

Analysing turbulent energy cascade in a coronal mass ejection using empirical mode decomposition

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ABSTRACT

Context. Coronal mass ejections (CMEs) are large-scale expulsions of plasma and magnetic flux that emanate from the Sun's corona and travel into the heliosphere. Once in interplanetary space, they are referred to as interplanetary coronal mass ejections (ICMEs) and are often characterised by a shock wave, a sheath region, and, in some cases, a magnetic cloud. ICMEs are capable of driving magnetic disturbances that can trigger geomagnetic storms and significantly influence space weather.

Aims. The turbulent nature of CMEs has been well established by previous studies using Fourier and wavelet-based methods. In the present work, we applied empirical mode decomposition (EMD) in conjunction with Hilbert spectral analysis (HSA) to investigate the turbulence characteristics at different stages of the ICME event observed on 27 June 2013 by the MAG instrument on board NASA's ACE spacecraft.

Methods. We divided the ICME event into four regions: (i) the preceding solar wind, (ii) the sheath region, (iii) the magnetic cloud, and (iv) the trailing solar wind. The magnetic field components (B_x , B_y , and B_z) of the four regions were decomposed into intrinsic mode functions (IMFs) using EMD. The instantaneous frequencies and amplitudes of the extracted IMFs were derived using HSA to generate the Hilbert spectra. The energy distribution across frequencies was computed from the second-order marginal Hilbert spectra, and the spectral slopes in the inertial range were calculated from linear fits.

Results. For the solar wind preceding the ICME shock, the HSA shows a slope close to the Kolmogorov value ($\alpha_{HHT} \approx -1.68$), indicating a fully developed turbulence at 1 AU. A clear steepening is observed in the sheath and in the trailing solar wind ($\alpha_{HHT} \approx -1.78$ and -1.79), consistent with increased intermittency and intensified non-linear activity associated with shock compression and solar wind-ICME interactions. Within the magnetic cloud, the scaling exponent becomes slightly less steep ($\alpha_{HHT} \approx -1.71$), suggesting that the effects that cause the spectral steepening in the sheath and downstream wind are less prevalent inside the large-scale flux ropes.

Conclusions. Our results show that ICME passage modifies the turbulent energy distribution across scales. The EMD-HSA method provides smoother and more stable spectral estimates than the conventional Fourier approach, making it well suited for analysing turbulence in non-stationary solar wind structures.

Key words. Sun: coronal mass ejections (CMEs) – Sun: magnetic fields – solar wind – Turbulence

1. Introduction

Coronal mass ejections (CMEs) are eruptions of tremendous amounts of plasma and magnetic flux from the Sun's corona that propagate into the heliosphere. The matter expelled comprises primarily charged particles in the form of protons and electrons that are carried with the solar wind towards interplanetary space. These particles are embedded in the ejected magnetic field along twisted helical coherent structures, known as flux ropes, which result from the magnetic reconnection of field lines in the Sun's corona (Chintzoglou et al. 2015; Chen 2017; James et al. 2017; James et al. 2018). The first evidence of a documented CME dates back to 1971 (Tousey et al. 1973); it was recorded by the white-light coronagraph on board Orbiting Solar Observatory 7 (OSO 7) (Koomen et al. 1975), and since then, CMEs have continued to garner significant interest in the field of solar physics.

Past studies attempted to classify CMEs based on their structural and intrinsic properties. Howard et al. (1985) studied 998 CMEs observed from 1979 to 1981 and categorised them into

nine major classes based on their morphological characteristics, thereby suggesting that a CME's properties strongly depend on its structure. Nicewicz & Michalek (2016) conducted a quantitative analysis of 6621 CMEs recorded between 1996 and 2004, and proposed four categories based on their acceleration, angular width, velocity, and mass. In 2013, the Space Weather Research Center at NASA's Goddard Space Flight Center introduced the CME SCORE scale, which categorises CMEs into five classes based on their speeds: S (Slow, <500 km/s), C (Common, 500-999 km/s), O (Occasional, 1000-1999 km/s), R (Rare, 2000-2999 km/s), and ER (Extremely Rare, >3000 km/s) (Evans et al. 2013). However, no past studies have reliably classified CMEs based on their turbulence properties determined via remote imaging.

Coronal mass ejections travelling farther away from the Sun and entering interplanetary space are referred to as interplanetary coronal mass ejections (ICMEs) (Gosling et al. 1991; Kilpua et al. 2017a; Song et al. 2020; Zhang et al. 2021; Davies et al. 2021). *In situ* observations have shown that ICMEs often exhibit a forward shock that accelerates the charged particles from the

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solar ejecta towards interplanetary space. These charged particles are capable of triggering disturbances in the magnetosphere, resulting in magnetic storms and indicating the arrival of a possible ICME. The passage of the ICME-driven shocks is followed by a region with a relatively strong magnetic field, known as the ICME sheath, which forms due to the combined mechanism of CME propagation and expansion (Siscoe & Odstrcil 2008). It is characterised by an abrupt increase in the solar wind temperature, density, and speed, making it an extensive laboratory to study the plasma properties of the solar wind (Kilpua et al. 2017b; Richardson & Cane 2024). An ICME-driven shock is usually accompanied by a magnetic cloud (MC), a term introduced by Burlaga et al. (1981) to denote the gas clouds emitted from the Sun into the interplanetary medium. An MC can be distinguished from its surrounding solar wind by its relatively strong magnetic field, smoothly rotating magnetic field components due to the presence of flux ropes, reduced plasma beta ratio, i.e. a plasma pressure to magnetic pressure ratio (β) < 1 and lower proton temperature and density resulting from its expansion into the interplanetary space (Burlaga et al. 1981; Klein & Burlaga 1982; Gosling & McComas 1987; Rouillard 2011). ICMEs play a crucial role in influencing space weather and are responsible for the origin of some of the most intense geomagnetic storms (Wu & Lepping 2002; Wu et al. 2006).

Investigations have shown that there is more intense and more intermittent turbulence in the sheaths of ICMEs than in the preceding ambient solar wind (Sorriso-Valvo et al. 2021; Kilpua et al. 2021a; Ghuge et al. 2025). This can be attributed to the compressed nature of plasma in the sheath, which in turn results from the power injected earlier by the shock. Moreover, the solar wind itself is known to exhibit turbulent, anisotropic, and intermittent behaviour (Bruno & Carbone 2013), resulting in energy-transfer processes that govern plasma heating and particle acceleration. Early evidence of turbulence in the solar wind was reported by Coleman (1968), who found turbulent fluctuations in the magnetic field and the radial velocity component by analysing their spectral densities using data from the Mariner 2 spacecraft at 1 AU. Subsequent studies have shown that cross-scale energy transfer due to turbulence in the solar wind follows a power-law behaviour across the injection, inertial, and dissipation ranges. For fully developed turbulence observed at 1 AU via in situ measurements, it was found that the power-law scaling resembles that of the hydrodynamic turbulence, as described by Kolmogorov (1941).

Turbulence in solar wind and CMEs has been studied extensively using well-established methods of Fourier analysis and Morlet wavelet analysis (Zhao et al. 2021; Soljento et al. 2023; Ruohotie et al. 2025). In this work, however, we employed the novel technique of empirical mode decomposition (EMD) (Huang et al. 1998) to analyse the turbulence properties across different regions of an ICME event. This method breaks down the signal into a finite set of simpler modes. The Hilbert transform was applied to each of the obtained modes to extract its instantaneous frequency and amplitude, a process known as Hilbert spectral analysis (HSA). While the Fourier and wavelet-based methods assume local stationarity and linearity in the signal data, the EMD-HSA framework is not restricted to these constraints and is shown to work well with non-linear, non-stationary, and turbulent data, which are some of the common characteristics of solar wind signals. The technique has previously been applied to solar wind data to study the scaling properties and identify the spectral exponents associated with turbulence (Carbone et al. 2018; Alberti et al. 2019; Carbone et al. 2020, 2021), to examine the temporal behaviour of the solar

magnetic field at different heliographic latitudes (Vecchio et al. 2012), to derive the rotational cycle and stability of solar mean magnetic flux elements (Xiang & Qu 2016), and to analyse the long-term solar variability and grand minima occurrence (Vecchio et al. 2017). However, to the best of our knowledge, the EMD-HSA methodology had not been used to analyse the turbulence characteristics across different ICME stages.

Empirical mode decomposition has been widely used in many fields that deal with non-linear and non-stationary real time-series data. These include a broad spectrum of scientific and applied domains such as seismology (Battista et al. 2007; Raghukanth & Sangeetha 2012; Han & van der Baan 2013), marine sciences (Schmitt et al. 2009; Ezer et al. 2013; Huang & Schmitt 2014), meteorology (Coughlin & Tung 2005; Molla et al. 2006; Capparelli et al. 2013; Martins et al. 2017), engineering (Loutridis 2004; Xu & Chen 2004; Lei et al. 2013), and medicine (Echeverria et al. 2001; Liang et al. 2005), as well as strategic planning domains such as economics and finance (Zhang et al. 2008; Zhu et al. 2015).

In this study, we present our findings on the turbulence power spectra derived using the EMD-HSA framework applied to magnetic field data (B_x , B_y , and B_z) measured in Geocentric Solar Ecliptic (GSE) coordinates across different regions of an ICME event. Section 2 outlines the characteristics of the ICME selected for this analysis, along with a description of the data. The EMD-HSA methodology is explained in Section 3. The results of the analysis are presented in Section 4, which is followed by our conclusions in Section 5.

2. Data

We studied the ICME event observed on 27 June 2013 at 13:30 UTC by NASA's Advanced Composition Explorer (ACE) spacecraft located at the Sun-Earth's L1 Lagrange point. The event has also been previously analysed by Prete et al. (2024) using the EUHFORIA simulation model. Operating in a Lissajous orbit, the primary mission of the ACE spacecraft is to study energetic particles originating from the Sun, which can contribute to our understanding of the solar system and the Milky Way galaxy. Additionally, ACE was used to continuously monitor space weather conditions near the L1 point, until its replacement by DSCOVR in 2015 (Burt & Smith 2012).

The observational data for the ICME under investigation were collected by the Magnetometer (MAG) instrument on board the ACE spacecraft (Chiu et al. 1998). The ICME was preceded by a fast forward shock and featured an embedded MC (Burlaga et al. 1981), characterised by the dominance of magnetic pressure over plasma pressure, and exhibiting a rotating magnetic field with signatures consistent with flux rope structures and field rotations between 90° and 180° (Nieves-Chinchilla et al. 2018). The World Data Center for Geomagnetism, Kyoto¹ recorded a minimum geomagnetic equatorial Dst index of -101 nT during the MC passage, indicating a geomagnetic storm that can be classified as 'strong' (Gonzalez et al. 1994; Loewe & Prölss 1997). A commonly used indicator to measure geomagnetic storm intensity, the Dst index is defined as the drop in the Earth's horizontal magnetic field component resulting from ring current enhancements.

The data products were downloaded in the Level 2 format with a time resolution of $\Delta t = 1$ second, comprising the magnetic field measurements in the GSE coordinate system. The downloaded data spanned a four-day period, from 26 June 2013 at

¹ <https://wdc.kugi.kyoto-u.ac.jp/index.html>

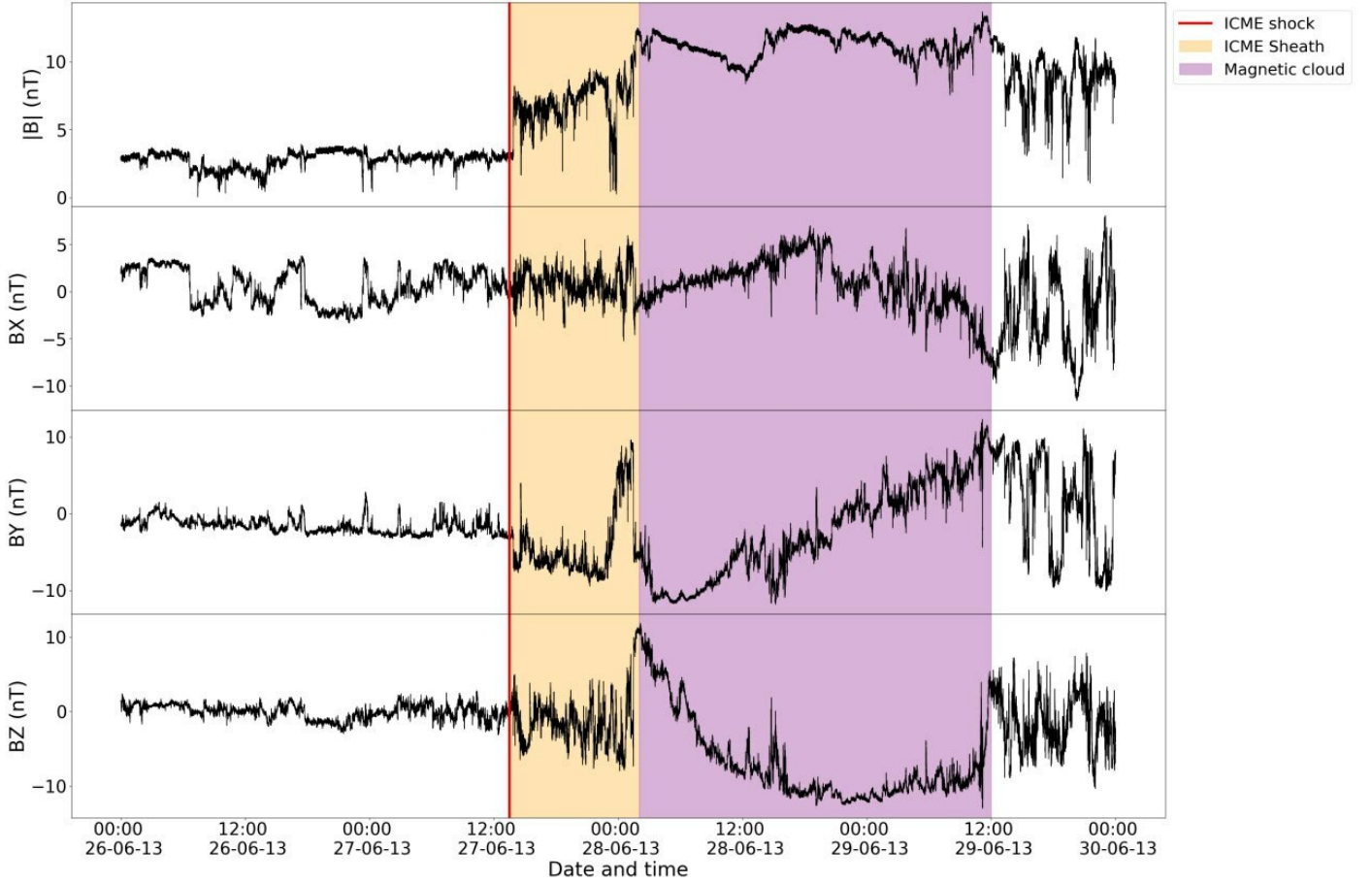


Fig. 1: Magnetic field data recorded by NASA’s MAG instrument on board ACE. The panels represent the signal for the field magnitude, $|B|$, and the component vectors (B_x , B_y , and B_z) in the GSE coordinate system. The red vertical line denotes the shock arrival resulting in the ICME sheath indicated by the orange-shaded region. This is followed by the MC, shown as the violet-shaded region. The onset of the sheath and the end of the MC spans the ICME event.

00:00:00 UTC to 29 June 2013 at 23:59:59 UTC, capturing the key features of the ICME event — the shock, sheath, and MC region. The ICME was characterised by the arrival of a shock on 27 June 2013 at 13:30 UTC² and the termination of the MC on 29 June 2013 at 12:00 UTC. The sheath spanned from 27 June 2013, 13:30 UTC to 28 June 2013, 02:00 UTC, and the MC extended from 28 June 2013, 02:00 UTC to 29 June 2013, 12:00 UTC (Richardson & Cane 2024). Fig. 1 represents the total magnetic field magnitude, $|B|$, and the magnetic field components (B_x , B_y , B_z) in GSE coordinates for the different ICME stages. The ICME shock is followed by the ICME sheath and later by the MC. The mean field magnitude (B) and the mean solar wind velocity in the ICME (V_{SW}) were reported to be 10 nT and 390 km/s, respectively.

The turbulence characteristics were analysed separately for each region and component. The approximate duration of each region is presented in Table 1.

3. Methodology

We applied the methods of EMD and HSA to the magnetic field component signals (B_x , B_y , and B_z) to study the nature of turbulence across the different ICME regions defined above. The

Table 1: Approximate duration (in hours) for each region of the ICME event.

ICME region	Duration (hours)
Preceding trailing solar wind	37.5
Sheath	12.5
MC	34.0
Trailing solar wind	12.0

EMD method decomposes the original signal into simpler components, each representing a distinct oscillatory mode, while the HSA method extracts the instantaneous quantities from these modes. The combined approach of EMD and HSA is designated by NASA as the Hilbert-Huang transform (HHT) (Kizhner et al. 2004; Huang 2005; Huang & Wu 2008; Huang 2012). This section offers a detailed overview of these techniques and their application to our data.

3.1. Empirical mode decomposition

Empirical mode decomposition is a robust, data-driven technique for analysing complex signals by decomposing them into simplified components known as intrinsic mode functions (IMFs). It is both adaptive and efficient for processing non-linear and non-stationary time-series, providing insights into the intrinsic

² http://www.ssg.sr.unh.edu/mag/ace/ACELists/obs_list.html

sic characteristics of the data. Each IMF represents a characteristic timescale and frequency that captures a principle mode of oscillation embedded in the signal. A component signal can be classified as an IMF if it satisfies the following two conditions:

- (i) The total number of local extrema (minima and maxima) must be equal to or one greater than the zero-crossings present in the component signal.
- (ii) The mean value calculated from the upper and lower envelopes, constructed from the local maxima and minima, respectively, must be zero at every point along the signal.

These conditions ensure that the resulting IMF is symmetric with respect to the zero mean and eliminate any unwanted large fluctuations in the instantaneous frequencies. The IMFs are extracted from the original signal through an iterative procedure, known as the sifting process. The EMD method operates by iteratively identifying and extracting the dominant oscillatory modes present in a time-series signal. In this work, the ICME data of the magnetic field components (B_x , B_y , and B_z) measured across the four ICME regions served as the primary signals. We denote this using the generic term $B(t)$. The local extrema, determined within $B(t)$, were used to construct an upper envelope, $\varepsilon_{up}(t)$ and a lower envelope, $\varepsilon_{down}(t)$ around $B(t)$ using spline interpolation. The mean of these two envelopes $\varepsilon_{mean}(t)$ was calculated and subtracted from the original signal, $B(t)$ to derive the first component signal,

$$f_1(t) = B(t) - \varepsilon_{mean}(t). \quad (1)$$

The function $f_1(t)$ is considered an IMF if it satisfies the conditions outlined earlier. If the criteria are not met, then a new mean envelope $\varepsilon_{mean1}(t)$ is computed for $f_1(t)$ and subtracted from it to yield $f_{1(1)}(t)$,

$$f_{1(1)}(t) = f_1(t) - \varepsilon_{mean1}(t). \quad (2)$$

This sifting process was repeated p times until the function $f_{1(p)}(t)$ satisfied the criteria to be classified as an IMF. Once this condition was met, the resulting function was identified as the first IMF, denoted by $C_1(t)$. This quantity was then subtracted from the original signal to compute the first residual of the data,

$$r_1(t) = B(t) - C_1(t). \quad (3)$$

The residual $r_1(t)$ then served as the new signal on which the sifting process was repeated to extract the next IMF.

The objective of the sifting process is to isolate oscillatory modes by smoothing out irregular amplitude fluctuations. However, excessive sifting could also result in the loss of crucial signal information. Therefore, to preserve the important signal components, the process was controlled by implementing a stopping criterion. In this work, we adopted the stopping criterion proposed by Huang et al. (1998), who introduced a standard deviation term, σ , between two consecutive siftings such that

$$\sigma = \sum_{t=0}^T \left(\frac{|f_{1(p)}(t) - f_{1(p-1)}(t)|^2}{f_{1(p-1)}^2(t)} \right), \quad (4)$$

where T denotes the total duration of the signal. For our dataset, a threshold of $\sigma = 0.1$ was selected to terminate the sifting process, ensuring a balance between retaining signal features and avoiding excessive iterations.

For a signal containing N data points, the approximate number of IMFs that can be extracted is $s \approx \log_2 N$. The first IMF

captures the highest frequency components of the signal, typically corresponding to the smallest timescales and often dominated by the noise present in the signal. The subsequent IMFs represent progressively lower frequencies (longer time scales), as the higher-frequency components get filtered out in the previous IMFs. Consequently, the IMFs obtained from EMD are inherently ordered from high to low frequency. The sifting process was repeated until a monotonic function or a function from which no further IMFs could be extracted was reached. We call this the final residue, $r(t)$. The original signal, $B(t)$, can then be reconstructed by summing all the IMFs and the residual,

$$B(t) = \sum_{j=1}^s C_j(t) + r(t). \quad (5)$$

The extracted IMFs from B_x , B_y , and B_z for the ICME sheath region are respectively shown in panels (a), (b), and (c) of Fig. 2. The IMFs depict enhanced fluctuations, capturing the heightened magnetic activity following the shock.

3.2. Hilbert spectral analysis

Following the extraction of IMFs from the component magnetic field signals, HSA was performed on each of the resultant IMFs to extract its instantaneous quantities. The procedure involves applying the Hilbert transform to each IMF,

$$\mathcal{H}\{C_j(t)\} = \frac{p}{\pi} \int_{-\infty}^{+\infty} \frac{C_j(\tau)}{t - \tau} d\tau, \quad (6)$$

where p denotes the Cauchy principal value. The application of the Hilbert transform results in a real-valued signal having a phase shift of $\pm 90^\circ$ in the frequency domain, allowing the construction of a complex analytic signal. By combining $C_j(t)$ and $\mathcal{H}\{C_j(t)\}$, the analytic signal $z(t)$ can be written as follows,

$$z(t) = C_j(t) + i\mathcal{H}\{C_j(t)\} = a_j(t)e^{i\phi_j(t)}. \quad (7)$$

Here, $a_j(t)$ and $\phi_j(t)$ represent the instantaneous amplitude and instantaneous phase, respectively of the j^{th} IMF, and are defined as

$$a_j(t) = \sqrt{(C_j(t))^2 + (\mathcal{H}\{C_j(t)\})^2}, \quad (8)$$

$$\phi_j(t) = \tan^{-1} \left(\frac{\mathcal{H}\{C_j(t)\}}{C_j(t)} \right). \quad (9)$$

The instantaneous frequency was then computed as

$$\omega_j(t) = \frac{d\phi_j(t)}{dt}. \quad (10)$$

Using Eq. 7, the original signal can then be reconstructed by summing the real parts of the analytic signals corresponding to each IMF,

$$B(t) = \text{Re} \sum_{j=1}^s a_j(t) e^{i \int \omega_j(t) dt}. \quad (11)$$

Here, $r(t)$ was dropped as it represented a constant or monotonic function. The measure of amplitude across the frequency-time domain yields the Hilbert spectrum, $H(\omega, t)$. The total energy contribution from each frequency can be obtained by integrating $H(\omega, t)$ over the complete time interval T , resulting in the marginal Hilbert spectra,

$$h(\omega) = \frac{1}{T} \int_0^T H(\omega, t) dt. \quad (12)$$

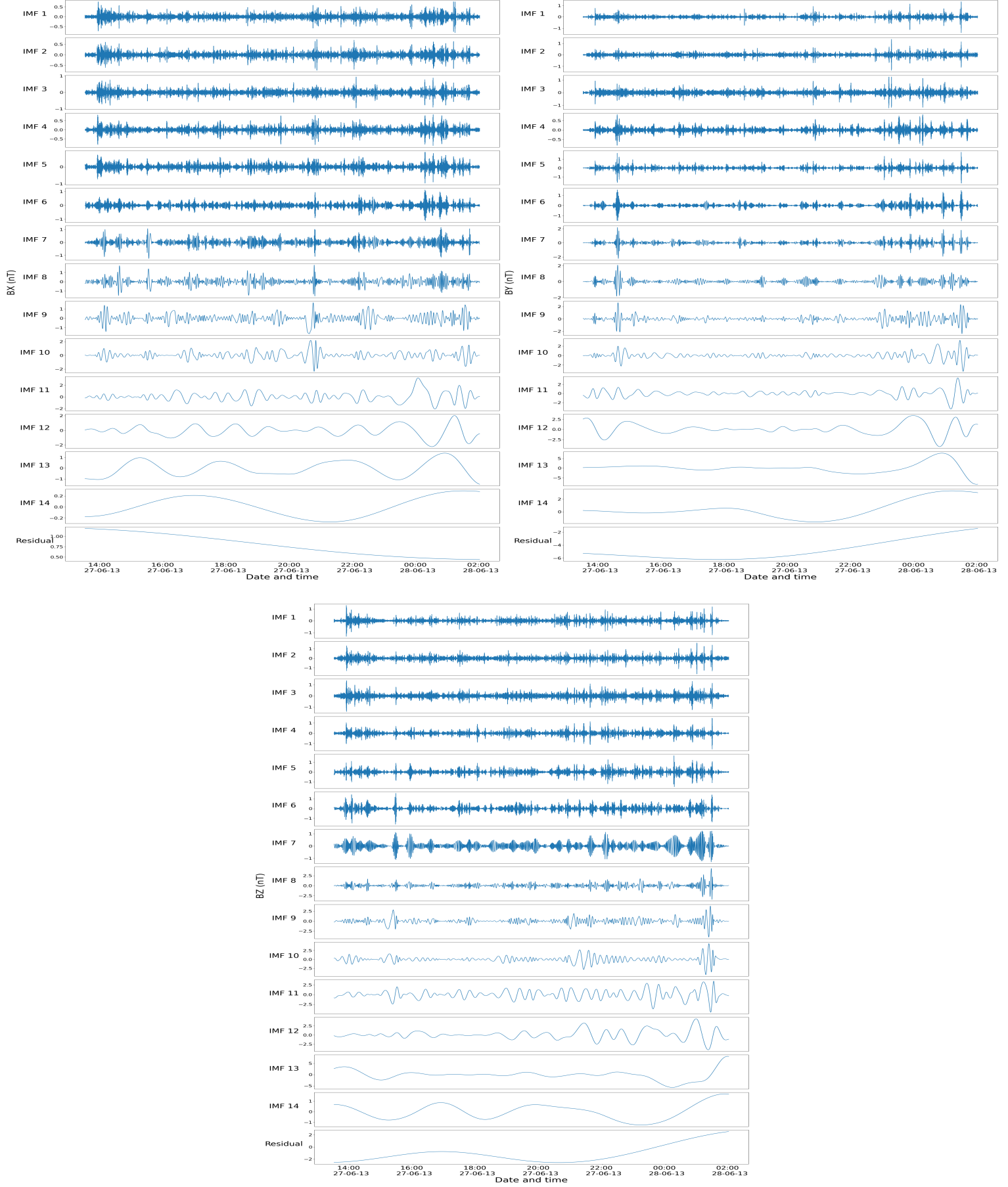


Fig. 2: IMFs obtained for the magnetic field components (B_x , B_y , and B_z) for the ICME sheath. The y-axis represents the magnitude (in nT) and the x-axis denotes the time duration of the interval.

4. Analysis and results

In this section, we report our findings regarding the energy contributions associated with different frequencies present in the magnetic field of the selected ICME. The analysis includes all three magnetic field components, B_x , B_y , and B_z across the four ICME regions. For each case, the EMD-HSA method was applied to construct the Hilbert spectrum, providing the amplitude distribution over the time-frequency domain. This was followed by the computation of the second-order marginal Hilbert spectrum for each region. A linear best-fit analysis was performed on the second-order marginal spectra and the resulting slopes were compared with the theoretical Kolmogorov scaling. The detailed results and interpretations are discussed in the following subsections.

4.1. Hilbert spectra

The Hilbert transform was applied to all the extracted IMFs from the magnetic field components across the ICME regions to compute their corresponding instantaneous amplitudes and frequencies. Fig. 3 shows the distribution of the instantaneous frequencies for each IMF across all magnetic field components and ICME regions. The instantaneous frequency distribution was grouped into 2160 equal-width logarithmic bins, spanning from 0 to 0.5 Hz.

To construct the Hilbert spectrum, we divided the range of instantaneous frequencies into 2160 equally spaced bins to resolve fine-scale features in the signal. Unlike Fourier spectral analysis, where frequency range is determined by the total duration of the signal (T) and its sampling frequency ($\Delta\omega$), the instantaneous frequencies (ω_j) obtained by the HSA method represent the occurrence of specific frequencies at a local time instance t . Consequently, the frequency resolution in HSA can be adjusted by modifying the bin size that stores these instantaneous frequencies. While this flexibility enables the examination of fine spectral details, selecting an arbitrary frequency resolution might lead to an erroneous interpretation of the spectrum (Huang et al. 2011). Broad bins can merge distinct frequencies, obscuring fine details, whereas narrower bins improve frequency resolution but increase computational demands, particularly when analysing large datasets.

For a signal sampled at a time resolution Δt , the highest frequency that can be recorded after applying HSA is given by the Nyquist frequency, $f_q = 1/(2\Delta t)$ Hz. In our case, where the signal duration differs for each ICME region, the finest resolvable frequency structure, $\Delta f = 1/T$ is given by the region with the shortest duration. The bin size b to generate the Hilbert spectrum can then be determined by the ratio of the Nyquist frequency to the fundamental frequency resolution. We scaled this with respect to a binning factor, F_b , to prevent noise domination at higher frequencies and to manage computational efficiency:

$$b = \frac{f_q}{\Delta f} \times \frac{1}{F_b}. \quad (13)$$

To maintain uniform resolution, F_b was kept constant across all bins. In our case, the shortest region corresponds to the trailing solar wind ≈ 12 hours, yielding $f_q = 0.5$ Hz and $\Delta f = 2.32 \times 10^{-5}$ Hz. Through empirical testing to balance spectral resolution and computational efficiency, we selected $F_b \approx 10$, which gives

$$b = \frac{1/(2\Delta t)}{1/T} \times \frac{1}{F_b} \approx 2160 \text{ bins}. \quad (14)$$

Thus, the frequency resolution for each bin becomes

$$\Delta f_b = \frac{f_q}{b} \approx 2.3 \times 10^{-4} \text{ Hz}. \quad (15)$$

The Hilbert spectrum was generated by summing the amplitude contributions of all IMFs within each frequency bin at every time point. Fig. 4 illustrate the resulting Hilbert spectra for the ICME event. The top, middle and bottom panels represent the magnetic field components, B_x , B_y , and B_z , while each subplot in the panel corresponds to the ICME regions. A Gaussian filter was applied while generating the heatmaps to produce smoother and visually continuous spectra. The Hilbert spectra indicate that the smaller instantaneous frequencies (< 0.1 Hz) dominate the ICME signal, contributing to the strongest observed amplitudes.

In the first region corresponding to the solar wind preceding the ICME shock, weaker amplitudes are observed particularly in the B_y and B_z components, suggesting lower levels of magnetic turbulence, consistent with relatively undisturbed background solar wind conditions. Following the shock, sharp fluctuations in the amplitude levels are observed within the ICME sheath, indicating enhanced magnetic field variations. Being highly compressed plasma structures, the sheath region experiences strong turbulent fluctuations following the shock passage. The trend continues to be observed within the MC, which is characterised by large-scale magnetic flux ropes. The peaks become sharper and more clearly distinguishable, suggesting the presence of intermittent turbulence. Following the termination of the MC, the trailing solar wind displays the strongest amplitudes in all the three magnetic field components of the ICME event, highlighting continued magnetic field variability in the aftermath of the event. Furthermore, the presence of a constant frequency at $\omega_{sc} \approx 0.083$ Hz was observed that appeared as a horizontal feature in all the Hilbert spectra. This constant frequency corresponds to the spin rate of the ACE spacecraft, which is 5 revolutions per minute (rpm), with the spin axis orientated along the Sun-Earth line (Chiu et al. 1998; Stone et al. 1998).

The marginal Hilbert spectra for the magnetic field components for each ICME region were computed using Eq. 12 and are shown in Fig. 5. Each panel depicts the marginal Hilbert spectrum for the extracted IMFs, represented in a distinct colour, while the black curve depicts the total marginal spectrum obtained by summing the spectrum of each IMF. The results of Fig. 5 demonstrate the capability of the EMD-HSA method in filtering the signal into finite frequency components. Modes 1 and 2 correspond to timescales shorter than the proton gyrofrequency (marked by the vertical dashed green line) that fall within the turbulence dissipation range. Modes 5 to 12 represent longer timescales and correspond to the inertial range of the turbulence scale. The mode corresponding to ω_{sc} (indicated by the vertical dashed magenta line) was captured by modes 2, 3, and 4 and appears as a small bump in each panel. This feature is more enhanced in the marginal spectra of the components B_y and B_z compared to the component B_x , possibly due to the orientation of the spacecraft's spin-axis along the Sun-Earth line (Chiu et al. 1998; Stone et al. 1998). In all cases, the total marginal spectrum (black curve) exhibits a behaviour consistent with the energy cascade that dissipates below the proton gyrofrequency.

4.2. Arbitrary-order Hilbert spectra

Turbulent flows exhibit intermittency and scaling behaviours across various statistical moments and scales. For a generic field component $x(t)$, these properties are analysed through field

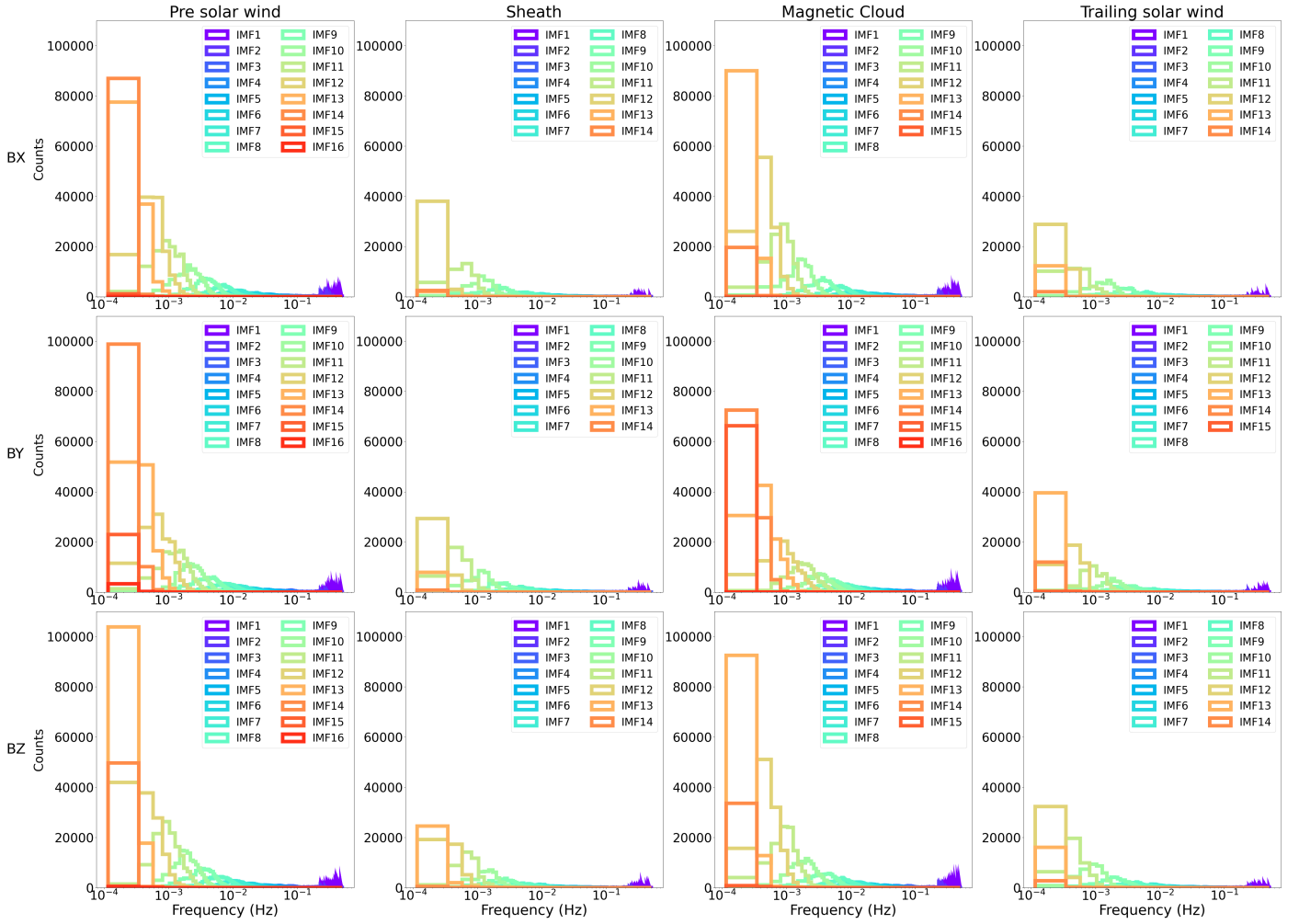


Fig. 3: Instantaneous frequency distribution for each IMF for all the magnetic field components (B_x , B_y and B_z) across different ICME regions. The instantaneous frequencies are binned into 2160 equally spaced logarithmic bins ranging from 0 to 0.5 Hz. Each IMF order is represented by a distinct colour to enhance clarity and differentiation.

fluctuations and defined as increments separated by time τ (Bruno & Carbone 2013),

$$\Delta x_\tau = x(t + \tau) - x(t). \quad (16)$$

These fluctuations characterise the intermittency and multi-scaling properties of the system and are quantified using a structure function of order q ($q > 0$), S_q . Mathematically, this is represented as

$$S_q \equiv \langle |\Delta x_\tau|^q \rangle \sim \tau^{\zeta(q)}, \quad (17)$$

where $\zeta(q)$ is the scaling exponent function of order q that characterises these fluctuations. In a fully developed turbulence, structure functions describe the evolution of fluctuations across different scales. For mono-fractal systems, $\zeta(q)$ follows a linear trend, but deviates towards non-linear behaviour for multi-fractal systems, displaying the intermittent nature of turbulence (Bruno et al. 1998).

To compute an arbitrary higher-order ($q > 0$) marginal Hilbert spectrum, $\mathcal{L}_q(\omega)$, Huang et al. (2008) proposed a method based on the joint probability density function, $p(\omega, a)$ of the instantaneous frequency (ω) and instantaneous amplitude (a),

$$\mathcal{L}_q(\omega) = \int_0^\infty p(\omega, a) a^q da. \quad (18)$$

For an arbitrary order q , the power spectra follows the scaling relation, $\mathcal{L}_q(\omega) \sim \omega^{-\alpha_q}$, where α_q is the spectral slope. The scaling exponent $\zeta(q)$ can then be related to α_q computed from Eq. 18 as

$$\zeta(q) = \alpha_q - 1. \quad (19)$$

The spectral exponent α_q can then be considered analogous to the $\zeta(q)$ exponents obtained from S_q to identify intermittency in the signal (Huang et al. 2011; Carbone et al. 2018).

For the second-order case, the marginal Hilbert spectrum takes the form

$$\mathcal{L}_2(\omega) = \int_0^\infty p(\omega, a) a^2 da. \quad (20)$$

Equation. 20 is comparable to the Fourier power spectral density (PSD), which provides energy distribution across different frequencies. Following this, $\mathcal{L}_2$ spectra were generated for each magnetic field component across the ICME regions. The $\mathcal{L}_2$ spectra of the field components, B_x , B_y , and B_z were added together to obtain the second-order marginal Hilbert spectrum of the complete region, as shown by the black curve in Fig. 6.

The plots show distinct scaling behaviours corresponding to the inertial and dissipation ranges. The inertial range is associated with longer timescales (lower frequencies), while the dissipation range is associated with shorter timescales (higher frequencies).

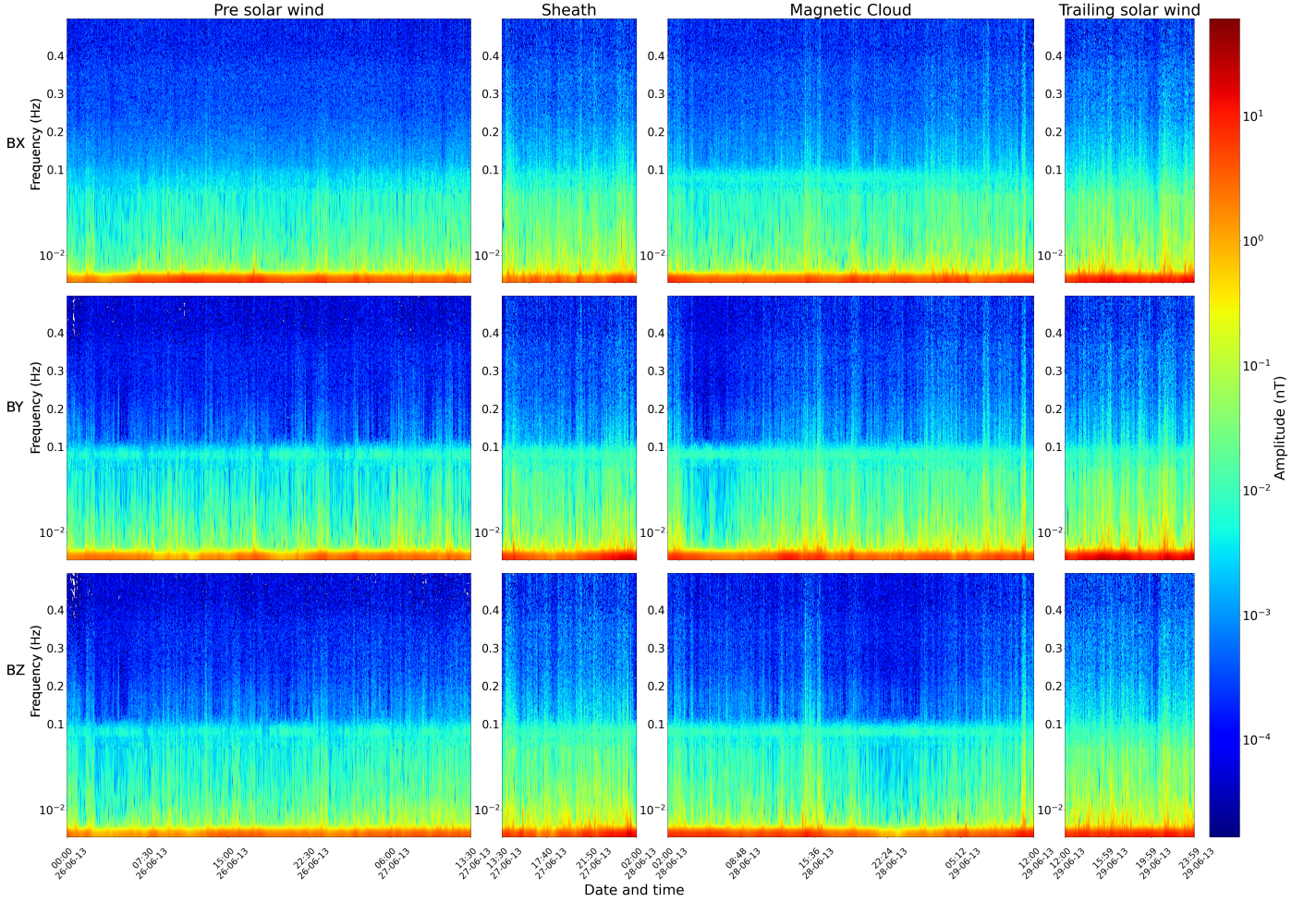


Fig. 4: Hilbert spectra for magnetic field components across different ICME regions. *From left to right:* Regions corresponding to the preceding solar wind, sheath, MC and trailing solar wind. *From top to bottom:* Magnetic field components for B_x , B_y , and B_z . The y-axis is represented on the logarithmic scale up to 0.032 Hz to visually emphasise the contribution of the dominating low frequencies.

pation range corresponds to smaller timescales (higher frequencies), occurring beyond the proton gyrofrequency (indicated by the dashed green line). To analyse the statistical properties of our data, we selected a region within the inertial range using piece-wise linear fitting, as indicated by the blue-shaded region in Fig. 6. Based on the $\mathcal{L}_2(\omega)$ spectra, the inertial range was selected separately for each ICME region but was restricted within $\approx 8.1 \times 10^{-4}$ to 4.86×10^{-2} Hz. We confined our analysis within this range to exclude the influence of two known spectral artefacts: the spectral break at $\approx 3.4 \times 10^{-4}$ Hz and the spacecraft spin frequency ω_{sc} .

The component associated with the spin rate of the spacecraft is identified in the second-order marginal Hilbert spectra as a distinct bump that peaks at ω_{sc} . The effect of this feature appears to become less prominent with the increasing spectral power as the ICME propagates from the pre-shock to post-MC stages. This results in a flattening of the spectrum around $\approx 4.86 \times 10^{-2}$ Hz, occurring just before the spectral bump observed at ω_{sc} . In the absence of this instrumental effect, a smoother spectral profile would be expected. However, removing or filtering out the spin-frequency components associated with ω_{sc} is not a straightforward task, as these appear across different oscillatory modes, particularly in IMFs 2, 3 and 4 (Fig. 5). Filtering out these frequency components while preserving the signal information re-

quires specialised techniques, which is beyond the scope of this work but may be addressed in future studies.

The spectral break observed at $\approx 3.4 \times 10^{-4}$ Hz arises from the binning scheme used to construct the marginal Hilbert spectrum. Instantaneous frequencies were grouped into 2160 equally spaced bins with a resolution of $\Delta f_b = 2.3 \times 10^{-4}$ Hz (as discussed in section 4.1). The first bin contains all instantaneous frequencies between 0 and Δf_b Hz and therefore exhibits the highest number of counts compared to the subsequent bins (Fig. 3). Consequently, the spectral value in this bin reflects the cumulative background energy at low frequencies ($\omega_j < \Delta f_b$ Hz), resulting in a relatively elevated value. Although increasing the bin size would provide finer frequency resolution and produce a more gradual spectral decay, such changes would have a negligible impact on the overall statistical properties of the data within the inertial range. Keeping the above two constraints in consideration, we restricted our analysis of the inertial range to frequencies between $\approx 8.1 \times 10^{-4}$ and 4.86×10^{-2} Hz.

The second-order marginal spectra for each ICME region presented in Fig. 6 follow a scaling behaviour that can be characterised by a power law of the form

$$\mathcal{L}_2(\omega) = e^c \cdot \omega^\alpha, \quad (21)$$

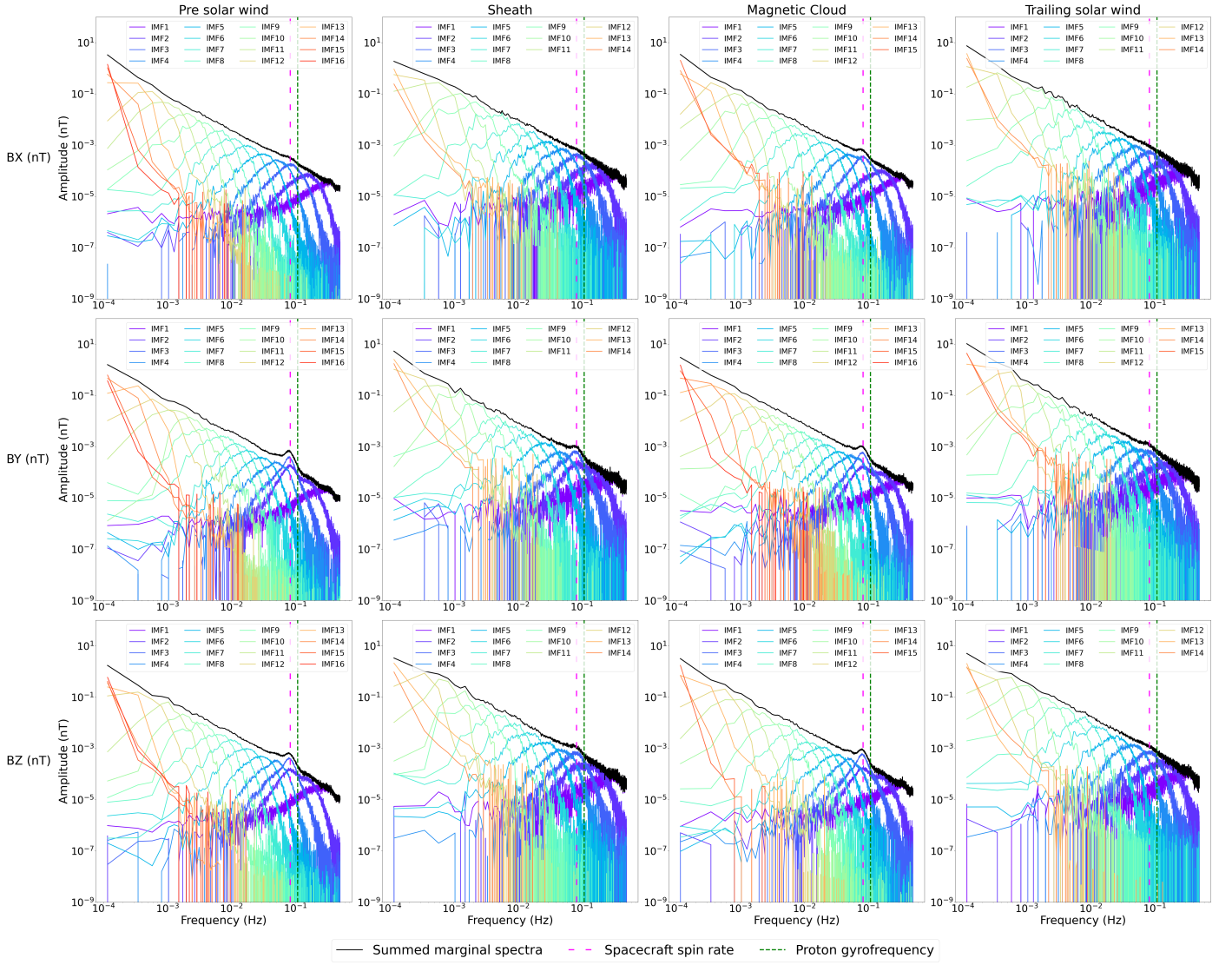


Fig. 5: Marginal Hilbert spectra for each IMF representing the total amplitude contribution across the frequency domain. Each IMF order is depicted using a distinct colour for clarity. The black curve in each panel represents the total marginal spectrum obtained by summing the marginal spectra of each IMF order. The vertical dashed magenta and green lines mark the spacecraft spin rate and proton gyrofrequency, respectively.

where c is a constant, and α is the spectral index. Applying the logarithmic function on both sides of Eq. 21, we obtain

$$\log(\mathcal{L}_2(\omega)) = c + \alpha \log(\omega), \quad (22)$$

which corresponds to a linear relationship. A linear regression was performed within the selected inertial ranges for each region to estimate α from the resulting line of best fit, as indicated in red in Fig. 6. The estimated values of α for each ICME region are provided within the respective panels, denoted α_{HHT} .

Furthermore, we compared the $\mathcal{L}_2(\omega)$ with the standard Fourier PSD for each ICME region (see Fig. 6). The best-fit lines for $\mathcal{L}_2(\omega)$ and Fourier PSD in the selected inertial range for each ICME region are also shown. From Fig. 6, we notice a better fit obtained for the $\mathcal{L}_2(\omega)$ spectra as compared to that of the Fourier PSD. The second-order marginal Hilbert spectrum is noticeably smoother than the Fourier PSD, which exhibits significant noise levels across the frequency range. While the energy at a given frequency in the Fourier PSD implies the presence of wave activity throughout the duration of the event, contrarily, the marginal

Hilbert spectrum suggests the existence of the wave to have appeared locally, resulting in a cleaner spectral profile and allowing a clearer identification of the turbulent scaling behaviour within different ICME regions.

The analysis of the second-order marginal Hilbert spectra reveals clear variations in the inertial-range spectral slopes across the different ICME regions, indicating changes in the nature of the turbulent cascade throughout the event. The preceding solar wind records an energy transfer in the inertial range with a spectral decay of $\alpha_{HHT} = -1.677 \pm 0.006$. This value is equivalent to Kolmogorov's theoretically derived slope of $-5/3$, indicating the presence of a fully developed magnetohydrodynamic turbulence. The results are in agreement with previous studies that reported the presence of fully developed turbulence in the solar wind at 1 AU (Podesta et al. 2007; Telloni et al. 2021).

In the sheath, the second-order marginal Hilbert spectrum within the inertial range exhibits a notably steeper slope, measured at $\alpha_{HHT} = -1.784 \pm 0.011$, suggesting a more rapid energy decay at smaller scales. This feature is consistent with the

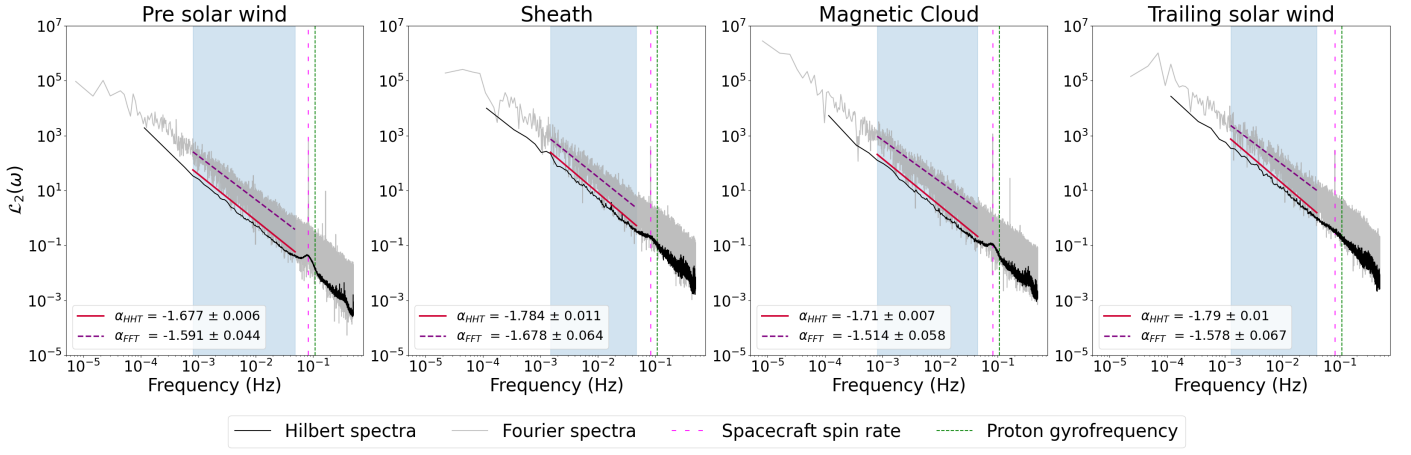


Fig. 6: Second-order marginal Hilbert spectra $\mathcal{L}_2(\omega)$ (black curve) plotted against the Fourier spectra (grey curve) for the different ICME regions. The spectra were obtained by adding the second-order marginal Hilbert spectra of the components, B_x , B_y , and B_z for each region. The selected inertial ranges are marked by the blue-shaded region. The best-fit lines for $\mathcal{L}_2(\omega)$ and the Fourier PSD within this range are shown by the red line (vertically shifted for clear representation) and the dashed purple line, respectively. The corresponding spectral indices are denoted α_{HHT} and α_{FFT} in each panel. The vertical dashed magenta and green lines mark the spacecraft spin rate and proton gyrofrequency, respectively.

typical low Alfvénic nature of the slow solar wind, where the turbulence energy is increased following the passage of the ICME shock. The shock-wave is capable of compressing and heating-up the solar wind plasma, leading to enhanced non-linear interactions, stronger intermittency, and anisotropic behaviour (Yordanova et al. 2009; Bruno & Carbone 2013; Teodorescu et al. 2015; Kilpua et al. 2021a,b).

The MC region reported a slower energy cascade following the sheath with $\alpha_{HHT} = -1.71 \pm 0.007$. This behaviour likely indicates that the mechanisms responsible for the spectral steepness in the sheath region are diminished in the large-scale flux ropes. A similar reduction in magnetic field spectral steepening in the MC, compared to the sheath, has also been reported in previous studies by Sorriso-Valvo et al. (2021) and Riazantseva et al. (2024).

Lastly, the second-order marginal Hilbert spectrum for the trailing solar wind region reveals an even steeper slope of $\alpha_{HHT} = -1.79 \pm 0.01$, indicating the most rapid energy decay observed during the event, particularly towards its termination. This steepening is likely associated with the large-scale magnetic field fluctuations observed in the later stages of the MC and the trailing solar wind, as illustrated in Fig. 1. From the results of the Hilbert spectra (Fig. 4), the fluctuations exhibit enhanced amplitudes, particularly in the trailing solar wind region. This may be related to the interaction of a fast solar wind stream with the ICME after 30 June 00:00, thereby contributing to the increased power observed in this interval.

Overall, our results obtained from the EMD-HSA framework provide a smoother energy spectra as compared to the standard Fourier PSD approach. The results also show that the turbulent energy cascade spectra changes with each region as the ICME progresses.

5. Conclusions

In this work, we analysed the ICME event of 27 June 2013 (Prete et al. 2024) recorded by the MAG instrument on board NASA’s ACE spacecraft to study the turbulent behaviour at different stages of the ICME. The event was characterised by the onset of a shock that led to the formation of a sheath region with

increased magnetic field activity, followed by an expanding MC. The event was divided into four distinct regions — the solar wind preceding the ICME shock, followed by the sheath, the MC and the trailing solar wind.

To study ICME turbulence, the magnetic field data in the GSE coordinates for the components, B_x , B_y , and B_z across the four ICME regions were analysed using the EMD-HSA methodology. The magnetic field signals were decomposed into simpler, finite IMFs ordered from the highest to the lowest oscillatory frequency modes through EMD. The extracted IMFs were subjected to HSA to derive their corresponding instantaneous frequencies and amplitudes as functions of time. These quantities were used to generate the Hilbert spectrum for each magnetic field component within each region, providing a time-frequency distribution of the amplitude. According to the resulting spectrograms, the dominant amplitude contributions developed from the low instantaneous frequencies (< 0.1 Hz) present in the magnetic field components in the four regions. The Hilbert spectra for the sheath and MC show sharp peaks, particularly in the B_y and B_z showing enhanced magnetic activity within these regions. Following the termination of the MC, the Hilbert spectra for the trailing solar wind combined with a fast stream after 30 June 00:00:00, also indicate heightened magnetic field fluctuations in all the three components, suggesting that the significant aftereffects of the ICME event persist even after the cloud’s passage.

The second-order marginal Hilbert spectra, $\mathcal{L}_2(\omega)$, were computed to map the PSD for each ICME region: we did so by combining the individual PSDs of the magnetic field components within the interval and a power-law fit was derived for each region within the selected inertial range. The lower bound of the inertial range was selected to avoid energy contributions from frequencies below $\Delta f_b = 2.3 \times 10^{-4}$ Hz due to the adopted frequency-binning scheme, while the upper bound was chosen to exclude frequencies beyond 4.86×10^{-2} Hz, affected by the spin frequency of the spacecraft.

The second-order marginal Hilbert spectra revealed noticeable variations in the turbulent cascade across the ICME structure. The preceding solar wind exhibits a spectral slope close to the Kolmogorov value ($\alpha_{HHT} \approx -5/3$), indicating the fully developed turbulence typical of ambient solar wind conditions at 1

AU. In contrast, the sheath and trailing solar wind regions show noticeably steeper spectra ($\alpha_{HHT} \sim -1.78$ to -1.79), suggesting enhanced intermittency and an increased presence of discontinuities and current sheets generated by shock compression and subsequent solar wind–ICME interactions. These findings are consistent with previous observations of ICME-driven turbulence in sheath regions. Within the MC, the spectral slope is found to be less steep, possibly due to the influence of the large-scale flux-rope structure. Furthermore, the EMD-HSA spectral approach provides smoother and more stable estimates of inertial-range scaling compared with the conventional Fourier PSD, thus highlighting its capability to characterise turbulence in highly non-stationary solar wind structures such as ICMEs.

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This work made use of the Python programming language and the following software packages for analysis: JUPYTER (Granger & Pérez 2021) ; MATPLOTLIB (Hunter 2007) ; NUMPY (Harris et al. 2020) ; PANDAS (Wes McKinney 2010) ; PIECEWISE LINEAR FIT (Jekel & Venter 2019) ; PYEMD (Laszuk 2017) ; ScIPY (Virtanen et al. 2020).

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References

- Alberti, T., Consolini, G., Carbone, V., et al. 2019, *Entropy*, 21, 320
- Battista, B. M., Knapp, C., McGee, T., & Goebel, V. 2007, *Geophysics*, 72, H29
- Bruno, R. & Carbone, V. 2013, *Living Rev. Sol. Phys.*, 10, 2
- Bruno, R., Carbone, V., Sorriso-Valvo, L., et al. 1998, *Mem. Soc. Astron. Ital.*, 69, 721
- Burlaga, L., Sittler, E., Mariani, F., & Schwenn, a. R. 1981, *J. Geophys. Res. Space Phys.*, 86, 6673
- Burt, J. & Smith, B. 2012, in 2012 IEEE Aerospace Conference, IEEE, 1–13
- Capparelli, V., Franzke, C., Vecchio, A., et al. 2013, *J. Geophys. Res. Atmos.*, 118, 7427
- Carbone, F., Sorriso-Valvo, L., Alberti, T., et al. 2018, *ApJ*, 859, 27
- Carbone, F., Sorriso-Valvo, L., Khotyaintsev, Y. V., et al. 2021, *A&A*, 656, A16
- Carbone, F., Telsoni, D., Sorriso-Valvo, L., et al. 2020, *Universe*, 6, 116
- Chen, J. 2017, *Phys. Plasmas*, 24
- Chintzoglou, G., Patsourakos, S., & Vourlidas, A. 2015, *ApJ*, 809, 34
- Chiu, M., Von-Mehlem, U., Willey, C., et al. 1998, *Space Sci. Rev.*, 86, 257
- Coleman, Jr., P. J. 1968, *ApJ*, 153, 371
- Coughlin, K. & Tung, K. K. 2005, in *Hilbert-Huang Transform and Its Applications* (World Scientific), 149–165
- Davies, E. E., Möstl, C., Owens, M., et al. 2021, *A&A*, 656, A2
- Echeverria, J., Crowe, J., Woolfson, M., & Hayes-Gill, B. 2001, *Med. Biol. Eng. Comput.*, 39, 471
- Evans, R. M., Pulkkinen, A. A., Zheng, Y., et al. 2013, *SWE*, 11, 333
- Ezer, T., Atkinson, L. P., Corlett, W. B., & Blanco, J. L. 2013, *J. Geophys. Res. Oceans*, 118, 685
- Ghughe, D., Bhattacharjee, D., & Subramanian, P. 2025, *Sol. Phys.*, 300, 47
- Gonzalez, W., Joselyn, J.-A., Kamide, Y., et al. 1994, *J. Geophys. Res. Space Phys.*, 99, 5771
- Gosling, J. & McComas, D. 1987, *Geophys. Res. Lett.*, 14, 355
- Gosling, J., McComas, D., Phillips, J., & Bame, S. 1991, *J. Geophys. Res. Space Phys.*, 96, 7831
- Granger, B. E. & Pérez, F. 2021, *Comput. Sci. Eng.*, 23, 7

- Han, J. & van der Baan, M. 2013, *Geophysics*, 78, O9
- Harris, C. R., Millman, K. J., van der Walt, S. J., et al. 2020, *Nat.*, 585, 357
- Howard, R., Sheeley Jr, N., Koomen, M., & Michels, D. 1985, *J. Geophys. Res. Space Phys.*, 90, 8173
- Huang, N. E. 2005, *Empirical mode decomposition for analyzing acoustical signals*, Tech. rep.
- Huang, N. E. 2012, *AADA*, 04, 1203001
- Huang, N. E., Chen, X., Lo, M.-t., & Wu, Z. 2011, *AADA*, 3, 63
- Huang, N. E., Shen, Z., Long, S. R., et al. 1998, *Proc. R. Soc. Lond. A*, 454, 903
- Huang, N. E. & Wu, Z. 2008, *Rev. Geophys.*, 46
- Huang, Y. & Schmitt, F. G. 2014, *J. Mar. Syst.*, 130, 90
- Huang, Y., Schmitt, F. G., Lu, Z., & Liu, Y. 2008, *EPL*, 84, 40010
- Huang, Y. X., Schmitt, F. G., Hermand, J.-P., et al. 2011, *Phys. Rev. E*, 84, 016208
- Hunter, J. D. 2007, *Comput. Sci. Eng.*, 9, 90
- James, A. W., Green, L. M., Palmerio, E., et al. 2017, *Sol. Phys.*, 292, 71
- James, A. W., Valori, G., Green, L. M., et al. 2018, *ApJL*, 855, L16
- Jekel, C. F. & Venter, G. 2019, *pwlf: A Python Library for Fitting 1D Continuous Piecewise Linear Functions*
- Kilpua, E., Balogh, A., Von Steiger, R., & Liu, Y. 2017a, *Space Sci. Rev.*, 212, 1271
- Kilpua, E., Good, S., Ala-Lahti, M., et al. 2021a, *Front. Astron. Space Sci.*, 7, 610278
- Kilpua, E., Good, S., Dresing, N., et al. 2021b, *A&A*, 656, A8
- Kilpua, E., Koskinen, H. E., & Pulkkinen, T. I. 2017b, *Living Rev. Sol. Phys.*, 14, 1
- Kizhner, S., Flatley, T. P., Huang, N. E., Blank, K., & Conwell, E. 2004, in 2004 IEEE Aerospace Conference Proceedings (IEEE Cat. No. 04TH8720), Vol. 3, IEEE, 1961–1979
- Klein, L. & Burlaga, L. 1982, *J. Geophys. Res. Space Phys.*, 87, 613
- Kolmogorov, A. 1941, *Dokl. Akad. Nauk SSSR*, 30, 301
- Koomen, M., Detwiler, C., Brueckner, G., Cooper, H., & Tousey, R. 1975, *Appl. Opt.*, 14, 743
- Laszuk, D. 2017, *Python implementation of Empirical Mode Decomposition algorithm*, <https://github.com/laszukdawid/PyEMD>
- Lei, Y., Lin, J., He, Z., & Zuo, M. J. 2013, *Mech. Syst. Signal Process.*, 35, 108
- Liang, H., Lin, Q.-H., & Chen, J. D. Z. 2005, *IEEE Trans. Biomed. Eng.*, 52, 1692
- Loewe, C. & Prölss, G. 1997, *J. Geophys. Res. Space Phys.*, 102, 14209
- Loutridis, S. 2004, *Eng. Struct.*, 26, 1833
- Martins, L. G. N., Miller, S. D., & Acevedo, O. C. 2017, *Bound.-Lay. Meteorol.*, 163, 123
- Molla, M. K. I., Rahman, M. S., Sumi, A., & Banik, P. 2006, *Discrete Dyn. Nat. Soc.*, 2006, 045348
- Nicewicz, J. & Michalek, G. 2016, *Sol. Phys.*, 291, 1417
- Nieves-Chinchilla, T., Vourlidas, A., Raymond, J. C., et al. 2018, *Sol. Phys.*, 293, 25
- Podesta, J., Roberts, D., & Goldstein, M. 2007, *ApJ*, 664, 543
- Prete, G., Niemela, A., Schmieder, B., et al. 2024, *A&A*, 683, A28
- Raghukanth, S. & Sangeetha, S. 2012, *AADA*, 4, 1250022
- Riazantseva, M. O., Treves, T. V., Khabarova, O., et al. 2024, *Universe*, 10, 417
- Richardson, I. & Cane, H. 2024, *Near-Earth Interplanetary Coronal Mass Ejections Since January 1996*
- Rouillard, A. 2011, *J. Atmos. Sol.-Terr. Phys.*, 73, 1201
- Ruhotie, J., Good, S., Möstl, C., & Kilpua, E. 2025, *ApJL*, 986, L27
- Schmitt, F. G., Huang, Y., Lu, Z., Liu, Y., & Fernandez, N. 2009, *J. Mar. Syst.*, 77, 473
- Siscoe, G. & Odstreil, D. 2008, *J. Geophys. Res. Space Phys.*, 113
- Smith, C. W. & Ness, N. F. 2022, *ACE Magnetic Field (MAG) Geocentric Solar Ecliptic, GSE, and Geocentric Solar Magnetospheric, GSM, Coordinates, Level 2 (H3), 1 s Data*
- Soljento, J. E., Good, S. W., Osmann, A., & Kilpua, E. K. 2023, *ApJL*, 946, L19
- Song, H., Zhang, J., Cheng, X., et al. 2020, *ApJL*, 901, L21
- Sorriso-Valvo, L., Yordanova, E., Dimmock, A. P., & Telsoni, D. 2021, *ApJL*, 919, L30
- Stone, E. C., Frandsen, A., Mewaldt, R., et al. 1998, *Space Sci. Rev.*, 86, 1
- Telsoni, D., Sorriso-Valvo, L., Woodham, L. D., et al. 2021, *ApJL*, 912, L21
- Teodorescu, E., Echim, M., Munteanu, C., et al. 2015, *ApJL*, 804, L41
- Tousey, R., Austin, W., Purcell, J., & Widing, K. 1973, *Rycroft, MJ, Runcorn SK*, 173
- Vecchio, A., Laurenza, M., Meduri, D., Carbone, V., & Storini, M. 2012, *ApJ*, 749, 27
- Vecchio, A., Lepreti, F., Laurenza, M., Alberti, T., & Carbone, V. 2017, *A&A*, 599, A58
- Virtanen, P., Gommers, R., Oliphant, T. E., et al. 2020, *Nat. Methods*, 17, 261
- Wes McKinney. 2010, in *Proceedings of the 9th Python in Science Conference*, ed. Stéfan van der Walt & Jarrod Millman, 56 – 61
- Wu, C., Lepping, R., & Gopalswamy, N. 2006, *Sol. Phys.*, 239, 449
- Wu, C.-C. & Lepping, R. 2002, *J. Geophys. Res. Space Phys.*, 107, SMP
- Xiang, N. & Qu, Z. 2016, *AJ*, 151, 76
- Xu, Y. L. & Chen, J. 2004, *J. Eng. Mech.*, 130, 1279
- Yordanova, E., Balogh, A., Noullez, A., & von Steiger, R. 2009, *J. Geophys. Res. Space Phys.*, 114
- Zhang, J., Temmer, M., Gopalswamy, N., et al. 2021, *Prog. Earth Planet. Sci.*, 8, 1
- Zhang, X., Lai, K. K., & Wang, S.-Y. 2008, *Energy Econ.*, 30, 905
- Zhao, L.-L., Zank, G., He, J., et al. 2021, *A&A*, 656, A3
- Zhu, B., Wang, P., Chevallier, J., & Wei, Y. 2015, *Comput. Econ.*, 45, 195