Multi-wavelength investigation of coronal holes and associated solar wind flows

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Subject of the study

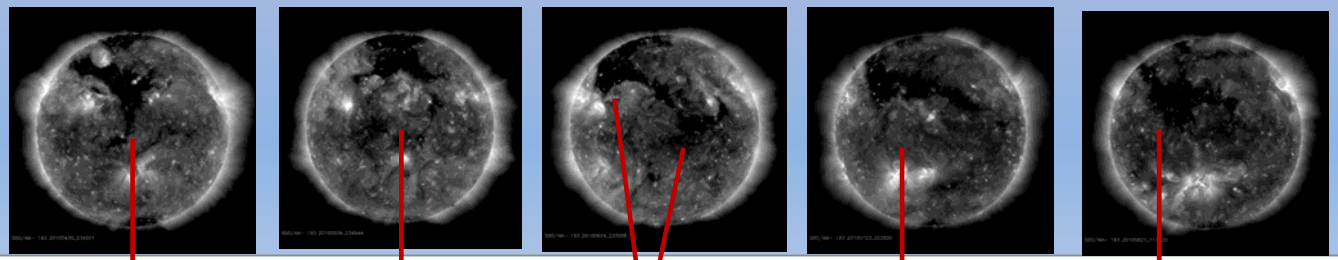
- Analysis of the coronal holes (CH) of different polarity and configuration based on UV-images from different spectral bands and spacecraft, and their footprints on the magnetograms
- Study of relationship between CH areas obtained in various spectral bands and the velocity of recurrent solar wind (SW) streams

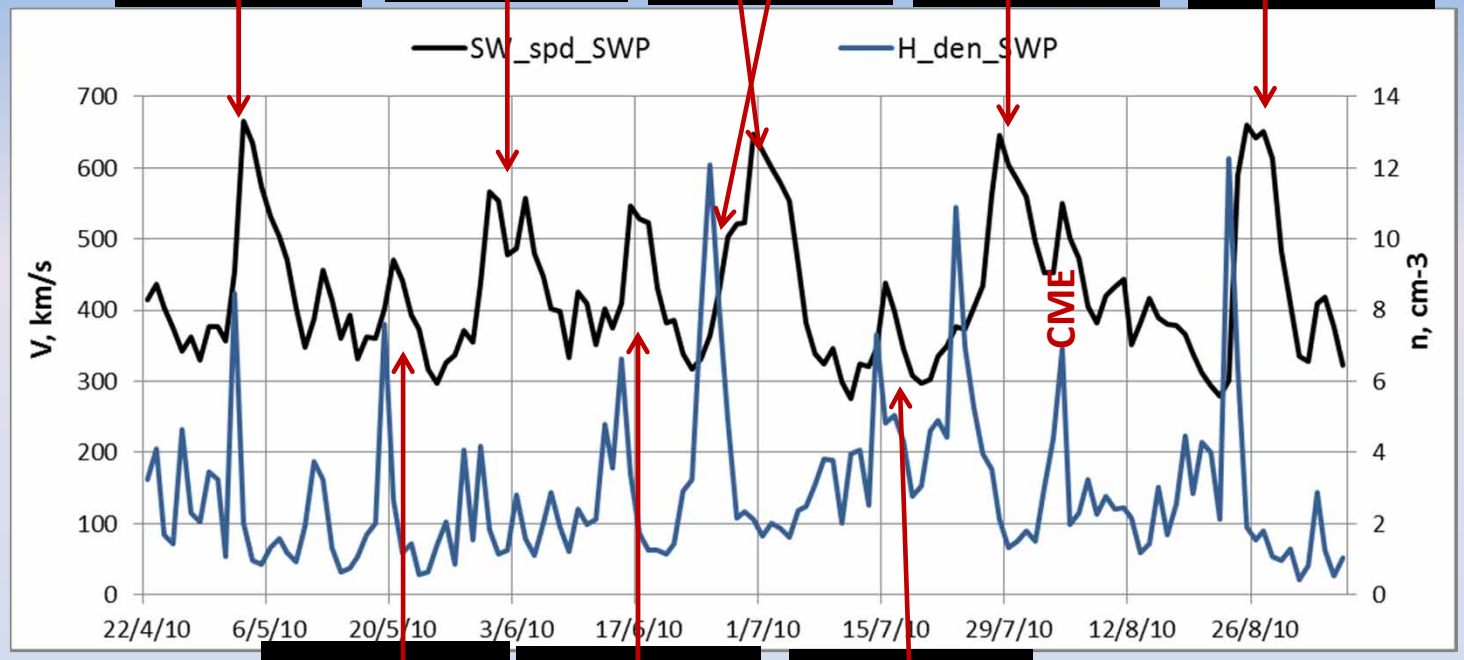
Data analyzed

- Period **from May to August 2010** were studied
- SW velocity daily average from **ACE** spacecraft
- Daily “synoptic” images from **AIA/SDO** at wavelengths 193 and 211Å (since 13.05.10)
- Daily “synoptic” magnetograms constructed from 720s line-of-sight magnetograms from **SDO/HMI** (since 01.05.10)
- Images from **PROBA2/SWAP** at 174Å (***prepared in collaboration with SWAP team, Royal Observatory of Belgium***)
- Solar images from SDO/HMI were scaled to SDO/AIA and PROBA2/SWAP images
- Time difference between SWAP, AIA and HMI images was several minutes as a rule

Recurrent SW streams and their sources (SDO/AIA 193Å)

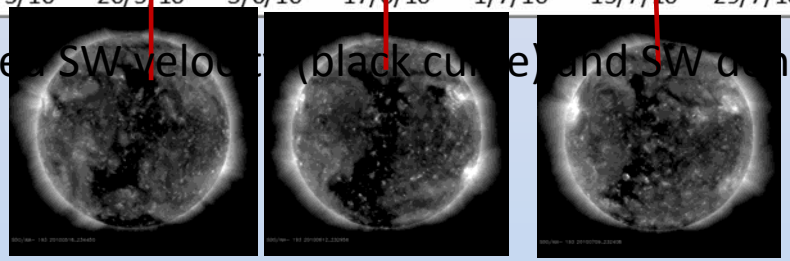
CH negative polarity (PCH) 520-660 km/s



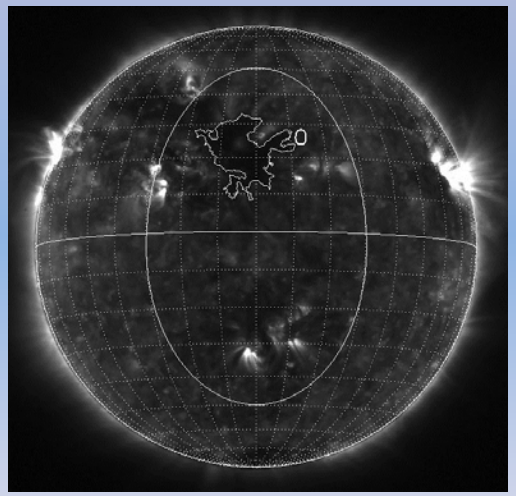


Observed SW velocity (black curve) and SW density (blue curve)

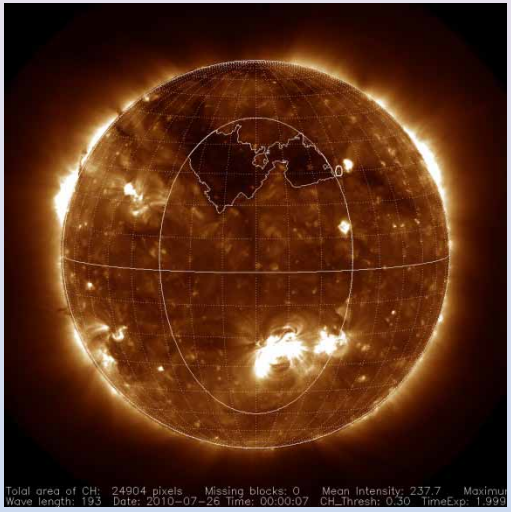
CH positive polarity (ECH) 440-550 km/s



CH areas



PROBA2/SWAP at 174Å
CH areas 01.05.2010



SDO/AIA at 193Å
CH areas at 25.07.2010

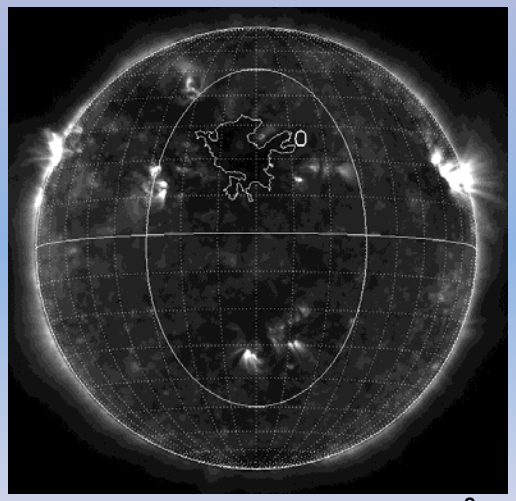
CH areas (relative units, % from solar disk) were calculated using threshold algorithm.
Regions with intensity lower than threshold and size larger than 0.4% of the solar disk were selected

- Threshold intensity calculated as $\mathbf{I_{mean}}$*$\boldsymbol{k}$,
  - $\mathbf{I_{mean}}$ is mean intensity of image without limb brightness,
  - $\boldsymbol{k}$ is the threshold coefficient
- three $\boldsymbol{k}$ values used for each wavelength
  - **0.4, 0.35 and 0.3** for PROBA2/SWAP
  - **0.3, 0.25 and 0.2** for SDO/AIA at 211 and 193Å

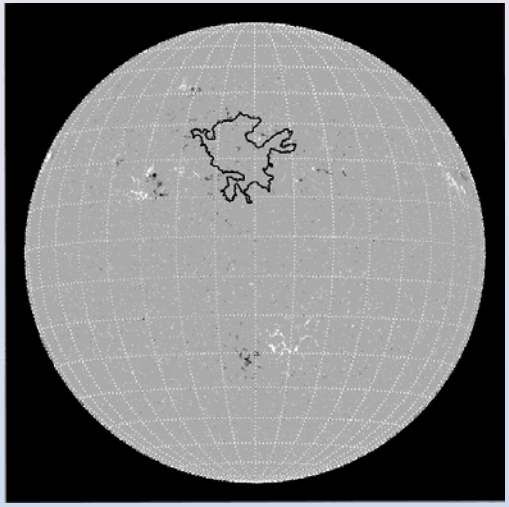
Most informative for forecasting the SW stream velocities in Earth orbit:

±30° longitude and ±50° latitude (not always)

CH base (footprint) at magnetogram



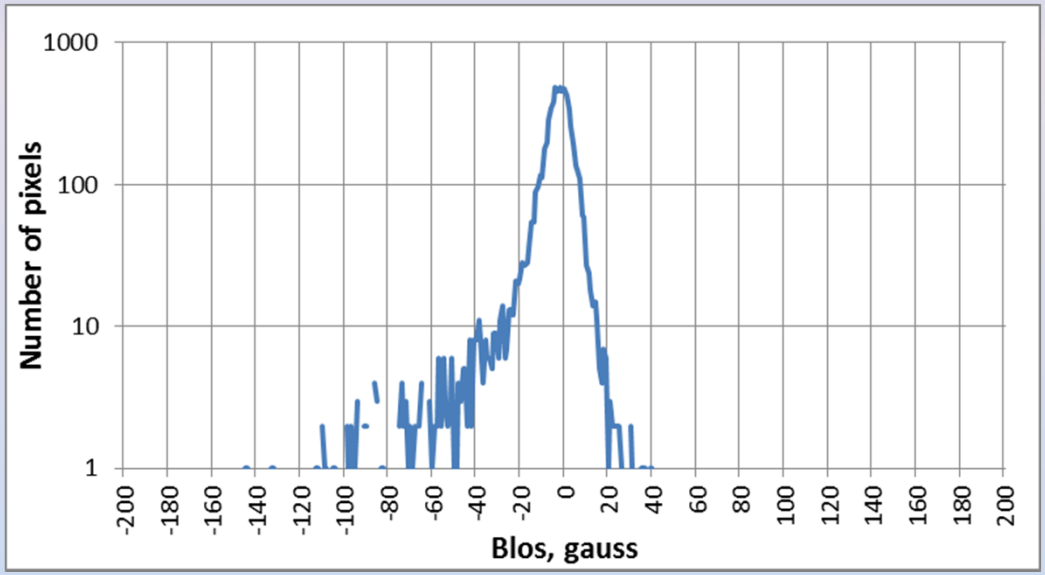
PROBA2/SWAP at 174Å
CH areas 01.05.2010



CH boundary is mapped at LOS magnetogram from SDO/HMI

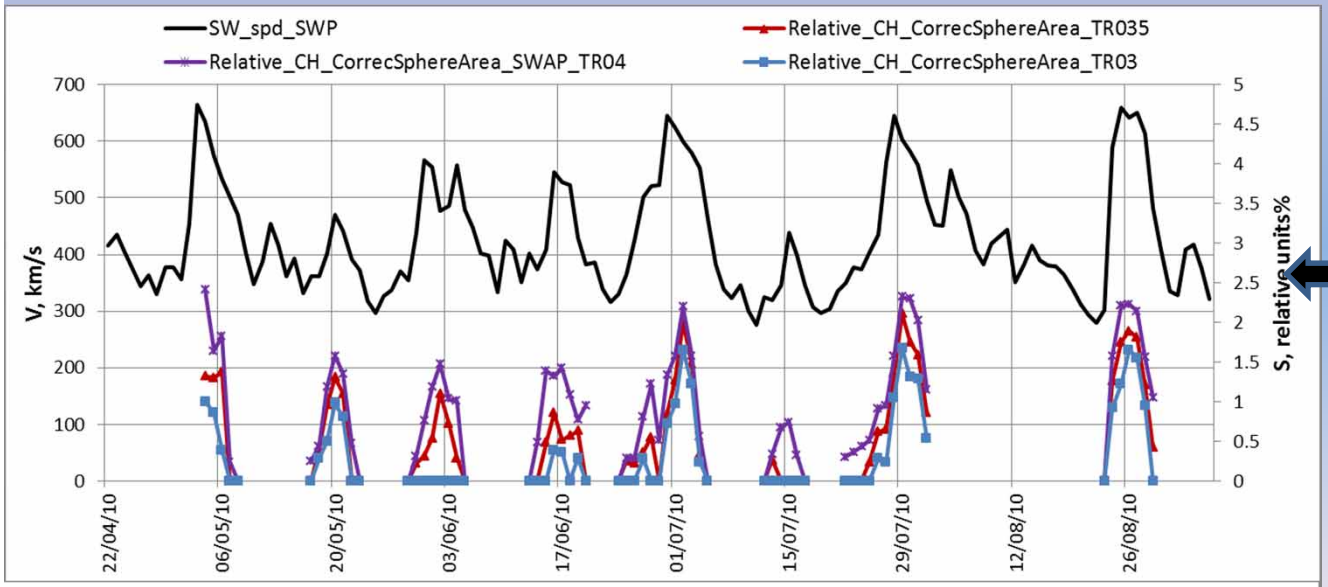
CH boundaries were mapped on line-of-sight (LOS) **SDO/HMI** magnetogram
Magnetic field (Blos) statistics and histograms were calculated:

Max	Min	Mean	MeanPos	MeanNeg
56	-292	-3.37	4.31	-8.94

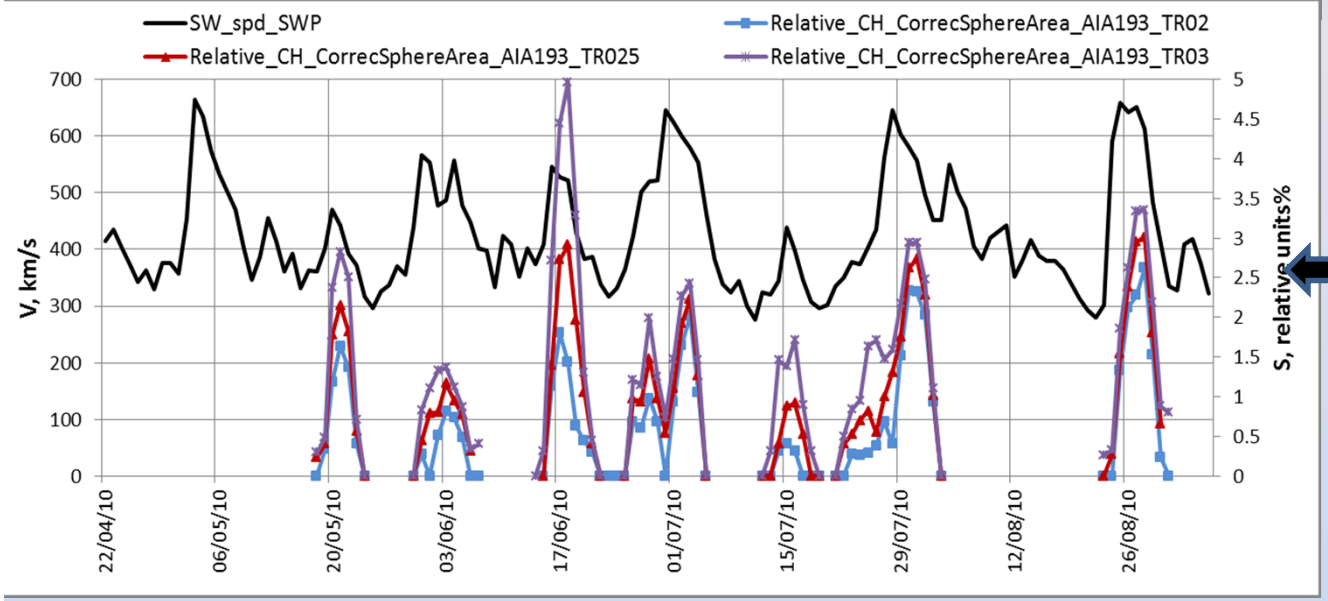


Blue curve - histogram of magnetic field (Blos) distribution inside CH; X-axis is logarithmic

CH areas & SW velocity for 174 and 193Å



CH areas were calculated using SWAP images at **174Å**
For 3 thresholds:
0.3 - blue curve
0.35 - red curve
0.4 – purple curve



CH areas were calculated using AIA images at **193Å**
For 3 thresholds:
0.2 - blue curve
0.25 - red curve
0.3 – purple curve

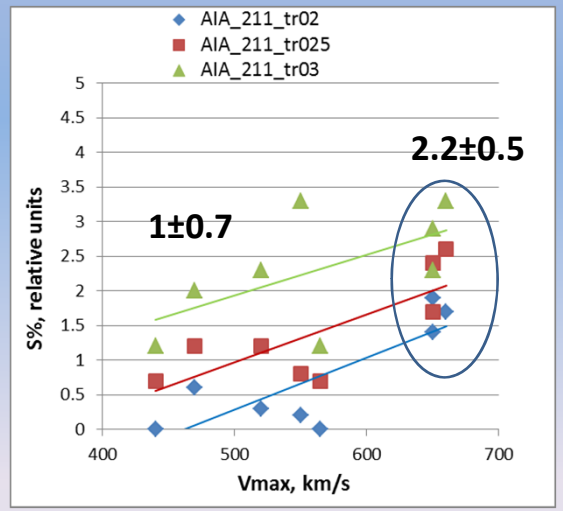
Black curves - observed SW velocity (V); **Color curves** - CH areas (S) with 3 days shift

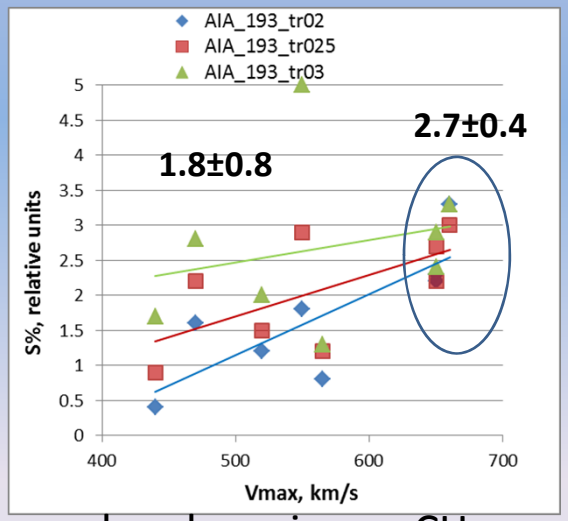
Maximum CH areas & Maximum V

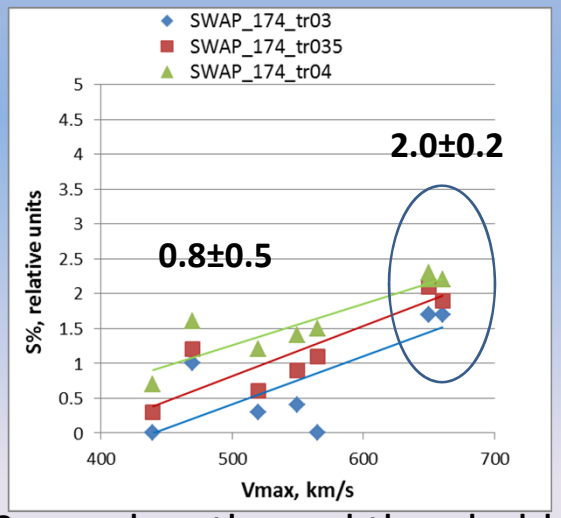
Separate group (**in circles**) - large PCH extended to low latitudes

Second group – ECH, equatorial parts of PCH and high-latitude (above 35°) PCH

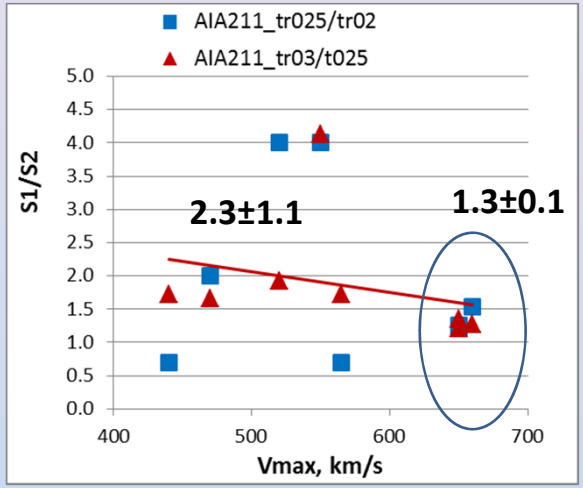
Mean values with standard deviations presented for each group

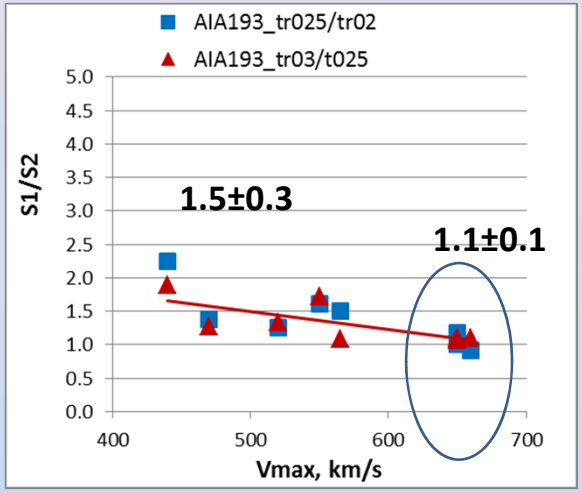


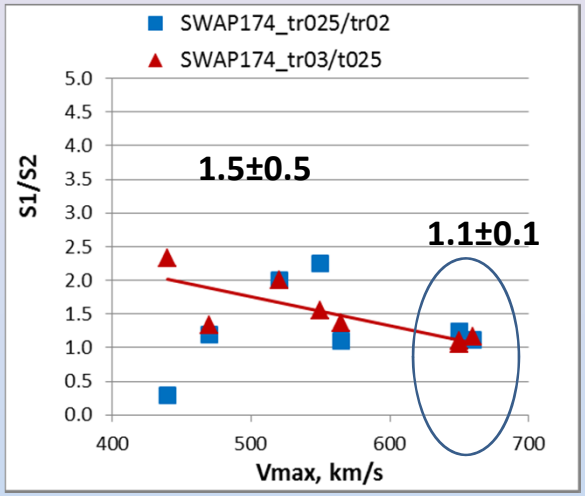




Relation between maximum SW speed and maximum CH area for 3 wavelengths and thresholds

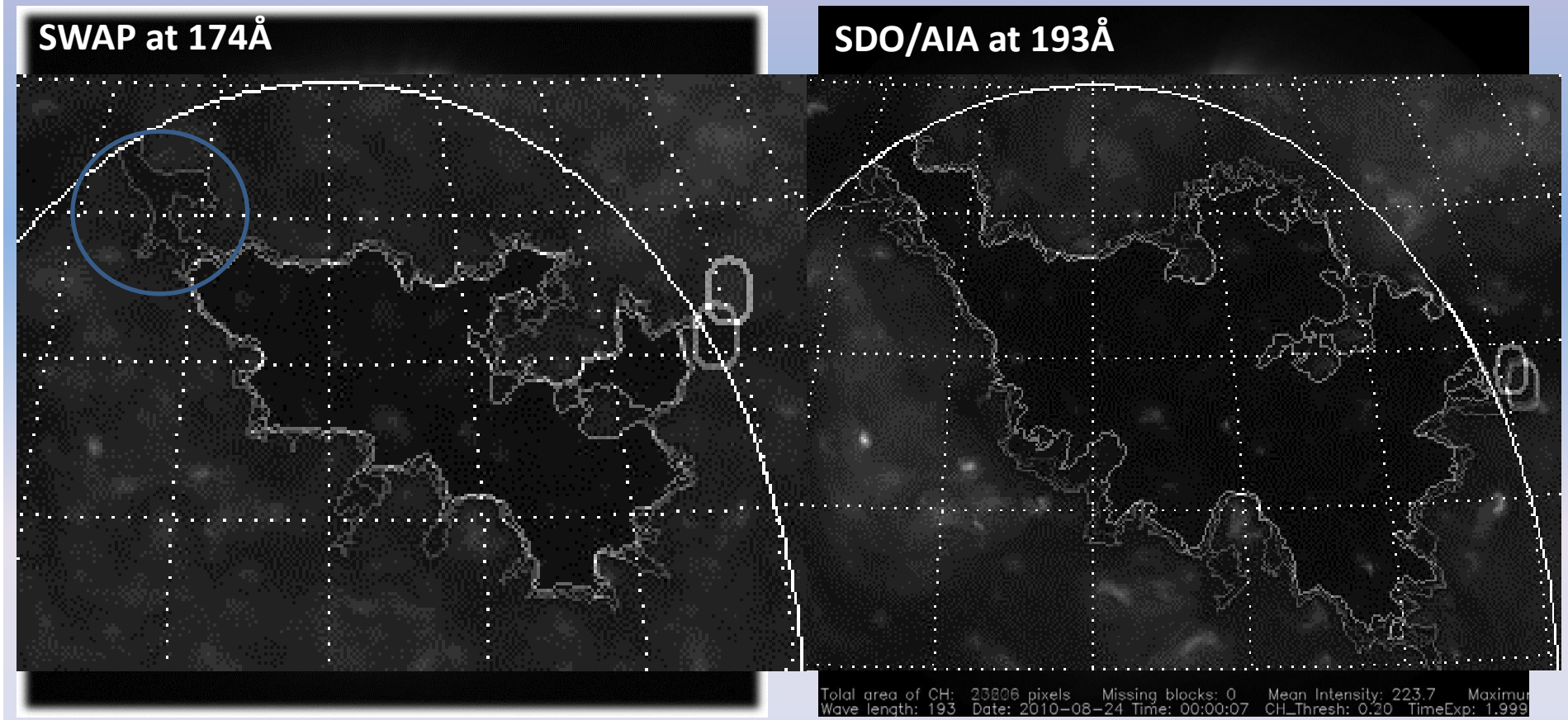






Ratio between maximum values of CH areas calculated for two nearest thresholds

PCH: sensitivity to threshold for 193 and 174Å

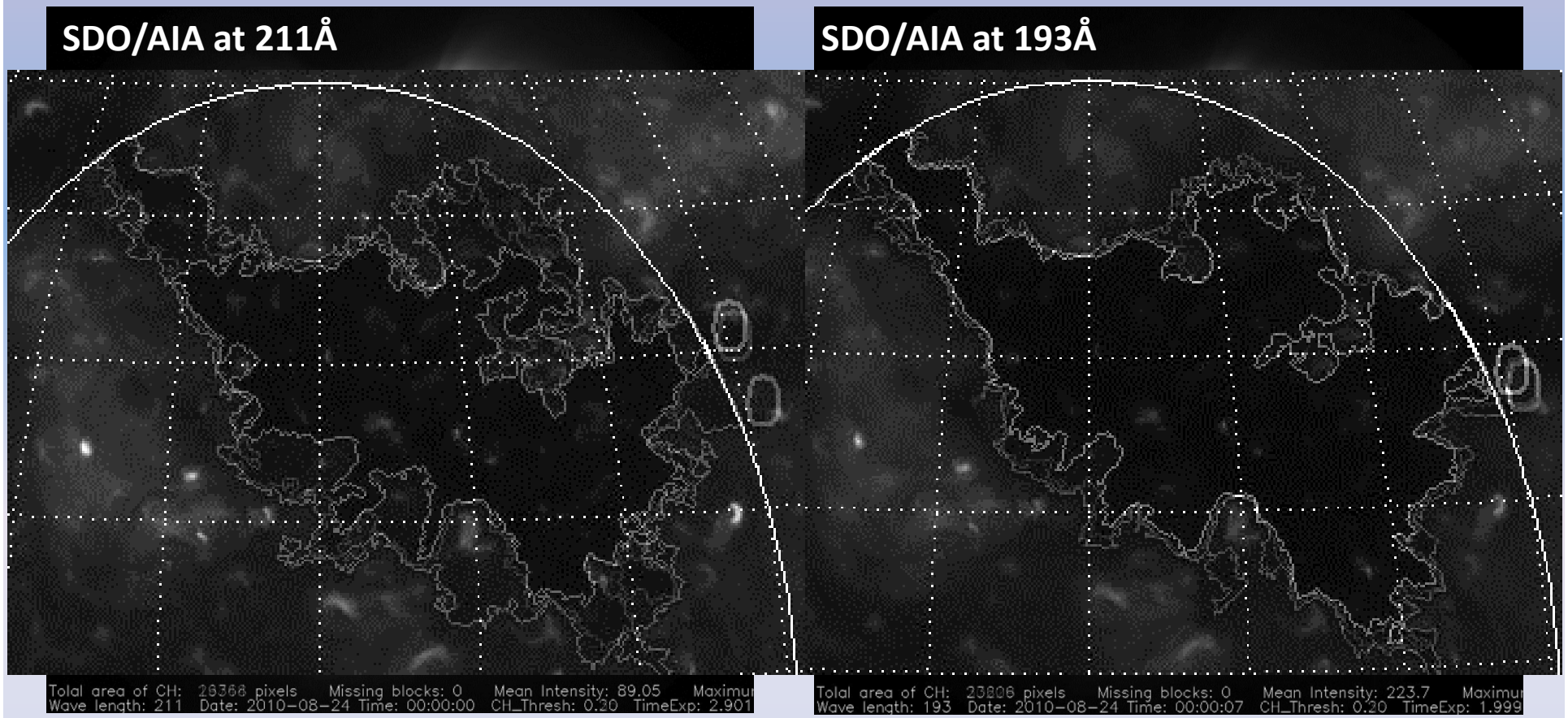


Negative polarity PCH, observed on 24.08.10 (Max SW velocity 660 km/s)

Left image - CH contours calculated from images obtained by **SWAP at 174Å** for 3 thresholds.
Right image - CH contours obtained by **SDO/AIA at 193Å** for 3 thresholds.

CH areas calculated at 193Å are higher than at 174Å for any threshold
Changes in CH areas are small with increasing threshold (mainly on CH edge and filling cavities)
For **174Å** largest increment is at threshold value of 0.4 (blue circle)

PCH: sensitivity to threshold for 211 and 193Å



Negative polarity PCH, observed on 24.08.10 (Max SW velocity 659 km/s)

Left image - CH contours calculated from images obtained by **SDO/AIA at 211Å** for 3 thresholds.

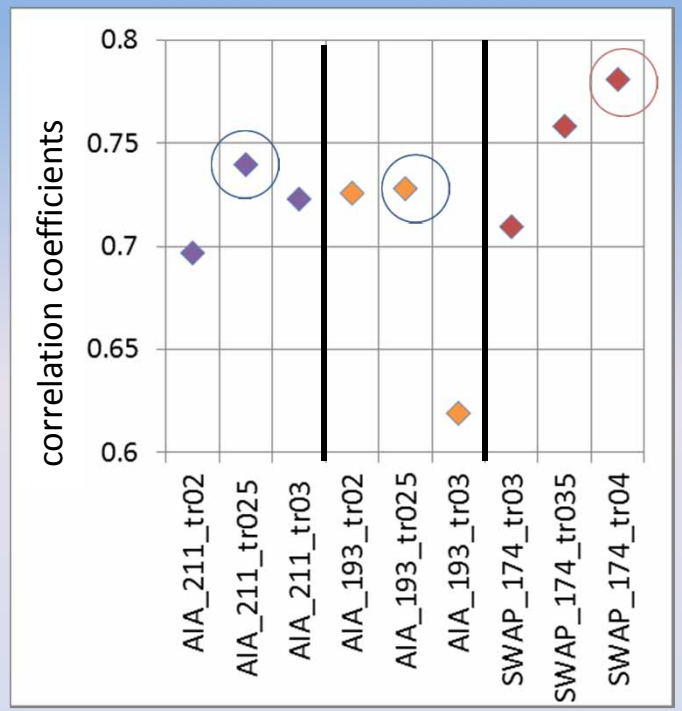
Right image - CH contours obtained by **SDO/AIA at 193Å** for 3 thresholds.

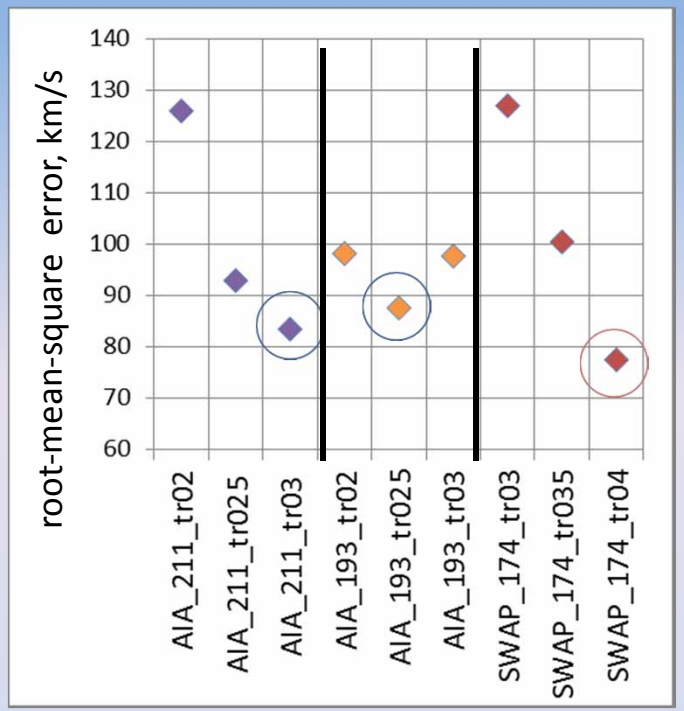
CH borders for 211Å vary strongly with changes in threshold

CH area for 211Å at small threshold is similar to the obtained at 174Å, but increases rapidly with the threshold and reaches the level of 193Å

SW velocity estimated

SW velocity values were estimated with linear model $V(S,t) = V_{\min} + A * S(t - t_0)$
Parameter **A** is estimated using least squares for each wavelength and threshold;
t=3 days and $\mathbf{V_{min}}$=300km/s for investigation periods

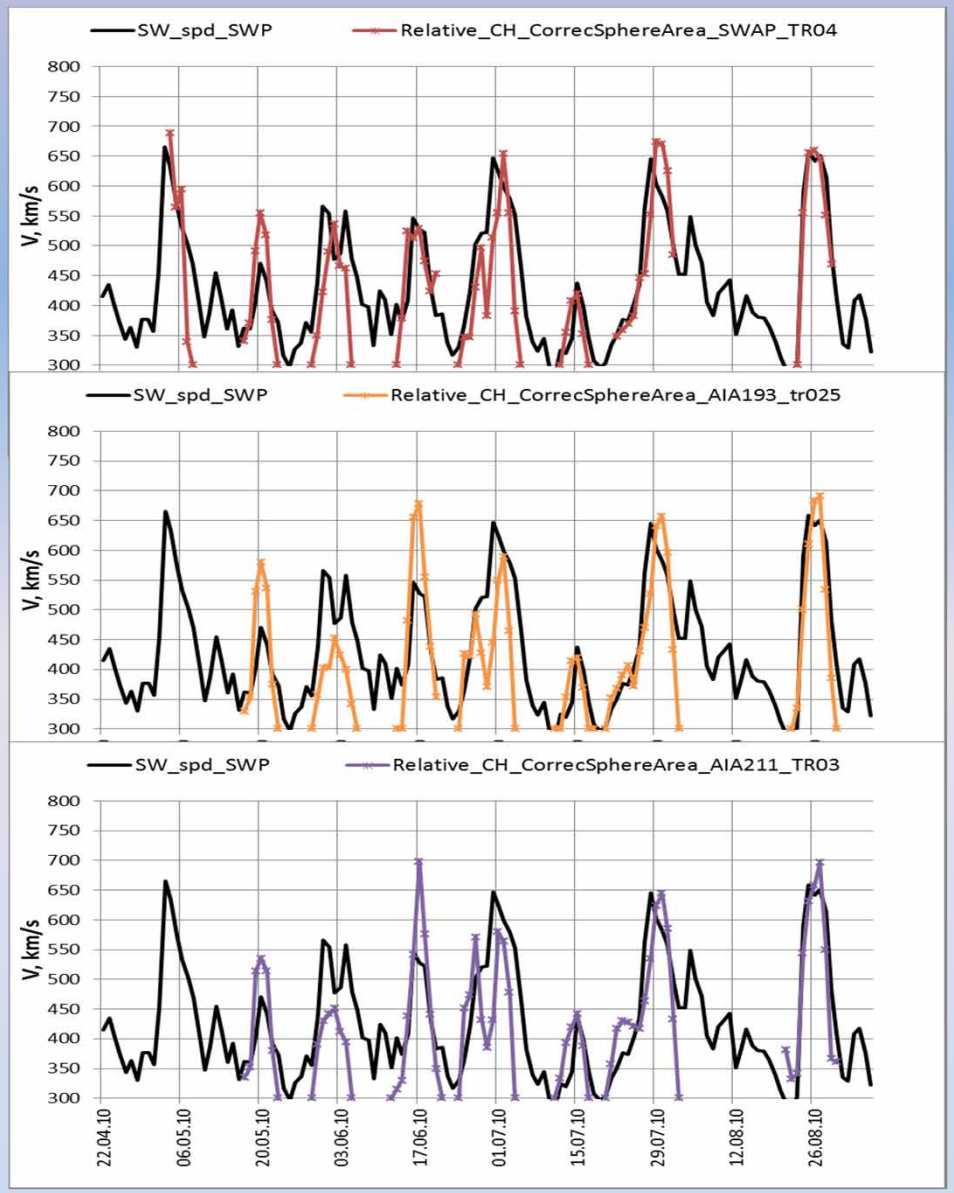




The best threshold for each wavelength was determined on the basis of correlation coefficients and root-mean-square error values between observed and estimated SW velocity values

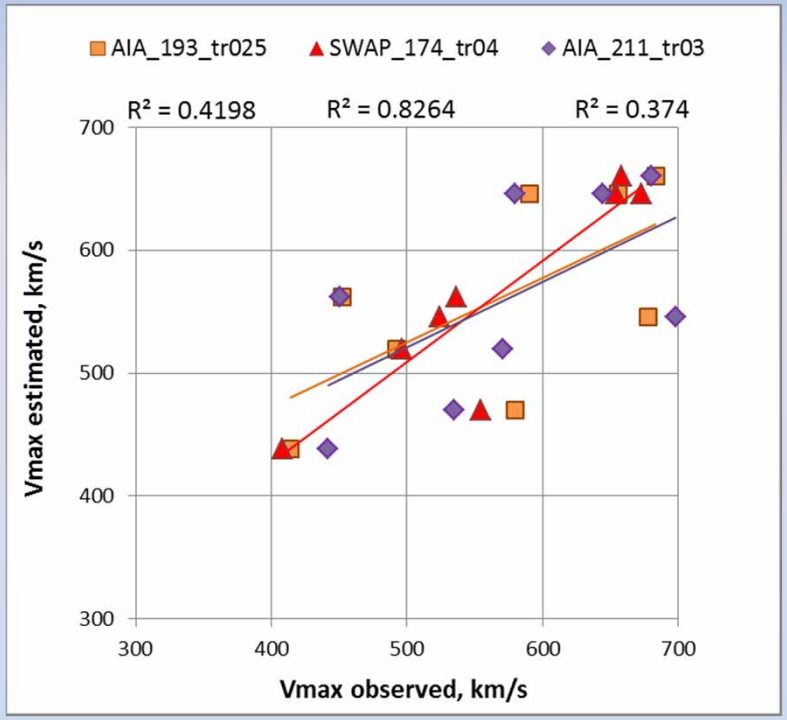
Best thresholds for each wavelengths are enclosed in circles (**red circle is** the best value)

V observed & V estimated



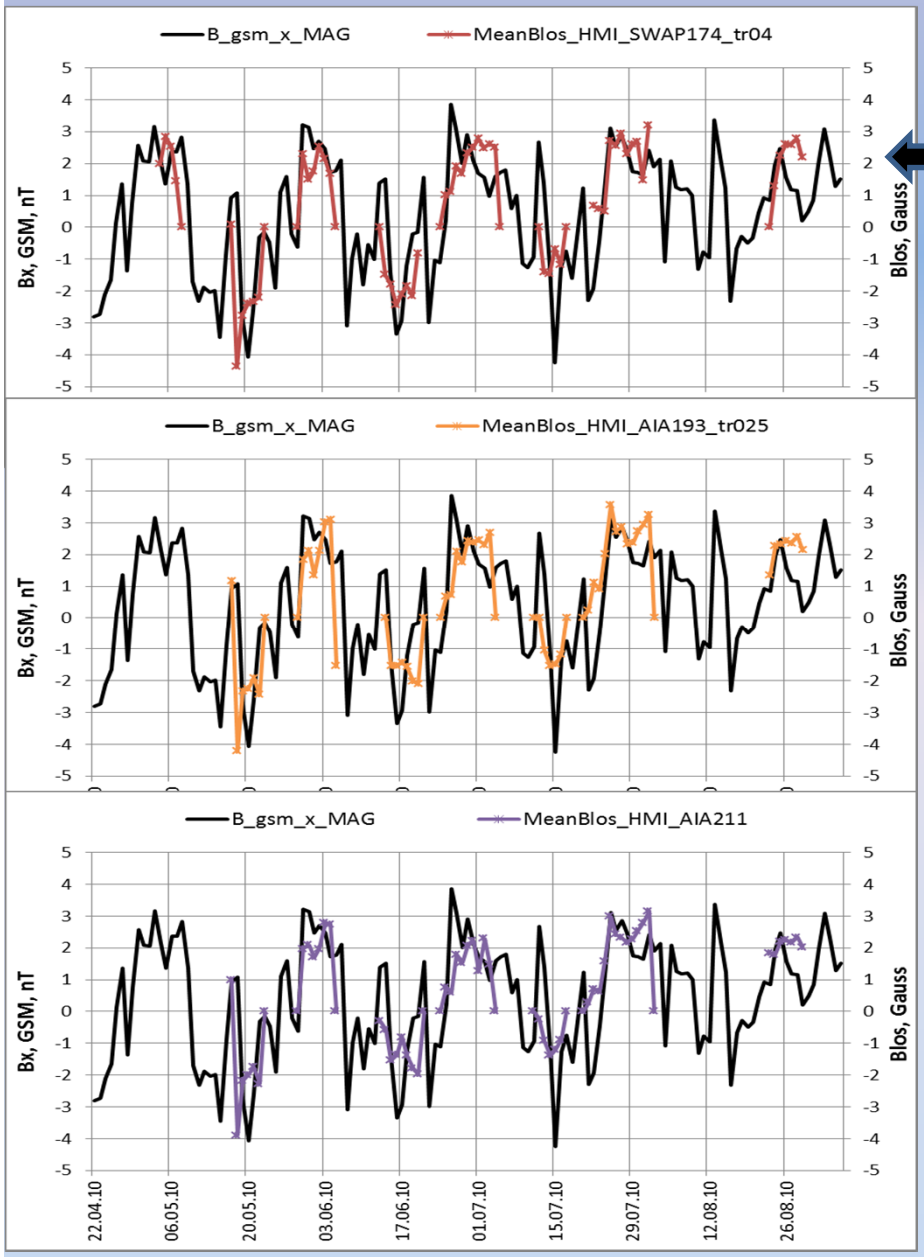
Black curves - observed SW velocity;
Color curves - CH areas with 3 days shift

3 wavelengths, best threshold
Correlation coefficient:
0.8 for SWAP; 0.7 for AIA **193** and **211**Å,
RMSE (root-mean-square error) :
73 km/s for SWAP **174Å**
87 km/s for AIA **193Å**
83 km/s for AIA **211Å**



RMSE between V_{max} observed and V_{max} estimated is **37 km/s** for SWAP

Mean Blos for CH base for best thresholds



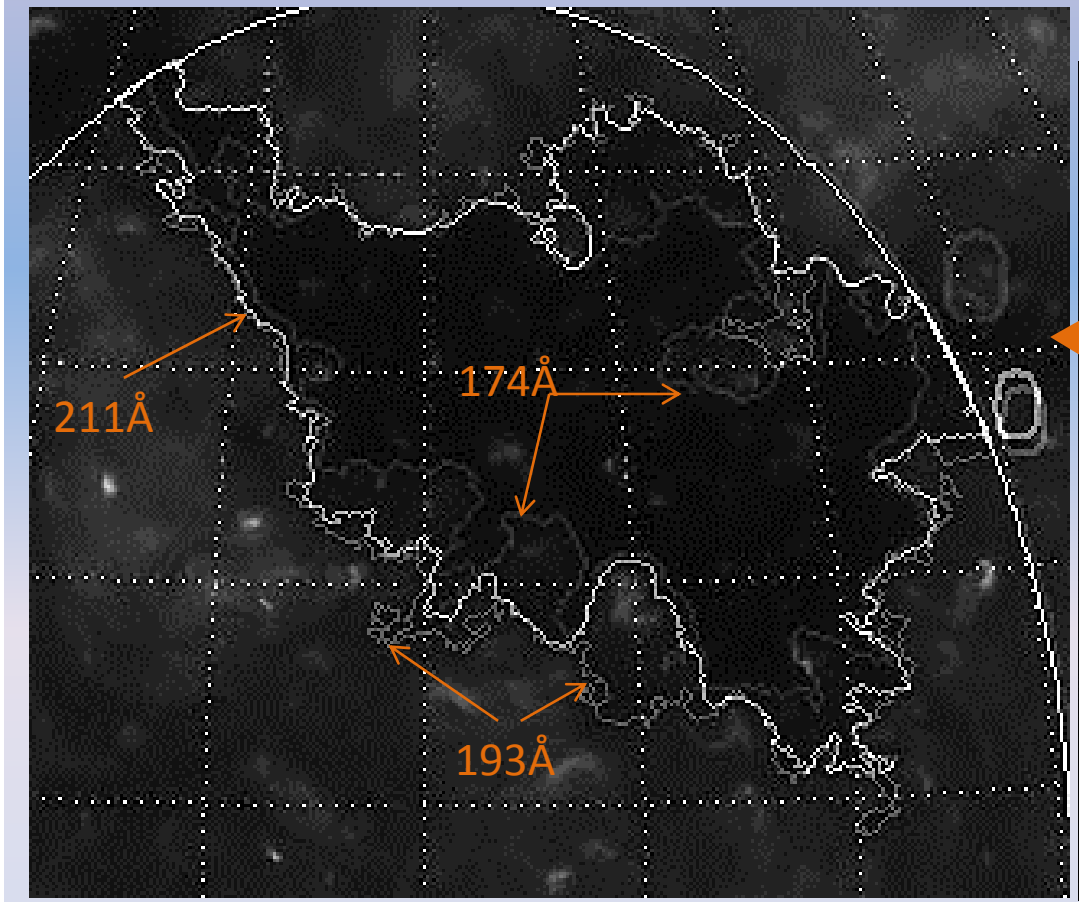
For best thresholds and 3 wavelengths

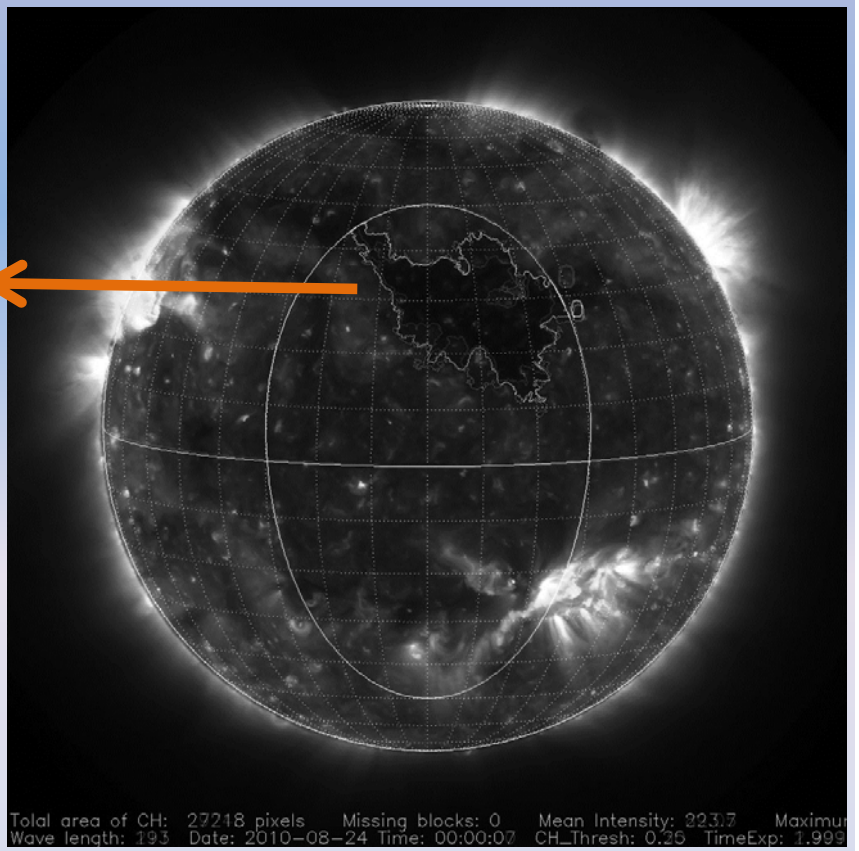
Black curves - observed Bx-component interplanetary magnetic field (IMF);

Color curves – Mean Blos in CH base with 3 days shift

If Bx-component IMF values are estimated as
10^{-5}* Blos, then
Correlation coefficient between estimated and observed Bx-component IMF:
~ 0. 7 for **SWAP,** AIA **193** and **211**Å,
RMSE :
1.7 nT for SWAP **174Å**
1.8 nT for AIA **193** and **211**Å

PCH borders for best threshold values



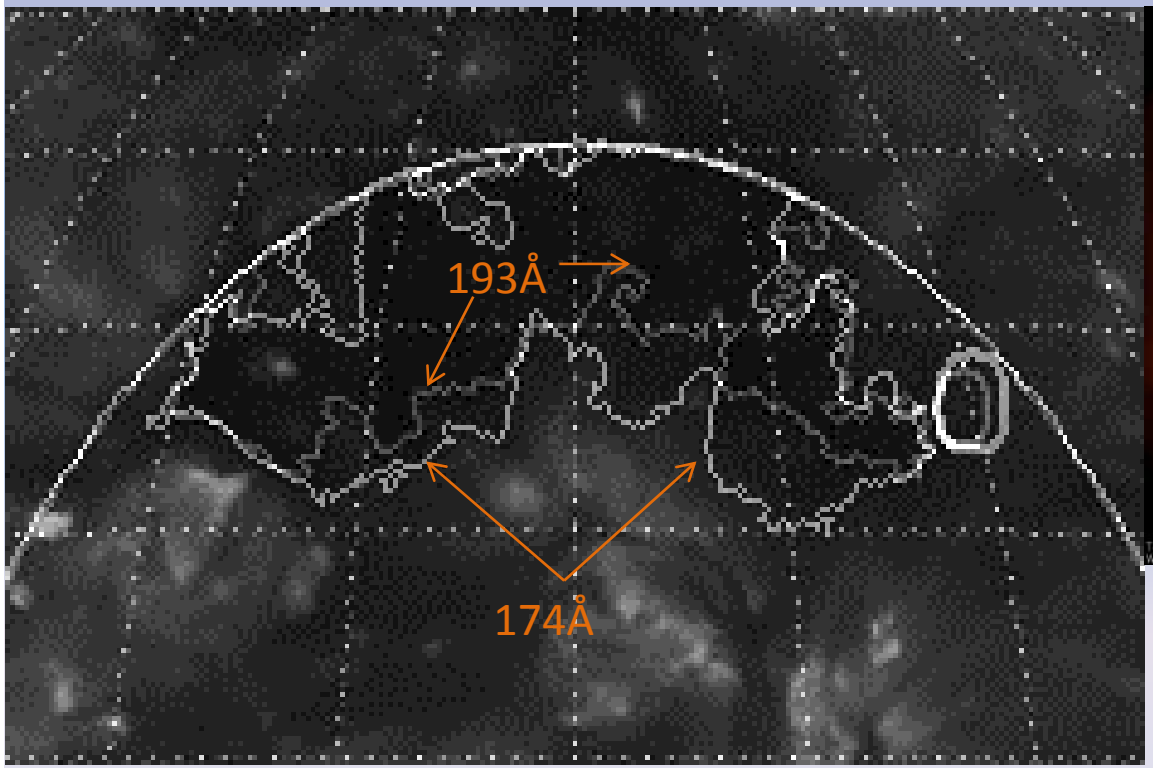


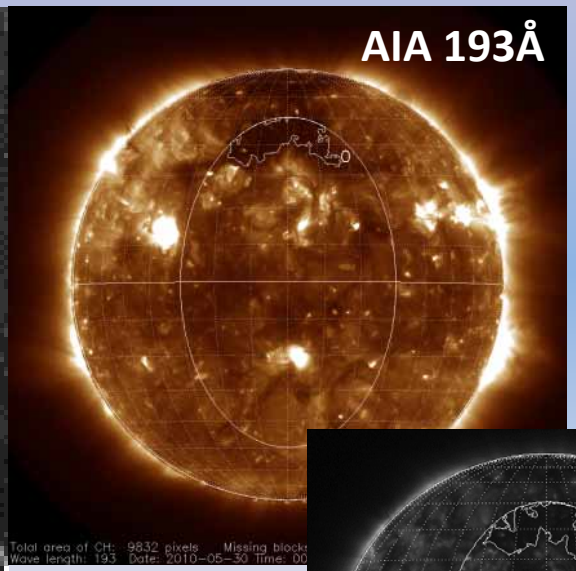
Negative polarity PCH, observed on 24.08.10 (Max SW velocity 659 km/s)

Boarders of PCH calculated using best thresholds: 0.3 - 211Å, 0.25 - 193 and 0.4 - 174Å;
CH area for 193Å is the largest; CH area for 174Å is the smallest one; CH borders for 211Å are much closer to 193Å.

Linear model gives maximum SW velocity **683** and **680** km/s for AIA **193** and **211**Å,
658 km/s for SWAP **174**Å. **Observed** SW velocity - **659** km/s

PCH borders for the best thresholds 174&193Å

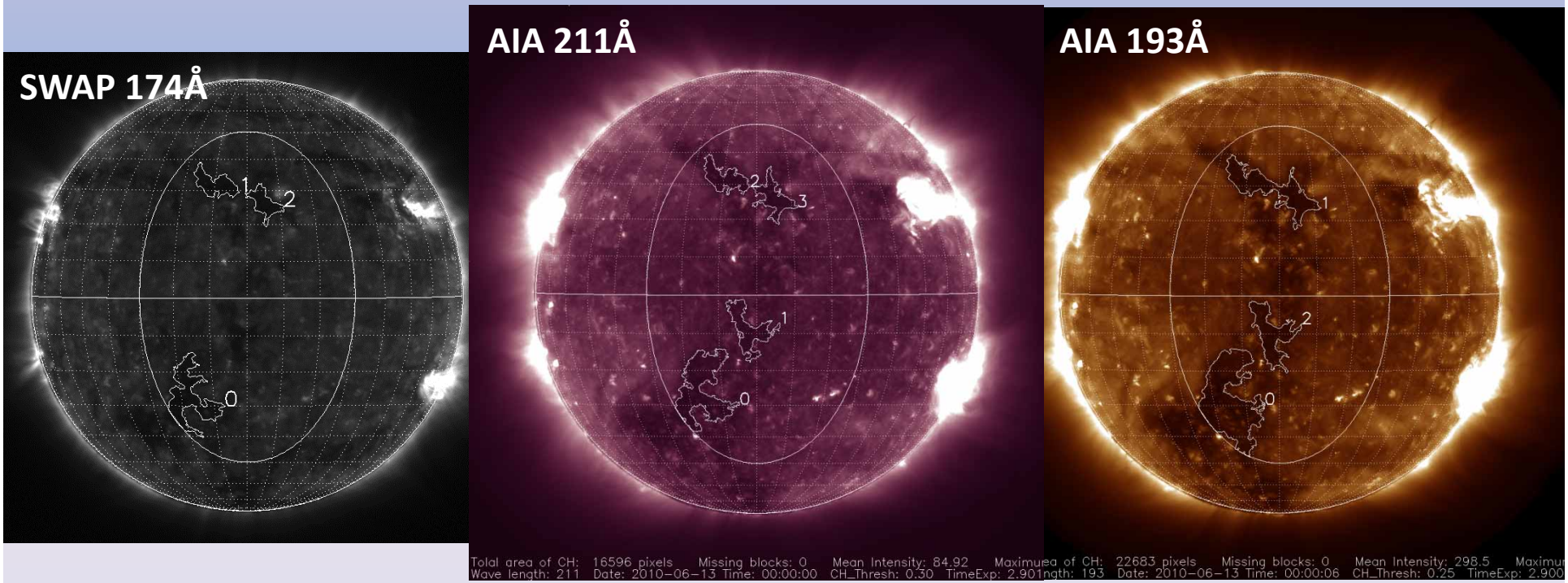




PCH negative polarity was observed 30.05.10 (Max SW velocity 562 km/s

Boarders of PCH calculated with the best thresholds: 0.3 - 211Å, 0.25 - 193 and 0.4 - 174Å;
CH areas for 174Å (white curve) is the largest; CH area for 193Å (gray curve)is the smallest one;
Linear model gives maximum SW velocity **452** and **451** km/s for AIA **193** and **211**Å,
536 km/s for SWAP **174**Å. **Observed** SW velocity - **562** km/s
Hot loops of active regions close part of CH regions at 193Å?

ECH borders for best threshold values

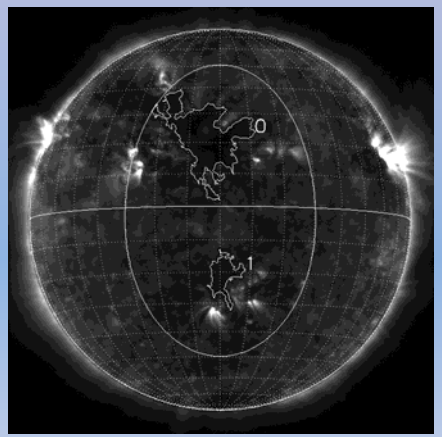


Positive polarity ECH, observed on 13.06.10 (Max SW velocity 546 km/s)

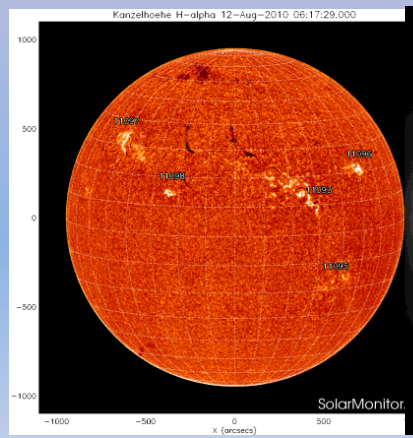
Borders of ECH calculated using best threshold values: 0.3 - 211Å, 0.25 - 193 and 0.4 - 174Å;
The largest total CH area was obtained for AIA 193Å.
The areas #0 is the largest for 193Å. New areas near equator appears at 211 (#1) and 193Å (#2).
Northern CH are almost identical for all wavelength at these thresholds.

Linear model predicts maximum SW velocity **678** and **683** km/s for AIA **193** and **211**Å,
524 km/s for SWAP **174**Å. **Observed** SW velocity - **546** km/s
The best linear fit is obtained using SWAP 174Å.

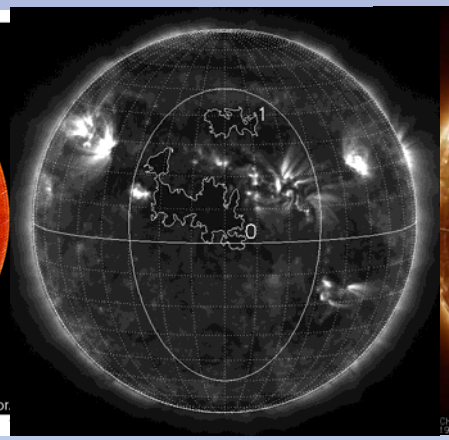
Dark areas (“canopies”) at SWAP 174Å



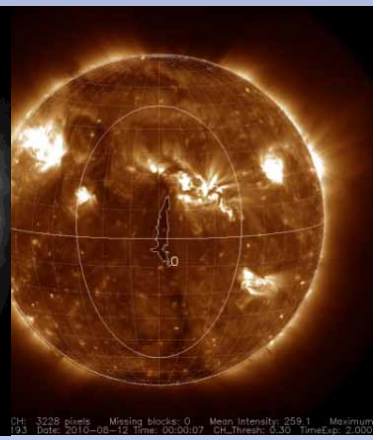
SWAP 174Å



Kanzelhoehe Hα

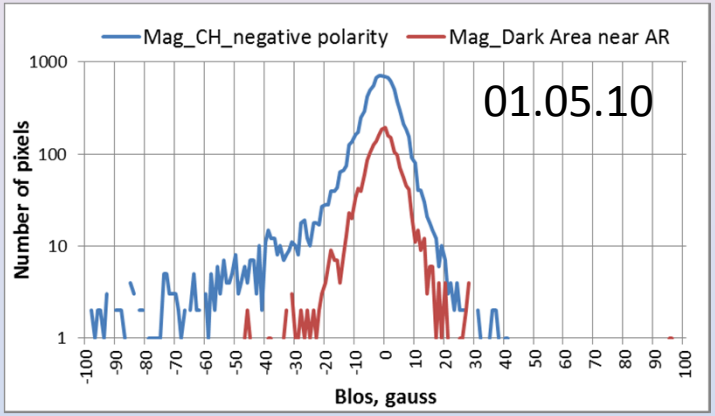


SWAP 174Å

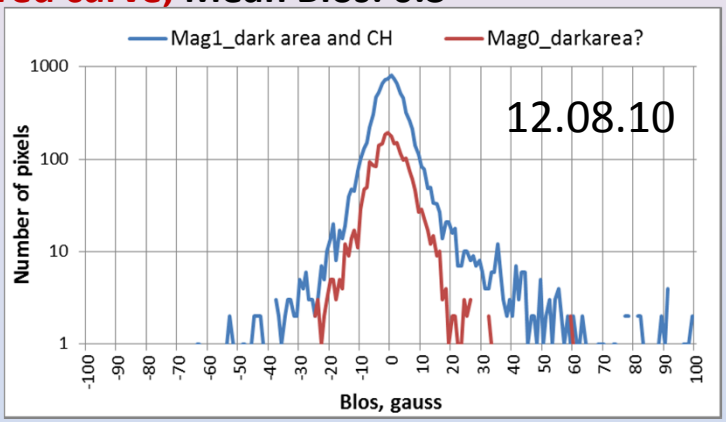


AIA 193Å

CH #0 - - blue curve; Mean Blos: **-3.3**
Dark area #1- red curve; Mean Blos: **0.7**



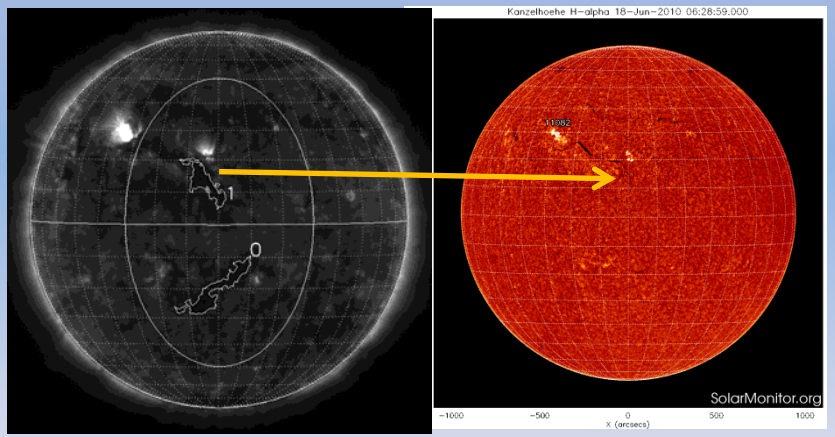
Dark area + CH #0 - blue curve; Mean Blos: 1.3
Dark area #1- red curve; Mean Blos: 0.3



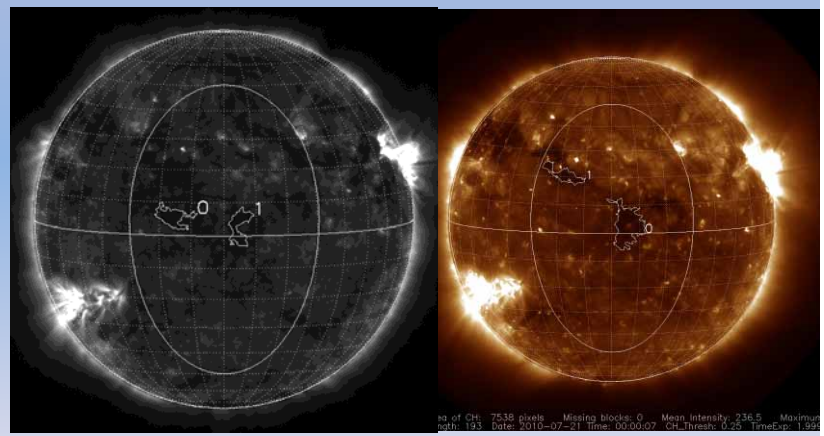
The Astrophysical Journal, 2011 Y.-M. Wang, E. Robbrecht, K. Muglach: “Active regions are surrounded by an extensive “circumfacular” area which is darker than the quiet Sun at 171Å SDO/AIA. “Dark canopies” surrounding active regions are dark fibril-like structures that appear as soon as the active regions emerge. The 17.1 nm fibrils are often rooted in mixed-polarity regions.

Filaments & small CHs at 174Å images

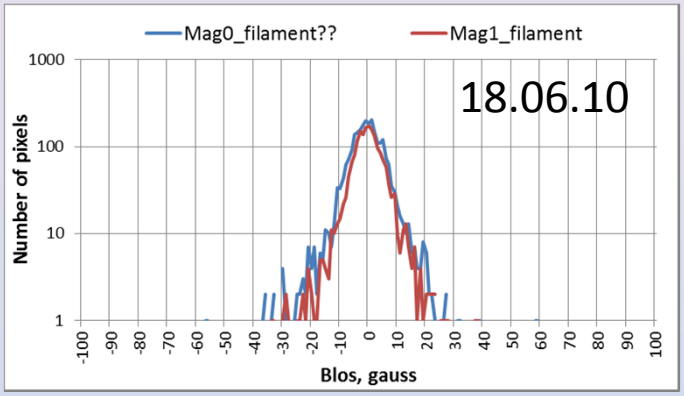
It is quite difficult to distinguish small CHs and filaments using only magnetograms



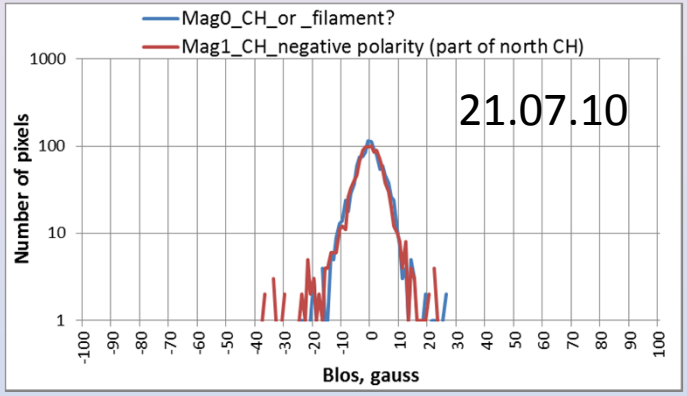
SWAP 174Å Kanzelhoehe Hα



SWAP 174Å AIA 193Å

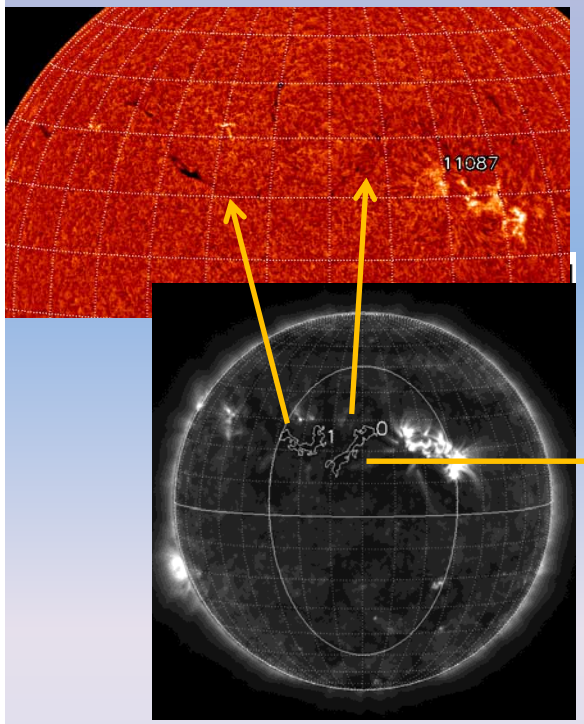


Filament #1 - **red curve;** Mean Blos: **0.0**
Filament #0**??** - **blue curve;** Mean Blos: **-0.1**
CH areas are not observed at AIA 193 and 211Å images

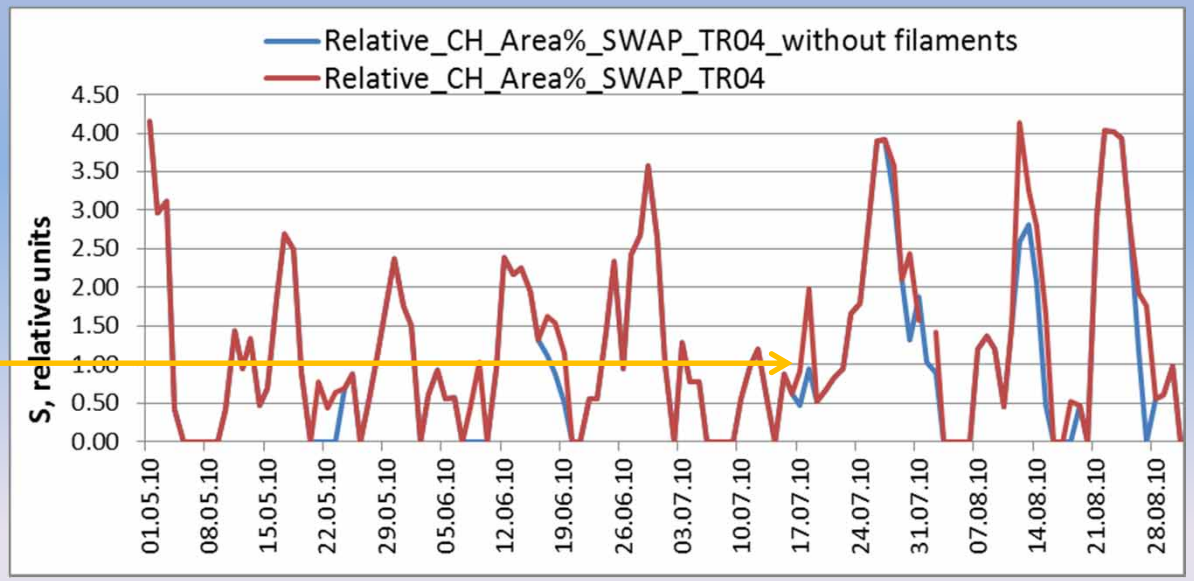


Small CH# 1 **red curve;** Mean Blos: **-0.6**
CH #2**??** - **blue curve;** Mean Blos: **0.2**
CH: area #1 at SWAP image are observed as area #0 at AIA 193Å image

Filaments & CH at SWAP 174Å images



Kanzelhoehe Hα and SWAP images with filaments 17.07.10



Red curve - CH areas were calculate at SWAP images with threshold 0.4

Blue curve - CH areas, excluding areas of filaments

Data for investigation periods from May to August 2010

"CH areas" that fully or partially coincide with filament channels observed at Hα-images were eliminated from total CH area value

Areas of filament channels compose ~25% of CH areas obtained by SWAP (± 30° latitude and ±50° longitude and threshold 0.4) from February 2010 to February 2011

Conclusions

- CH areas obtained from various wavelengths 211 and 193Å from SDO/AIA and 174 from PROBA2/SWAP as a rule have correspondence with each other
- While CH areas calculated at 174Å wavelength are generally smaller, they provide better SW velocity estimates than 193 and 211Å
- Sensitivity to the choice of threshold parameter and prediction accuracy are generally better for CH, that are the sources of SW flows with velocities above 600 km/s compared to low-velocity ones
- CH areas calculated from images obtained at 211Å are most threshold-dependent

Conclusions

- Best linear fit between CH area and SW velocity was obtained for PROBA2/ SWAP images at the highest threshold (Correlation coefficient of 0.8 and RMSE of 73 km/s)
- Regions seen on images obtained from spacecraft SWAP on the wavelength 174Å with this threshold can be either CH, filaments or “dark canopies”
- Additional data required to discriminate the type of region: magnetograms, images at wavelengths 211 and 193Å, Hα images
- However, these resources do not always help to distinguish small CHs from other objects

Conclusion

- The usage of data from various wavelengths (this is also true for magnetograms and H-alpha images) allows to interpret results of threshold-based algorithm more accurately, as well as understand how CH properties vary depending on their height (from photosphere to corona)