Gradient Path Labeling Method Used to Refine the Solar Corona Differential Rotation Profile

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Abstract
Coronal Bright Points (CBPs) allow researchers to trace the solar differential rotational profile up to almost polar latitudes detecting and tracking them, over a sufficiently long sequence of images. In this work we discuss the suitability of using an automatic image segmentation algorithm, called Gradient Path Labelling (GPL), for CBP detection and tracking. The GPL algorithm was applied to high-resolution images from the AIA instrument onboard the SDO satellite (19.3 nm channel data with a 10 min cadence and from 3 days interval) to detect and locate CBPs. Their heliographical position was then used for tracking them on a sequence of images. Our test results show that this algorithm is a promising tool to obtain more precise measurements of the solar rotational speed and the meridional motions of CBPs. Moreover, we are developing an interactive website, where the SDO images are continuously downloaded and analysed allowing users to explore selected periods for the corresponding solar rotational profile and some other characteristics of CBPs.

1. MOTIVATION

Coronal Bright Points (CBPs) are small and bright structures observed in the extreme ultraviolet (EUV) part of the spectrum. CBPs occur when the regions of opposite polarity encounter each other and cancel out, releasing energy that heats the gas above the photosphere. Opposed to sunspots, CBPs can be found all over the Sun, even appearing at the poles and in coronal holes. CBPs allow to trace the solar differential rotational profile up to almost polar latitudes detecting and tracking them over a sufficiently long sequence of images. Therefore, we proposed a CBP tracer method to determine the solar rotation profile and assessed the results in a 3-day period.

Figure 1. Illustrative image of the solar corona recorded in the 193 nm channel.

2. DATA

We used high spatial resolution solar images in the FITS format taken by the AIA (Lemen et al., 2012) on-board the SDO (Pesnell et al., 2012) in the EUV channel 19.3 nm (Fe XII, 1.25 MK). For the time interval of 3 days 432 images with temporal cadence of 10 minutes were exploited (August 9 – 11, 2010). Raw AIA dataset in full resolution (4096 x 4096 pxs, 0.6 arcsec/px) was pre-processed as follows:

- the dataset was first corrected for the effect of the instrument PSF function using data and method provided by Poduval et al. (2013),
- the basic photometric reduction was performed (*aia prep.pro* routine) and intensities were normalized to 1 second exposure time,
- image noise filtering was applied using Lee box algorithm (Lee, 1986).

3. GRADIENT PATH LABELLING (GPL) SEGMENTATION ALGORITHM FOR DETECTION OF CBPS

For the detection of the CBPs' contours in the SDO images the Gradient Path Labelling (GPL) segmentation algorithm was used. This algorithm was initially designed and proposed by Mora et al. (2011) to segment retinal images. It is a four-step process:

1. Create an Active Regions mask;
2. Divide SDO image in 9 x 9 smaller images to reduce complexity;
3. Apply the GPL segmentation;
    a. Filter segmented regions that are larger than specified area to select only the regions that matches a CBP;
    b. GPL remerge and filter again;
    c. Determine CBP centroid and maximum intensity locations.
4. Remove CBPs inside the Active Regions mask.

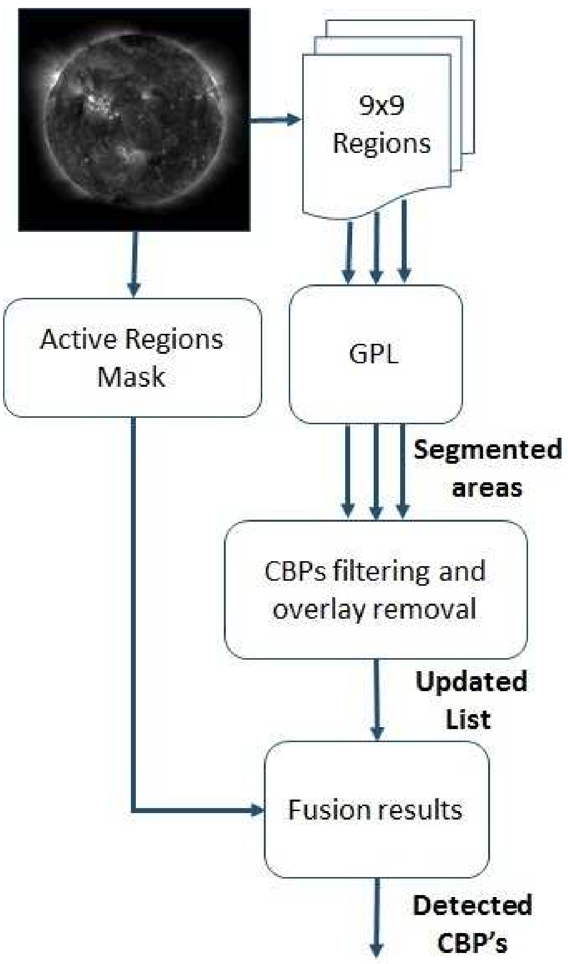


Figure 2. Applied methodology for CBPs detection using GPL segmentation.

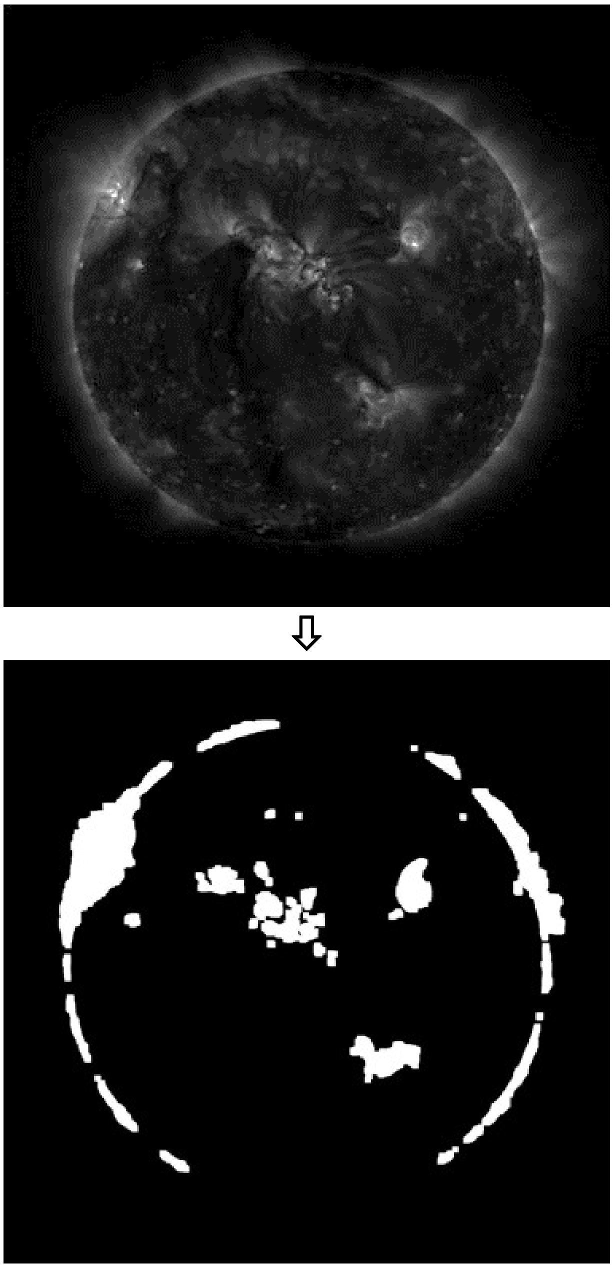


Figure 3. Rough segmentation of active regions for the CBPs filtering after applying the Otsu thresholding and a morphological closing.

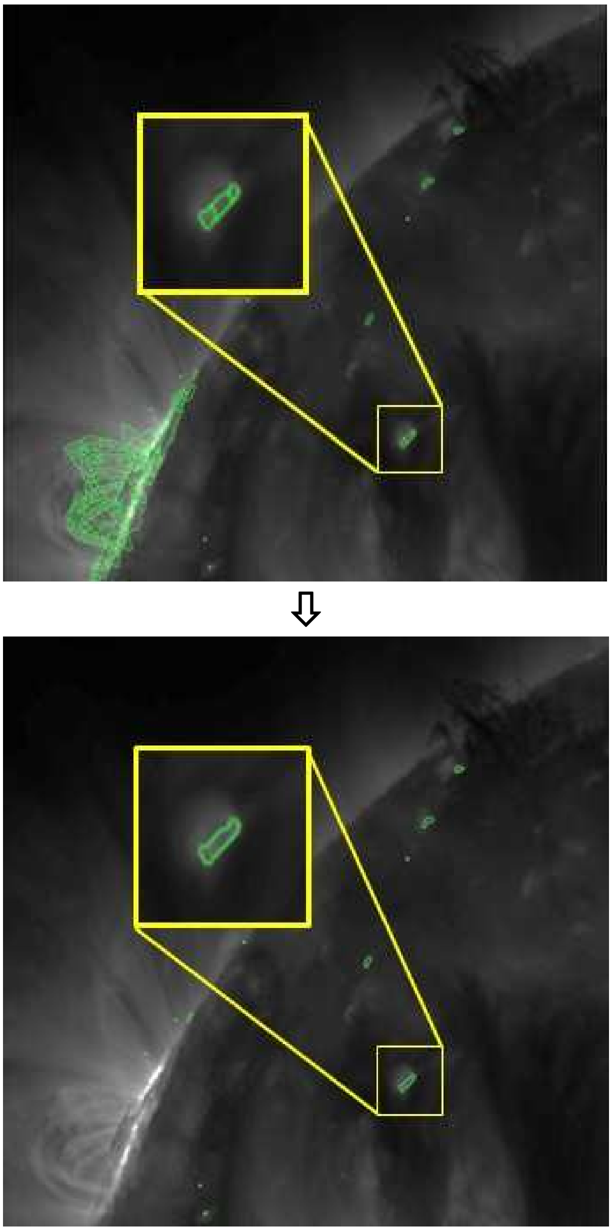


***Figure 4**. Merging illustration for a highlighted region: result of GPL segmentation (top) and after the remerge operation (bottom). The contour of the GPL segmented objects is displayed in green.*

4. CBP TRACKING METHOD

A total of 31183 individual identifications of CBPs were obtained in the 3-day image dataset. To be able to successfully retrieve solar rotational profile based on tracers, it is necessary to observe motion on a sufficiently long time interval. The first step is to specify spherical coordinates, of a given CBP, and its corresponding heliographic coordinates. The heliographic coordinates (the longitude *l* and the latitude *b*) were calculated as described in Lorenc et al. (2012). Both CBP centroid and maximum intensity coordinates are evaluated as positions of the CBP tracers. The CBPs are tracked by searching the closest CBPs in the three previous images (*t-1*, *t-2* and *t-3*), using the (x,y) location in pixels and the Euclidean distance. If no CBP is found a new unique identifier is assigned, otherwise, the CBP receives the identifier of the closest one. In total, we identified 2655 tracked CBPs from all individual identifications. Average positions of tracked CBPs are displayed in Fig. 6.

CBPs contour can be in many cases irregular. Although, centroid would be more precise, it displayed more imprecision than the maximum intensity location, due to CBP shape modifications along the tracking period (Fig. 7). Therefore, since the centroid might not be stable, the maximum intensity position was used for the tracking.

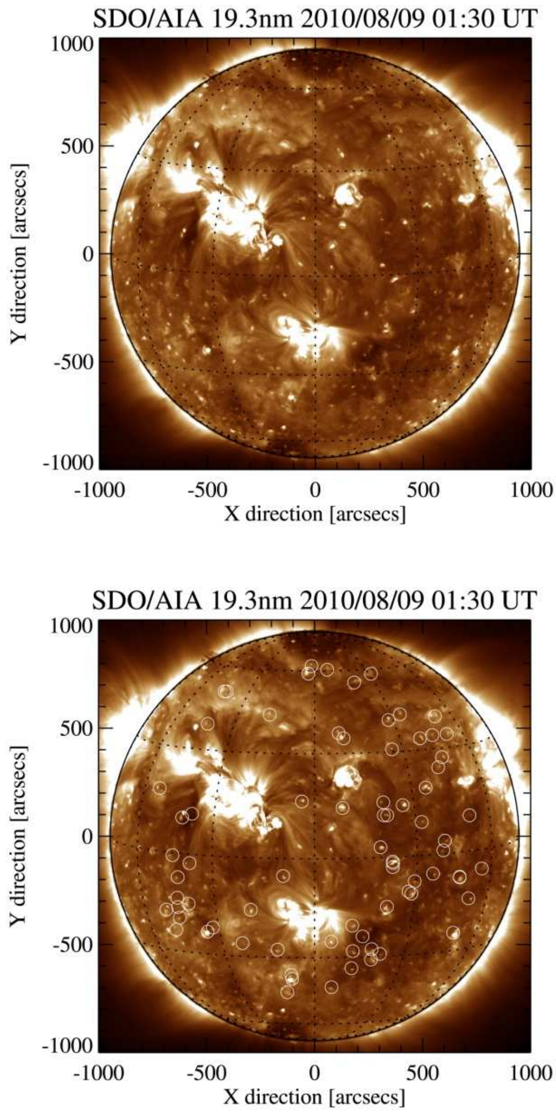


Figure 5. SDO/AIA 19.3nm solar image (top panel) and the same image with the all (also tracked) CBP identifications marked by white open circles.

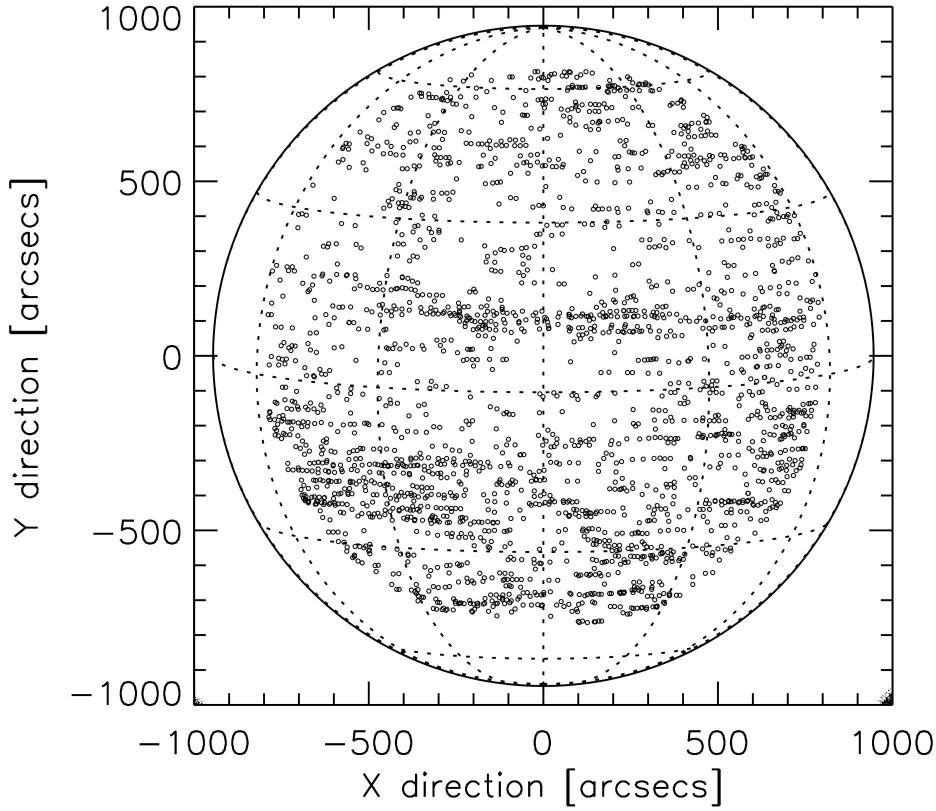
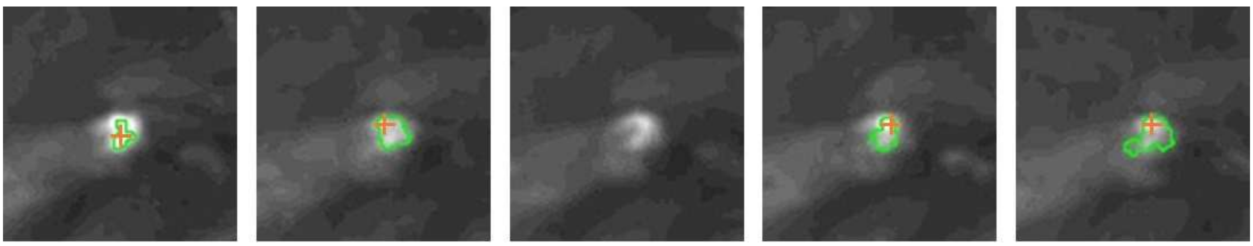


Figure 6. Average positions of all tracked CBPs detected in the SDO/AIA 19.3nm solar images used in this study marked by white open circles.



t = 10 ***t = 20*** ***t = 30*** ***t = 40*** ***t = 50***

Figure 7. Illustration of the tracking method: at t=30 no CBP was detected by the GPL and at t=40 tracking needs to search CBP at t=20.

5. DISSEMINATION WEBSITE

A dissemination website is being developed at the UNINOVA/CA3 research group to enable to investigate the differential rotation of the solar corona for any interested persons. The website is composed by three tabs, Now, Archive, and About. The homepage (Fig. 8) presents the updated and actual results (real-time solar differential rotation, active CBPs lifetime and identification histograms and solar rotational profile). The Archive module shows the data from the time interval introduced by the user, covering similar charts to the tab 'Now' and a datatable with all the tracked CBPs and respective information, which can be searched and sorted for user preferences. The About section has a brief description of the context behind the tool and links to the related groups websites and references. Every chart/table can be exported in different image formats or as a data table, both in .xls or in .csv. This allows any user to perform posterior analyses. The website is hosted at The Space-Planetary Interactions monitoring and forecasting Laboratory (SPINLab).

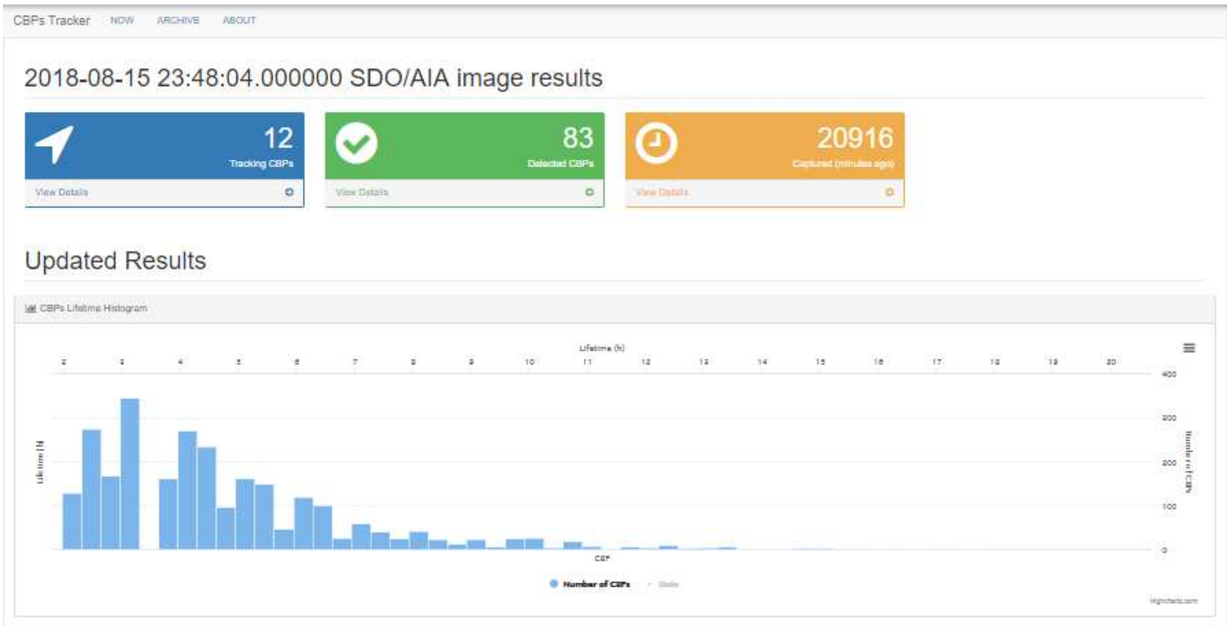


Figure 8. Layout of the website homepage.

6. ROTATION AND MERIDIONAL MOTION DETERMINATION

All (l, b) positions of the tracked CBP were fitted by a linear relation to derive the best fit of the relation (*Press et al. (1992),* We applied further a special procedure described in detail in Dorotovič et al. (2018) to all 2655 tracked CBPs and then we obtained an original set of rotation and meridional motion results with 28984 individual identifications. For comparison purposes with (Sudar et al., 2015, 2016), we selected from the obtained set of results, only those velocities which confirm the additional filtering criteria: $8° < vel_{rot} < 19°\ day^{-1}$, $-4° < vel_{mer} < +4°\ day^{-1}$, minimum number of identifications 10, and minimum CBP lifetime 100 minutes, creating the final set of the rotation and meridional motion results used for analysis in this study. This conservative approach chose, from the total number of 2655, only 933 of the tracked CBPs for the rotation velocity and 925 for the meridional motion velocity. An example of a temporal evolution of a longer-lived CBP longitude *l* and latitude *b* coordinates is shown in Fig. 9.

In addition, we applied a correction of the projected coordinates using the optimum average CBP height of 6331 km above the solar photosphere (Sudar et al., 2016). The sidereal rotation velocity was calculated from the synodical rotation velocity data using the relation of Skokić et al. (2014).

7. RESULTS

Individual measurements of rotational velocity, relatively to mean latitudes of the tracked CBPs, satisfying the limitation criteria, are shown in Fig. 10. This figure illustrates the solar differential rotation profile. There are more CBP identifications at the north hemisphere and less at the south one, which is in accordance with the actual value of the heliographic latitude of the solar disc centre ($B0 = +6.35°$). There is a big scatter of CBP identifications and also an asymmetry between the slowly and rapidly rotating CBPs - the number of CBPs with sidereal rotation velocity between 8° and 12°/day is significantly higher than the number of CBPs with the velocity between 16° and 20°/day. We used the common fitting relation to that latitudinal dependence of the rotational velocity

$$\omega(b) = A + B\sin^2(b) + C\sin^4(b) \qquad (1)$$

where *b* is the latitude, to quantify this relation. The values of the optimum fit parameters *A*, *B*, *C* obtained by the least-squares fitting algorithm are 14.187 ± 0.0159, -0.43 ± 0.157, and -5.09 ± 0.267, respectively. we followed the suggestion of Snodgrass (1984) and use Gegenbauer orthogonal polynomials as terms for the fitting equation

$$\omega(b) = A_G T_0^1 + B_G T_2^1\,(\sin(b)) + C_G\,T_4^1\,(\sin(b)) \quad (2)$$

where A_G, B_G, C_G are parameters of the fitting and T_0^1, T_2^1, T_4^1 are Gegenbauer polynomials.

8. DISCUSSION AND CONCLUSIONS

We have developed a software code that *automatically detects and tracks* CBPs in 19.3 nm RAW solar images from the SDO/AIA instrument at 10 min cadence. Since our CBP detection algorithm uses an active region mask to filter out the CBPs whose location is inside the ARs, the number of identifications clearly depends on the level of the solar activity: *the lower activity means less CBPs filtered out***.** The course of the *differential rotational profile* is consistent with the results of other authors cited in the caption of the figure. The results obtained in this paper confirmed that the proposed approach constitutes a *promising tool for*

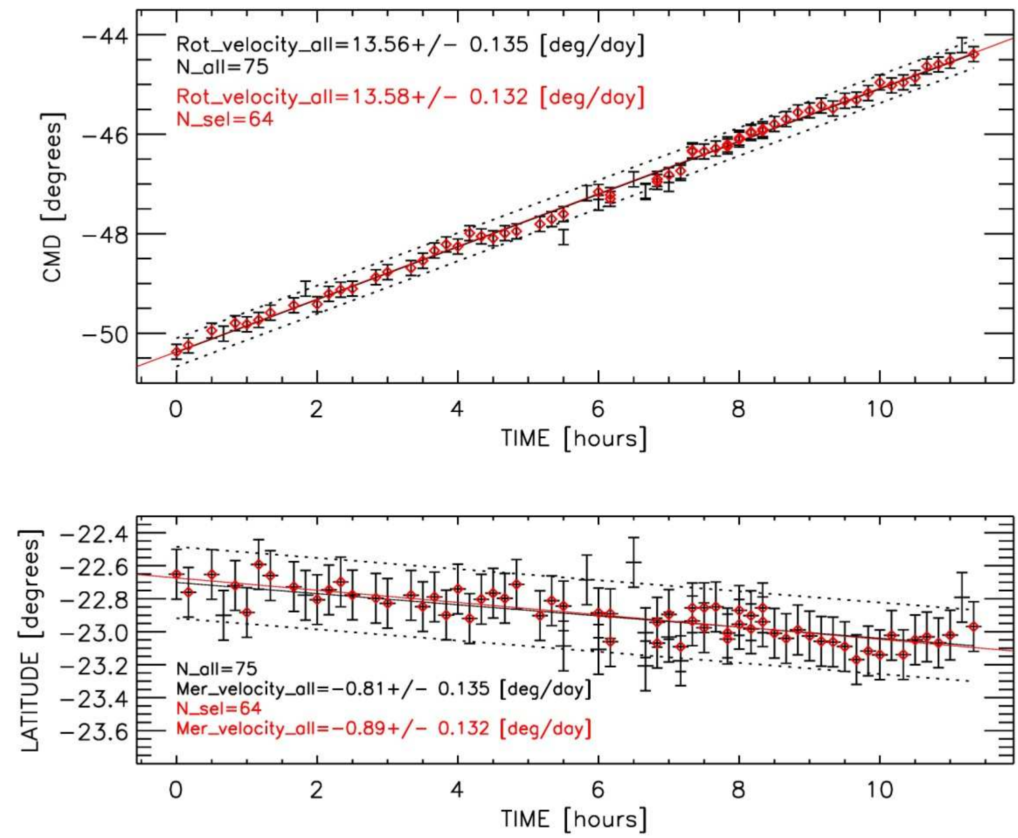


Figure 9. Temporal evolution of the identified longitude (upper panel) and latitude (lower panel) positions of a longer-lived CBP. The error bars display all measured coordinates and estimation of their uncertainty of the CBP (black). The solid and dotted lines show a linear fit and the 1-sigma error of the fit respectively.

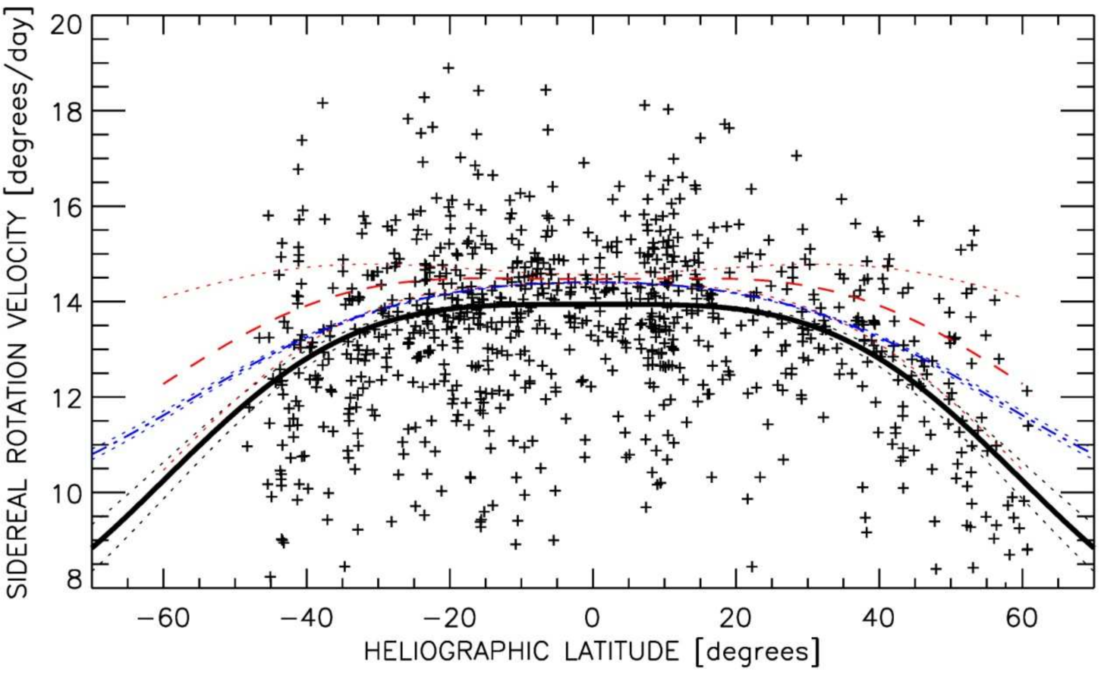


Figure 10. Individual measurements of rotational velocity in respect to latitude. Thick solid black line indicates the best fit to these values using the relation 1. Thin dotted black lines mark the fit uncertainty using the 1-sigma of the A, B, C parameters. Dashed and dotted lines show the rotational profile derived from two days of the similar SDO/AIA 19.3nm data (Sudar et al., 2015) (red) and the profile obtained from more than 5 months of such data (Sudar et al., 2016) (blue), respectively.

processing massive solar image archives and subsequently also for investigating the evolution of solar activity. The next step is therefore to use this tool to process further available SDO images for the *solar cycle 24*.

Acknowledgments

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