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Diffusion of emerging bipolar magnetic pairs in solar photosphere

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Summary. — Magnetic element tracking has been widely used to study the transport and diffusion of the magnetic field on the solar photosphere. From the analysis of the displacement spectrum of these tracers, it has been recently agreed that a regime of super-diffusion dominates the solar surface. We present in this work the analysis of the diffusion of emerging new bipolar magnetic elements for different initial separation of the footpoints. The displacement spectrum for bipolar couples interestingly shows a similar behaviour with respect to the case where all magnetic pairs are considered. To understand how such peculiar diffusion in the solar atmosphere takes places, we compare the displacement spectrum exploring the initial maximum separation parameter.

1. – Introduction

The turbulent nature of the photospheric plasma is a well established property of solar atmosphere and a key ingredient in all dynamo theories used to model the solar magnetic field [1]. In particular, the measure of the diffusivity of the magnetic field in the photosphere is a crucial aspect to properly set the plasma parameters of numerical models on diverse spatial scales [2]. Diffusivity is usually described in terms of normal or anomalous diffusion, with the latter being related to a scale dependent transport coefficient.

In recent years it has been proved that, at least in quiet Sun regions, plasma flow tracers have a superdiffusive nature [3-13]. Different techniques have been used to track passively advected tracers derived from solar features in the atmosphere, mostly using Bright Points or small magnetic elements derived from magnetograms.

In this work we present the analysis on the diffusion of magnetic elements identified as emerging new bipolar elements. The displacement spectrum for bipolar couples is computed using different thresholds for the initial maximum separation.

2. – Observations

In this work we make use of an exceptional data-set from the *Hinode* satellite, characterized by a duration of 25 hours, an uninterrupted sequence of magnetograms free from atmospheric seeing effects. The data-set was obtained within the *Hinode Operation Plan* (HOP) 151 entitled *Flux replacement in the solar network and internetwork* (PI L.R. Bellot Rubio), it was first described by [14], and it is composed by a sequence of 995 *Hinode*-NFI magnetograms [15, 16], acquired on November 2, 2010. The spatial resolution is $0.3''$, the field of view, after co-alignment is ~ 50 Mm, while the noise for a single frame is $\sigma_B = 6$ G. The data-set was filtered out for oscillations at 3.3 mHz. A full supergranule has been observed on a time scale comparable with its life-time, with a cadence of 90 s. This, together with high spatial resolution, allows us to study the dynamics of a large number of small magnetic elements on temporal scales ranging from minutes to a day. The magnetograms were further analyzed in [5, 6, 10], where the diffusion of single magnetic elements was studied, and in [7], where the pair separation analysis was introduced, being applied to all the possible couples of small magnetic elements, without considering the magnetic polarity of the element.

3. – Data analysis

We used the same method described in [17] to track the small magnetic elements and used a variable threshold as in [18] to recover the weak field elements together with the largest magnetic features characterized by clustered peaks. All the small magnetic elements exceeding the speed of $7\,\mathrm{km\,s^{-1}}$, i.e. the sound speed in the photosphere, were discarded. The algorithm labels as magnetic elements all the areas whose associate magnetic field strength $|B(x, y)| > T_0$, $T_0 = 3\sigma_B$. At the end of the identification and tracking procedure, a total of 20145 magnetic elements were selected in 25 hours. Their lifetimes range from 7.5 minutes (5 frames) to 11.1 hours (444 frames).

In order to study the diffusion of new emerging bipolar small magnetic elements, we have considered all pairs satisfying a number of selection criteria, following the procedure described in [19]. In [19] they analyzed 200 SOT/*Hinode* magnetograms at the disk center with a field of view of $= 835 \times 600$ pixel (99×70 Mm), a cadence of 90 s and a duration of 5 hours, defining as emerging bipolar pair the couples born at a distance less than or equal to 7 pixels (~ 0.8 Mm). Our analysis is performed under the assumption of small magnetic elements being passively transported by the plasma flow, i.e. passive flow tracers.

i) Bipolar pairs identification:
We compute the Euclidean distance between two small magnetic elements, we retain all the couples that have an initial maximum separation, δ, below a certain threshold. We vary this parameter, creating different data-sets to compare the dynamical properties for various initial maximum separation of the couples.

ii) Sign of the magnetic field:
We retain only the bipolar pairs, i.e. those couples that have opposite sign magnetic field, $S_B = \frac{\vec{B}}{|\vec{B}|}$.

iii) Emergence and time evolution of the bipolar pairs:
Within pairs, we further select those small magnetic elements born within 180 seconds. This criterion is more stringent with respect to the one adopted by [19], where the time

frame of emergence of the second footpoint of the magnetic loop was set to 15 min (10 frames). For the ending point of the sequence of the magnetic couple, we consider the less long-lived element of the couple.

A relevant point to emphasize is that the data-set analyzed in the present study provides only line of sight magnetograms and no linear net polarization signal could be analyzed to obtain information on the horizontal magnetic field [20]. Thus, it is not possible to retrieve the complex topology of the emerging magnetic loop and to identify the magnetic pairs as elements belonging to the loop structure. We therefore assume, as in [19] that the identified bipolar pairs, with a selection based on time and spatial scale appearance, are really emerging loops with Ω-shape, or sub-merging loops with U-shape.

Having thus identified all bipolar pairs and calculated the distance $\mathbf{R}(t) = \mathbf{r}_i(t) - \mathbf{r}_j(t)$ between the elements of the pairs for each time, we compute the pair displacement spectrum:

$$\Delta^2(t,\delta) = \langle[\mathbf{R}(t) - \mathbf{R_0}]^2\rangle. \tag{1}$$

with the mean defined over all of the pairs, for each time frame. We find, as in [7], that the pair displacement spectrum is best-fitted by a power law:

$$\Delta^2(t,\delta) = t^\gamma. \tag{2}$$

4. – Results and conclusions

The results of the analysis are reported in table I. We find a spectral index γ between $1.4 \div 1.7$ ($\gamma \sim 3/2$). The errors on the spectral indexes γ were evaluated with a bootstrap on the data-set, extracting 10 random subsets of pairs evolution containing 30% of the whole data-set, and computing the standard deviation from the 10 fits.

We notice that the index γ for a shallower prescription of the δ parameter is slightly lower than the value found for all the possible couples of small magnetic elements in the field of view. Besides, a more stringent prescription for δ results in enhanced superdiffusivity, with a higher value for γ. This seems to suggest that magnetic pairs are not

TABLE I. – *Magnetic pairs separation spectrum results, presented for four different thresholds for the selection criterion of the initial maximum separation δ (first column). For comparison, we show in the last row results from the analysis for all the identified pairs. The number of identified pairs is shown in the second column, while the pair spectrum index γ is in the third column.*

δ	Pairs number	γ
2.3 Mm	2408	1.42 ± 0.08
1.9 Mm	1739	1.43 ± 0.08
1.1 Mm	456	1.70 ± 0.09
0.7 Mm	114	1.69 ± 0.15
all pairs	20145	1.55 ± 0.05

only superdiffusive, but are more superdiffusive than a randomly chosen couple of small magnetic elements.

Nevertheless, the three regimes are comparable and in a range for the γ index around $\gamma \sim 3/2$, in between normal diffusion and the $\gamma = 2$ ballistic motion of the tracer. Further analysis is needed to confirm this trend, involving spectropolarimetrically identified magnetic pairs and other analysis on unpaired small magnetic elements that could be related to open field magnetic flux tubes and long-range closed fields.

A possible extension of the work is to compute the pair displacement spectrum in a numerical simulation based on n-body approach, where magnetic loops linked to bipolar magnetic pairs are advected [21]. In this simulation diffusivity can be turned on and off, testing the collective advection of granular downflows as a possible source of superdiffusivity. This kind of approach has been already tested in single small magnetic elements in [22] both from the simulation and observational point of view. In particular, the observational data-set, based on high-resolution spectropolarimetric inversions and further described in [23, 24], can be analyzed again in search for bipolar magnetic pairs.

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