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Small scale structures of the heliospheric magnetic field and the propagation of cosmic rays

G. Erdös[1], **Z. Németh**[1], **and A. Balogh**[2]

[1]KFKI Research Institute for Particle and Nuclear Physics, Hungary
[2]The Blackett Laboratory, Imperial College, London, U.K.

Abstract. The heliospheric magnetic field is rich in highly fragmented small-scale structures. The magnetic background strongly influences the motion of the charged particles of relatively low rigidity. Using high time resolution magnetic field data measured by the magnetometer onboard Ulysses, we study the small-scale magnetic structures, including fractal structures and discontinuities. We describe the small-scale magnetic structures with some parameters, including the fractal dimension and frequency of discontinuities. The dependence of these parameters on the heliospheric location and on the sunspot cycle is determined. The implications of the observations on the theories of cosmic ray modulation are discussed.

1 Introduction

In the modulation theory of cosmic rays, the diffusion coefficient is assumed to be a function of several parameters such as the heliospheric location, the time according to the solar sunspot cycle, and the rigidity of particles. Moreover, the random motion of particles is anisotrop with respect to the magnetic field lines. In principle, the parallel and perpendicular diffusion coefficients are fully determined by the fluctuations of the heliospheric magnetic field. It would be useful to calculate the transport parameters of particles from the heliospheric magnetic field, which would give us constraints on the modulation theories. However, model calculations face several difficulties. Some of the problems are connected to the inadequate knowledge of the magnetic field vector, as a function of space and time from a single spacecraft measurement. For instance, particles travel along the field lines therefore, to calculate the resonant scattering of particles, we have to know the fluctuations with respect to the distance along the field line rather, than along the path of the spacecraft. Further, the fluctuations of the magnetic field are usually large, suggesting the importance of nonlinear interaction of particles with the field. It is well known that the commonly used quasi-linear theory predicts about an order of magnitude smaller mean free path of particles, as calculated from the measured field fluctuations than that determined from the characteristics of energetic particle fluxes (Palmer, 1982). It is suspected that there are an amount of the measured fluctuations, which do not scatter the particles considerably. A possible scenario is if the bulk of the fluctuations propagate perpendicular to the field lines (Bieber et al., 1996), so the correlation length along the field direction is much longer than those perpendicular to the field direction. Several papers suggest that this type of magnetic fluctuations go hand in hand with very complex spatial magnetic structures. Bieber et al. (1996) have shown the development of flux tubes to highly fragmented objects, based on a mostly 2D fluctuation model. On the other hand MHD numerical simulations show that turbulence, leads to fluctuations with wave vectors mostly perpendicular to the field direction (Shebalin et al., 1983; Oughton et al., 1994). In this paper we search the spacecraft data for the complex spatial structures caused by the mixing of the plasma.

Most of the models use the power spectrum of the field fluctuations as input for the determination of the scattering mean free path. However, the heliospheric field is likely to be more complex. In this paper we investigate the fluctuations of the heliosperic magnetic field with new methods, because the fluctuations are not fully characterised by its spectrum. We use the high time resolution (1-2 s) magnetic field measurements by Ulysses in the off-ecliptic orbit, from 1992 to present. This set of data is unique, especially those measured in the fast solar wind at high latitude, since they are free from transient events.

Earlier Horbury and Balogh (1997) have shown that the turbulence in the heliosphere is intermittent, resulting in a magnetic field which should be described by structure

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Correspondence to: G. Erdős (erdos@rmki.kfki.hu)

functions rather than by power spectrum. Further, earlier analysis of the magnetic field time profiles showed fractal properties (Burlaga and Klein, 1986; Burlaga, 1991; Polygiannakis and Moussas, 1994; Marsch and Tu, 1997). Here we step beyond, by demonstrating the existence of spatial fractal structures in the heliospheric magnetic field, which can be explained by reasonable assumptions on field line mixing. The method, which we use to discover the spatial fractal structures, was introduced earlier (Németh and Erdõs, 2001). Our present analysis covers about one and a half Ulysses orbit, sunspot cycle minimum and maximum, and we show a simple scale transformation, which can transform out the spatial variations of the fractal dimension. Now we can present the fractal dimension as a universal parameter of the magnetic structure, which is independent from the heliospheric coordinates and the sunspot cycle.

To understand better the structure of the magnetic field, and its effect on the particle transport, we also examined the magnetic discontinuities. Discontinuity is a fast change in the magnetic field direction, which also scatters the particles. We have investigated the spatial distribution of the discontinuities along the orbit of Ulysses, which suggests the importance of the turbulent decay of those structures.

2 Fractal structures

Field line mixing is a good candidate to produce the observed complex magnetic structures. That process is well known in the context of the perpendicular scattering. If we begin with a relatively smooth magnetic field and we mix the plasma, we find that the originally neighboring regions travel far away, and the originally distant regions may become neighboring. So we can find very different magnetic field values in a little space volume. A portion of the space, where the initial magnetic field was smooth and nearly uniform develop to a fractal structure during the mixing, as it is well known from the theory of chaos.

Fractals are complex geometrical structures. They are fragmentary and at least statistically self-similar. One of the most important parameters of a fractal is the dimension. The fractal dimension is non-integer in general, and can be defined by the coverings of the fractal. The following relation is valid for a fractal point set:

$$N_n = A \cdot l_n^{-d} \qquad (1)$$

where l_n $(n=1,2,...)$ is a sequence of length scales, N_n is the number of l_n long intervals which need to cover the point set, and d is the dimension of the fractal. For a more detailed review of chaos and fractals, see McCauley (1993).

The method, which we have used to find these self-similar structures in the magnetic field data, is the following: We assume that before the mixing the value of the magnetic field vector falls into a pre-defined relatively small interval, in a little volume of the plasma. We want to find this volume after the mixing. The original, close to uniform magnetic field domain flows to a fractal. The magnetic field falls to the pre-defined interval inside the fractal region but changes to other values outside. The pre-defined interval has to be small. Small compared to the magnitude of the field, because in a larger portion of the space the variations of the magnetic field vector can be as large as the field itself. We used the $\boldsymbol{B}_R$ radial field component in the selection.

Space probes sample the intersection of the fractal and their path. They measure rapidly changing magnetic field, because the probe crosses narrow offshoots of different fractal regions. When the probe is in the intersection, the magnetic field must be in the selected range, thus we can identify points, which belongs to the same specified fractal domain.

The set of selected points also show fractal characteristics. This is a so-called physical fractal, which means that the self-similarity is limited. The smallest scale, which we can examine, is determined by the time resolution of the data set. Structures, below this scale are averaged. The dimension of this point sets depends on the width of the magnetic field interval in the selection criterion. The reason of this dependence is that the fractal dimension measures how the fractal fills the space. But as we broaden the selection interval, our fractal becomes more and more space-filling therefore, the fractal dimension increase. In the extreme limit when the selected interval covers the range of the measured magnetic field vectors, the selected "fractal" fills the space in 3 dimensions, thus the dimension of the intersection is 1. In the heliosphere, the average of the field changes with R distance from the Sun. Since the selection of interval affects the fractal dimension, we need to normalize the selected interval to $R_0 = 1$ AU. Our choice was

$$\left|B_R\right| < \frac{0.25}{\left(R/R_0\right)^2} \text{ nT} \qquad (2)$$

We have tested the power law in expression (1) on high time resolution magnetic field data. The self-similarity was proved in four orders of magnitude of scales. Fig. 1 shows N_n with respect to l_n on day 222 of 1995, similar good agreement with power law was obtained for other days.

Our analysis shows that the mixing is an important process in the formation of the measured fluctuations. Because the turbulent mixing leads to fluctuations with wave vectors mostly perpendicular to the field direction (Shebalin et al., 1983; Oughton et al., 1994), our results give an experimental argument that a considerable amount of the fluctuations do not scatter the particles.

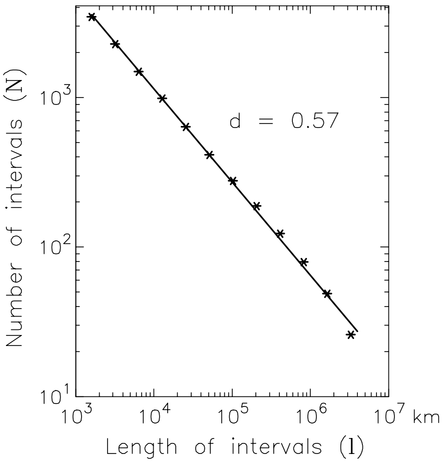

Fig. 1. Fractal property of magnetic field observed by Ulysses

3 Discontinuities

The method of data analysis was similar to our earlier work (Erdős et al., 2001), but here we have extended the investigation to more recent data of Ulysses. We have identified the discontinuities by searching for fast rotation of the magnetic field vector. We have performed running averaging over 10 s long time intervals on the high resolution Ulysses magnetic field data. Using the v_{SW} solar wind velocity measured onboard by the SWICS instrument, the Δt time lapsing between two successive measurements were converted to distance along the plasma flow line. A $\Delta\Phi$ rotation of the field vector was considered as a discontinuity, if the attitude gradient exceeded the threshold

$$\frac{\Delta\Phi}{\Delta t \cdot v_{SW}} > 0.01 \,\text{degree/km}. \tag{3}$$

This selection is arbitrary; the number of discontinuities strongly depends on the level of the threshold.

Figure 2 shows Ulysses observations, from February 1992 to March 2001. This time interval covers the first off-ecliptic orbit, and the beginning of the second one, from the aphelion in December 1997 to the southern polar pass in November 2000, and slightly beyond, see the top scales for the orbital parameters. The top and bottom lines display the magnitude of the field and the velocity of the solar wind, respectively. The second line is the λ_{DIS} averaged distance between discontinuities, as determined with the method above. The third line is the d fractal dimension, as determined from one-day measurements through the off-ecliptic mission of Ulysses. Both lines are fluctuating, even though averaging over the values of several successive days was performed. However, the values scatter considerably less during the fast solar wind observations, i.e., from mid-1993 to mid-1996, excluding the equatorial crossing at early 1995. We may notice that λ_{DIS}, unlike the fractal dimension, changes along the orbit of Ulysses. Those changes mainly follows the R radial distance of the spacecraft from the Sun. This was investigated in more detail by organizing the data according to R, as show on Fig. 3.

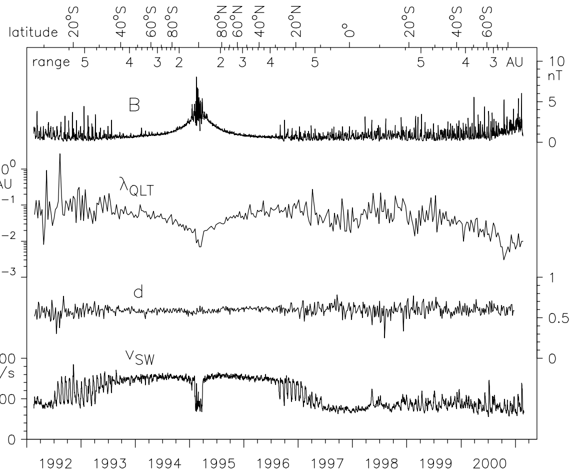

Fig. 2. Magnetic field magnitude (B), distance between discontinuities (λ_{DIS}). fractal dimension (d), and velocity of solar wind (v_{SW}) along the orbit of Ulysses

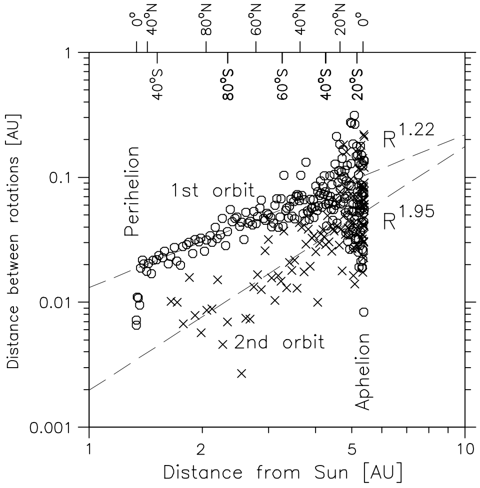

Fig.3. Distance between discontinuities, as a function of the radial distance from the Sun. Open circles and crosses are for the first and second orbit of Ulysses, respectively

The λ_{DIS} inter-event distance increase with increasing R distance from the Sun. This can be explained by the turbulent decay of discontinuities. A similar conclusion was reached earlier by Tsurutani and Ho (1999). An interesting finding, however, is that λ_{DIS} is larger in the fast solar wind (see the open circles representing the data of the first orbit), then in the slow solar wind (crosses, second orbit). This is a surprise, meaning that the discontinuities are less frequent in the fast solar wind, just opposite to the generally accepted idea. The discrepancy is caused by our selection criteria (Eq. (3)), which hinge on the change of the field direction by distance rather, than by time (spatial gradient rather, than time derivative).

Although the discontinuities are more frequent in the slow solar wind, those discontinuities tend to decay faster with increasing *R* distance from the Sun. A simple power law fits to the first and second orbit data (excluding the streamer belt at heliolatitude 30 degree from south to north), has shown the difference in the exponent in the fast and in the slow solar wind, respectively, see the dashed lines on Fig. 3. This means, that in the outer heliosphere (beyond about 10 AU), the discontinuities can be more frequent in the fast solar wind than in the slow one, just the opposite as in the inner heliosphere. If the discontinuities are the main agents for particle scattering, this may lead to interesting speculations about the diffusion coefficient, as a function of spatial position in the heliosphere and as a function of solar cycle.

On the Figure 3 we can study the latitudinal dependence of the distance between discontinuities. Ulysses was close to the equator at R=1.34 AU (perihelion) and at R=5.36 AU (aphelion). The polar passes happened at about 2.2 AU distance from the Sun, see the top scales for the latitudinal position of Ulysses, both North and South. We may notice that during the first orbit when Ulysses was in the fast wind, the data points follow the radial dependence $R^{1.22}$, therefore, no significant latitudinal change can be established. During the second orbit when Ulysses was in the slow wind, there might be a minimum at the southern polar pass (at about 2.5 AU from the Sun). However, the data points scatter, and we have to wait for the northern pass data for conformation.

4 Conclusion

We have investigated the fluctuations of the heliospheric magnetic field, by using different methods than the spectral analysis, including fractal and discontinuity analysis. Our interest was the better understanding of particle propagation in stochastic field therefore, we have looked at the spatial variations of the field rather, than the time variations which a spacecraft experiences. The main results are as follows:

Fractal analysis:

- Fractal structures were found in the magnetic field data. The existence of the structures can be explained by assuming a mixing of the plasma. Such a mixing naturally produces fluctuations, which are likely to weakly scatter particles
- The fractal dimension is uniform along the orbit of Ulysses

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Discontinuity analysis:

- The frequency of discontinuities decreases with radial distance from the Sun, which can be explained by turbulent decay.
- There is a difference between fast and slow solar wind. The frequency is larger in the slow wind, but it decrease faster by radial distance than in the slow wind.
- No latitudinal dependence was found in the fast solar wind.

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