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Intermittent structures and magnetic discontinuities on small scales in MHD simulations and solar wind

A. Greco [a,*], S. Servidio [a], W.H. Matthaeus [b], P. Dmitruk [c]

[a] Dipartimento di Fisica, Università della Calabria, 87036 Rende (CS), Italy
[b] Bartol Research Institute and Department of Physics and Astronomy, University of Delaware, Newark, DE 19716, United States
[c] Departamento de Física (FCEN-UBA), Buenos Aires, Argentina

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ABSTRACT

In this work we review some recent studies, in which properties of the magnetic field in high resolution simulations of MHD turbulence with spacecraft data are compared, focusing on methods used to identify classical discontinuities and intermittency statistics. Comparison of ACE solar wind data and simulations of MHD turbulence showed good agreement in waiting-time analysis of magnetic discontinuities, and in the related distribution of magnetic field increments. Further analyses showed that the magnetic discontinuities are not distributed without correlations, but rather that non-Poisson correlations, possibly in the form of burstiness or voids, are present in the data at least up to the typical correlation scale. The discontinuities or bursty coherent structures represent in this view the current sheets that form between magnetic flux tubes which may be a signature of intermittent, anisotropic, fully developed MHD turbulence.

1. Introduction

A well known feature of solar wind observations is the appearance of sudden changes in the magnetic field vector, defined as directional discontinuities (DDs), which are detected throughout the heliosphere (Burlaga, 1968; Tsurutani and Smith, 1979; Ness and Burlaga, 2001; Neugebauer, 2006). Many studies identify these as statistically advected tangential discontinuities (TDs), characterized by small components of the magnetic field normal to them, large variations of magnetic field intensity and density jumps across them, separating two different plasma regions, or propagating rotational discontinuities (RDs), which have large normal components of the magnetic field, but small variations of magnetic field intensity and of density (Hudson, 1970). There is still debate regarding the relative frequency (Neugebauer, 2006) and the origin of these structures (Vasquez et al., 2007). There are also ambiguities in identification of TDs and RDs, and differences in the defining criteria (Horbury et al., 2001; Knetter et al., 2004; ErdoS and Balogh, 2008).

Changes are often seen at time scales of 3–5 min, although similar discontinuities are seen at smaller time scales (Vasquez et al., 2007). A familiar interpretation is that these are classical ideal magnetohydrodynamic (MHD) discontinuities (Burlaga, 1968; Tsurutani and Smith, 1979; Ness and Burlaga, 2001). An alternative viewpoint is that both the fluctuations and discontinuities are facets of a nonlinear MHD cascade (Politano et al., 1998; Biskamp and Muller, 2000), and that these are interacting, not passive, and contribute to heating of the interplanetary plasma. In the former view the interplanetary medium evolves very little, and its features can be traced back to features in the lower corona, possibly even to the photosphere (Borovsky, 2008).

In this work, we are not examining the normal magnetic field which is, at least, required to distinguish between tangential and rotational discontinuities (Neugebauer, 2006). Our intention is to review observational and theoretical issues related to interplanetary discontinuities, making comparisons with MHD simulations, without regard to whether they are tangential or rotational.

It was found that methods for identifying classical discontinuities and for computing quantities related to intermittency are closely related (Greco et al., 2008). These approaches give very similar results when used as a basis for identifying "events" in either simulation data or in ACE solar wind magnetic field data (Greco et al., 2009a). In the simulations, we found that the typical events are connected with current sheets that form between adjacent magnetic flux tubes (Greco et al., 2008, 2009a). Indeed this is consistent with the fact that the solar wind exhibits many properties associated with intermittent turbulence (Burlaga, 1991; Marsch and Tu, 1994; Horbury et al., 1997; Sorriso-Valvo et al., 1999; Burlaga et al., 2006), but the question persists as to whether these properties arise locally or if they are remnants of coronal processes (e.g., Borovsky, 2008). The results show that coherent structures and discontinuities can arise rapidly, and

* Corresponding author. Tel.: +39 0984 496132.
E-mail address: greco@fis.unical.it (A. Greco).

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therefore we suggest that at least some of the observed interplanetary discontinuities are formed locally. This conclusion is not in contrast with conclusions drawn in Bruno et al. (2004), where magnetic field directional changes were compared with increments computed from 1D parametric decay simulations. As in the present paper, the authors (Bruno et al., 2004) concluded that the distributions of increments provide important information concerning the turbulent cascade and the structure of interplanetary magnetic fluctuations.

2. Turbulence and discontinuities

The presence of discontinuities in the observed interplanetary magnetic field is suggestive of some kind of internal boundaries in the plasma. The main diagnostic we examined, describes properties of the magnetic field which is assumed to consist of a mean part $\mathbf{B}_0$ and a fluctuation $\mathbf{b}$, namely $\mathbf{B}=\mathbf{B_0}+\mathbf{b}$. The former may vary slowly in space while $\mathbf{b}$ is a complex turbulent field that varies in space and time. To describe rapid changes in the magnetic field, we looked at the increments $\Delta\mathbf{B}_s=\mathbf{B}(s+\Delta s)-\mathbf{B}(s)$ at points in space separated by Δs along some trajectory. When s is an inertial range separation, the increments have properties characteristic of the inertial range of turbulence (Monin and Yaglom, 1975). A slightly more economical description, and one that relates well to discontinuity analysis is obtained by looking at the time series and statistics of the magnitude of the vector increments,

$$|\Delta\mathbf{B}|=|\mathbf{B}(s+\Delta s)-\mathbf{B}(s)|, \tag{1}$$

once again Δs is the separation and we now suppress the argument s where convenient. Note that Eq. (1) takes into account both directional changes (such as TDs) as well as compressions due to magnetic field intensity fluctuations (Bruno et al., 2004).

In Fig. 1 we show two samples of time series of $|\Delta\mathbf{B}|$, one obtained from a 2D MHD simulation by sampling along box diagonals and another obtained from interplanetary magnetic field data measured by the ACE spacecraft (Greco et al., 2008, 2009a). We took a time interval from ACE data of 27 days (one Bartel rotation) in 2001, characterized by an average bulk velocity of 400 km/s (slow wind). The resolution is 16 s. To plot Fig. 1 we used a time separation of $\Delta t=32$ s and a separation length $\Delta s=2\Delta x$, where Δx is the spatial grid size of the simulation box. Simulation data are normalized to the correlation scale λ_c, which we chose to be equal $\frac{1}{15}$ of the box size, and ACE data are normalized to the correlation time $t_c=50$ min (Matthaeus et al., 2005). To compare MHD simulations with the solar wind dataset, the ratios $\Delta s/\lambda_c$ and $\Delta t/t_c$ are of the order of 0.08. It is apparent that both datasets are spiky, and the events that might be identified as discontinuities are evident. While discontinuities are sometimes picked out using more elaborate methods (e.g., Vasquez et al., 2007), the baseline property that there is a large sudden change of direction, can be associated with a simple cutoff or threshold applied to the datasets.

In the case of the simulation data it is possible to unambiguously identify what structures are associated with these discontinuity "events". This is particularly straightforward in two dimensions, as illustrated in Fig. 2. This illustrates field lines, associated magnetic islands and intensity of electric current density for a 2D incompressible MHD simulation of fully developed turbulence. It is a decaying turbulence run at kinetic and magnetic Reynolds numbers $R_v=R_m=1700$, carried out with a very accurate and well resolved 4096^2 Fourier pseudo-spectral code. The 2D approximation may be valid when a strong magnetic field is present (this may happen, in some circumstances, in the solar wind). Moreover, using 2D MHD can attain higher spatial resolution.

The picture shows the system when the mean square current density $\langle j^2\rangle$ is very near to its peak value. At this instant of time the peak of turbulent activity is achieved. When the turbulence is fully developed, coherent structures appear. They can be identified as magnetic islands that have different size and energy. At the regions between islands the perpendicular (out-of-plane) component of the current density j becomes very high (Matthaeus and Montgomery, 1980). As reported in Fig. 2, the out-of-plane component of the magnetic potential a shows a collection of

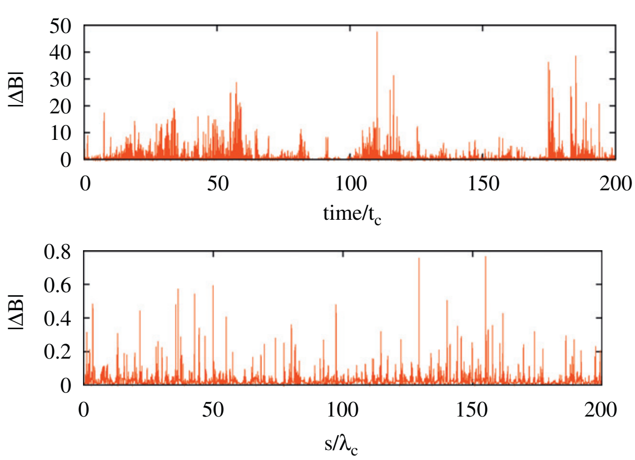

Fig. 1. Time/space series of the magnitude of magnetic vector increments computed from 2D MHD simulation (bottom) and solar wind ACE (top). In both cases data are acquired along a linear path (in solar wind using frozen-in flow) and normalized to the respective correlation scales. Here the scales are roughly comparable in terms of correlation scales, and the appearance of the datasets is similar, with spiky changes seen in both cases.

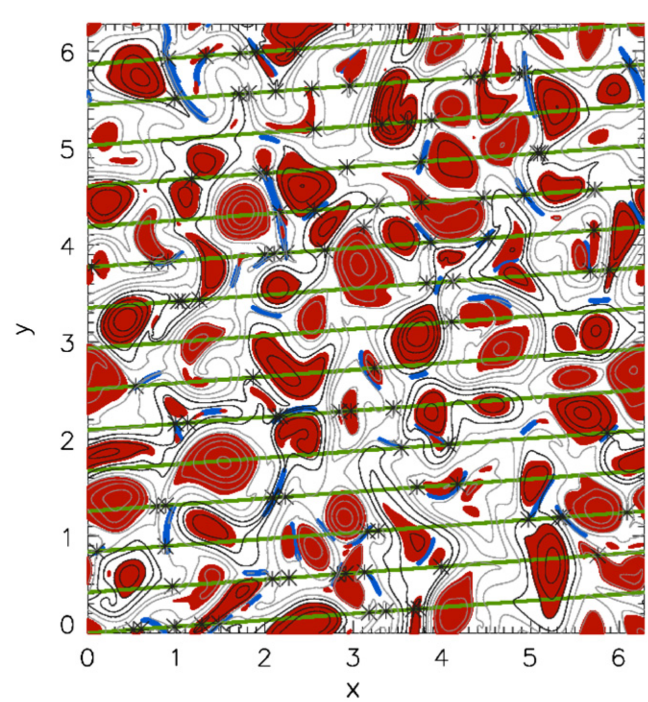

Fig. 2. A contour map of the out-of-plane vector potential (field lines) for $a>0$ (black contour lines) and $a<0$ (gray contour lines). The superposed colors represent magnetic islands (red) and strong current regions (blue) identified with a cellular automata technique (Servidio et al., 2009). Green lines represent a sample path through the simulation box. Gray stars are placed at the center of a discontinuity, selected in this case by the PVI method. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)