Analysing Turbulence in Coronal Mass Ejections Using Empirical Mode Decomposition

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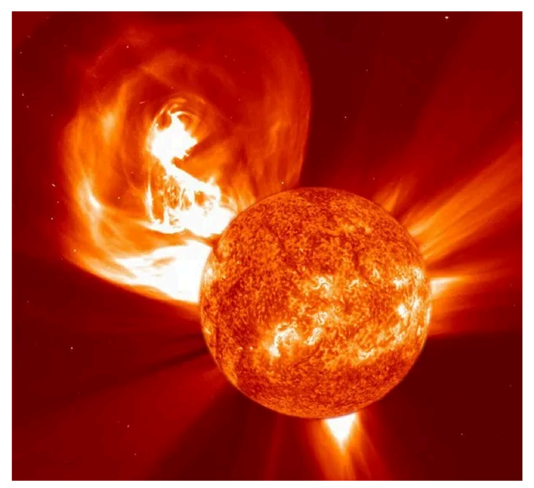
Introduction

This study aims to investigate the role of turbulence at different stages in a coronal mass ejections (CME) using the technique of empirical mode decomposition (EMD). It is established that the CMEs are turbulent in nature where energy transfer takes place in a cascade process from larger structures to smaller structures in the form of eddies. The stages considered here are characterised by the shock arrival time and the magnetic cloud region in a CME, dividing the signal into three main intervals. We applied the EMD method on the magnetic field components (Bx, By, Bz) to break the signal into intrinsic mode functions (IMFs) that represent inherent oscillation modes within the data signal. The IMFs are utilised to generate the Hilbert spectra for the three intervals with the aim to study the relation between turbulence and CME strength.

Coronal Mass Ejections

A coronal mass ejection (CME) is a tremendous emission of plasma and magnetic field from the Sun's corona that travels outward at speeds ranging from 250 km/s to 3000 km/s.

A CME entering the interplanetary space directed towards Earth is usually accompanied by a shock wave followed by a dense region of magnetic cloud.



A visual representation of a coronal mass ejection. (Image credit: SOHO (ESA/NASA))

Turbulent Scales and Energy Cascase

Turbulence is characterised by the chaotic and unsteady motion of a fluid. In turbulent flow, the kinetic energy is injected at large scales (large eddies) and then transferred down to smaller and smaller scales through a process called the energy cascade. This continues until the energy reaches scales small enough that it is dissipated by viscosity.

The length scales of the eddies can be classified under three main representative length scales:

- injection range
- inertial range
- dissipative range

The energy spectrum $E(k)$, which is a function of wavenumber k, decays with a power law of -5/3, as represented by the Kolmogorov spectrum law

$$E(k) = C_k \kappa^{-5/3} \epsilon^{2/3}$$

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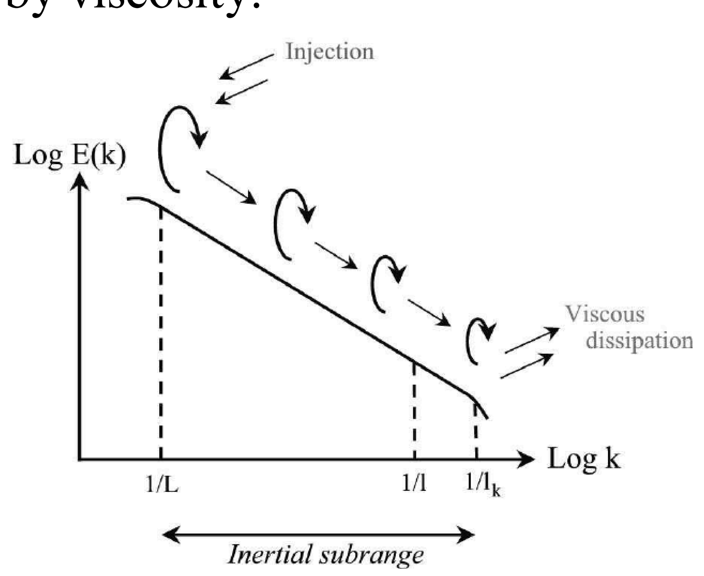
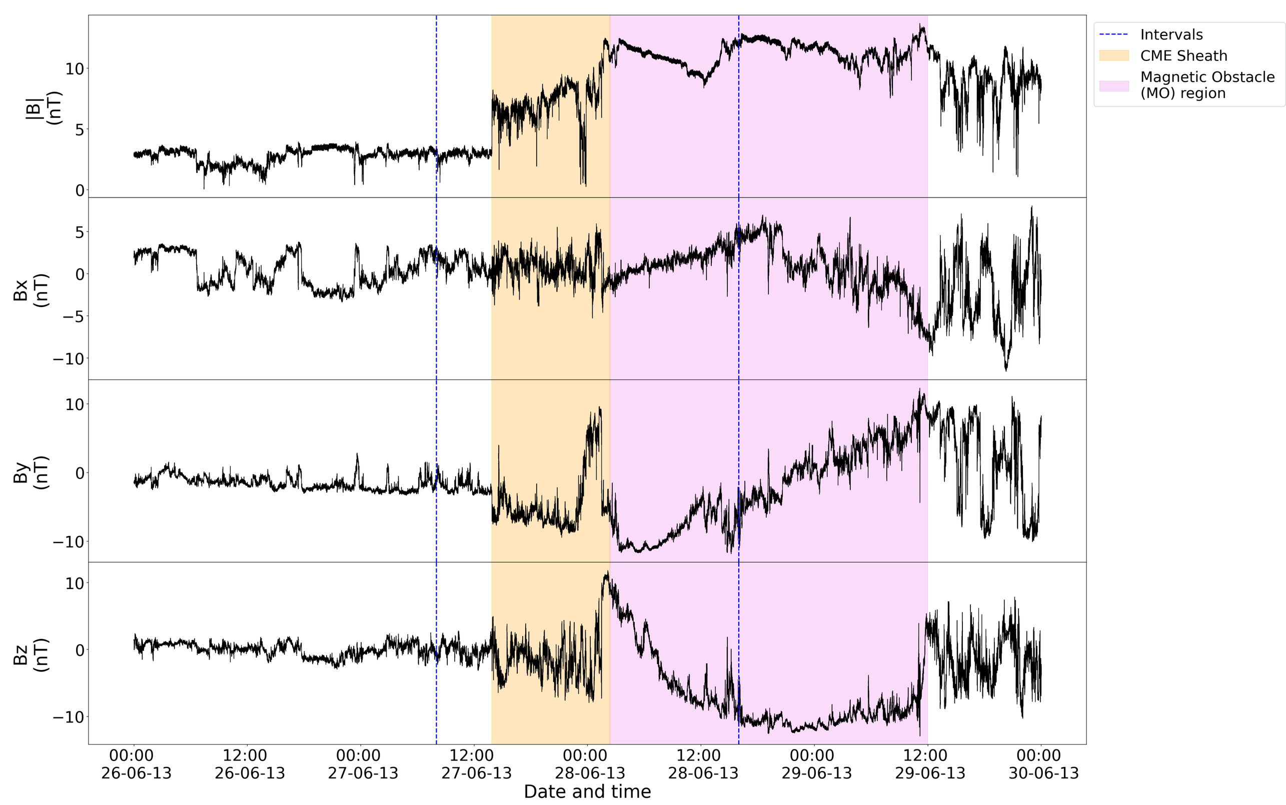


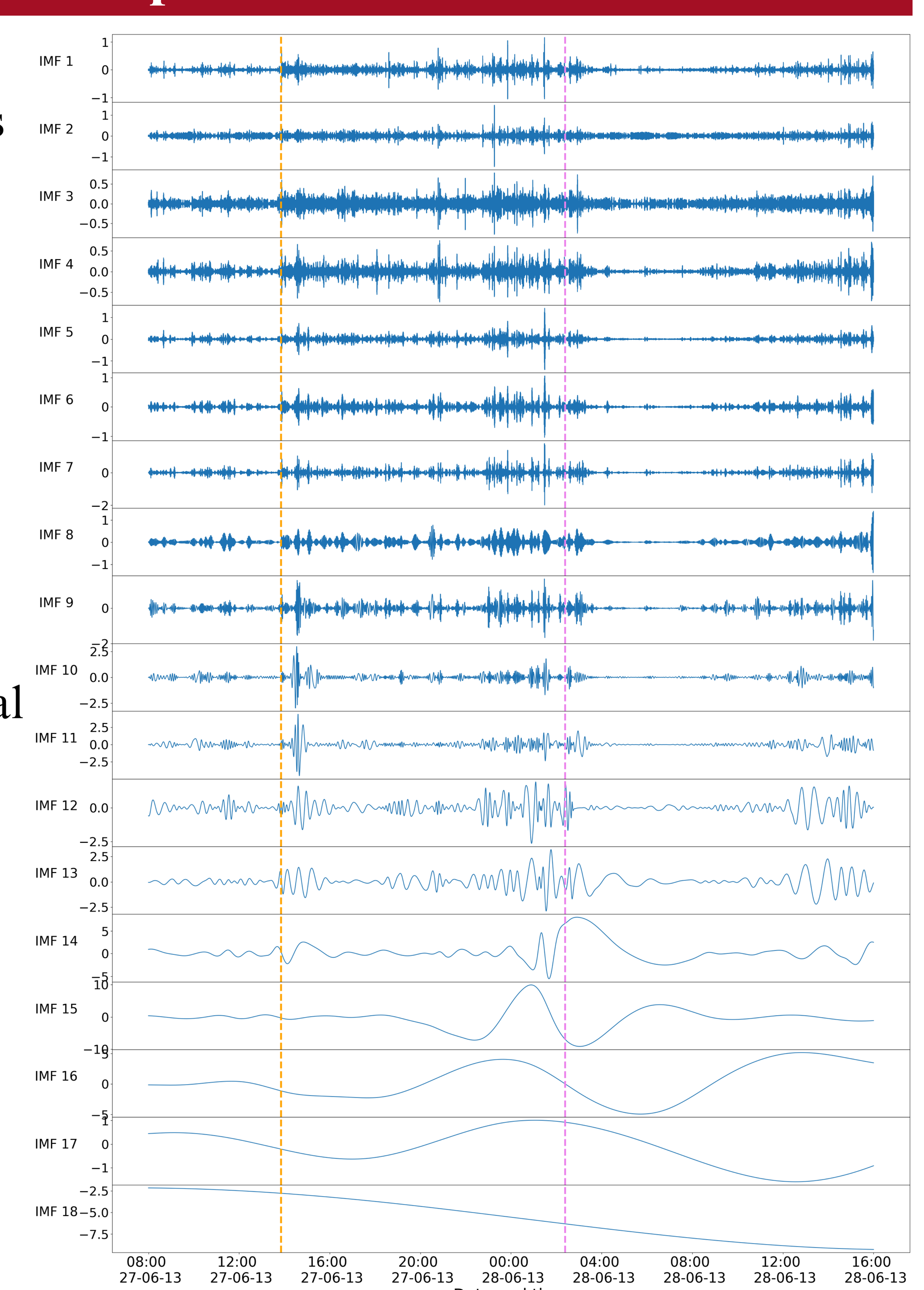
Schematic illustration of production, energy cascade and dissipation in the energy spectrum of turbulence. (Image credit: Aakash Patil, Stanford University)

Data



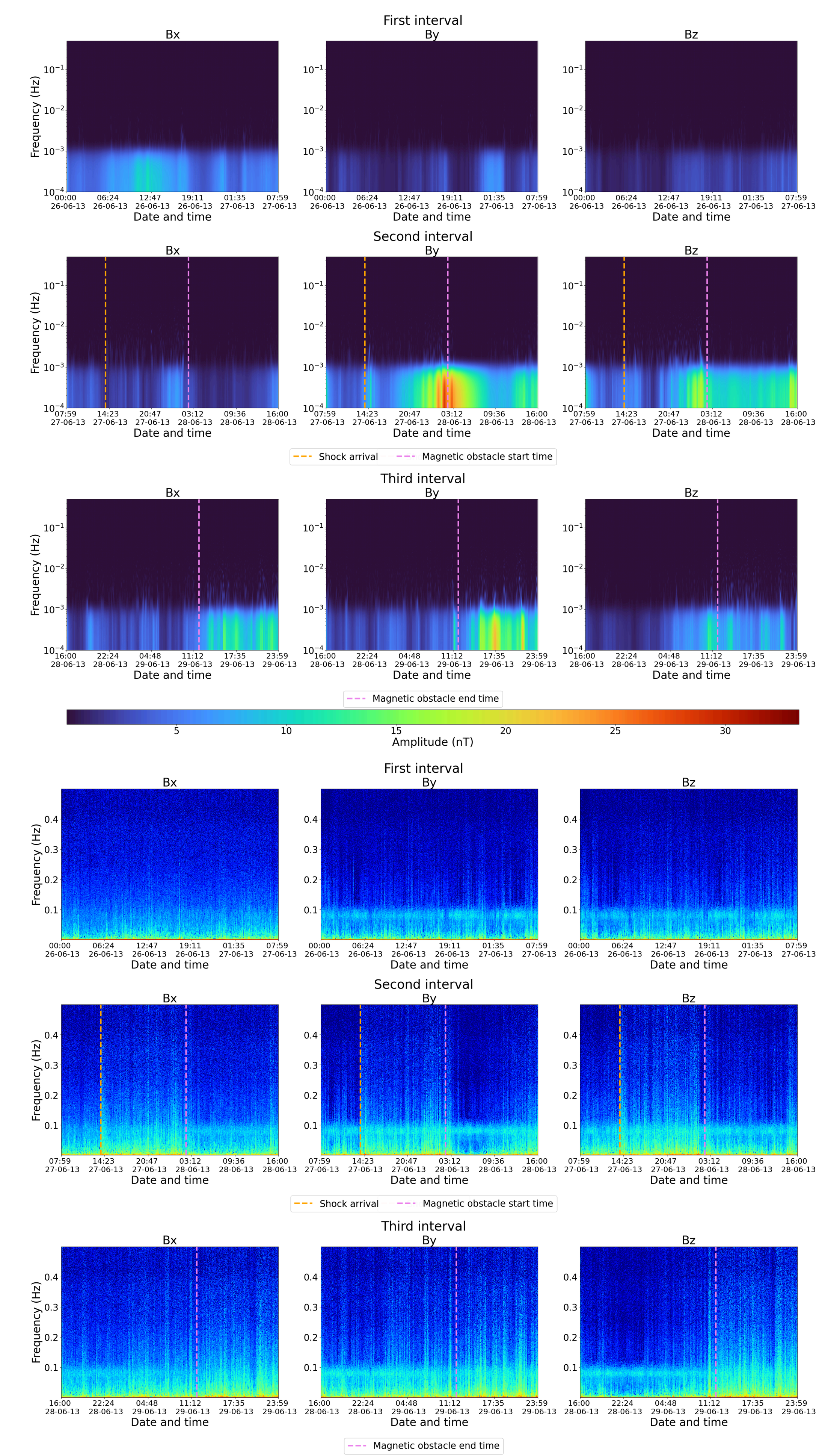
Empirical Mode Decomposition

The empirical mode decomposition (EMD) is a robust technique to break down a complex signal into simpler components called the intrinsic mode functions (IMFs). The first IMF contains the most dominant oscillation frequencies in the original data and is subtracted from the original data to obtain the second IMF. This is repeated in a sifting process to obtain the subsequent IMFs until a monotonic function is reached.



Hilbert Spectral Analysis

After obtaining the IMFs using the EMD method, the Hilbert transform is applied to each IMF to obtain the instantaneous frequency and amplitude. These quantities are used to generate the Hilbert spectrum that offers a measure of the total amplitude contribution from each frequency present in the signal.

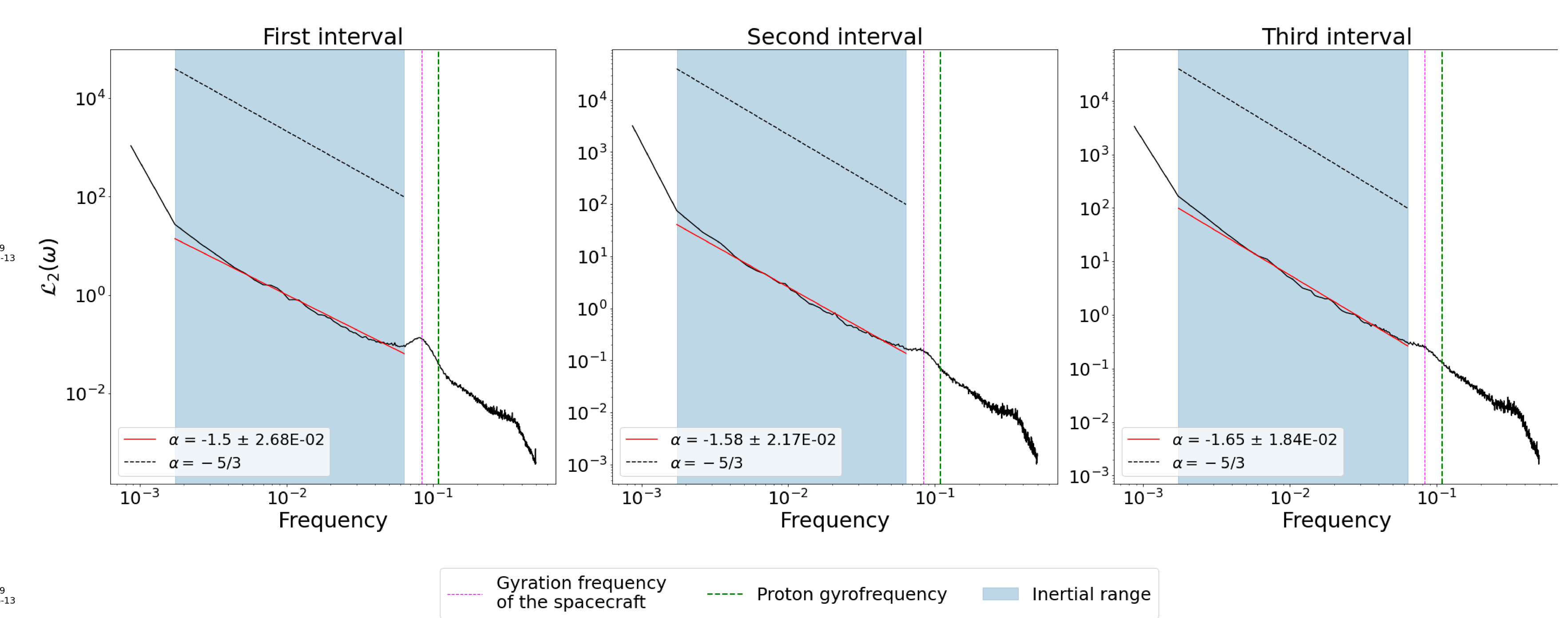


The spectograms illustrate the Hilbert spectra for the CME signal on linear and logarithmic colour scales, respectively.

Second Order Marginal Hilbert Spectra

Second order marginal Hilbert spectra is analogous to the Fourier power spectral density, providing energy distribution across different frequencies, and is represented using the equation,

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



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