A SEARCH FOR THE SOURCE SPECTRUM OF SOLAR WIND FLUCTUATIONS

Alexander Ruzmaikin

Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA

ABSTRACT

The Solar Orbiter will open a unique opportunity to measure for the first time the spectrum of fluctuations in the solar wind produced by localized solar source. It can be done during the co-rotation phase of the Solar Orbiter mission. All previous measurements have averaged the fluctuations over many sources distributed on the Sun. The spectrum of magnetic (as well as perpendicular velocity) fluctuations in the low-frequency spectral range is predicted to be very different from the 1/f spectrum measured in the absence of co-rotation.

Key words: Solar Wind, Magnetic fluctuations, Corotation.

1. INTRODUCTION

The spectrum of magnetic fluctuations measured in the solar wind can be divided into very low, low, and high-frequency parts (Roberts & Goldstein, 1981; Tu & Marsch, 1995). The very low part is dominated by structures coming from the Sun and is not self-similar. The low and high frequency parts are self-similar (follow a power-law) with different spectral exponents: -1 for the low and -5/3 for the high part. The break frequency point between the low-frequency part decreases systematically with increasing heliospheric distance (Bavassano et al. 1982; Tu & Marsch, 1995; Feynman et al., 1995). At 1 AU in the ecliptic plane the break frequency is at about 3.5 hours. The high-frequency spectrum is commonly believed to be the result of non-linear interactions of magnetic and velocity perturbations which lead to a turbulent cascade (Mangeney et al. 1991; Roberts & Goldstein, 1991). However there is not enough time to develop non-linearities *in situ* for the low-frequency range because fluctuations are transported with the supersonic velocity of the solar wind (Matthaeus & Goldstein, 1986). Thus the 1/f fluctuations originate on the surface or near the surface of the Sun. The analysis of the Ulysses magnetic field data for the solar wind from the south polar hole shows that, similar to the solar wind in the ecliptic plane, there is a 1/f low- frequency spectrum and 5/3 high- frequency spectrum at higher solar latitudes (Ruzmaikin et al., 1995;Horbury & Tsurutani, 2001).

An early explanation of the origin of the 1/f spectrum of magnetic fluctuations, suggested by Matthaeus and Goldstein (1986), involved reconnections in the low solar corona so that magnetic structures of different sizes merged and reconnected to form progressively larger and larger size structures. After many steps the size of the structures, as a multiplicative random variable, is expected to be lognormally distributed. The sampling of these magnetic structures could simulate a 1/f spectrum. One might expect, however, that multiple reconnections would instead lead to progressively decreasing scales.

An alternative explanation suggested that the 1/f spectrum arises because a spacecraft samples magnetic fields and plasma coming from the rotating Sun (Ruzmaikin, 1996). The spacecraft motion can be neglected at distances from the Sun exceeding several solar radii. If the Sun were non-rotating, the spacecraft at a given point in space would detect a time series that would reflect time perturbations from a fixed site on the Sun. Due to the solar rotation, however, spacecraft samples signals coming from different sites on the Sun. A time scale $\delta t = t_1 - t_2$ at the spacecraft position corresponds to a spatial scale $\delta l = v_{rot}\delta t$ on the Sun, where t_1, t_2 are the times needed for the solar wind to reach the spacecraft from two points on the Sun separated by δl, and $v_{rot} = 2\pi R/27^d = 2$ km/s is the solar rotation speed ($R = 7 \times 10^5$ km is the solar radius). The minimum spatial scale is characteristic of the smallest size solar wind source region at the Sun. The maximum scale L, at least in the case of the fast solar wind, is expected to be the size of a coronal hole.

The driving random process producing outgoing perturbations at the Sun is unknown at present although several processes have been suggested (see Solar Wind 8-9 Proceedings). The simplest driver can be characterized by one parameter, say a characteristic time for this process τ. An example is a driver with a spectrum of the Lorentz shape $e(f) \propto \zeta/(1+f^2\zeta^2)$.

The parameter τ can be considered as a random variable taking different values at different sites on the solar surface or near the surface. Sampling perturbations coming along radial paths is equivalent to averaging over this random variable. The resulting spectrum is given by

$$E(f) = \int e(f,\tau)\rho(\tau)d\tau \qquad (1)$$

where $\rho(\tau)$ is the distribution function of τ. A natural way to estimate the form of this distribution function is to think of τ, the characteristic time of the perturbation process, as being determined by many effects (Ruzmaikin, 1996). Indeed, the probability P of sending out a perturbation is determined by the product of many other probabilities p_j: of having a flow on the Sun with a specific velocity, of having a magnetic field of a specific geometry and strength, temperature, density, composition, etc., and of producing a flow driving the material out of the solar surface. Hence $P = p_1 p_2 p_3 \cdots$. The log of P is the sum of a large number of random variables. If we assume that they are independent or weakly correlated, then log p according to the central limit theorem is distributed normally. Hence P itself, and $\tau = 1/P$, is distributed log- normally. The log-normal distribution can be effectively mimicked by a simple $1/\tau$ law (Montroll & Shelisinger, 1982). The scale-invariant weight $\rho(\tau)d\tau \propto D\tau/\tau$ in Eq.(1) immediately results in the 1/f spectrum

$$E(f) = \int \frac{d\tau}{1+f^2\tau^2} \propto \frac{1}{f}\int \frac{dx}{1+x^2} \qquad (2)$$

The same 1/f result can be obtained with more general types of spectra of the driver law (Montroll & Shelisinger, 1982; Matthaeus & Goldstein, 1986). Thus information on the real spectrum generated by the Sun is lost due to the sampling from the rotating Sun. This spectrum and hence the nature of the driver can be unveiled by the data collection when a spacecraft is co-rotating with the Sun. The spectrum of magnetic (as well as perpendicular velocity) fluctuations in the 1/f range is predicted to be very different form 1/f spectrum measured in the absence of co-rotation.

2. SUGGESTED MEASUREMENTS AND EXPECTED GAIN OF KNOWLEDGE ABOUT THE SOURCE

The spectra of magnetic and velocity fluctuations can be routinely measured by the magnetometer and a plasma instrument. The limits of the 1/f spectrum can be found, in principle, by knowing the limits of the characteristic time τ of the driving mechanism. In the absence of such information we can only use the observational limits of the 1/f spectrum obtained from earlier spacecraft observations and the Solar Orbiter observations in non-co-rotating periods. Thus the break point found by Helios (Tu & Marsch, 1995) at 0.3 AU is about 8 minutes which corresponds to a scale on the Sun smaller than 10^3 km. While this scale is about the size of a granule it can only be an upper limit of the minimum scale because the break point between the 1/f and $f^{-5/3}$ parts of the spectrum is expected to shift to higher frequencies (smaller time lags) at the distances closer to the Sun, 0.2 AU.

The uniformity of the perturbations and closeness of the smallest scale (estimated above) to the size of granules make solar convection a candidate for the driver of the perturbations. The idea that the magnetic field fluctuations, observed in the solar wind in the form of Alfvén waves, are produced by supergranule-scale motions in the solar photosphere was put forward by Jokipii & Parker (1968). The 1/f spectrum confined between the smallest scale ($\leq 10^3$ km) and the large scale (about the size of a coronal hole), however, shows no characteristic at the supergranulation scale (1.5×10^4 km). In addition, in this explanation the magnetic field plays only a passive role.

The solar magnetic network with multiple reconnections of the magnetic field is expected to play an important role in these mechanisms (Axford & McKenzie, 1995). The network is a product of convection because convective flows concentrate the magnetic field near the boundaries of convective cells. Thus, many degrees of freedom are involved leading to power-law distribution of characteristic times of the driver. A new interesting hint comes from a statistical study of X-ray jets found on solar images taken by Yohkoh (Shimojo et al., 1996). Jets widths are found from $\leq 3.5 \times 10^3$ to about 10^5 km. The observed lower boundary is due to the 5 arcsec Yohkoh resolution. Their lifetime extends to about 10 hours, and the distribution of the observed lifetimes has a power-law form with the exponent $\propto 1.2$.

Hence the measuring of the spectrum of the driver, and the spectral limits, will help in understanding of the origin of the solar wind.

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