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SOLAR VELOCITY FIELD DETERMINED TRACKING CORONAL BRIGHT POINTS

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Abstract. Preliminary data from Atmospheric Imaging Assembly (AIA) instrument on board Solar Dynamics Observatory (SDO) satellite were used to determine solar differential rotation and related phenomena. A segmentation algorithm, which uses multiple AIA channels in search for intensity enhancements in EUV and X-ray parts of the spectrum compared to the background intensity, was applied to obtain positional information of coronal bright points (CBPs). More than 60000 position measurements of more than 10000 identified CBPs from the period 1 - 2 January 2011 were analyzed. Rotational and meridional velocities were determined by tracking identified CBPs and various filters were used to exclude erroneous results. Also, proper motions of CBPs were calculated from rotation velocity residuals and meridional velocities. Proper motions of CBPs were investigated using a random walk model and the diffusion constant was calculated. These results were compared with the previous ones obtained by other instruments and methods (especially with the SOHO-EIT and Hinode data) and a striking agreement of the obtained diffusion constant with results from other studies was found.

Key words: Sun - rotation - coronal bright points - proper motions - random walk - diffusion model

1. Introduction

Solar differential rotation is one of the fundamental properties of the Sun as a star and it is deeply related to the solar MHD dynamo, which is obviously responsible for the 11-year solar activity cycle. Both solar dynamo and solar cycle belong to the solar physics problems which are still not fully understood.

The solar rotation velocity can be measured in different ways (Beck, 2000); the tracking of appropriate, identifiable objects being the most common one. Coronal bright points (CBP) are good tracers having many advantages against other objects, notably sunspots (Brajša *et al.*, 2001b).

Measurements of the solar differential rotation and related phenomena by using CBPs and other localized tracers can be divided in the three subtopics, according to the underlying physics: (*i*) the precise measurement of the solar differential rotation profile and its dependence on the height/depth and time; (*ii*) the measurements of the meridional motions and rotation velocity residuals with the aim to calculate Reynolds stresses and other angular momentum transporters, as well as torsional oscillations of the Sun, and (*iii*) an investigation of tracers proper motions on the solar surface for the study of diffusion processes of magnetic elements with the random walk model.

CBPs and small magnetic features related to them have been used in the last two decades for the determination of the solar velocity field using data from various satellites: Yohkoh (*e.g.*, Brajša *et al.*, 2001a; Kariyappa, 2008; Hara, 2009), SOHO-EIT (*e.g.*, Brajša *et al.*, 2001b, 2002, 2004; Karachik *et al.*, 2006; Wöhl *et al.*, 2010), Hinode (*e.g.*, Kariyappa, 2008) and SDO-AIA (*e.g.*, Lorenc *et al.*, 2012; Brajša *et al.*, 2014; Dorotovič *et al.*, 2014; Sudar *et al.*, 2015a). We give now some examples of studies on the three above mentioned subtopics. Precise measurements of the solar differential rotation was performed by *e.g.*, Brajša *et al.* (2004), Wöhl *et al.* (2010), and Sudar *et al.* (2015a). Meridional motions, Reynolds stress and torsional oscillations were analyzed by *e.g.*, Vršnak *et al.* (2003) and Sudar *et al.* (2015b). Finally, proper motions, diffusion processes and random walk models were studied by *e.g.*, Brajša *et al.* (2008), Abramenko *et al.* (2011), and Iida *et al.* (2012).

In this work we present first results on proper motions, diffusion processes and random walk model using test CBPs data obtained with the SDO-AIA during 1-2 January 2011. The data set and the method of data reduction are described in Section 2., the analysis of proper motions and the random walk model are presented in Section 3., while the final result, the diffusion constant, is compared with other studies, both experimental and theoretical, in Section 4.

2. The Data Set and Method of Data Reduction

In present analysis we have used preliminary data from the Atmospheric Imaging Assembly (AIA) instrument on board the Solar Dynamics Observatory (SDO) spacecraft (Lemen *et al.*, 2012). The images used were taken with a cadence of 10 minutes and the instrument has a high spatial resolution of about 0.6 arcsec per pixel. The reduction method relies on a segmentation algorithm which identifies small structures brighter than the smoothed average background intensity level in the 19.3 nm AIA images (Martens *et al.*, 2012). Using this procedure solar coordinates of more than 66000 objects from the test period 1-2 January 2011 were measured and from these position measurements more than 13000 CBPs were identified. The main criterion for a CBP identification was at least 10 consecutive position measurements. Synodic solar rotation velocity was then calculated by the linear least square fit of the central meridian distance as a function of time. Sidereal rotation velocity was calculated by applying a time dependent synodic-sidereal transformation (Roša *et al.*, 1995; Skokić *et al.*, 2014). Similarly, meridional motions were calculated by the linear least square fit of the latitude as a function of time for each CBP.

The test data set used in present work is described in more detail in papers by Brajša *et al.* (2014) and by Sudar *et al.* (2015a). In the first paper (Brajša *et al.*, 2014) excluding of erroneous rotation velocity values using multiple step filters was developed, while in the second paper Sudar *et al.* (2015a) the first results on the solar differential rotation were presented.

3. Results

We now completely follow the procedure developed by Brajša *et al.* (2008). In that paper the analysis was applied to the CBPs from the SOHO-EIT data set, while we here repeat the method using the CBP test data from the SDO-AIA instrument (described in Section 2).

The rotation velocity residuals Δv_{rot} were calculated as differences from the mean differential rotation profile as measured in Sudar *et al.* (2015a) and this values are combined with the meridional velocities v_{mer} to obtain the absolute velocity of proper motions:

$$v_{abs} = \sqrt{v_{mer}^2 + \Delta v_{rot}^2}. \tag{1}$$

The mean free path, l, is defined as the product of the average time between "collisions", τ, and the mean velocity, v:

$$l = \tau \cdot v. \tag{2}$$

Finally, the diffusion coefficient D of the random walk process caused by the supergranular motions can be estimated by combining the characteristic length scales, l, and corresponding lifetimes, τ, of CBPs:

$$D = \frac{\langle l^2 \rangle}{4\tau}. \tag{3}$$

Table I: Mean values of meridional velocity (v_{mer}), residual azimuthal velocity (Δv_{rot}) and absolute velocity (v_{abs}), numbers of tracers (n), standard deviations (σ), and standard errors ($M = \sigma/\sqrt{n}$) for velocity distributions of coronal bright points. Positive (negative) meridional velocity is directed towards the poles (equator) and positive (negative) residual azimuthal velocity represents faster (slower) rotation than the average.

	n	$\overline{v}$ [m s^{-1}]	σ [m s^{-1}]	M [m s^{-1}]
v_{mer}	906	7.46	197	6.54
Δv_{rot}	906	0.00	221	7.34
v_{abs}	906	249	159	5.27

Table II: Mean values of the absolute velocity (v_{abs}), the mean free path (l), the lifetime (τ), and the diffusion constant (D) for various subsets of lifetimes.

	n	v_{abs} [m s^{-1}]	l [km]	τ [h]	D [km^2 s^{-1}]
$0 < \tau < 10$ h	831	261	3420	3.64	223
$10 < \tau < 20$ h	61	127	6310	13.8	200
$20 < \tau < 30$ h	13	98	7940	22.5	195
all	906	249	4150	4.63	258

In Figure 1 the distribution of meridional velocities, residual azimuthal velocities, and absolute velocity values of CBPs are presented, while in Figure 2 the lifetimes of CBPs from the same data set are given. In Table I the mean values of the above mentioned quantities are given together with corresponding errors and in Table II those values are presented separately for different lifetime spans with calculated diffusion constants. Finally, in Table III the result is compared with values from different papers. All these quantities were calculated using Equations (1), (2), and (3).

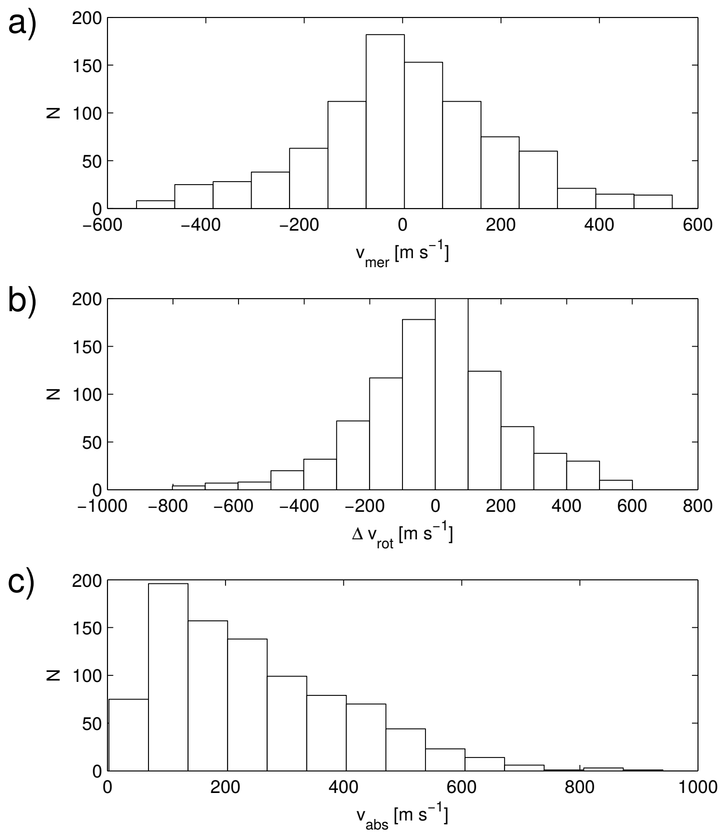

Figure 1: a) Distribution of meridional velocities of CBPs. The positive (negative) meridional velocity is directed towards poles (equator). b) Distribution of residual azimuthal velocities of CBPs. Positive (negative) residual azimuthal velocity represents faster (slower) rotation than the average. c) Distribution of absolute velocities of CBPs. In all three Figures N represents the number of data points in each bin.

4. Discussion and Conclusions

In present analysis we used proper motions of CBPs as tracers of small magnetic elements which were regarded as "atoms", similarly as by Leighton (1964). Motions of CBPs were considered as a random walk process (for a general discussion of random walk see *e.g.*, Feynman, Leighton and Sands, 1963; Reif, 1965). The mean free path is described as the average distance between collisions of e.g. molecules and here it is calculated by Eq. (2). The

Table III: The mean free path (l), corresponding tracing time (τ) and diffusion coefficient (D). In the first line results of the present analysis obtained by CBPs (SDO data), in the lines 2–4 results obtained by CBPs (SOHO data), in the lines 5–7 the ones obtained by tracing magnetic flux concentrations in the solar photosphere, and in the lines 8–9 the values from various models are presented.

Line	Source	l [km]	τ [h]	D [km^2 s^{-1}]
1	Present work	4150	4.63	258
2	Brajša *et al.* (2008)	5200	12	160
3	Brajša *et al.* (2008)	8600	30	170
4	Brajša *et al.* (2008)	15100	60	260
5	Hagenaar *et al.* (1999)		< 3	70-90
6	Hagenaar *et al.* (1999)		> 8	200-250
7	Iida (2014)		6	200
8	DeVore *et al.* (1985)			200-400
9	Wang (2004)			500-600

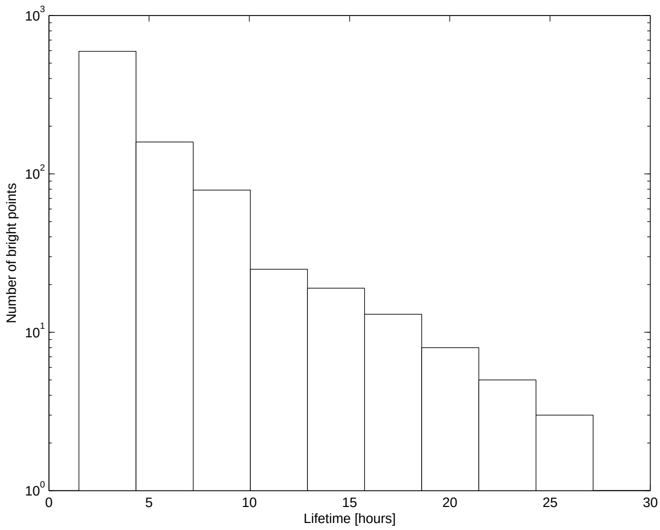

Figure 2: Lifetime of CBPs in hours.

diffusion coefficient was calculated using Eq. (3) and the results of present work are summarized in Table II.

In Table III we compare the diffusion coefficient obtained in present work using CBP data from the SDO-AIA instrument with other observational and theoretical results. Our result for D is very similar to the earlier results obtained by CBPs using SOHO-EIT data and long living small magnetic elements (Table III). This excellent agreement is the main result of this study because different tracers from various instruments give a strikingly similar final results. Moreover, it agrees fairly well with at least one important theoretical model.

We conclude that CBPs from the SDO-AIA data set are very good tracers to study solar velocity field and in the future work we will continue to use this valuable data set to explore various aspects of solar differential rotation, tracers proper motions and related phenomena.

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