Solar and Stellar Magnetic Fields: Origins and Manifestations
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Coherent structures and magnetic reconnection in photospheric and interplanetary magnetic field turbulence

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Abstract. In this paper it is shown that rope-rope magnetic reconnection in the solar wind can enhance multifractality in the inertial subrange and drive intermittent magnetic field turbulence. Additionally, it is shown that Lagrangian coherent structures can unveil the transport barriers of magnetic elements in the quiet Sun.

Keywords. turbulence, photosphere, intermittency, solar wind plasma

1. Introduction

Magnetic reconnection in plasmas refers to the conversion of magnetic energy into kinetic and thermal energy, resulting in a change of the topology of magnetic field lines (Yamada *et al.* 2010; Treumann & Baumjohann 2013; Lazarian *et al.* 2015). The study of magnetic reconnection is key to understand the dynamical manifestations of solar and stellar magnetic fields such as solar and stellar flares, coronal mass ejections, and their effects on star-planet interactions. Several models have been proposed to understand magnetic field reconnection (e.g., Parker 1957; Sweet 1958; Petschek 1964; Sonnerup *et al.* 1981; Lazarian & Vishniac 1999).

The interplanetary medium is permeated by the solar wind and provides a natural laboratory in which theoretical models of magnetic reconnection can be validated. The solar wind can be regarded as a network of entangled magnetic flux ropes and Alfvénic fluctuations propagating within each flux rope (Bruno et al., 2001; Borovsky, 2008). Flux ropes can emerge locally in the turbulent solar wind (Mattheaus and Montgomery, 1980, Greco et al., 2009; Telloni et al., 2016) or can be advected from the solar surface to the interplanetary medium by the solar wind (Bruno et al., 2001; Borovsky, 2008). The interaction between flux ropes can lead to magnetic reconnection and the generation of intermittent magnetic field turbulence.

The quiet Sun is the region of the solar photosphere outside of sunspots, plages and active regions (Bellot Rubio & Orozco Suárez 2019). It holds a significant fraction of the

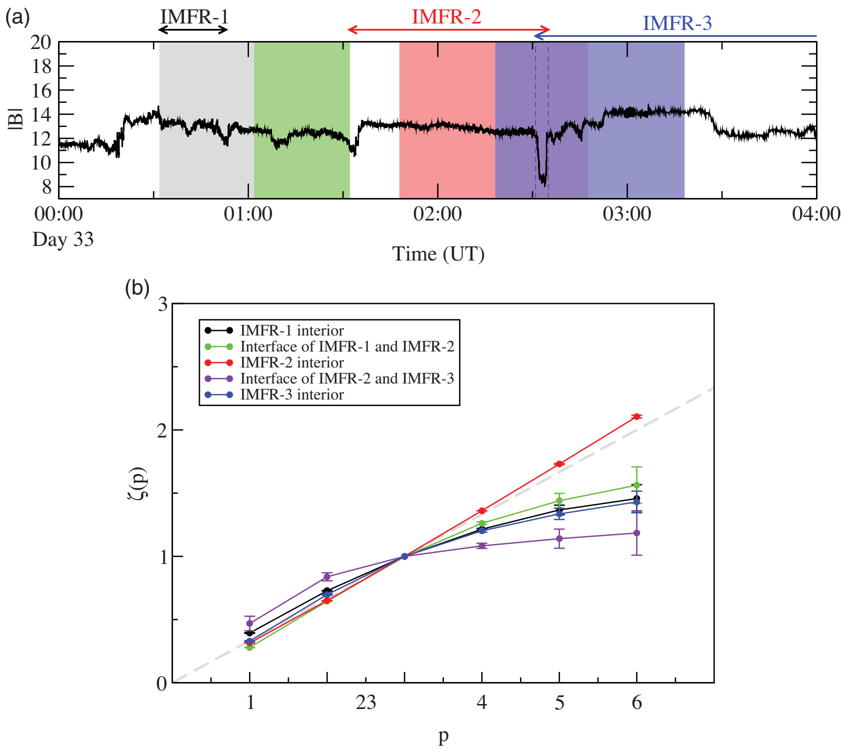

Figure 1. Upper panel: the modulus of the magnetic field detected by Cluster-1 during a rope-rope magnetic reconnection event. Horizontal lines indicate the duration of three ropes, and the violet vertical dashed lines indicate the reconnection site between the second and third IMFRs. Lower panel: the scaling exponents as a function of the order of the structure function. The grey dashed line corresponds to the K41 monofractal scaling.

photospheric magnetic flux, which emerges and disappears through cancellation processes in short time scales. For this reason, the magnetic flux observed on the quiet Sun can contribute effectively to the heating of the chromosphere and the corona. The quiet Sun displays patterns of intense magnetic fields known as the magnetic network that coexist with small-scale weaker magnetic fields called the solar internetwork. The magnetic network outlines the boundaries of supergranule cells within which the internetwork is found.

In this paper, we focus on the role of coherent structures in solar and interplanetary magnetic field turbulence. First, we show that rope-rope reconnection in the solar wind is the source of coherent structures and multifractality in the inertial subrange and drives intermittent magnetic field turbulence. Next, we detect Lagrangian coherent structures (LCS) using surface velocity data in the quiet Sun and discuss the role of LCS on the dynamics of magnetic elements in supergranular cells.

2. Magnetic reconnection in the solar wind

Figure 1(a) shows the time series of the modulus of the magnetic field $|\mathbf{B}|$ (black line) detected by Cluster-1 on 2 February 2002. During this period, Cluster collected data from the solar wind upstream of the Earth's bow shock (Chian & Miranda 2009). In this event, three interplanetary magnetic flux ropes (IMFRs) were identified, as well as magnetic reconnection and a bifurcated current sheet in the interface region between two IMFRs (Chian *et al.* 2016). The duration of each IMFR is indicated in Fig. 1(a) by

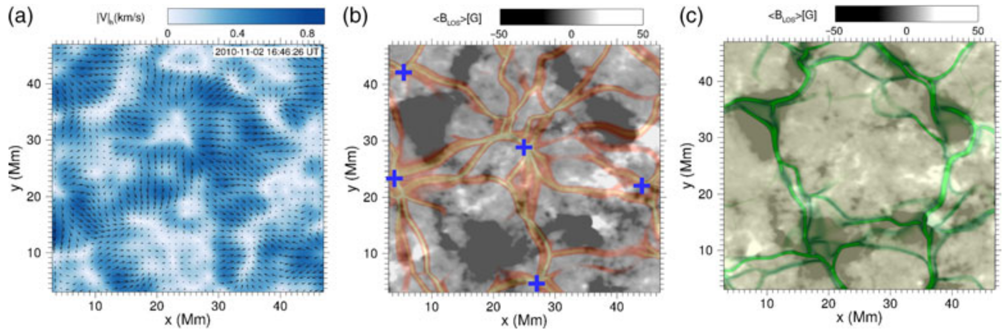

Figure 2. (a) The 2-hourly time-averaged horizontal velocity field (black arrows) deduced by applying LCT to the intensity maps and the horizontal velocity modulus (the background image) at 16:46:26 UT. (b) The forward-time FTLE field (orange), and (c) the backward-time FTLE field (green) computed for τ = 7 h. The background grey-scale images represent the line-of-sight magnetic field averaged over 7 h. The value of the FTLE field is proportional to the colour intensity. Ridges of the FLTE fields are located in regions in which the colour intensity is higher. Blue crosses in (b) mark the Lagrangian centre of supergranular cells.

horizontal arrows. Five intervals with a duration of 30 minutes were selected during this interval, indicated by different background colors. These intervals represent the interior region of IMFR-1 (grey), the interface between IMFR-1 and IMFR-2 (green), the interior of IMFR-2 (red), the interface between IMFR-2 and IMFR-3 (violet) and the interior of IMFR-3 (blue). Magnetic reconnection occurs at the interface between the IMFR-2 and IMFR-3, bounded by the two dashed vertical lines.

In order to characterize the multifractality of each interval, we compute the scaling exponents ζ of structure functions within the inertial subrange. Figure 1(b) shows ζ as a function of the p-th order structure function. The Kolmogorov (K41) monofractal scaling is represented by a dashed line. Departure from the K41 scaling indicates multifractality due to the presence of coherent structures at scales within the inertial subrange. The interval with the strongest departure corresponds to the interface between the IMFR-2 and the IMFR-3, during which rope-rope magnetic reconnection occurs. This suggests that magnetic reconnection acts as the source of the intermittent magnetic field turbulence.

3. Lagrangian coherent structures in the quiet Sun

We detect LCS using data of photospheric horizontal velocity fields derived from continuum intensity images of the quiet Sun taken at the disc centre. The image data was captured by Hinode on 2 November 2010. The data have a cadence of 90 s, a field of view of 80 arcsec x 74 arcsec, a pixel size of 0.16 arcsec and spatial resolution of 0.3 arcsec (Gošić *et al.* 2014). The horizontal velocity fields shown in Fig. 2(a) for t =16:46:26 UT were extracted using the local correlation tracking method (November & Simon 1988; Molowny-Horas 1994; Requerey *et al.* 2018).

Figure 2 (b) and (c) show the forward and backward finite-time Lyapunov exponents (FTLE), superposed by the line-of-sight component of the magnetic field on a quiet sun observed by Hinode. The value of the FTLE field is proportional to the colour intensity. Ridges of the forward-FTLE and backward-FTLE indicate the locations of repelling and attracting LCS, respectively. These ridges are visualized in Fig. 2 as regions in which the corresponding colour (orange for the forward-FTLE, green for the backward-FTLE) is more intense. The blue crosses mark the centre of supergranular cells obtained by the Lagrangian method. Magnetic elements located in the interior of supergranular cells are advected by the turbulent convective flow along the repelling LCS and reach the boundaries of the supergranular cell where they are advected along the attracting LCS (Chian *et al.* 2019). From this figure it is clear that the internetwork dynamics are dominated by the repelling LCS, whereas the attracting LCS mark the Lagrangian boundaries of supergranular cells. The forward-FTLE has been shown to be closely related to the squashing Q-factor (Yeates, Hornig & Welsch 2012; Chian *et al.* 2014), therefore the repelling LCS indicate regions where magnetic elements are most likely to interact and reconnect.

4. Conclusions

Magnetic reconnection is a fundamental process of solar and stellar magnetic fields. We demonstrated that rope-rope magnetic reconnection enhances multifractality and intermittent turbulence in the solar wind. We also showed that LCS can unveil the paths of magnetic elements advected by photospheric flows, and can detect the regions where magnetic elements are most likely to interact and reconnect in the quiet Sun. These results can contribute to the understanding of magnetic reconnection and the heating processes of the solar and stellar chromospheres and coronae.

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