Exploring Low Frequency Interplanetary Magnetic Field Spectra at ~0.4 AU using MESSENGER Data

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1. Introduction

The 1/f frequency spectra has been observed in various physical systems ranging from solid state physics (Van der Ziel, 1979; Dutta & Horn, 1981) to geophysics (Machlup, 1981). It is explained in Montroll & Shlesinger (1982) that a superposition of random time series with a lognormal distribution of correlation times has an overall 1/f power spectrum, that is scale-invariant, within a certain range of frequencies. Matthaeus & Goldstein (1986) have shown, through spacecraft observations, that the interplanetary magnetic field at 1 AU follows this spectral dependence (Figure 1). In particular the 1/f signature was seen in the frequency interval 2.7×10^{-6} and 8.0×10^{-5} Hz.

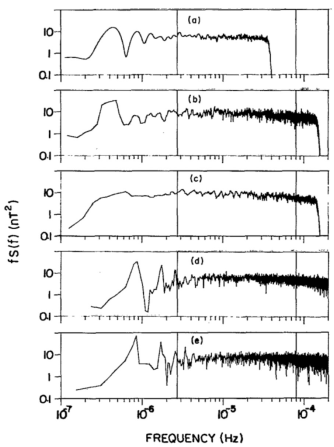

Fig. 1: 1/f spectral signature found in various intervals at 1 AU (from Matthaeus & Goldstein, 1986). This is immediately followed by an $f^{-5/3}$ dependence.

Matthaeus & Goldstein (1986) argued that the signature was due to scale-invariant reconnections in the lower corona. They ruled out the possibility of the signal being generated locally, due to the insufficient number of characteristic times elapsed as the solar wind travels to 1 AU. Later, Matthaeus et. al (2007) suggested the other possibility that it could be generated from the interior of the Sun (such as scale-invariant processes in the internal dynamo).

For this study, we are looking into the IMF spectra at a closer distance to the Sun (~0.4 AU). We are using solar wind magnetic field data collected from the MESSENGER spacecraft (Solomon et al., 2007), which orbited Mercury, throughout the year 2013, with perihelion 0.3 AU and aphelion 0.467 AU. Our goal is to look for the 1/f signature in a specific frequency range given the duration of the data.

2. Methodology

MESSENGER orbits Mercury at an average period of 12 hours. Only part of this time does the spacecraft pass through the upstream solar wind. Hence, these intervals are collected to form a long time series of solar wind at Mercury in the year 2013, at 1-second resolution.

The spectrum of the magnetic field is represented by the equation:

$$S(f) = \frac{1}{2\pi}\int dt\, R(t) e^{-2\pi i f t} \qquad (1)$$

in which

$$R(t) = Tr R_{ij}(t) = Tr\langle B_i(\tau) B_j(\tau + t)\rangle. \qquad (2)$$

In this study, the Blackman-Tukey technique (Blackman & Tukey, 1958) is utilized to compute eqn. (2) due to the occurrence of quasiperiodic gaps in the time series. In addition, this correlation function *R(t)* is also computed for each solar wind interval, in which a $f^{-5/3}$ dependence can be seen in Figure 2, indicating the scale of turbulent velocity fluctuations based on Kolmogorov (1941). The resulting correlation times exhibit a lognormal distribution (Figure 3). Therefore, the superposed time series should be bound to have a spectral 1/f dependence according to Montroll & Shlesinger (1982).

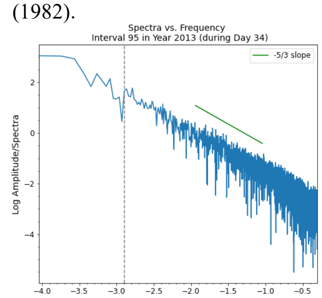

Fig. 2: Spectrum of a sample solar wind interval, with correlation time (τ_C) = 790 s. The spectra has an $f^{-5/3}$ dependence after 1.26×10^{-3} Hz (marked by the dashed line), which agrees to Matthaeus & Goldstein (1982) that this slope is known to occur at frequencies higher than $\frac{1}{\tau_C}$.

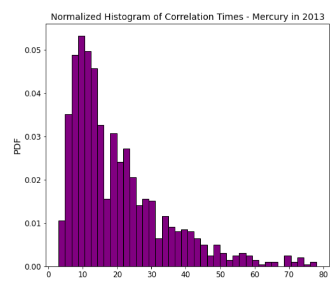

Fig. 3: Distribution of correlation times (in minutes) for Mercury solar wind intervals in 2013. The intervals range from 51 to 393 minutes (6 hours and 33 minutes). The total duration of solar wind data is 186 days and 117 minutes. The minimum and maximum values are 180 and 4680 s respectively.

3. Results

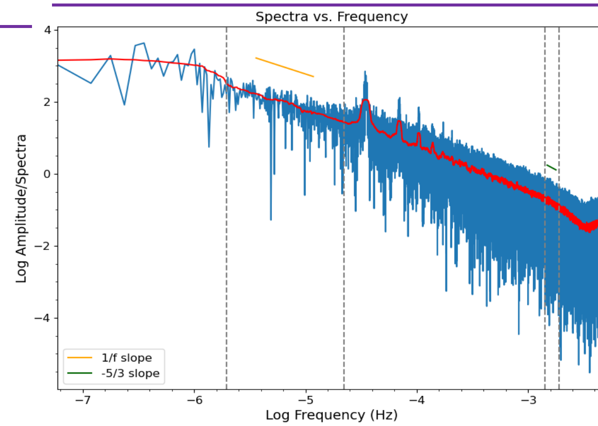

Fig. 4: Magnetic field spectrum of the superposed solar wind time series during 2013, with τ_C = 45101 s.

- An approximate 1/f dependence is shown to occur in the frequency range 1.95×10^{-6} to 2.36×10^{-5} Hz (marked by the first 2 dashed lines), where the upper limit is near $1/\tau_C$.
- The 1/f range is generally consistent with that found by Matthaeus & Goldstein (1986). This further supports the suggestion that the generating mechanism might happen well beneath the Sun (in the corona or lower in the dynamo), and not locally.
- However, the $f^{-5/3}$ dependence does not appear until 1.4×10^{-3} to 1.9×10^{-3} Hz. The intermediate spectrum between the 1/f and $f^{-5/3}$ is thus under current investigation.
- In addition, this range has "peaks", most noticeable one at 3.4×10^{-5} Hz. We suspect this to correspond to the period of the MESSENGER orbit around the planet, or "gaps" in the time series.

4. Future work

Conducting a similar process to Solar Orbiter data during periods when it is at 0.3 AU, to make comparisons and gain insight on the 1/f, $f^{-5/3}$, and the intermediate range.

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