PROPER MOTIONS OF CORONAL BRIGHT POINTS

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Abstract. Full-field full-resolution solar images obtained by the Extreme Ultraviolet Imaging Telescope on board the Solar and Heliospheric Observatory are used to analyse proper motions, velocity distributions, lifetimes, and diffusion coefficient of coronal bright points. The results obtained by the interactive method for three tracer subtypes (point-like structures, small loops, and small active regions) of coronal bright points for the period 4 June 1998 to 22 May 1999 are presented and compared. Distributions of meridional velocities, residual azimuthal velocities and velocities of proper motions are presented for the three tracer subtypes. Lifetimes up to 54 hours are found for 98 % of all observed coronal bright points. Small active regions last on the average longer than point-like structures and small loops. The correlation between the absolute velocity of proper motion and lifetime is investigated and the mean free path (in the range from 3000 km to 15000 km) and the diffusion coefficient (approximately 200 km²/s) of coronal bright points are estimated. Finally, characteristics of the random walk process associated to the motions of coronal bright points are discussed in the Appendix.

Key words: solar rotation - coronal bright points - SOHO-EIT

1. Introduction

Coronal bright points can be observed at extreme-ultraviolet (EUV) wavelengths (e.g., McIntosh and Gurman, 2005) or in soft X-rays (e.g., Hara

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Hvar Observatory, Faculty of Geodesy • Provided by the NASA Astrophysics Data System
and Nakakubo-Morimoto, 2003). They are magnetic tracers cospatial with bipolar magnetic features observed in the photosphere (Harvey-Angle, 1993; Webb et al., 1993). Coronal bright points belong to the low corona and have been associated with places of local magnetic reconnection (Priest, Parnell, and Martin, 1994; Brown et al., 2002). The total energy release during their lifetime spanning from a few hours to a few days is between $10^{26}$ and $10^{28}$ erg (Aschwanden, 2004).

Manifestations of solar magnetic activity appear on different temporal, spatial and magnetic field strength scales (Golub et al., 1974; Withbroe, 1977; Messerotti, 2001). The division between various scales are sometimes loose and determined by instrumental capabilities and observers conventions (for the case of coronal bright points, see Golub and Pasachoff, 1997). Often there exists a proportionality between the duration and size of the features (Golub et al., 1974; Harvey-Angle, 1993; Berghmans, McKenzie, and Clette, 2001). In addition, it was reported that the residual rotation velocity of magnetic field elements nearly linearly depends on their magnetic field strength (Zhao, Kosovichev, and Duvall, 2004); magnetic elements with larger magnetic field strength rotate also faster.

Full-disc solar images obtained by the Extreme Ultraviolet Imaging Telescope (EIT) on board the Solar and Heliospheric Observatory (SOHO) are used to analyse the solar differential rotation and related phenomena by tracing coronal bright points. Using computer programs written in the Interactive Data Language (IDL), two different procedures of data reduction were developed: an interactive and an automatic method (Brajša et al., 2001). A small north-south rotational asymmetry and subtle differences in rotation between several tracer subtypes, point-like structures (PLS), small loops (SL), and small active regions (SAR), were determined using the data obtained from mid-1998 to mid-1999 (Brajša et al., 2002). The same data set was reduced to analyse the properties of the solar surface velocity field (Vršnak et al., 2003). Zones of slow and fast rotation consistent with the pattern of torsional oscillations were found, indicating that the statistical velocity pattern of bright points reflects the large-scale plasma flows. Equatorward meridional motions at low and high latitudes and poleward motions at mid-latitudes were inferred. The subsample of point-like structures showed a latitude-dependent horizontal Reynolds stress revealing an equatorward transport of angular momentum. Further, a method for the simultaneous determination of the true solar synodic rotation velocity and
the height of tracers was applied (Brajša et al., 2004). The average height of coronal bright points was found to be 8000 - 12000 km above the solar photosphere and the corrected rotation velocities were compared with the results obtained by various methods and tracers. The differential rotation profile obtained applying the interactive method corresponds roughly to the profile determined correlating photospheric magnetic fields and the profile obtained applying the automatic method corresponds roughly to the rotation of sunspot groups. Finally, the spatial distribution and north–south asymmetry of coronal bright points from mid-1998 to mid-1999 were investigated by Brajša et al. (2005).

In the present paper we continue this analysis and after describing the data set and methods of data reduction in Section 2, in Section 3 we present the results and discussions for different subtopics: velocity distributions, lifetimes and estimates of the mean free path and the diffusion coefficient. Finally, results and conclusions are summarized in Section 4, while in the Appendix characteristics of the random walk process associated to the motions of coronal bright points are discussed.

2. The Data Set and Method of Data Reduction

The data set consists of 463 full-disc solar filtergrams recorded in the Fe XV line at the wavelength of 28.4 nm with the EIT instrument (Delaboudinière et al., 1995) on board the SOHO spacecraft. Usually images were taken every 6 hours, i.e., with a regular cadence of 4 images per day, although sometimes there were gaps of 12 hours or more between the successive images. Measurements performed in June, November, and December 1998 and in March, April, and May 1999 are used in this paper. Among the four EIT channels we have chosen the 28.4 nm one since it corresponds to the highest temperature and appears to enable the sharpest image contrast suitable for an identification of small bright coronal structures, at least according to our experience. The contamination with the transition region emission (Mg VII, Si VII) is not a serious problem, since the magnetic field lines are anchored down to the photosphere.

We apply the interactive method of data reduction, introduced by Brajša et al. (2001a), where coronal bright points are traced visually in at least 3 consecutive images on a computer screen. Two data sets obtained with the interactive method were established for the whole observing period, June
4, 1998 to May 22, 1999 (Brajša et al., 2002). The tracing was performed in up to 11 consecutive images for the "data set 1", while the tracing was possible in up to 24 consecutive images for the "data set 2". So, the same set of 463 images was used to get these two sets of positions and velocities and the difference between them is only in the upper limit of the duration of tracing, and consequently in the number of obtained data points. The distinction between three different tracer subtypes: PLSs, SLs, and SARs is also possible within the interactive method.

In this paper we use the interactive method of data reduction, since it is more appropriate than the automatic one for the aims of the present work. The relevant advantages of the interactive method over the automatic one include longer tracing times, a better and a more reliable object identification and the possibility to distinguish between different tracer subtypes (PLSs, SLs, SARs). Further, the visual identification of tracers within the interactive method enables to take into account the intensity and area variations of coronal bright points during their lifetime (e.g., McIntosh, 2007; Mulec et al., 2007). This also reduces the possibility that at least some of the longest-living structures may have been coincidental disappearances and appearances of bright points at nearby locations. The interactive method is reproducible to a large extent (Brajša et al., 2001a, 2001b; Mulec et al., 2007; Brajša et al., 2008) and up to now nine observers have used it. In the present analysis we are interested in some statistical properties of coronal bright points that should be independent from the individual differences of various observers (see also the Appendix). On the other hand the automatic method is still under development and in it’s present version some false tracer identification unfortunately can not be excluded.

3. Results and Discussion

3.1. Velocity Distributions

In Figures 1–4 the velocity distributions of coronal bright points (data set 1, interactive method) are presented. In Figure 1 distributions of meridional velocities (\(v_{mer}\)) for the three tracer subtypes (PLSs, SLs, SARs) are given. Positive meridional velocities are directed towards the solar poles and the negative ones towards the equator. In Figure 2 the distributions of residual azimuthal velocities (\(\Delta v_{rot}\)) for the three tracer subtypes are shown.
Figure 1: Distribution of meridional velocities of coronal bright points (data set 1, all data) for the three tracer subtypes, as indicated in the legend. The positive (negative) meridional velocity is directed towards the poles (equator). The mean values are calculated for the velocity ranges 0-50 m/s (the symbols are placed at 25 m/s), 50-100 m/s (the symbols are placed at 75 m/s), etc.

Positive values represent rotation velocities faster than the average and the negative ones rotation velocities slower than the average. Finally, these two velocity components are combined together into the absolute velocity of proper motion:

$$v_{\text{abs}} = \sqrt{v_{\text{mer}}^2 + \Delta v_{\text{rot}}^2}. \quad (1)$$

The distributions of absolute velocities of proper motions of coronal bright points (data set 1) are presented in Figures 3 and 4 using different bin widths for the three tracer subtypes separately and taken together, respectively.
Figure 2: Distribution of residual azimuthal velocities of coronal bright points (data set 1, all data) for the three tracer subtypes, as indicated in the legend. Positive (negative) residual azimuthal velocity represents faster (slower) rotation than the average. The mean values are calculated for the velocity ranges 0-50 m/s (the symbols are placed at 25 m/s), 50-100 m/s (the symbols are placed at 75 m/s), etc.

The typical errors of the individual rotation velocity determination are in the range (0.0005 – 1.0) deg/day, and only in a few exceptional cases larger than 1.0 deg/day. For the meridional velocities, the typical errors are in the range (0.0005 – 0.5) deg/day, corresponding to (0.072 – 72.0) m/s, and only exceptionally larger, in the range (0.5 – 2.0) deg/day.

In Table I we present the mean values of the meridional velocity ($v_{mer}$), the residual azimuthal velocity ($\Delta v_{rot}$), and the absolute velocity ($v_{abs}$), the numbers of tracers ($n$), the standard deviations ($\sigma$), and standard errors $M$ for the velocity distributions of coronal bright points. Positive and negative velocity values are presented separately in Table II, where an asymmetry in
Figure 3: Distribution of absolute velocities of coronal bright points (data set 1, all data) for the three tracer subtypes, as indicated in the legend. The mean values are calculated for the velocity ranges 0-50 m/s (the symbols are placed at 25 m/s), 50-100 m/s (the symbols are placed at 75 m/s), etc.

distribution can be seen. The differences between the three tracer subtypes are distinct for the distributions of the meridional velocity and the residual azimuthal velocity (Figures 1 and 2, respectively), but they are much less pronounced in the distribution of absolute velocities (Figure 3). This behaviour can also be seen in Table I.

3.2. LIFETIMES

The lifetime of coronal bright points is estimated from the number of successive images in which they could be identified. This was performed only for the interactive data set 2 (long tracing times). The visual tracing was
Figure 4: Similar to Figure 3 for all three tracer subtypes taken together and with a finer division of velocities.

intentionally kept shorter for the interactive data set 1 (short tracing times). In Figure 5 the distribution of lifetimes of coronal bright points determined by the data set 2 is presented. The lifetime is estimated as:

$$\tau = (m - 1) \times 6 \text{ [hours]},$$

(2)

where $m$ represents the number of successive images in which a bright point was traced. The images were mostly 6 hours apart, in about 5% of the measurements the difference was 12 hours (and only exceptionally it was longer), so that the calculated lifetimes in hours are somewhat underestimated.

The histogram in Figure 5 indicates an exponential decrease of the number of bright points from the lifetime of 12 hours to the lifetime of 54 hours followed by a long-duration tail. Before the tail in the distribution ending
Proper Motions of Coronal Bright Points

Table I: Mean values of meridional velocity \( (v_{mer}) \), residual azimuthal velocity \( (\Delta v_{rot}) \) and absolute velocity \( (v_{abs}) \), numbers of tracers \( (n) \), standard deviations \( (\sigma) \), 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.

<table>
<thead>
<tr>
<th></th>
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<th>( \sigma )</th>
<th>( M )</th>
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<tr>
<td></td>
<td>(m/s)</td>
<td></td>
<td>(m/s)</td>
<td>(m/s)</td>
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<tr>
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<td>79.39</td>
<td>3.31</td>
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<td>459</td>
<td>76.99</td>
<td>3.59</td>
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<tr>
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<td>202</td>
<td>73.69</td>
<td>5.18</td>
</tr>
<tr>
<td>All</td>
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<td>1235</td>
<td>77.68</td>
<td>2.21</td>
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<table>
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<th>( \sigma )</th>
<th>( M )</th>
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<td></td>
</tr>
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<td>110.36</td>
<td>4.61</td>
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<tr>
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<td>459</td>
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<tr>
<td>All</td>
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<td>1235</td>
<td>107.86</td>
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<table>
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<th>( \sigma )</th>
<th>( M )</th>
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<td>574</td>
<td>75.22</td>
<td>3.14</td>
</tr>
<tr>
<td>Small active regions</td>
<td>108.09</td>
<td>459</td>
<td>71.11</td>
<td>3.32</td>
</tr>
<tr>
<td>Small loops</td>
<td>110.91</td>
<td>202</td>
<td>70.05</td>
<td>4.93</td>
</tr>
<tr>
<td>All</td>
<td>110.93</td>
<td>1235</td>
<td>72.86</td>
<td>2.07</td>
</tr>
</tbody>
</table>

At approximately 138 hours, there is perhaps a secondary maximum at lifetimes between 60 and 66 hours. The distributions for all tracer subtypes taken together (full line) and separately (different symbols) are presented. The observed exponential behaviour of the lifetime distribution of coronal bright points was also reported by McIntosh and Gurman (2005).

Approximately 98% of all coronal bright points in our data set had lifetimes between 12 and 54 hours. We examine now the part of the distribution representing the longest lifetimes, 54 hours and longer. Although this data subset is relatively small, from Figure 5 it can be seen that SARs have a more pronounced tail and on the average longer lifetimes than the other
two tracer subtypes, PLSs and SLs. We point out that some small structures with dimensions less than 4 Mm observed with the EIT live much shorter, having a power law lifetime distribution with lifetimes up to 12 hours (Hochedez, private communication; McIntosh and Gurman, 2005).

The lower lifetime limit, 12 hours, Figure 5, is determined by the data reduction procedure in which bright points were followed in at least 3 successive images. Coronal bright points observed in soft X-rays from Skylab had lifetimes between 2 and 45 hours with the maximum at 8 hours (Golub et al., 1974; Golub, Krieger, and Vaiana, 1976; Golub and Pasachoff, 1997) and the ones observed at 19.5 nm with the EIT had lifetimes between 5 and 40 hours with the maximum at 20 hours (Zhang, Kundu, and White, 2001). We note that the shapes of these distributions were different. Zhang,
Figure 5: Lifetime of coronal bright points in hours (interactive method, data set 2). The full line represents the distribution for bright points of all three subtypes taken together. Distributions for the three tracer subtypes, point-like structures (PLS), small loops (SL), and small active regions (SAR) are given by different symbols, as indicated in the legend. The last entry (84 hours) refers to the lifetimes between 84 and 138 hours.

Kundu, and White (2001) have suggested that the longer average lifetimes of coronal bright points observed in EUV, in comparison with soft X-rays, are due to a higher temperature threshold for the visibility of structures in soft X-rays. Lower temperature thresholds in EUV enable to follow coronal bright points on longer time scales than in soft X-rays. It is also interesting that all three histograms of coronal bright points’ lifetimes (Figure 1 in Golub et al., 1974; Figure 10 in Zhang, Kundu, and White, 2001; Figure 5 in the present paper) have a small secondary maximum in the long-lifetime tail of the distribution. However, they are at different lifetimes: at 35–40 hours (Golub et al., 1974), at 40 hours (Zhang, Kundu, and White, 2001) and at approximately 63 hours (present work), respectively. We note that some fine structures in the exponential tail of the coronal bright points lifetime distribution can be seen in Figure 3 in the paper by McIntosh and
Gurman (2005) for lifetimes larger than 50 hours.

We have found that SARs live on the average longer than the other two tracer subtypes, PLSs and SLs, which has some implications on the interpretation of large-scale motions of coronal bright points (present work and Vršnak et al., 2003). Since SARs have also larger sizes, this is in agreement with the proportionality between lifetimes and areas of magnetic complexes (Harvey-Angle, 1993). It is also noteworthy that the lifetime distribution of ephemeral regions (Harvey-Angle, 1993) has some similarities with our distribution of coronal bright points (Figure 5). The distribution for ephemeral regions has its maximum at about 1 day followed by a gradual decrease.

Figure 6: Correlation of absolute velocity of coronal bright points vs. their lifetime (data set 1, filtered data) for the three tracer subtypes, as indicated in the legend.
3.3. AN ESTIMATE OF THE MEAN FREE PATH

In the following, similarly as in the paper by Leighton (1964) where the magnetic elements were regarded as "atoms", we consider the motion of coronal bright points as random walk. In the Appendix we discuss which part of the coronal bright points’ motions can be regarded as a random walk process and which one shows a systematic behaviour. The mean free path \( l \) is usually described as the average distance between molecular collisions (e.g., Feynman, Leighton, and Sands, 1963). It is defined as the product of the average time between collisions, \( \tau \), and the mean velocity \( v \):

\[
 l = \tau \times v.
\]

This concept was generalized to particles in the field of a force, e.g., charged particles in a magnetic field (e.g., Wibberenz, 1973). In the present work,
Figure 8: Correlation of absolute velocity of coronal bright points vs. their lifetime for data set 1 and data set 2, together with the corresponding mean values, as indicated in the legend.

we apply the notion of the mean free path $l$ simply as the product of the typical lifetime $\tau$ and the typical average absolute velocity $v_{abs}$ of coronal bright points, which are here considered as "particles" in the sense of Leighton (1964). The concept of random walk has later been successfully used for different purposes in solar physics (e.g., Sheeley, Nash, and Wang, 1987; Wang and Sheeley, 1994; Hagenaar et al., 1999; Hathaway, 2005, and references therein).

From Figures 4 and 5 the typical absolute velocity of proper motion $v_{abs} = 50–70$ m/s and the typical lifetime $\tau = 12–18$ h can be estimated which yield the mean free path $l \approx 3000$ km. In both cases we take the maximal values in the distributions. However, we can raise the question whether longer living coronal bright points reach also higher velocities, which leads
us to investigate the correlation $v_{abs}(\tau)$. This correlation is presented in Figures 6 and 7 for the data set 1 and 2, respectively. Further, the results for the two data sets are combined together in Figure 8, while the log-normal representation is used in Figure 9. In Table III the correlation coefficients are given for data presented in Figures 8 and 9. The correlation is highest when the mean values and the log-normal combination is used. The scatter of data points in these Figures means that the longer-living bright points do not have large absolute velocities. This is at least partly a consequence of reduced errors in velocity determination when longer tracing times are used.

Now, we can make a new estimate of the mean free path. From Figure 8 typical mean absolute velocities of proper motion can be read from the mean curves: $v_{abs} = 120 \text{ m/s}$, $\tau = 12 \text{ h}$, giving $l \approx 5200 \text{ km}$; $v_{abs} = 80 \text{ m/s}$, $\tau$
Table III: Correlation coefficients (absolute velocity of coronal bright points as a function of their lifetime) for data presented in Figures 8 and 9. The upper part refers to all data points and the lower part only to the mean values; $n$ stands for the number of data.

<table>
<thead>
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<th>Source</th>
<th>data set 1</th>
<th>data set 2</th>
<th>data sets 1 and 2</th>
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<tr>
<td>Figure 8 (linear)</td>
<td>-0.20</td>
<td>-0.19</td>
<td>-0.18</td>
</tr>
<tr>
<td>Figure 9 (log-normal)</td>
<td>-0.21</td>
<td>-0.20</td>
<td>-0.20</td>
</tr>
<tr>
<td>$n$</td>
<td>1179</td>
<td>919</td>
<td>2098</td>
</tr>
<tr>
<td>Figure 8 (linear)</td>
<td>-0.77</td>
<td>-0.84</td>
<td>-0.84</td>
</tr>
<tr>
<td>Figure 9 (log-normal)</td>
<td>-0.83</td>
<td>-0.86</td>
<td>-0.85</td>
</tr>
<tr>
<td>$n$</td>
<td>8</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

$= 30 \text{ h}$, giving $l \approx 8600 \text{ km}$; $v_{abs} = 70 \text{ m/s}$, $\tau = 60 \text{ h}$, giving $l \approx 15100 \text{ km}$. It is interesting to note that coronal bright points having larger absolute velocities on the average have shorter paths due to their shorter lifetimes.

So, the estimated mean free path of coronal bright points is in the range from 3000 km to 15000 km. As we have seen, the lower limit is probably underestimated and we deduced mean free path values from 5000 km to 15000 km for lifetimes between 12 and 60 hours. This is well above the pixel size, 2.629 arcsec, of the EIT instrument corresponding to about 1800 km not far away from the disc centre.

3.4. AN ESTIMATE OF THE DIFFUSION COEFFICIENT

Combining the characteristic length scales ($l$) and corresponding lifetimes ($\tau$) of coronal bright points estimated in the previous subsection, we can now investigate the diffusion coefficient $D$ of the random walk process caused by supergranular motions. It is defined by (e.g., Wang and Sheeley, 1994; Hagenaar et al., 1999):

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

In Table IV we present the values of the diffusion coefficients, calculated for our data in this way, together with the values from other studies. It is
proper motions of coronal bright points

interesting that our values in the range $D \approx (150 - 250) \ km^2/s$ (the mean value $D = 197 \ km^2/s$), correspond very well to the diffusion coefficient obtained tracing magnetic flux concentrations in SOHO-MDI images over longer timescales, $\tau > 8$ hours, $D \approx (200 - 250) \ km^2/s$ (Hagenaar et al., 1999). However, it is still significantly lower than the assumed supergranular diffusion rate, $D \approx (500 - 600) \ km^2/s$, required by the magnetic flux transport model (Wang, Nash, and Sheeley, 1989a; Wang, 2004). Finally, we note, that although $D = 600 \ km^2/s$ was mostly used in various applications of the model (Nash, Sheeley, and Wang, 1988; Wang and Sheeley, 1990; 1991; 1993), beside that value, also lower values in the range $D \approx (50-300) \ km^2/s$ were used in some cases (Sheeley, Nash, and Wang, 1987; Wang et al., 1988; Wang, Nash, and Sheeley, 1989b).

Finally, we address the question why we have used coronal bright points to study magnetic diffusion. As it is well known, coronal bright points are localized magnetic tracers anchored in the photosphere. They are more easily discernable than small magnetic structures in the photosphere (for the identification of the latter see, e.g., Hagenaar et al., 1999; Hagenaar, 2001; Hagenaar, Schrijver, and Title, 2003). On the other hand, we should also mention an alternative interpretation of coronal bright points’ motions, different from the diffusion process. In some cases the observed displacements may be a consequence of the magnetcic reconnection process known to be associated with coronal bright points (e.g., Longcope et al., 2001). However, it is important to consider the prevailing statistical nature of the observed velocity field (see also Vrsnak et al., 2003 and the Appendix in the present paper). Proper motions of coronal bright points can complement the magnetic diffusion analysis based on movement of photospheric magnetic structures.

4. Summary and Conclusions

The main conclusions of this work are:

- Distributions of meridional velocities, residual azimuthal velocities and velocities of proper motions are presented for the three tracer subtypes. The typical velocities amounted to less than $\sim 100 \ m/s$ in all cases, although tails in the distributions were also present. Differences in the velocity distributions of point-like structures, small loops and small active regions were indicated (Subsection 3.1).
Table IV: The mean free path ($l$), corresponding tracing time ($\tau$) and diffusion coefficient ($D$). In the upper part results of the present analysis obtained by tracing coronal bright points are presented, in the middle part the ones obtained by tracing magnetic flux concentrations in the solar photosphere, and in the lower part the values from various models.

<table>
<thead>
<tr>
<th>Source</th>
<th>$l$ (km)</th>
<th>$\tau$ (h)</th>
<th>$D$ (km$^2$/s)</th>
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<tbody>
<tr>
<td>Present work</td>
<td>5200</td>
<td>12</td>
<td>156</td>
</tr>
<tr>
<td>Present work</td>
<td>8600</td>
<td>30</td>
<td>171</td>
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<tr>
<td>Present work</td>
<td>15100</td>
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<td>Hagenaaar et al. (1999)</td>
<td>&lt; 3</td>
<td></td>
<td>70 – 90</td>
</tr>
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<td>&gt; 8</td>
<td></td>
<td>200 – 250</td>
</tr>
<tr>
<td>DeVore et al. (1985)</td>
<td></td>
<td></td>
<td>200 – 400</td>
</tr>
</tbody>
</table>

- Lifetimes from 12 to 54 hours were found for approximately 98 % of all coronal bright points observed in EUV at 28.4 nm. The remaining bright points have longer lifetimes (Subsection 3.2). This result complements previous findings obtained with the data in soft X-rays (lifetimes between 2 and 45 hours, Golub et al., 1974) and in EUV at 19.5 nm (lifetimes between 5 and 40 hours, Zhang, Kundu, and White, 2001).

- Small active regions last on the average longer than point-like structures and small loops. Small active regions also have larger sizes than the two other subtypes. This is consistent with the relationship between the duration and size of solar magnetic structures (Golub et al., 1974; Harvey-Angle, 1993).

- The velocity distributions and lifetimes of coronal bright points were combined to estimate their mean free path. To investigate this topic in more detail, the correlation of absolute velocity vs. their lifetime was analysed. The mean free path of coronal bright points was estimated to be in the range from 3000 km to 15000 km (Subsection 3.3).

- Combining the characteristic length scales and corresponding lifetimes of coronal bright points the average diffusion coefficient of the random walk process caused by supergranular motions was calculated: $D = 197$ km$^2$/s
(Subsection 3.4). This value is close to the diffusion coefficient obtained by tracing magnetic flux concentrations in SOHO-MDI images (Hagenaar et al., 1999).

- The meridional and residual azimuthal velocity components show a systematic velocity pattern consistent with the equatorward transport of angular momentum needed to maintain the observed solar differential rotation profile. However, transforming these components into the absolute velocity of proper motion such an order is lost and the behaviour is similar to the random walk process characteristic for the diffusion (one typical example is presented in detail in the Appendix).

Acknowledgements

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Appendix: Random Walk Properties of Coronal Bright Points’ Motions

Now we discuss the question under which circumstances the motions of coronal bright points represent a random walk process or, alternatively, in which cases they show a systematic behaviour. As already mentioned in the Introduction, an earlier analysis based on the same data set as in the present paper indicated that the coronal bright points’ subsample consisting only of point-like structures (PLS) showed a latitude-dependent horizontal Reynolds stress (Vršnak et al., 2003). This reveals an equatorward transport
Table V: Times of observation and positions ($b$ - the latitude, $CMD$ - the central meridian distance, both in degrees) of the PLS bright point identified on seven images during April 3–4, 1999.

<table>
<thead>
<tr>
<th>No.</th>
<th>Year</th>
<th>Month</th>
<th>Date</th>
<th>UT (h)</th>
<th>$b$ (°)</th>
<th>$CMD$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1999</td>
<td>April</td>
<td>3</td>
<td>7</td>
<td>15.611091</td>
<td>−28.123615</td>
</tr>
<tr>
<td>2</td>
<td>1999</td>
<td>April</td>
<td>3</td>
<td>13</td>
<td>15.459073</td>
<td>−24.904632</td>
</tr>
<tr>
<td>3</td>
<td>1999</td>
<td>April</td>
<td>3</td>
<td>19</td>
<td>15.843179</td>
<td>−21.803299</td>
</tr>
<tr>
<td>4</td>
<td>1999</td>
<td>April</td>
<td>4</td>
<td>1</td>
<td>15.872270</td>
<td>−18.558629</td>
</tr>
<tr>
<td>5</td>
<td>1999</td>
<td>April</td>
<td>4</td>
<td>7</td>
<td>15.588213</td>
<td>−15.228733</td>
</tr>
<tr>
<td>6</td>
<td>1999</td>
<td>April</td>
<td>4</td>
<td>13</td>
<td>15.682063</td>
<td>−12.128128</td>
</tr>
<tr>
<td>7</td>
<td>1999</td>
<td>April</td>
<td>4</td>
<td>19</td>
<td>15.976477</td>
<td>−9.0624293</td>
</tr>
</tbody>
</table>

of angular momentum consistent with the observed profile of solar differential rotation. We point out again that discriminating between different tracer subtypes is possible only applying the interactive method of data reduction, so that this type of analysis can only be performed with the interactive method and not with the automatic one.

Extending the previous analysis, when common statistical properties of coronal bright points were studied, we now investigate particular cases of coronal bright points’ tracings, i.e., following their positions in consecutive EIT images in which they were identified. Inspecting hundreds of cases, 11 coronal bright points traced long enough by three observers were studied in detail and here we present one typical example.

A coronal bright point of the PLS subtype was identified on seven consecutive EIT images taken on April 3–4, 1999. In Table V the times and positions of that bright point are presented. We note that in this Appendix we express the velocities in degrees per day unlike in the rest of the paper where we used meters per second.

By simple averaging we get the mean latitude $b = 15.72^\circ$ and the mean central meridian distance $CMD = −18.54^\circ$ of the tracer. The linear least-square fitting was applied to the data series $CMD(t)$ and $b(t)$ to obtain the observed sidereal rotation velocity.
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\[ \omega_{\text{obs}} = (13.77 \pm 0.06)^\circ \text{day}^{-1}, \]  

(5)

and the meridional velocity:

\[ v_{\text{mer}} = (0.18 \pm 0.13)^\circ \text{day}^{-1}. \]  

(6)

As usually, the transformation from the synodic to the sidereal rotation velocity was performed using a season-dependent procedure taking into account the non-uniform motion of the Earth around the Sun (e.g., Graf, 1974; Roša et al., 1995). By convention, a positive meridional motion is directed towards the North and in the present case for the bright point located in the northern solar hemisphere this means a poleward motion.

To find the residual azimuthal velocity we should take into account the average solar differential rotation profile obtained from all coronal bright points traced by this observer in images taken in April 1999 (Brajša et al., 2001b). There were 207 tracers identified in that month and the differential rotation is represented as usually:

\[ \omega(b) = A + B \sin^2 b , \]  

(7)

where \( \omega \) is the sidereal angular rotation velocity in \( ^\circ \text{day}^{-1} \), \( b \) the heliographic latitude in degrees, and \( A, B \) the solar differential rotation parameters. After applying the two-step filtering of the data (e.g., Brajša et al., 2001a, 2001b) the following parameters were found for April 1999:

\[ \omega(b) = (14.55 \pm 0.07) - (2.78 \pm 0.36) \sin^2 b . \]  

(8)

Using this expression we find now for the latitude of the bright point, \( b = 15.72^\circ \), the calculated sidereal rotation velocity \( \omega_{\text{calc}} = 14.346^\circ \text{day}^{-1} \). The residual azimuthal velocity is now determined as the difference between the observed and calculated rotation velocity:

\[ \Delta v_{\text{rot}} = \omega_{\text{obs}} - \omega_{\text{calc}} = -0.58^\circ \text{day}^{-1}. \]  

(9)

The negative sign of the residual azimuthal velocity means that the coronal bright point under consideration had a slower rotation velocity than the average of all bright points at the corresponding latitude.

Summarizing the characteristics of proper motion of this coronal bright point we see that it rotated slower than the average and simultaneously...
moved towards the pole. This is consistent with the concept of angular momentum transport towards the equator: slower moving objects have poleward meridional motions, while faster moving ones have equatorward meridional motions. When averaged over longitudes this yields a net negative latitude-dependent Reynolds stress for PLSs, as presented by Vršnak et al. (2003).

To check the random walk hypothesis of bright points’ motion we now study its velocities from all individual positions recorded during the tracing. We calculate the individual sidereal rotation velocity from each pair of position measurements:

\[ \omega_{\text{obs}}(i) = \frac{CMD(i + 1) - CMD(i)}{\Delta t}, \]  

where the time between the successive images was \( \Delta t = 6 \text{ hours} = 0.25 \text{ days} \) and \( i \) is the ordinary number of measurement from Table V. Similarly we get the individual meridional velocities:

\[ v_{\text{mer}}(i) = \frac{b(i + 1) - b(i)}{\Delta t}, \]  

the individual residual azimuthal velocities (see Equation (9)):

\[ \Delta v_{\text{rot}}(i) = \omega_{\text{obs}}(i) - \omega_{\text{calc}}, \]  

and the individual absolute velocities of proper motions (see Equation (1)):

\[ v_{\text{abs}}(i) = \sqrt{v_{\text{mer}}^2(i) + \Delta v_{\text{rot}}^2(i)}. \]  

These results (six values calculated from seven position measurements, for every of the four velocities mentioned above) are summarized in Table VI, where also the mean values are given at the end.

We now check if the motion of the coronal bright point is consistent with the random walk hypothesis. The absolute velocity of proper motion is calculated from the fitted values of velocity components, the meridional motion, Equation (6) and the residual azimuthal velocity, Equation (9):

\[ v_{\text{abs}} = \sqrt{v_{\text{mer}}^2 + \Delta v_{\text{rot}}^2} = 0.6073 \circ \text{day}^{-1}. \]  

We calculate which distance \( R_{\text{obs}} \) was travelled by the bright point during it’s whole observed lifetime if it was moving with that speed:
PROPREE MOTIONS OF CORONAL BRIGHT POINTS

Table VI: Velocity components of the coronal bright point observed on April 3–4, 1999 calculated using Equations (10)–(13) from positions listed in Table V. In the last row the mean values are given.

<table>
<thead>
<tr>
<th>i</th>
<th>( \omega_{\text{obs}}(i)/^{\circ}\text{day}^{-1} )</th>
<th>( v_{\text{mer}}(i)/^{\circ}\text{day}^{-1} )</th>
<th>( \Delta v_{\text{rot}}(i)/^{\circ}\text{day}^{-1} )</th>
<th>( v_{\text{abs}}(i)/^{\circ}\text{day}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13.8622</td>
<td>-0.6081</td>
<td>-0.4838</td>
<td>0.7771</td>
</tr>
<tr>
<td>2</td>
<td>13.3916</td>
<td>+1.5364</td>
<td>-0.9544</td>
<td>1.8087</td>
</tr>
<tr>
<td>3</td>
<td>13.9650</td>
<td>+0.1164</td>
<td>-0.3810</td>
<td>0.3984</td>
</tr>
<tr>
<td>4</td>
<td>14.3059</td>
<td>-1.1362</td>
<td>-0.0401</td>
<td>1.1369</td>
</tr>
<tr>
<td>5</td>
<td>13.3887</td>
<td>+0.3754</td>
<td>-0.9573</td>
<td>1.0283</td>
</tr>
<tr>
<td>6</td>
<td>13.2491</td>
<td>+1.1777</td>
<td>-1.0969</td>
<td>1.6094</td>
</tr>
<tr>
<td></td>
<td>+0.2436</td>
<td>-0.6523</td>
<td></td>
<td>1.1265</td>
</tr>
</tbody>
</table>

\[ R_{\text{obs}} = v_{\text{abs}} \times \tau = 0.91^{\circ} , \quad (15) \]

where the lifetime was calculated from Equation (2): \( \tau = 36\text{ hours} = 1.5\text{ days} \). On the other hand, from the last column in Table VI we find the average absolute velocity measured in each step: \( \langle v_{\text{abs}} \rangle = 1.1265^{\circ}\text{day}^{-1} \). From this value we can calculate the typical step length in the assumed random walk process:

\[ L = \langle v_{\text{abs}} \rangle \times \Delta t = 0.28^{\circ} , \quad (16) \]

where the time between the steps is again \( \Delta t = 6\text{ hours} = 0.25\text{ days} \). Finally, from the step length we can calculate the distance that should be reached if the movement is a random walk process (e.g., Feynman, Leighton, and Sands, 1963):

\[ R_{\text{calc}} = L \times \sqrt{N} = 0.69^{\circ} , \quad (17) \]

where the number of steps is \( N = 6 \). Both quantities are of the same order and the difference between the observed and calculated distance is only 32 \% (according to observation the bright point reached about 32 \% larger distance than calculated) and the absolute velocity of proper motion of this bright point can be approximately characterized as a random walk process.


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In an analogous way we now calculate the same quantities for the two velocity components, the meridional motion and the residual azimuthal velocity. For the meridional velocity we get: \( v_{\text{mer}} = 0.18^\circ\text{day}^{-1} \) (see Equation (6)), \( R_{\text{obs}} = 0.27^\circ \), \( L = 0.06^\circ \), and \( R_{\text{calc}} = 0.15^\circ \). For the residual azimuthal velocity we obtain: \( \Delta v_{\text{rot}} = -0.58^\circ \text{day}^{-1} \) (see Equation (9)), \( R_{\text{obs}} = -0.87^\circ \), \( L = -0.16^\circ \), and \( R_{\text{calc}} = -0.39^\circ \). We see that in these two cases the actually reached distance \( R_{\text{obs}} \) by proper motion of the bright point was 80% and 123% larger than the distance \( R_{\text{calc}} \) calculated according to the random walk model, for the meridional and residual azimuthal velocity, respectively. These are significant differences indicating that in these cases motions are not random, but show a systematic pattern. This is consistent with the concept that faster rotating tracers move equatorwards, and vice versa. Such velocity pattern was found for the PLS subsample of coronal bright points’ velocities by Vršnak et al. (2003).

Concluding we can say that the two velocity components, meridional motions and residual azimuthal velocities, show a systematic velocity pattern consistent with the equward transport of angular momentum needed to maintain the observed profile of the solar differential rotation. However, in case of the absolute velocity of proper motions the order is lost and movements are very close to the random walk process. This justifies that in this case we can use motions of coronal bright points to study magnetic diffusion, as is done in the present work. The transition from the systematic to the random behaviour is at least partly due to taking the square of velocity components (see Equation (1)), which leads to a loss of information on the direction of motion.

References

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