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DENSITY AND MAGNETIC FIELD SIGNATURES OF INTERPLANETARY 1/*f* NOISE

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ABSTRACT

We investigate the occurrence of 1/*f* noise in the interplanetary density and the magnetic field at varying heliocentric latitudes. The characteristic spectral amplitudes can be found in *Ulysses* density and magnetic data in the expected frequency ranges at all available latitudes, ranging from the ecliptic plane to more than 80°. Average spectra indicate a latitudinal variation, with a 1/*f* density signal becoming more pronounced in higher latitude bands. Azimuthal spectral analysis of solar magnetogram data using the *SOHO* Michelson Doppler Interferometer also shows 1/*f* noise in the photospheric magnetic field, most clearly at high latitude. Accordingly, we discuss possibilities that the 1/*f* signal arises at varying altitudes, possibly surviving coronal dynamics. This raises questions that may be addressed in future studies using spectroscopic, white light, and radio scintillation data.

Subject headings: MHD — plasmas — solar wind — turbulence — waves

1. INTRODUCTION

The presence of a broad band of "1/*f* noise," also known as flicker noise, in the interplanetary magnetic field has been known for some time through analysis of observations made at 1 AU near Earth's orbit (Matthaeus & Goldstein 1986; Ruzmaikin et al. 1996; Goldstein et al. 1995b). Its distinctive characteristic is a spectral density $S(f)$, the Fourier transform of the two time autocorrelation function,[2] which has the form $\sim 1/f$ for some range of frequency *f*. This implies equal energy per octave independent of *f* in this range of frequencies.

It was argued that the 1/*f* spectral feature cannot correspond to convection past the spacecraft of spatial structures that have been generated in the interplanetary medium by magnetohydrodynamic (MHD) processes in transit from the lower boundary of the super-Alfvénic wind (say, at 20 $R_\odot$). This is because MHD signals cannot have traveled the requisite distances during the convection time to the point of observation at 1 AU. Consequently, one turns to the possibility of dynamical explanations that originate lower in the solar atmosphere—in the corona or lower.

The explanation has been offered (Matthaeus & Goldstein 1986) that the interplanetary 1/*f* spectra are a consequence of a superposition of elementary signals (VanderZiel 1950; Machlup 1981; Montroll & Shlesinger 1982) in the corona that have varying statistical properties. The elementary contributions are characterized by varying stages of evolution of a scale-invariant coronal reconnection process that produces ever larger magnetic structures. Suppose that individual samples of the plasma are described by structures initially of size λ_0, and that after *N* stages of reconnection are of size $\lambda = \lambda_0(1+\epsilon)^N$. At the smaller scales in each sample, we assume there are fluctuations, characterized by a broadband spectrum in wavenumber *k* that has the form $S(k,\lambda) = C\lambda(1+k^2\lambda^2)^{-\nu/2}$, with λ the correlation scale and *C* a normalization constant. For $\nu = 5/3$ this is a Kolmogoroff spectrum at high *k*. We assume that the observed interplanetary spectrum is a superposition of samples with varying scale λ so that the observed frequency spectrum $P(f)$ at frequency *f* in a solar wind of speed $V_{\rm sw}$ becomes

$$P(f = k/2\pi V_{\rm sw}) = \int d\lambda G(\lambda) S(k,\lambda). \qquad (1)$$

Given the scenario of successive reconnections with some given probability for each step, we would expect $G(\lambda)$ to be a lognormal distribution appropriate to a multiplicative process. It then transpires (Machlup 1981; Montroll & Shlesinger 1982) that if the variance of the distribution *G* is large, there will be a correspondingly large range of scales over which $G(\lambda) \sim 1/\lambda$, that is, the distribution is approximately scale-invariant (VanderZiel 1950). Then from equation (1) a 1/*f* noise spectrum is produced over an associated range of frequencies (Matthaeus & Goldstein 1986). This is an example of how 1/*f* noise is produced by systems that lack preferred scales. In the coronal context, after some number of mergers the magnetic structures are accelerated with the solar wind and carried outward into interplanetary space, where the spatial signature of the merging process becomes the observed time signature in the spacecraft frame (Matthaeus & Goldstein 1986; Ruzmaikin et al. 1996; Mullan 1990).

Precisely how and where these reconnections occur was left open in the original formulation and has been interpreted in different ways in subsequent work (Ruzmaikin et al. 1996; Mullan 1990). However, in the past decade our ability to investigate this sequence of events has improved greatly with the availability of high-resolution measurements from the *Transition Region and Coronal Explorer* (*TRACE*) and from *Solar and Heliospheric Observatory* (*SOHO*) Michelson Doppler Imager (MDI), EUV Imaging Telescope (EIT), Ultraviolet Coronagraph Spectrometer

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[2] $S(f) = \int R(t)e^{-2\pi i f t}\,dt$, for time lag *t*, and autocorrelation $R(t) = \langle b_i(0)b_i(t)\rangle$ (sum on *i*) defined in terms of an appropriate average $\langle\ldots\rangle$ of the vector magnetic field fluctuation b_i. For the spectrum of density ρ, let $b_i \rightarrow \rho'$ for the density fluctuation $\rho' = \rho - \langle\rho\rangle$.

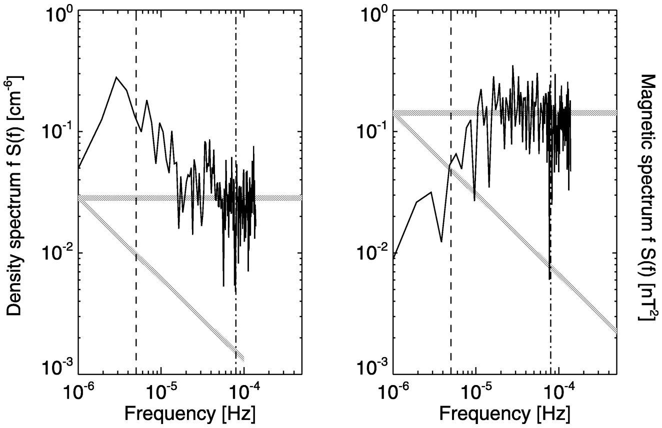

FIG. 1.—Examples of compensated spectra, *fS*(*f*), showing intervals of 1/*f* noise, in magnetic field (*right*) and density (*left*) , from *Ulysses* data at low latitude, near 43° latitude, for days 116–176, 1996. Vertical dashed lines indicate the approximate frequency range of 1/*f* noise reported by Matthaeus & Goldstein (1986). Shaded bars suggest $fS(f) \sim f \times 1/f$ variation (flat), and, for reference, $fS(f) \sim f \times 1/f^{5/3}$ "Kolmogoroff" variation.

(UVCS), and Large Angle and Spectrometric Coronagraph Experiment (LASCO). These measurements show that the solar atmosphere possesses structure across an extraordinary range of length scales. Dynamical evolution occurs across this entire observed range, requiring magnetic reconnection to constantly reorganize the topology of the magnetic field (Schrijver & Title 2003). Encouraged by the availability of these data sets, we seek to provide further details concerning the origin and nature of the 1/*f* noise in the magnetic field that has been known to be present at 1 AU in near Earth orbit, at low heliocentric latitudes. In the present study, we address the following questions: (1) Is the 1/*f* signal present in the interplanetary plasma density? (2) How pervasive is the 1/*f* signal present at different latitudes in the interplanetary medium? and (3) Is there evidence that the 1/*f* signal might originate deep in the corona, or even in the photosphere? To examine these questions we examine interplanetary data from the *Ulysses* spacecraft and magnetogram data from the MDI on the *SOHO* spacecraft.

2. INTERPLANETARY 1/*f* OBSERVED BY *ULYSSES*

The interplanetary analysis employs a Blackman-Tukey correlation analysis, a 95% cosine taper windowing of the symmetrized correlation function, and a Fourier transform to provide the spectrum.

First, we show that one can find interplanetary 1/*f* noise not only in the magnetic field spectrum, as has been previously reported, but also in some cases in the plasma density spectrum. For this demonstration we employ proton density data from the SWICS instrument on the *Ulysses* spacecraft (McComas et al. 2000). We carried out spectral analysis of the entire *Ulysses* data set near solar minimum, employing intervals having 60 consecutive days of 1 hr plasma data. Intervals with more than 30% missing data were rejected. From this mixed sample set of roughly 500 spectra at varying latitude and level of solar activity, we conclude that indeed 1/*f* noise is found in density data, as well as magnetic field data, in similar frequency ranges, comparable to that reported previously (Matthaeus & Goldstein 1986; see also Ruzmaikin et al. 1996; Goldstein et al. 1995a). We illustrate this result first by showing an example, in Figure 1, of flicker noise in a magnetic spectrum from *Ulysses* data at a latitude of 43°, at near solar minimum conditions in 1996. The density spectrum from the same interval (Fig. 1, *left*) shows a hint of 1/*f* behavior in the higher frequencies near 10^{-4} Hz but is less clear than the magnetic spectrum. Throughout the Letter, we present compensated spectra $fS(f)$ to facilitate identification of a 1/*f* range, which appears flat. We have found no systematic explanation for the absence of the 1/*f* spectra in many samples.

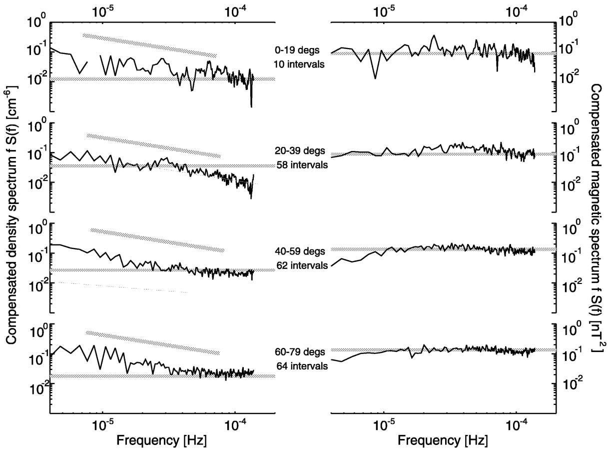

FIG. 2.—Compensated spectra *fS*(*f*) from (variance-averaged) spectra of *Ulysses* data, near solar minimum in several latitude ranges, indicated on the panels, along with the number of intervals in each average. A total of 194 intervals are employed in the analysis. *Right*: Magnetic spectra. *Left*: Density spectra. The horizontal bars are reference lines, and a line corresponding to a Kolmogoroff spectrum is also shown. The 1/*f* range is less evident in density at low latitude.

Second, we address the latitude variation and average properties of 1/*f* noise in both density and magnetic field spectra by analysis of *Ulysses* data. Average spectra based on a number of individual 60 day samples are computed after normalizing each sample by its variance. In Figure 2 we show average spectra from *Ulysses* data in solar minimum conditions, where the averages are accumulated separately for latitude ranges of about 20° width. There are 194 sample intervals contributing to the spectra in Figure 2. Normalization by the observed variance is appropriate when energy density is a similarity variable. This also helps to adjust for variation in heliocentric distance along the *Ulysses* orbit. The 1/*f* signal is seen clearly in all latitude ranges for the magnetic field spectra, but it appears in the density spectra more clearly in the higher latitude ranges. When it is present, the 1/*f* noise in density seems to be at somewhat higher frequency than in the magnetic field case. These features of the density spectra have been previously unknown as far as we are aware.

Ulysses provides the best available high-latitude data set but only sparse coverage of low latitudes due to its high orbital velocity during low-latitude scans. To confirm the contrast between density and magnetic spectra at low latitudes, we employ OMNI data in the ecliptic plane near solar minimum in 1974 when there is good coverage.[3] Results of that spectral analysis are shown in Figure 3, which lacks a 1/*f* signal in density but shows a clear 1/*f* signal in the magnetic field.

3. WHERE DOES THE 1/*f* SIGNAL ORIGINATE?

The existence of the 1/*f* signal in density data and at both high and low latitudes provides ample motivation for further study to examine what this might imply for coronal dynamics and the formation of the heliospheric plasma. In particular, one

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[3] For description of the OMNI interplanetary data set see http://omniweb.gsfc.nasa.gov.

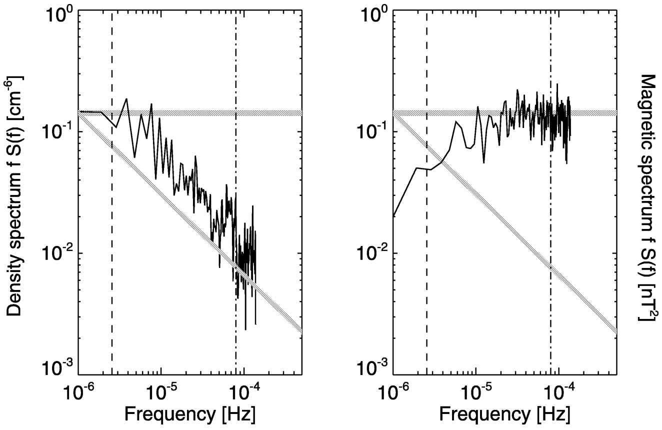

FIG. 3.—Compensated spectra *fS*(*f*) from (variance-averaged) spectra of OMNI data, in the ecliptic plane, near solar minimum in 1974. There are 28 intervals of 60 days duration in this averaged spectrum. *Right*: Magnetic spectra. *Left*: Density spectra. The horizontal bars are reference lines corresponding to a 1/*f* spectrum, which is evident in the magnetic data, but not the density data. A Kolmogoroff $fS(f) \sim f \times 1/f^{5/3}$ reference line is also shown.

might like to know at what stage of evolution the 1/*f* signal is formed. Does its presence tell us something about magnetic fields generation, or is it possibly better associated with the rearrangement of the magnetic field by photospheric motions? It is also possible that coronal dynamics contributes to this signal, as envisioned in earlier studies. If the signal appears at low altitude, one would like to understand how it survives further processing in the solar atmosphere. Furthermore, the observed latitudinal variation may provide further clues in understanding scale-invariant processes in the solar atmosphere.

These questions pose significant challenges, involving possibly a number of different types of observations, but we can begin by reexamining the analysis and conclusions based on previous analyses of magnetogram data at the relevant scales. Nakagawa & Levine (1974) examined wavenumber spectra derived from Carrington rotation maps (magnetograms) of the line-of-sight magnetic field (adjusted to estimate the radial magnetic field strength), using the Kitt Peak data set. They discussed the presence of two power-law regimes in wavenumber k (in inverse solar radii)—a $1/k$ range and a $1/k^3$ range. We find their suggestion of a $1/k^3$ spectral range proposed to be associated with a hydrodynamic cascade to be less than compelling. In particular, very long timescales and very large scale driving would be required to establish a true cascade at these large scales. An alternative view of this steeper spectral range is that it is the edge of the enhanced spectral power density associated with the solar rotation period near 4.2×10^{-7} Hz, which corresponds to Nakagawa & Levine's wavenumber $k = 1$. In contrast, the $1/k$ spectral region that they found in latitudinal wavenumber seems to be a clear candidate for involvement in the appearance of the interplanetary 1/*f* signal. In particular, their $1/k$ range from $k = 7$ to 70 corresponds approximately to 3×10^{-6} to 3×10^{-5} Hz, in accord with the low-frequency end of the 1/*f* range in the interplanetary medium (Matthaeus & Goldstein 1986).

4. 1/*f* SPECTRA IN THE PHOTOSPHERIC MAGNETIC FIELD

To begin a study of these possible connections, we carry out a magnetogram analysis using MDI data. To compute a frequency spectrum, we employ 10 solar (Carrington) rotations in each sample. Then we Fourier-analyze the data using the nominal solar rotation frequency to convert the longitudinal spatial signal to a time signal. We employ a fast Fourier transform (FFT) method with a Hanning windowing filter.

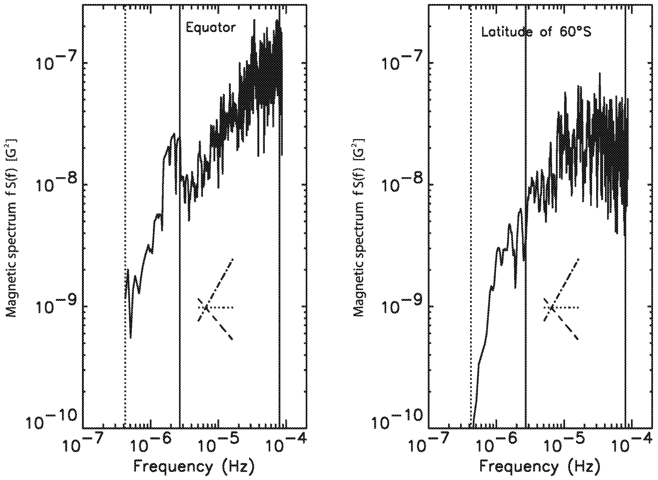

FIG. 4.—Compensated spectra of MDI line-of-sight photospheric magnetic field, *S*(*f*), plotted as *fS*(*f*) vs. frequency *f*, at two latitude bands, near the equator (*left*) and near 60° south latitude (*right*), near solar minimum (1996 May 5 to 1997 February 1). Frequency is computed by associating a 27 day rotation period to the 360° Carrington rotation. Vertical bars correspond to (*left*) solar rotations period and (*center and right*) approximate limits of 1/*f* signal in Matthaeus & Goldstein (1986). Dashed, dotted, and dash-dotted reference lines show the $f \times S(f)$ slope, respectively, for $S(f) \propto f^{-5/3}$, $S(f) \propto f^{-1}$, and constant *S*(*f*).

Figure 4 shows the results, as compensated spectra, for Carrington rotations 1909–1918. Each MDI Carrington rotation map is a 3600×1080 array, constructed from the nine maps nearest central meridian and interpolated to the disk center resolution (0.1° pixel^{-1} in the Carrington longitude). We have accumulated and analyzed the data in latitude bands, and in the figure we show the spectra for two bands, near the equator and near 60° South latitude. We take an average over ∼1° in order to improve the statistics. It is clear that the low-latitude band shows at most a hint of 1/*f* behavior at the upper frequency range near 10^{-4} Hz, whereas the higher latitude 60° band displays a full decade of a reasonable clear 1/*f* signal in the 10^{-5} to 10^{-4} Hz range. This partially supports the Nakagawa & Levine result while also suggesting a possible latitudinal structure in the manifestations of 1/*f* noise in the photospheric magnetic field.

5. POSSIBLE CONNECTION TO TURBULENCE, AND CONCLUSIONS

We conclude that flicker noise is a familiar signal in the interplanetary medium at moderate heliocentric distance and at varying latitude. We also confirm the report of Nakagawa & Levine that a similar signal is present in the longitudinal structure of the photospheric magnetic field, and we see some evidence that this signal is more clearly established at higher latitude. What is not clear at present is how, or even whether, the interplanetary and photospheric effects are related. If they are, the most obvious connection would be a quasi-static mapping of the photospheric field outward using a characteristic propagation speed, which most simply might be taken to be the solar wind speed. The quasi-static mapping has been used previously in discussion of low-frequency heliospheric fluctuations (Jokipii & Kota 1989; Giacalone et al. 2006). This may be a reasonable approximation for very large scale fluctuations in the super-Alfvénic and supersonic solar wind, in view of the time required for signals to propagate at MHD speeds over the requisite distances. However, for signals arising at the photo-

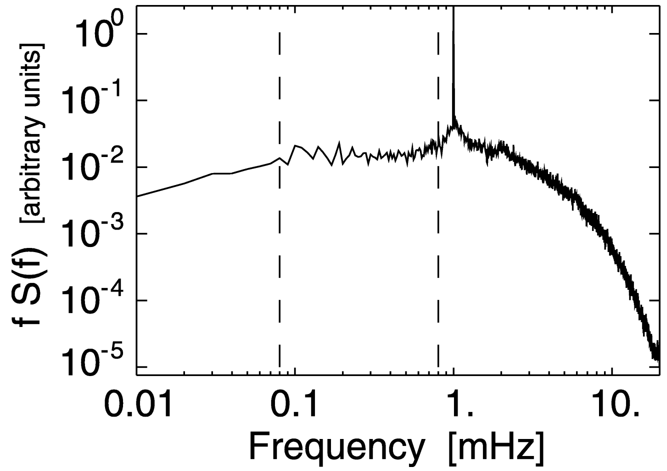

FIG. 5.—Spectrum of a magnetic field component vs. frequency f from a reduced MHD simulation designed to study coronal heating by wave driven turbulence cascade. There is clear indication of $1/f$ noise in this FFT spectrum of the time-varying magnetic field signal at a single point. Shown is an average of 64 such spectra obtained at different points. The peak at 1 mHz corresponds to the driving frequency. Vertical lines suggest the range of $1/f$ behavior. Note that this range does not correspond to the $1/f$ range seen in the observations (Figs. 1–3), presumably due to either numerical limitations or possibly differences in coronal and photospheric or interplanetary conditions. For details, see Dmitruk et al. (2002, 2004 and references therein).

sphere this argument does not follow readily due to the possibility of dynamical processing in the corona. On the other hand, some recent study (Dmitruk et al. 2004) shows that time-dependent signals survive through a turbulent coronal model layer much more robustly than do spatial structures associated with stirring at the coronal base. Pending further study, a possible connection between the photospheric and interplanetary flicker noise signals shown above can neither be firmly established nor ruled out.

In the present study we have answered the questions stated above: $1/f$ noise is seen in the magnetic field and in some cases in the plasma density, at both low and high latitudes in the interplanetary medium. Perhaps not surprisingly, it is not seen in all samples, but it is seen frequently and in some averages. There is a suggestion that $1/f$ is seen more frequently in the density data at higher latitudes. We also confirmed that flicker noise is seen in magnetogram data, and we found that its presence in the photospheric magnetic fields is more clear in the higher latitude samples. Many other questions are raised regarding the causal linkage between photospheric and interplanetary spectra, and the role of coronal dynamics. One would think that the rapid processing of the magnetic carpet establishes the necessity of a robust coronal reconnection process (Simon et al. 2001). Many other analyses of coronal processes either suggest or require reconnection (Mullan 1990; Fisk et al. 1999). One interpretation therefore is that the scenario of scale-invariant reconnection of flux structure remains feasible in some form. A very recent and relevant advance in the realm of numerical modeling is that reduced MHD models, driven by either a single frequency or a broadband spectrum of upward traveling low-frequency waves at the coronal base, are capable of self-generation of the flicker noise signal. It is notable that $1/f$ noise has been found to be *absent* in similar hydrodynamics simulations. This suggests that the magnetic field plays a key role in producing flicker noise, perhaps due to its capacity to induce self-organization. Generation of $1/f$ noise in this way is illustrated in Figure 5, which shows a compensated frequency spectrum from a reduced MHD coronal heating model (Dmitruk et al. 2002). More analysis of these and related numerical models will appear in a subsequent study. However, it is clear that there are a number of candidate possibilities for the origin of the observed solar and interplanetary signals.

Further study will be needed to clarify these issues, employing analytical, numerical, and observational input. We are currently developing an observational strategy that includes analysis of spectroscopic remote sensing data near 2 $R_\odot$ using the *SOHO* UVCS instrument, and white light coronagraph data from 3 to ~10 $R_\odot$ from the *SOHO* LASCO instrument. Including interplanetary scintillation data is also a possibility, if appropriate intervals are available. These analyses would provide further conclusions regarding the radial distances and latitudes at which $1/f$ noise is present. A particularly exciting prospect is to employ data from the recent and upcoming quadrature UVCS and *Ulysses*, which might provide observational tests for flicker noise in the same plasma at two widely separated positions.

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