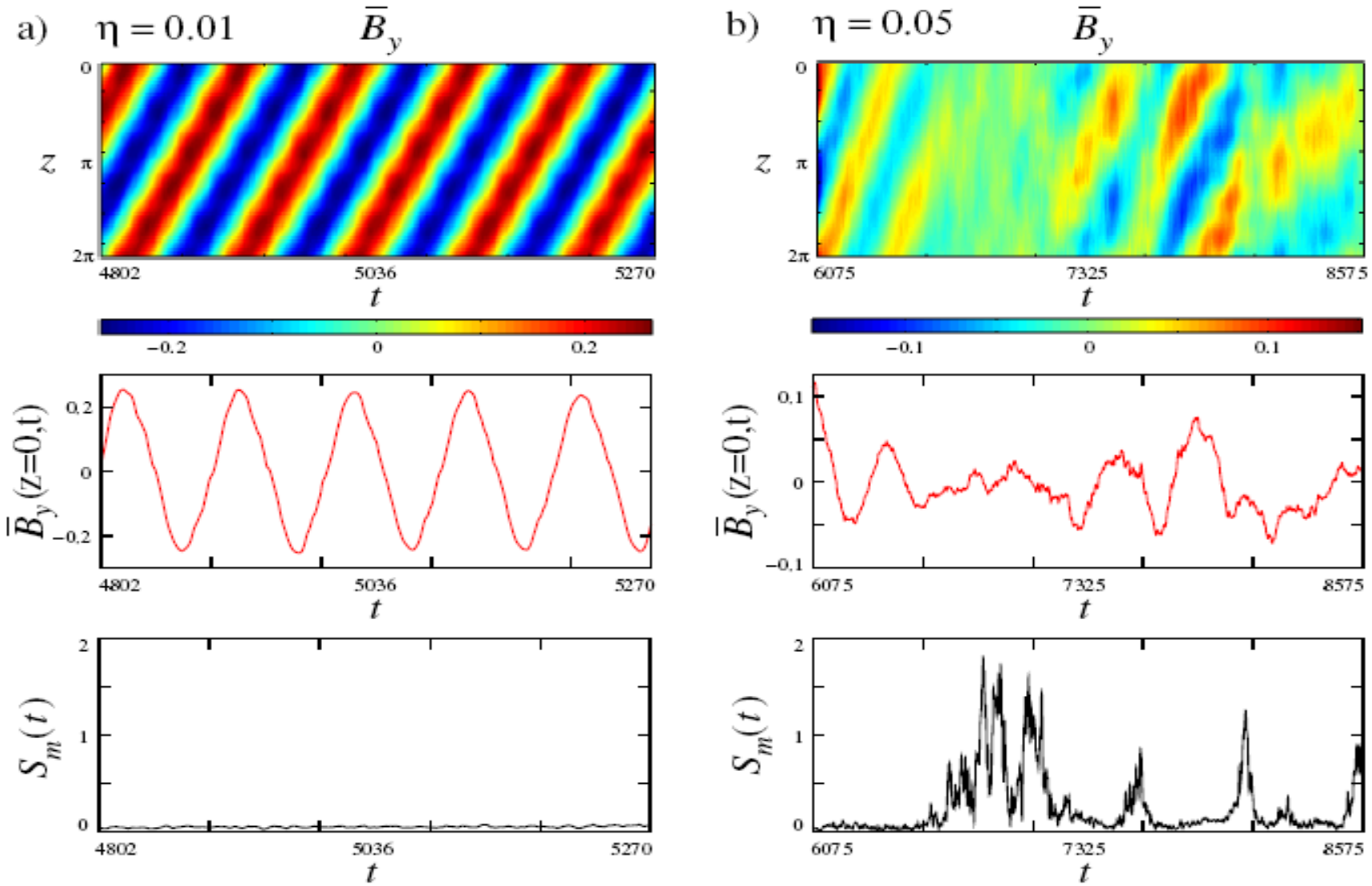

FIG. 2.— Dynamics of $\bar{B}_y$, the xy–average of the B_y component of the magnetic field. (a) Space–time evolution of $\bar{B}_y$ (upper panel), the time series of $\bar{B}_y$ at $z = 0$ (mid panel) and the spectral entropy $S_m(t)$ (lower panel) for $\eta = 0.01$. The space–time patterns of the mean field $\bar{B}_y$ display characteristics of a travelling–wave dynamo. (b) Same as (a) but for $\eta = 0.05$, displaying an intermittent dynamo.

Coherent structures in turbulence

Eulerian ***Lagrangian***

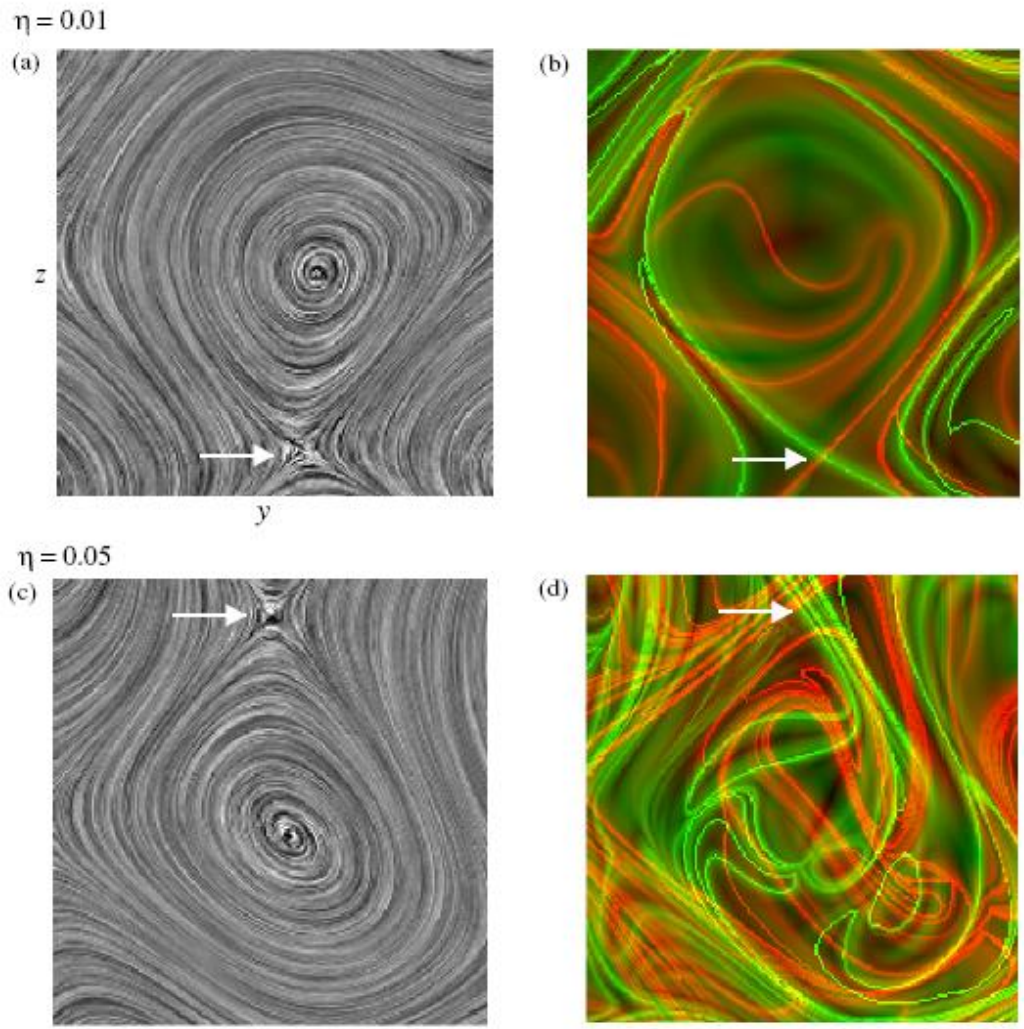

Figure 4. Enlargement of the rectangular areas in Figure 3. (a and b) The velocity field and Lagrangian coherent structures for $\eta = 0.01$. (c and d) Same as (a) and (b) but for $\eta = 0.05$.

Theory of turbulence in fluids & plasmas


冨嶽三十六景 神奈川沖
浪裏

Complex systems approach to turbulence

- **Phase synchronization in intermittent turbulence**

  He & Chian, PRL 2003

- **Chaotic transients in intermittent turbulence**

  Rempel & Chian, PRL 2007

- **Amplitude-phase synchronization in intermittent turbulence**

  Chian, Miranda, Rempel, Saiki & Yamada, PRL 2010

PRL 104, 254102 (2010) PHYSICAL REVIEW LETTERS week ending 25 JUNE 2010

Amplitude-Phase Synchronization at the Onset of Permanent Spatiotemporal Chaos

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Amplitude and phase synchronization due to multiscale interactions in chaotic saddles at the onset of permanent spatiotemporal chaos is analyzed using the Fourier-Lyapunov representation. By computing the power-phase spectral entropy and the time-averaged power-phase spectra, we show that the laminar (bursty) states in the on-off spatiotemporal intermittency correspond, respectively, to the nonattracting coherent structures with higher (lower) degrees of amplitude-phase synchronization across spatial scales.

Amplitude-phase synchronization due to NL multiscale interactions

On-off intermittency at the laminar-turbuence transition

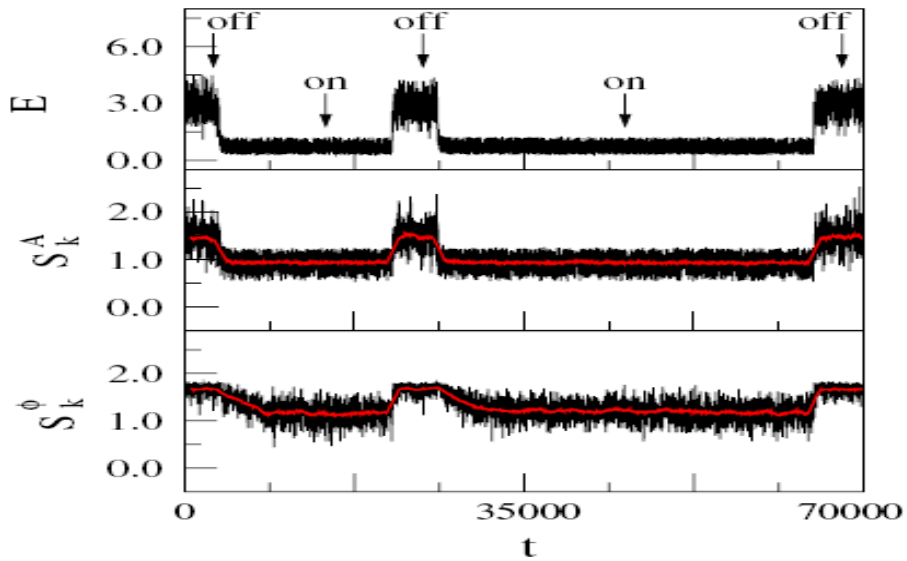

FIG. 1 (color online). Time series of E, S_k^A, and S_k^ϕ for on-off spatiotemporal intermittency at $\varepsilon = 0.20005$. The red lines denote averaged curves.

Fourier power-phase spectral entropy

Energy (E) time series of on-off spatiotemporal intermittency (STCA) at the onset of spatiotemporal chaos (ε = 0.20005). Two lower left panels show the amplitude dynamics quantified by the Fourier power spectral entropy (S_k^A) and the amplitude disorder parameter (D_k^A). Two lower right panels show the phase dynamics quantified by the Fourier phase spectral entropy (S_k^ϕ) and the phase disorder parameter (D_k^ϕ). The red lines denote the smoothed curves to identify the on-off states.

Ref: Chian et al. PRL 2010

Ann. Geophys., 27, 1789–1801, 2009
www.ann-geophys.net/27/1789/2009/

Annales Geophysicae

Cluster and ACE observations of phase synchronization in intermittent magnetic field turbulence: a comparative study of shocked and unshocked solar wind

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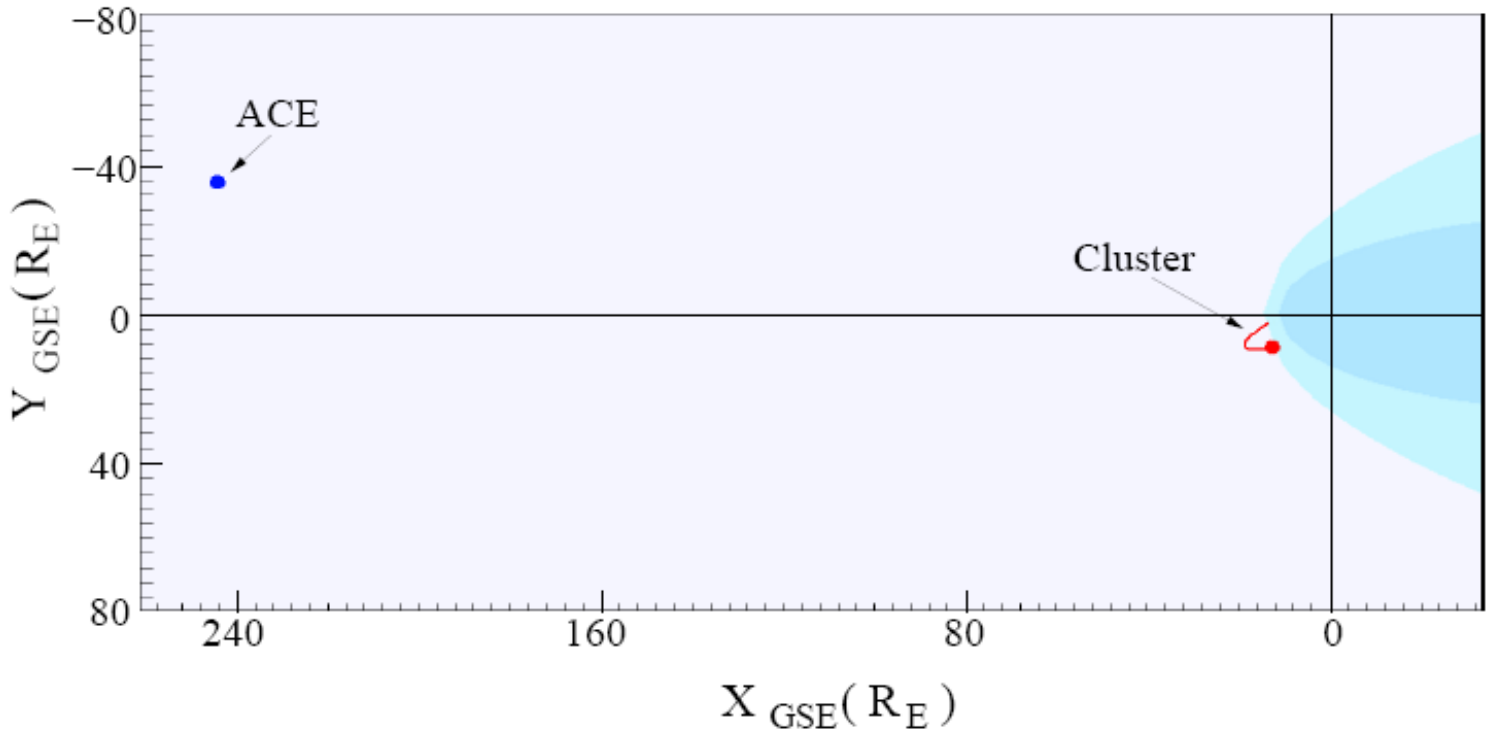

Fig. 1. Orbit trace of Cluster-1 and spacecraft position of ACE, in the GSE coordinate system, from 19:40:40 UT on 1 February 2002 to 03:56:38 UT on 3 February 2002. The starting position of Cluster is shown as a full circle.

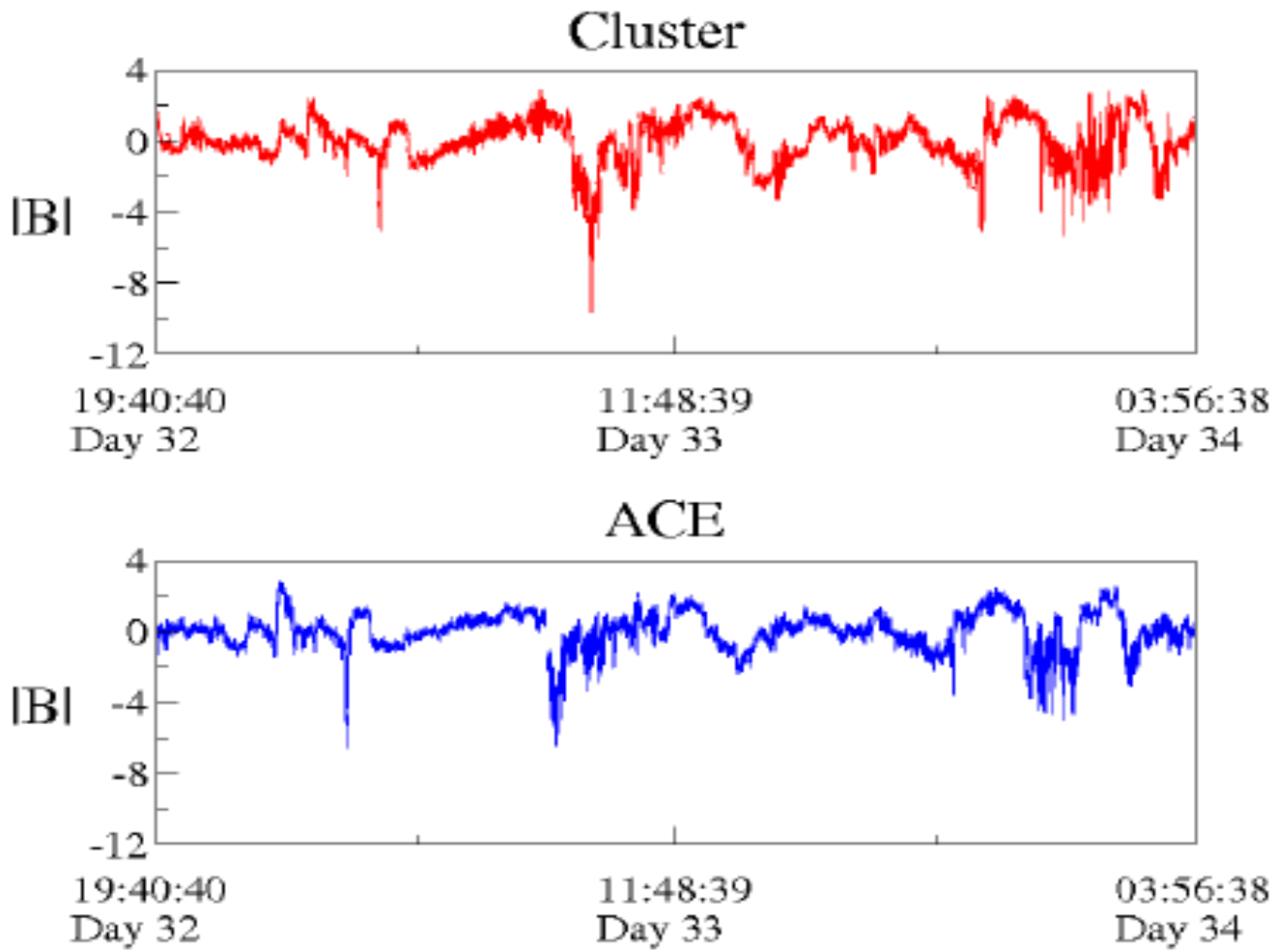

Fig. 4. Time series of the modulus of magnetic field $|B|$ (nT) of Cluster-1 and ACE, after removing the trend by computing a cubic fitting of the original data.

Amplitude-phase synchronization: NL multiscale interactions

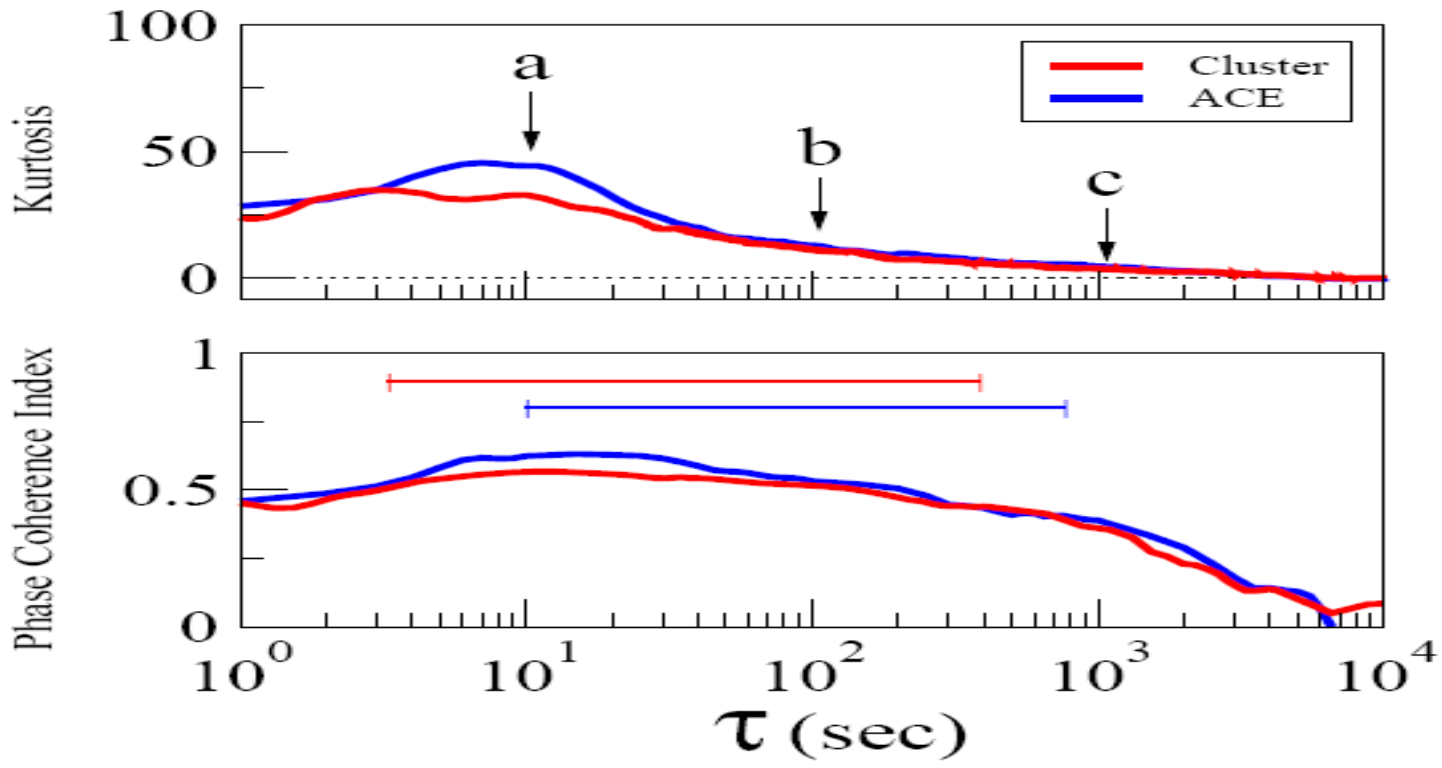

Fig. 10. Kurtosis and phase coherence index of $|B|$ measured by Cluster-1 (red) and ACE (blue). Letters a, b and c indicate scales $\tau = 10$, 100 and 1000 s, respectively. The bars indicate the inertial subrange of each spacecraft obtained from Fig. 5. The inverse of the ion cyclotron frequency $f_{ci} \sim 0.12$ Hz in the solar wind frame is $\tau \sim 8.3$ s, which is near the peak regions of kurtosis and phase coherence index.

Refs: Koga, Chian et al., PRE 2007; Chian & Miranda, AG 2009

Perspectives of ALMA/LLAMA: probing the astrophysical turbulence

(M100 observed by Hubble Space Telescope)

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Thank you !