Advances in Plasma Astrophysics
Proceedings IAU Symposium No. 274, 2010
A. Bonanno, E. de Gouveia Dal Pino & A.G. Kosovichev, eds.
doi:10.1017/S1743921311006697

Emergence of intermittent structures and reconnection in MHD turbulence

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Abstract. In recent analyses of numerical simulation and solar wind dataset, the idea that the magnetic discontinuities may be related to intermittent structures that appear spontaneously in MHD turbulence has been explored in details. These studies are consistent with the hypothesis that discontinuity events founds in the solar wind might be of local origin as well, i.e. a by-product of the turbulent evolution of magnetic fluctuations.

Using simulations of 2D MHD turbulence, we are exploring a possible link between tangential discontinuities and magnetic reconnection. The goal is to develop numerical algorithms that may be useful for solar wind applications.

Keywords. (magnetohydrodynamics:) MHD, turbulence, (Sun:) solar wind, methods: numerical

1. Introduction

Solar wind discontinuities are characterized by large and rapid changes in properties of the plasma and magnetic field (Burlaga, 1968; Tsurutani & Smith, 1979). One interpretation of the strong discontinuities is that they are the walls of a filamentary structure of a discontinuous solar-wind plasma (Borovsky, 2008). Another is that some strong discontinuities are fossils from the birth of the solar wind (Burlaga, 1968). We explored an alternative possibility, that observed discontinuities might be the current sheets that form as a consequence of the cascade of MHD turbulence to inertial scales (Greco *et al.*, 2008; Greco *et al.*, 2009a).

In the standard picture of solar wind turbulence where a temporal/spatial cascade of the fluctuations from large to small spatial scales produces the numerous thin current sheets that are a common aspect of the high-speed wind at 1 AU, the small-scale magnetic reconnection occurs relatively frequently at these thin current sheets (e.g., Matthaeus & Lamkin, 1986).

In this work, we start to explore the possibility that discontinuities and local magnetic reconnection events are linked. Magnetic reconnection has been often studied in simplified geometries and boundary conditions, but since it might occur in any region separating topologically distinct magnetic flux structures, it might be expected to be of importance in MHD turbulence. The latter possibility has been recently investigated, leading to the conclusion that in turbulence strong reconnection events locally occur (Servidio *et al.*, 2009; Servidio *et al.*, 2010). Previous studies on discontinuities and theories of reconnection in turbulence are being combined in order to identify possible reconnection events between the intermittent events. In the present report we consider a 2D model in order to simplify the problem.

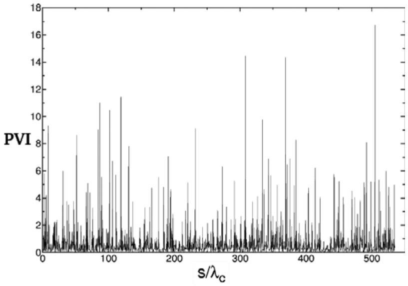

Figure 1. Spatial signal PVI obtained from the simulation by sampling along the trajectory s in the simulation box.

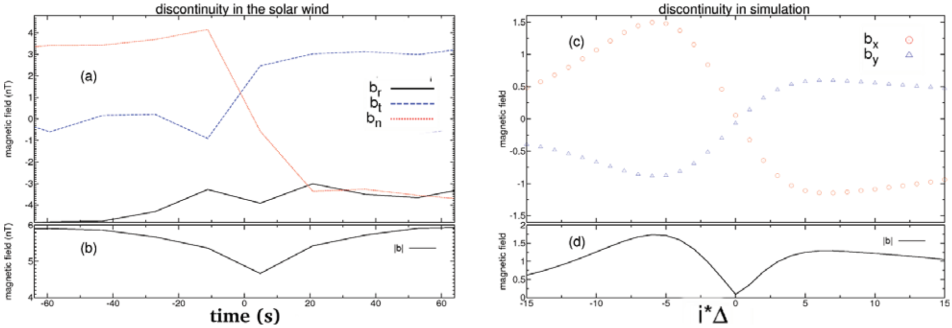

Figure 2. Examples of discontinuities selected by the PVI method. Panel a: the three RTN components of the magnetic field vector and Panel b: magnitude of the magnetic field vector in solar wind data. The discontinuity is centered around zero; Panel c: the two components of the magnetic field vector and Panel d: magnitude of the magnetic field vector in simulation data. Δ is the resolution data.

2. Magnetic discontinuities and intermittent current sheets

To describe rapid changes in the magnetic field, usually people look at the increments $\Delta\mathbf{b}(s,\Delta s)=\mathbf{b}(s+\Delta s)-\mathbf{b}(s)$, being $\mathbf{b}$ the magnetic field, s the 1D coordinate along the trajectory of the spacecraft , and Δs the related spatial increment. By using the magnetic increments, we computed the normalized (squared) Partial Variance of Increments (PVI) (Greco *et al.*, 2008):

$$PVI(\Delta s,\ell,s)=\frac{|\Delta\mathbf{b}(s,\Delta s)|}{\sqrt{\langle|\Delta\mathbf{b}(\mathbf{s},\mathbf{\Delta s})|^{\mathbf{2}}\rangle_{\ell}}}, \qquad (2.1)$$

where $\langle\bullet\rangle$ denotes a spatial average over the entire domain of total length ℓ. For the numerical analysis performed here $\ell\simeq 535\lambda_C$, being $\lambda_C=0.18$ the correlation length of turbulence. In Fig. 1, the time series of PVI with $\Delta s=0.67\lambda_d$, where $\lambda_d=4.6\times10^{-3}$ is the dissipation length of turbulence, is shown, and Fig. 3 shows an example of s-path in the simulation box along with Eq. 2.1 is computed. The PVI dataset is bursty, suggesting the presence of sharp gradients in the magnetic field, localized intermittently in space. These events may correspond to tangential discontinuities (TDs). Imposing a threshold on Eq. 2.1 a collection of discontinuities along s-path can be identified. An example of TD is displayed in Fig. 2. The figure shows that these events are characterized by a rotation of the magnetic field followed by a depression of the magnitude of B (panels c and d). None of these features were present at the initial time (not shown) in which the electric current is not concentrated but rather is randomly distributed by construction.

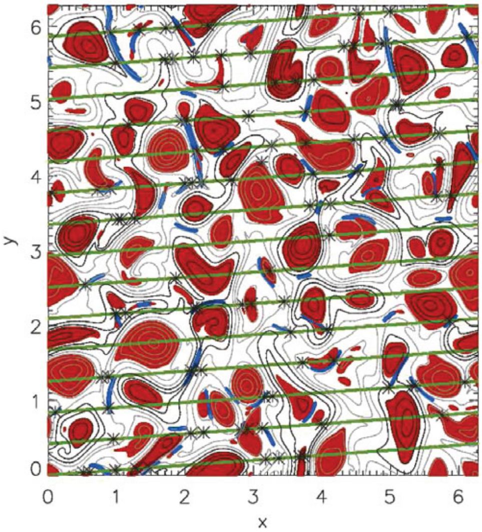

Figure 3. Contour lines of the magnetic field (red areas are the magnetic islands) together with the reconnection (blue) regions. The discontinuities identified by PVI technique are gray stars placed on an a sample path (green line) in the simulation box.

Greco *et al.*, (2008) looked at the distribution of waiting times between discontinuity events identified either by classical methods (e.g. Tsurutani & Smith, 1979) or by applying the thresholding technique based on Eq. 2.1. The authors found that the two methods performed almost interchangeably and the normalized waiting-time (WT) distributions between events were extremely similar in the solar wind and simulation datasets at (inertial range) separations shorter than the correlation scale (Greco *et al.*, 2009a). Fig. 2 shows a directional change, selected by the PVI algorithm in the ACE magnetic field data. Panel a gives the components and panel b the magnitude of the magnetic field vector with 16 s time resolution. More specifically, in Greco *et al.* (2008a) and (2009a) it was found that distributions of WTs between discontinuities for $s < \lambda_C$ were well described by a power law. This conclusion was true both in simulations and in solar wind. Further analysis were employed in Greco *et al.* (2009b) to examine the distribution of WTs for these events, showing that the discontinuities are not distributed without correlations, but rather that non-Poisson correlations are present in the solar wind data at least up to the typical correlation scale. A similar conclusion emerges from Poisson analysis of the simulation dataset.

3. Local reconnection

In previous studies (Servidio *et al.*, 2009; Servidio *et al.*, 2010) it has been confirmed that turbulence lead to the spontaneous formation of local and intermittent reconnection events. We employed a cellular automata's technique (Servidio *et al.*, 2010), applying to a 2D turbulent field, permitting to identify the diffusion regions. Using this cellular automata mapping, the shape and the position of each diffusion region, nearby each X-point of the vector potential a, are defined. The width d, the elongation l, and the respective reconnection rate E_X are computed as well. Note that only the strongest reconnection sites (RSs) are detected by the algorithm (Servidio *et al.*, 2010).

Varying the threshold for Eq. 2.1, we can count how many of the TDs are RSs as follows. Every discontinuity is characterized by a starting and an ending point (see Fig. 2). A set of discontinuities is identified but eventually only a certain number of discontinuities are reconnecting regions. In order to measure this number, we will make use of the cellular automata map. The latter is a 2D matrix that has 0 value out of the diffusion regions or 1 inside them. When at least one point of the discontinuity overlaps with one point of the diffusion region, the event is counted as success, otherwise it is a failure. In the latter case it means that the method is detecting a non reconnecting, high-stress, magnetic field structure. Using for example the threshold 6 in Eq. 2.1, 25 discontinuities have been identified and 18 correspond to reconnection regions. The efficiency of this method can be arbitrarily estimated as proportional to the number of the success over the total number of discontinuities. For this algorithm the goodness is $\simeq 70\%$. An example of discontinuities, together with the reconnecting regions, is shown in Fig. 3.

4. Conclusions

We can draw a firm conclusion for the numerical experiments, that the discontinuity events are formed spontaneously due to nonlinear couplings, cascade and turbulence. They were not present in the initial data. The extension of this conclusion to the solar wind is tempting.. Our studies are consistent with the hypothesis that solar wind intermittent discontinuities are produced by MHD turbulence, even if we have not ruled out that some of these features originate in the lower corona. It is possible that many inertial range structures that contribute to the tails of the PDFs of increments of $\mathbf{B}$ in the solar wind, are formed in situ by local rapid relaxation processes associated with turbulence. A further detailed analysis determined the non-Poisson character of these intermittent events from the shape of waiting time distributions.

Finally, a magnetic discontinuity is a rapid change of the field across a very narrow part of the space, so that strong changes of the magnetic topology are necessarily involved. This implies the possibility that discontinuities and local magnetic reconnection events may be linked. Magnetic reconnection has been often studied in simplified geometries and boundary conditions, but since it might occur in any region separating topologically distinct magnetic flux structures, it might be expected to be of importance in MHD turbulence. Previous studies on discontinuities and theories of reconnection in turbulence could be combined in order to identify possible reconnection events between the intermittent events.

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