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Analysis of solar wind sources during the rising phase of solar cycle 24 based on the AIA/SDO EUV images

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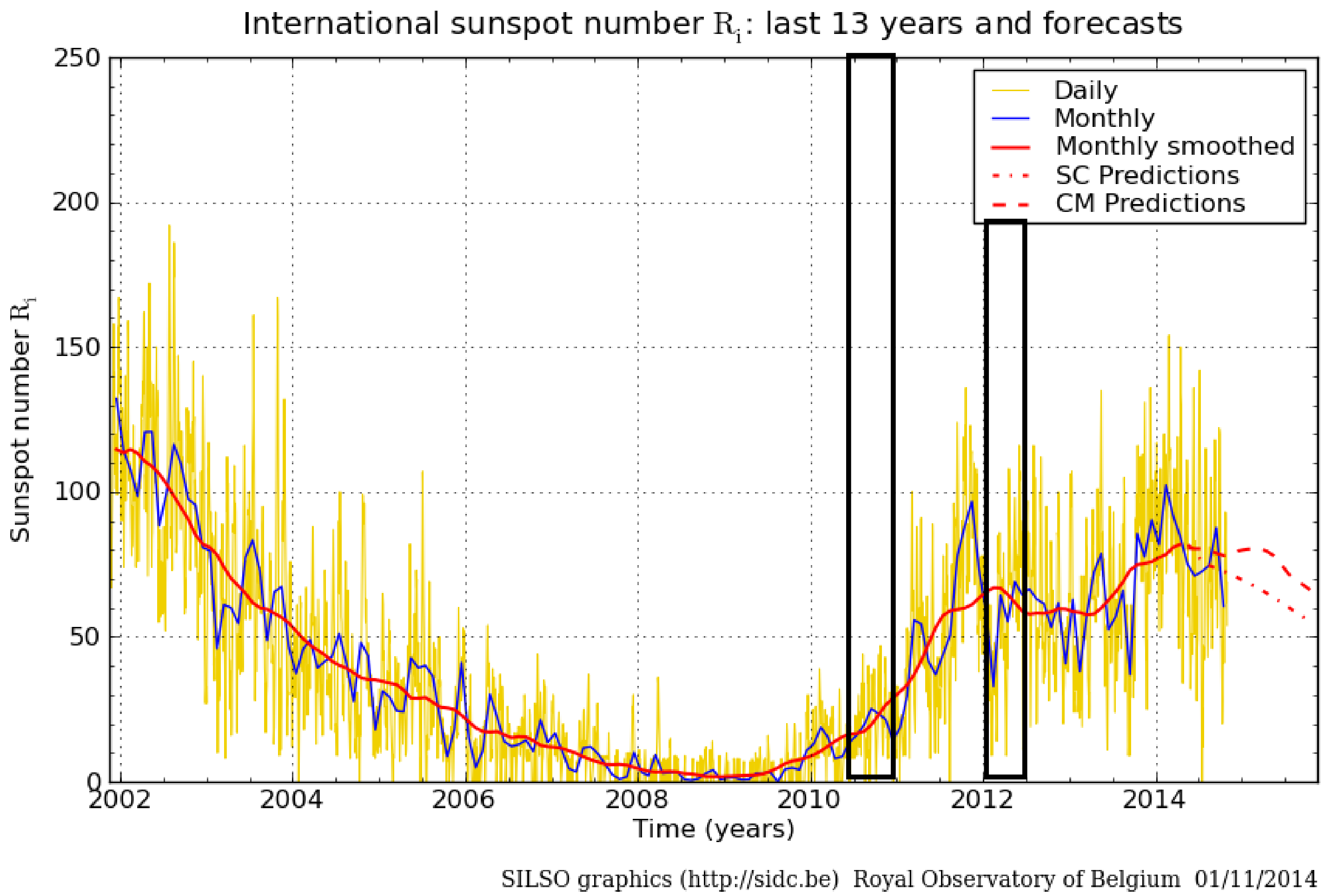
The aims of the work:

- Analysis of the SW sources during the rising phase and near maximum of the solar cycle 24
- Identification of the coronal sources prominent in this period: coronal holes (CH), small areas of open magnetic fields near active regions (AR) and some transient sources on the base of the multi-wavelength EUV solar images obtained by AIA/SDO using the HMI/SDO magnetograms
- Evaluation of the impact of different coronal sources on the solar wind (SW) speed using the empirical SW models, and comparison with measurements
- Studying the “in-situ” parameters of SW (speed, density, ion composition, etc.) associated with the different coronal sources

Investigation periods and data



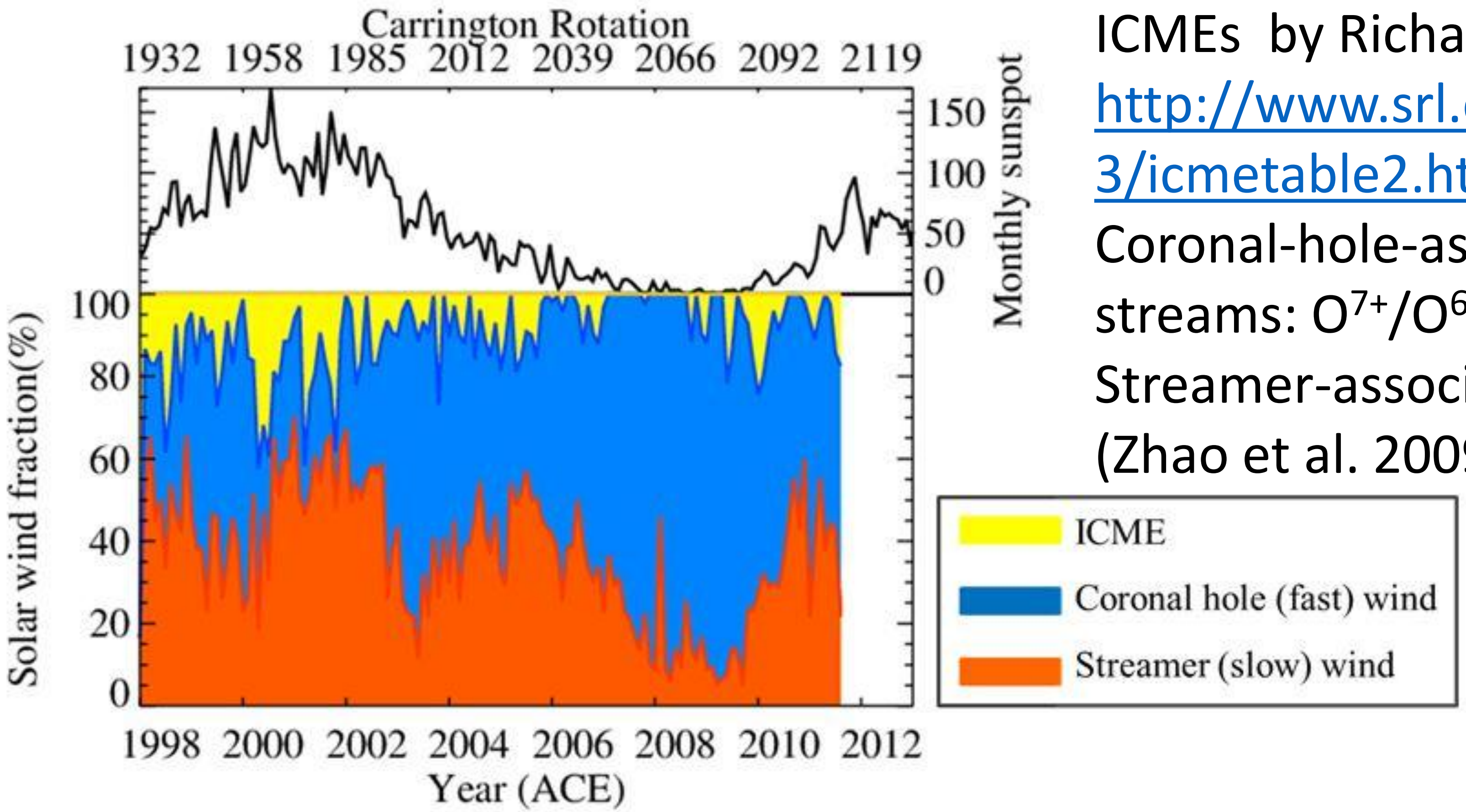
Two periods under study:

- At ascending phase of cycle 24:
  - near minimum - 2010
  - near maximum - 2012

Data sources

- Solar Images at 171 and 193Å from SDO/AIA
- Magnetograms from SDO/HMI
- Solar wind properties at near-Earth orbit from ACE: proton speed, density, kinetic temperature (SWEPAM), interplanetary magnetic field (MAG) and ion composition (SWICS/SWIMS)

Three types of solar wind during the solar cycle



ICMEs by Richardson and Cane catalog http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm).

Coronal-hole-associated fast solar wind (SW) streams: $O^{7+}/O^{6+} < 0.145$

Streamer-associated slow SW: $O^{7+}/O^{6+} > 0.145$ (Zhao et al. 2009).

L.Zhao and T. Zurbuchen ACE News #163 - August 28, 2013

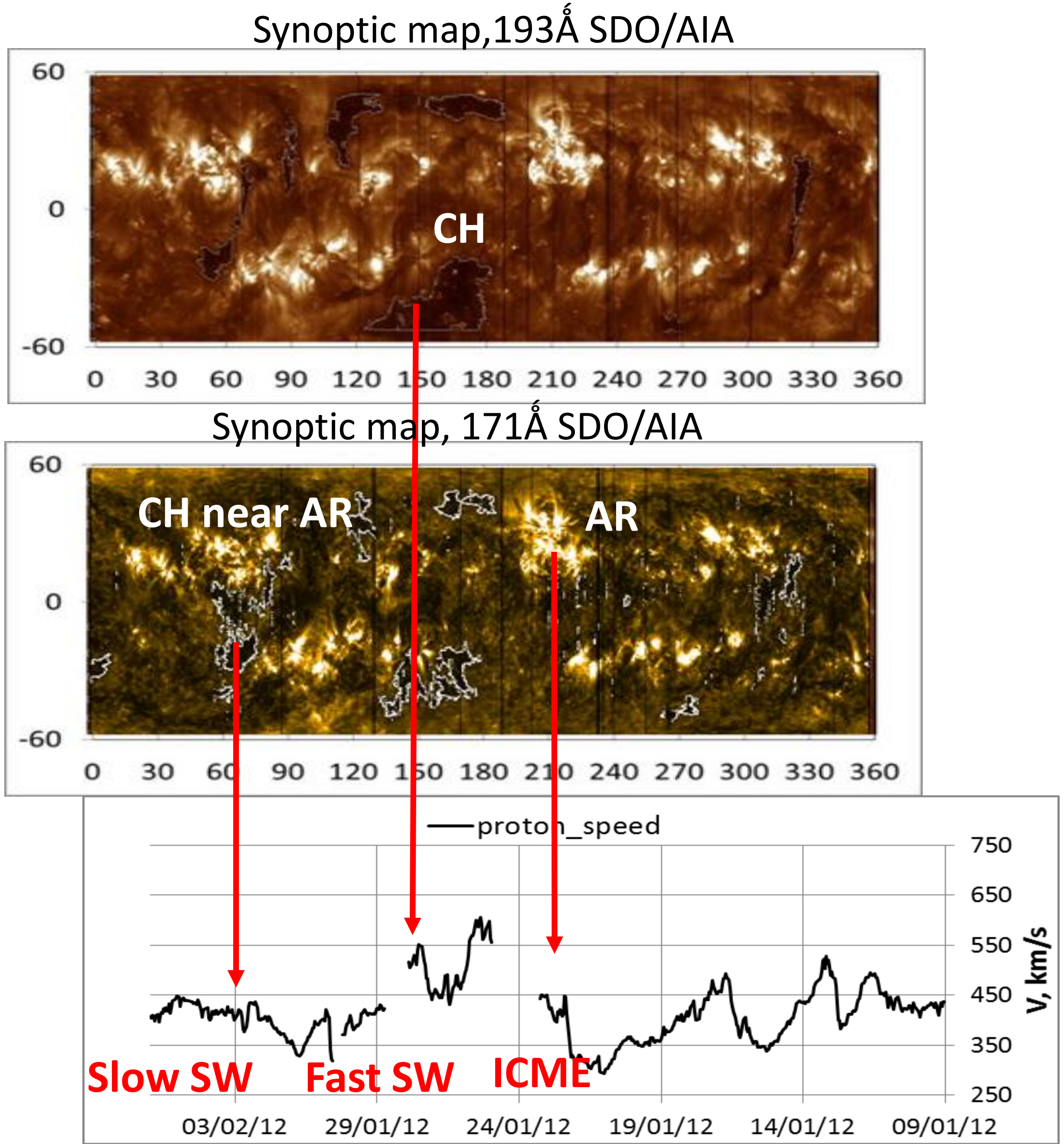
At the solar minimum phase 2008-2009:

Coronal-hole-associated fast wind - 90% of the total flux near the Earth

At ascending phase of cycle 24 (2011):

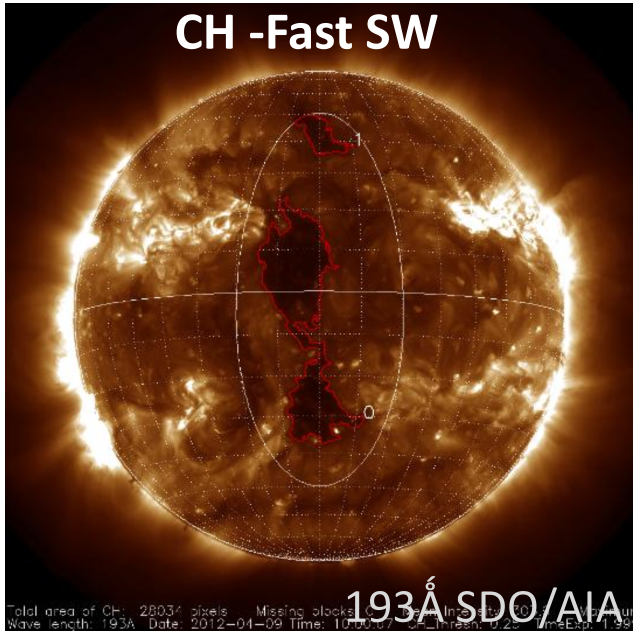
CH-associated fast wind – 50%, Streamer-associated slow wind - 40% and ICMEs - 10%.

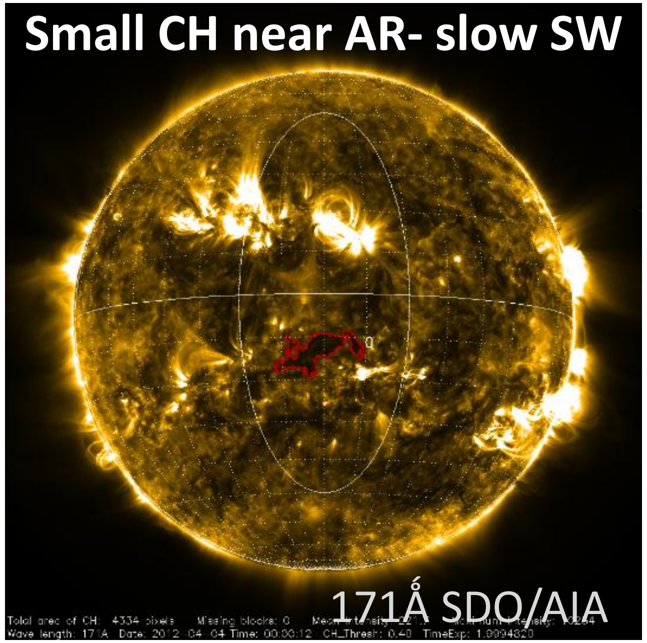
Coronal SW sources in different EUV lines

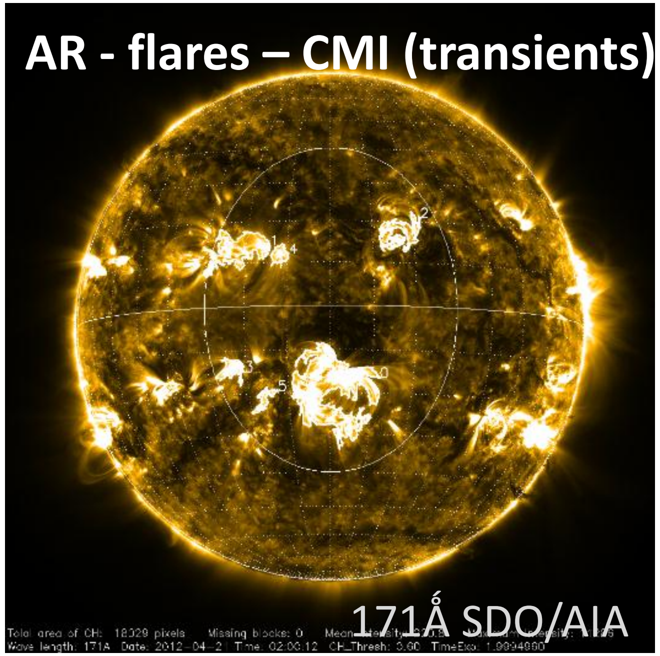


- **CHs (HSW) have the highest contrast** at the disk in 193, 195 Å or 211, 284 Å (T=1.5-2MK)
- **Small CHs near AR (SSW)** - in 171-174 Å (T=0.8 - 1MK), for example 171 SDO/AIA (Liewer et al. 2004; Harra et al. 2008; Del Zanna 2008; Wang 2009; Slemzin et al. 2013)
- The structures outside the large CHs have higher contrast in 171/174 Å than in 193 Å (Kojima et al. 1999).
- **Source of ICMEs** - flares and filament eruptions. Flares and AR are seen in both lines.
- **Example** – Jan. 2012, near solar maximum. SW sources in different EUV lines and SW streams from different Coronal sources

Automatic processing of solar images



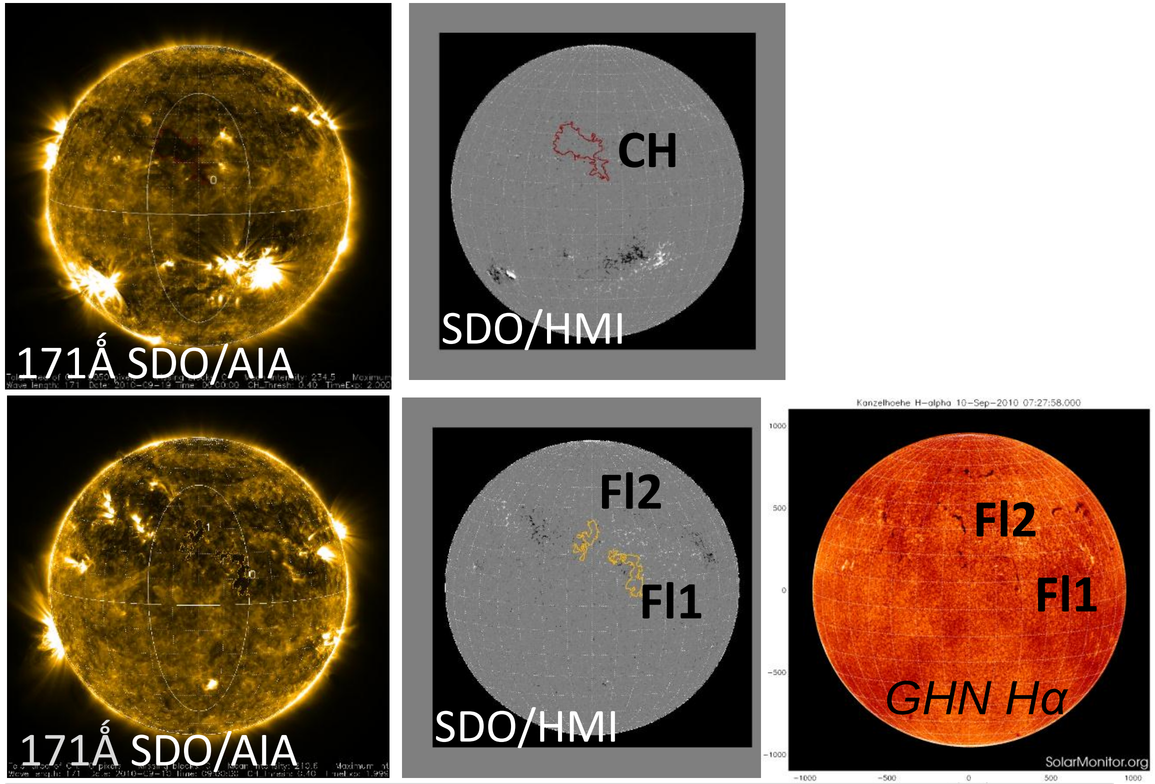


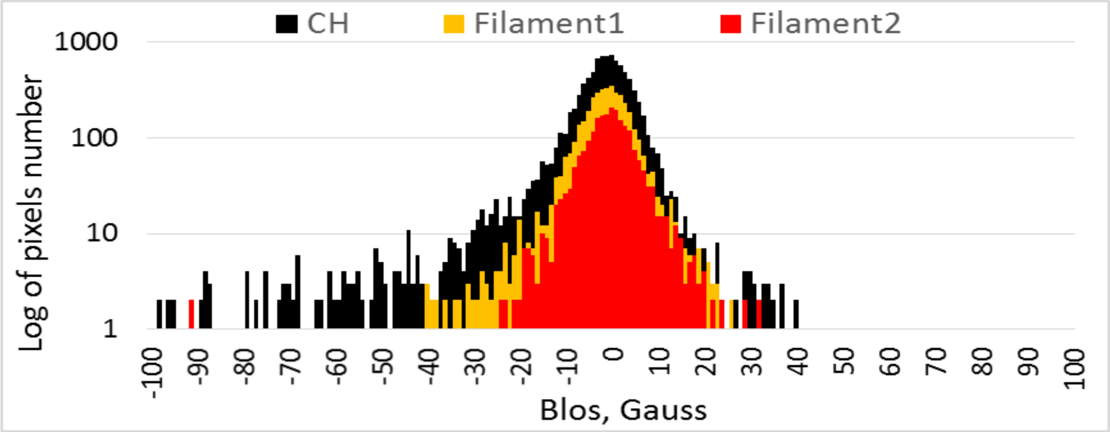


CH and small CH – intensity lower than threshold and AR - intensity higher than threshold

- Threshold intensity was calculated as **Imean****k***, where **Imean** is mean intensity of image without limb brightness, ***k*** is the threshold coefficient:
  - **0.4** for coronal sources areas at 171Å;
  - **0.6** - AR areas at 171Å
  - **0.25** - CH areas at 193Å
- between ±20° longitude and between ±50° latitude for CH (30° X 40° for AR)
- Relative units: % from solar disk

Identification and removing of filaments at 171-174 Å





Distribution of magnetic-field intensities

Intensity of 171 and 174 Å emission lines is also low near filaments (e.g., Munro and Withbroe, 1972)

- **CHs** - a skewed distribution of magnetic-field intensities (100 – 200 gauss), a relative magnetic-flux imbalance (Scholl&Habbal, 2009)
- **Filaments** - a symmetric distribution of field intensity values around zero, smaller magnetic-field intensity (Scholl&Habbal, 2009)
- The CH boundaries at 171 Å were mapped on magnetograms HMI/SDO, statistics calculated

Filaments have **imbalance value**:

$$\frac{\langle B_{los}\rangle}{\langle B_{los}\rangle^{+}+\left|\langle B_{los}\rangle^{-}\right|} \in [-0.08, 0.08]$$

Mean value:

$$\langle B_{los}\rangle \in [-0.8, 0.8]$$

Hierarchical approach to modeling SW on the basis of observations in XUV or EUV

On the **first hierarchical level**, several simple models were used for estimating the SW velocity using parameters of coronal SW sources in different spectral bands. As is known, Good estimates of high SW speed could be obtained from the position and size of CHs in the EUV images (Vrsnak et al. 2007; Krista & Gallagher 2009; Obridko et al. 2009).

The **second level prediction** is obtained by combining the results of various first level models.

As is known, the squared mean error of the committee of ***L*** experts does not exceed the mean value of the individual squared errors (Hansen&Nelson 2002; Terekhov 2008):

$$E_L^2 = \left[\frac{1}{L}\sum_{i=1}^{L}\varepsilon_i\right]^2 \le \frac{1}{L}\sum_{i=1}^{L}\varepsilon_i^2$$

and, if the errors of the experts are not correlated, the resulting performance can be improved

$$E_L = \frac{1}{\sqrt{L}}\langle E_1\rangle$$, where $\langle E_1 \rangle$ is the mean error of one expert<E$_1$>

The aim of the this approach is manage strength and weakness of every model and lead to the best possible result

Modeling of SW speed at near-Earth orbit

Quasi-stationary SW speed values were estimated using CH areas at 171 and 193Å with linear model and the ballistic method at **first level** of hierarchical algorithm (Shugay et al. 2011)

$$V(S_i,t) = V_{\min} + A_i * S_i(t_{i0})$$

S_i (t_{i0}) - relative area of CHs at the time ***t_{i0}*** in the spectral range λ_i ;

V_{min} - the background SW speed (270-300 km/s for the analyzed period);

A_i is a fitting parameter for a given wavelength λ_i estimated from the training dataset using the least squares method.

The time ***t*** of arrival of SW flow to the Earth's orbit was determined by the ballistic method based on the calculated SW velocity value.

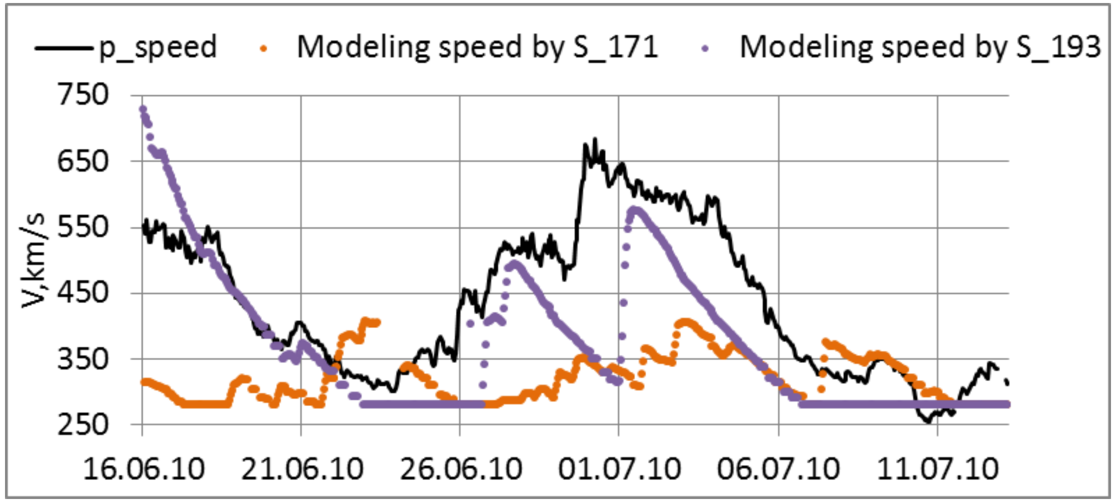
For transient component of SW associated with active phenomena we assume that the arrival time of transient flows depends on the area of AR:

$$t = \frac{L_{SE}}{B_i \cdot S_i(t_{i0})}$$

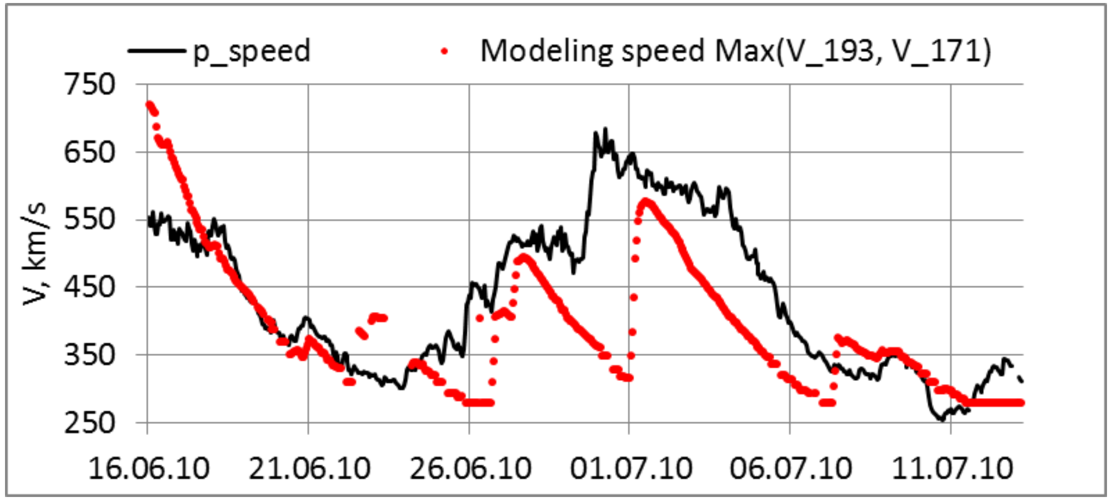
, ***B_i*** is a fitting parameter for wavelength λ_i =171Å; ***L_{SE}*** – Sun-Earth distance

Modeling of Quasi-stationary SW speed from CHs

First level of modeling (CH areas in different lines)



Second level of modelling (combination of 1st level results)



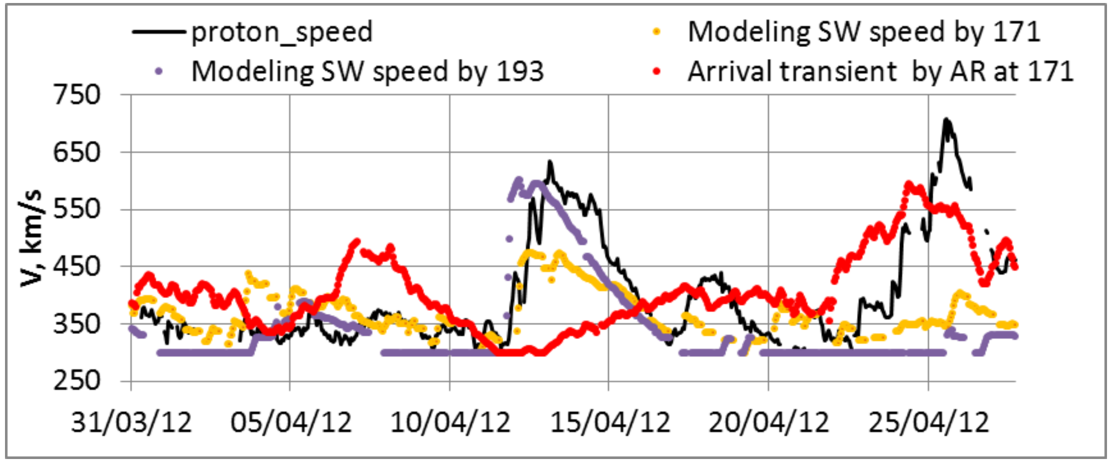
Example– June-July 2010

- **For period May-December 2010**
- **First level** models of SW speed:
  - by CH areas 193Å - $V(S_{193})$:
    - Correlation coefficient (CC) - 0.56; Standard deviation (SD) - 100 km/s, relative error (RE) – 19%
  - by CH areas 171Å - $V(S_{171})$:
    - CC - 0.1; SD - 86 km/s; RE– 23%
- **Second level** model rule:
  - $Max(V(S_{193}),V(S_{171}))$
    - CC - 0.50; SD - 91 km/s, RE – 16%

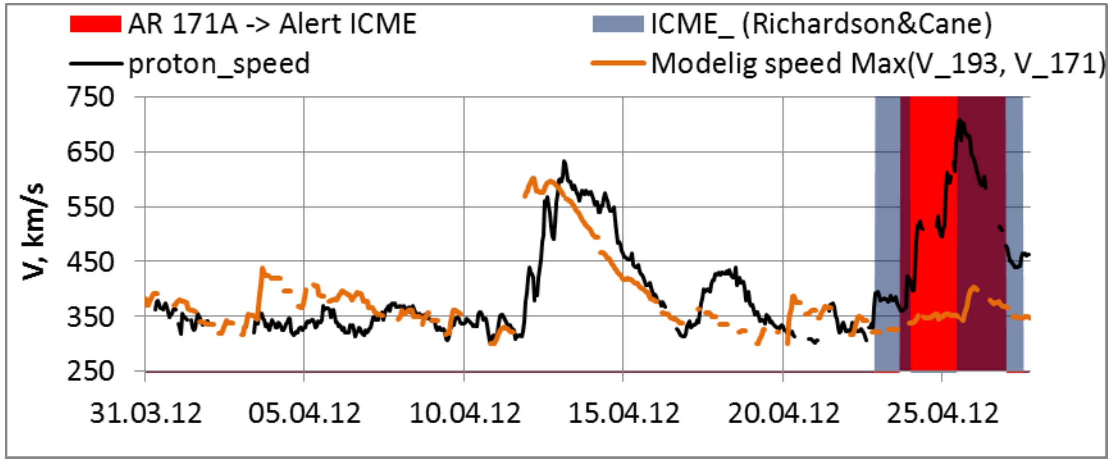
Accuracy at 2d level is better than each of 1st level results

Modeling of Quasi-stationary SW and ICME alerts

First level of modeling (CH areas in different lines)



Second level of modelling (combination of 1st level results and ICME Alert)



Example– April 2012

- **For period January-August 2012**

First level models of SW speed:

- by CH areas 193Ǻ - V(S193) :
  - CC - 0.54; SD - 91 km/s, RE – 17%
- by CH areas 171Ǻ - V(S171):
  - CC - 0.25; SD - 73 km/s, RE – 15%
- by AR areas at 171Ǻ - arrival transient flows

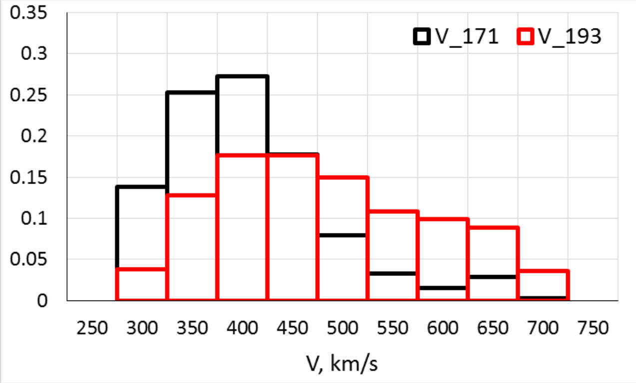
Second level model rules:

- Max(V(S193),V(S171))
  - CC - 0.53; SD - 82 km/s, RE –14%
- add ICME alert IF AR areas are more than threshold value (2% from solar disk)

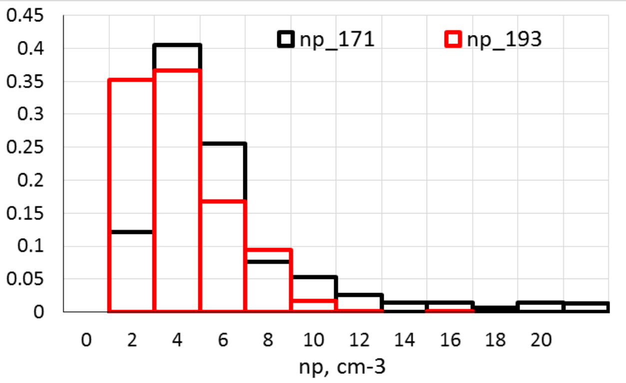
Currently the model predicts~30% ICMEs from Cane&Richardson catalog for Jan.-Aug. 2012 (statistics should be improved)

Parameters of SW in dependence on the SW source type identified by 171 and 193Å (2010, 2012)

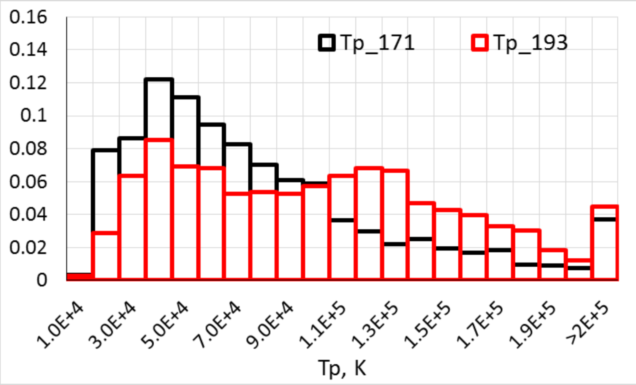
1. Kinetic parameters



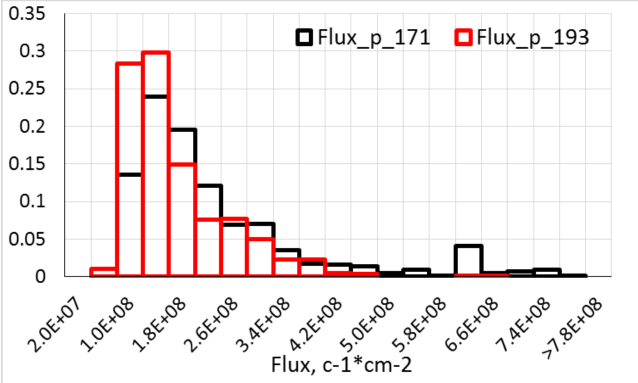
May-Dec 2010: proton speed



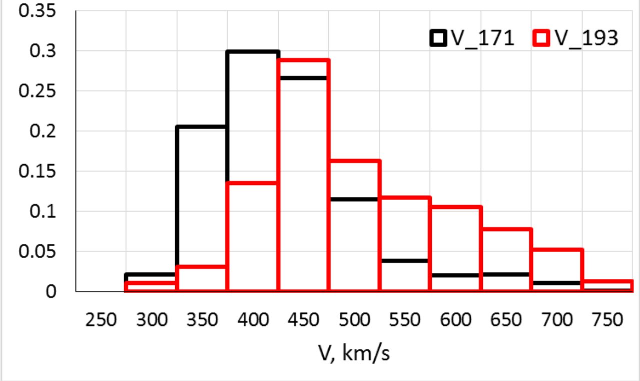
proton density



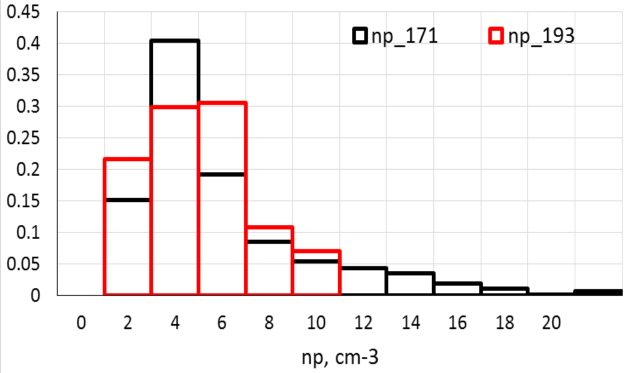
proton kinetic temperature



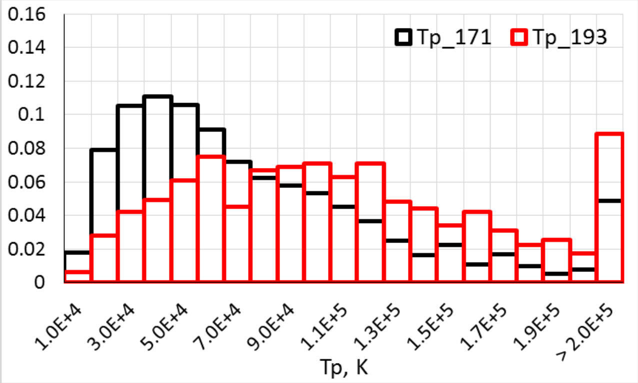
proton flux



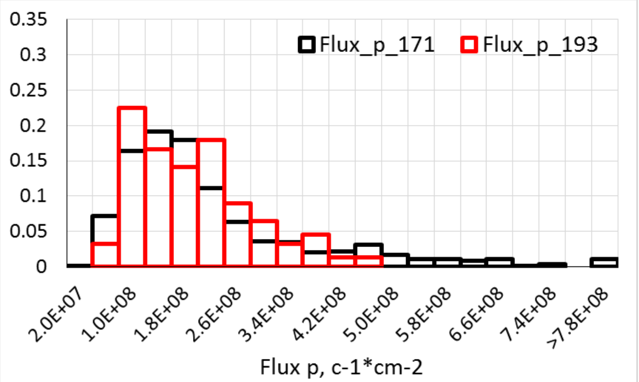
Jan-Aug 2012: proton speed



proton density



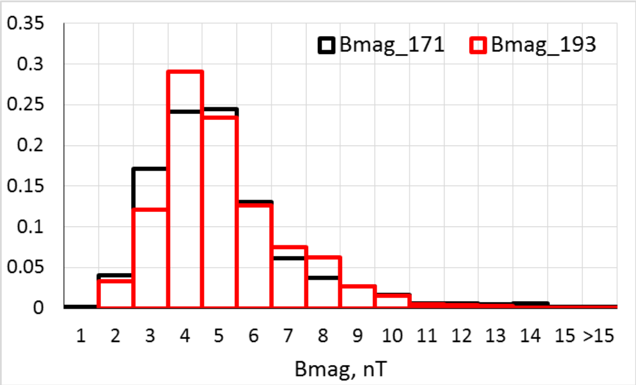
proton kinetic temperature

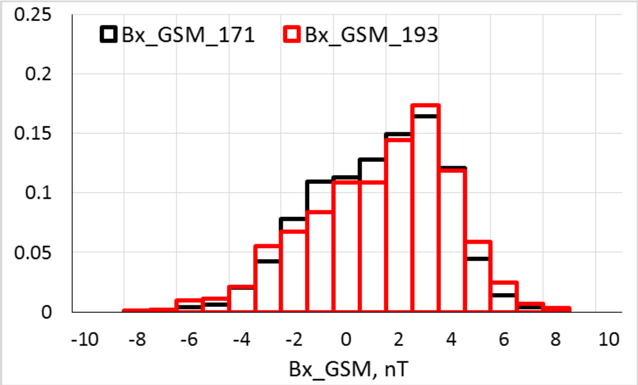


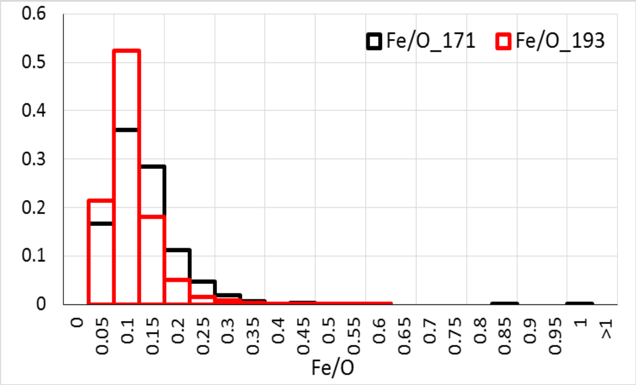
proton flux

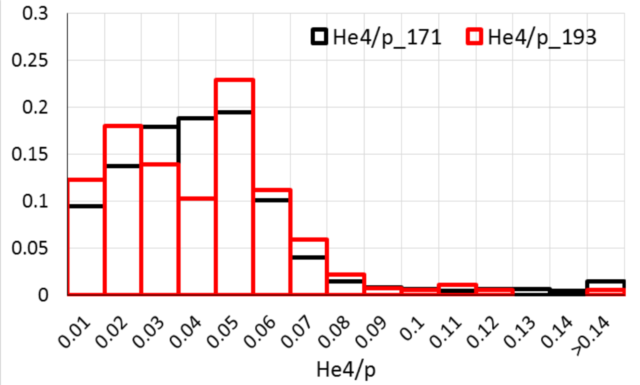
Red bars - normalized distribution of "in-situ" SW parameters associated with the SW sources identified from 193Å; **Black bars** - 171Å. Difference in distributions associated with the coronal sources identified from 171Å relative to 193Å observed in SW speed and temperature

2. Magnetic field and ionic composition

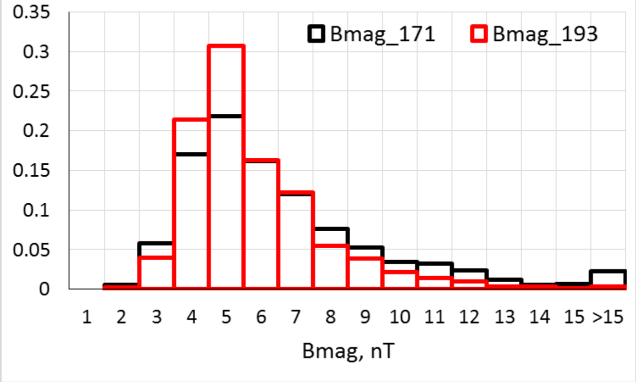


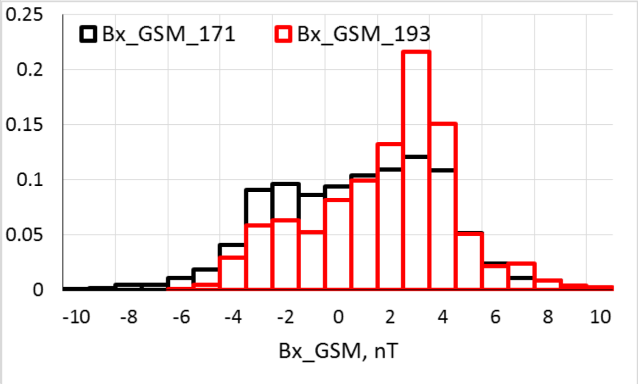


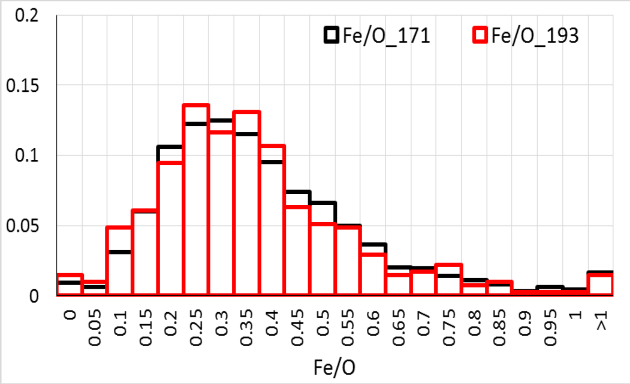


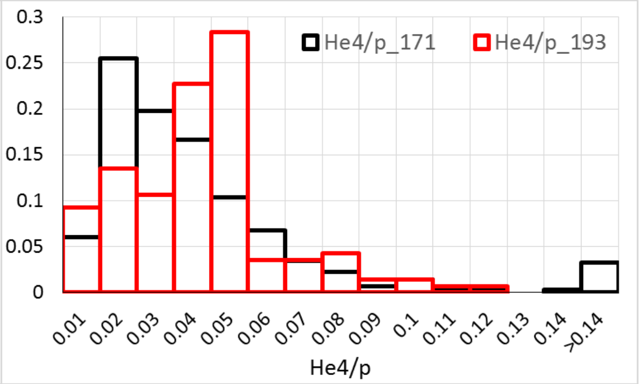


2010: module of IMF — Bx-component of IMF — Fe/O — He4/p









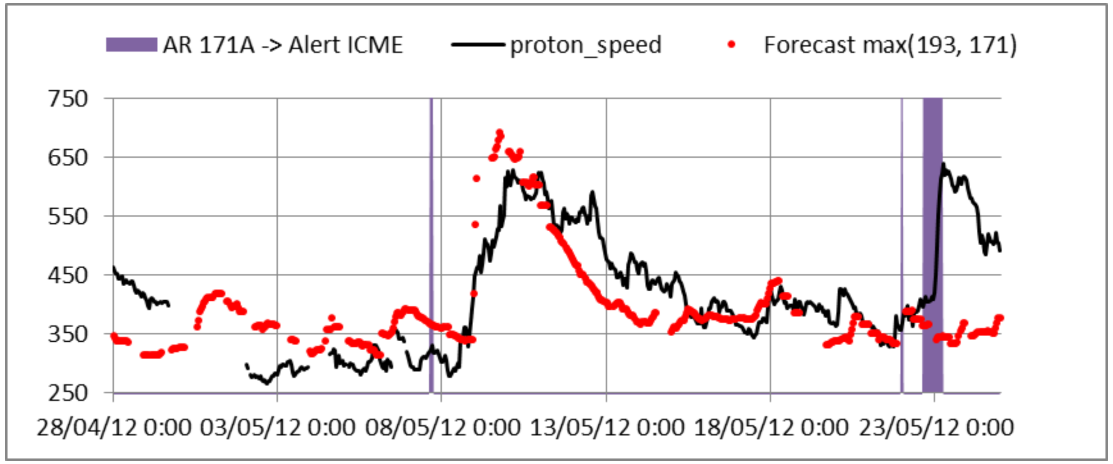
2012: module of IMF — Bx-component of IMF — Fe/O — He4/p

- Difference in distributions for 2010 and 2012 reflects evolution of the SW source identified from 171 and 193Å with growing solar activity
- Significant difference in distributions associated with the coronal sources identified from 171Å relative to 193Å observed in SW speed, kinetic temperature for 2010-2012 and Bx-components of IMF and He/p in 2012

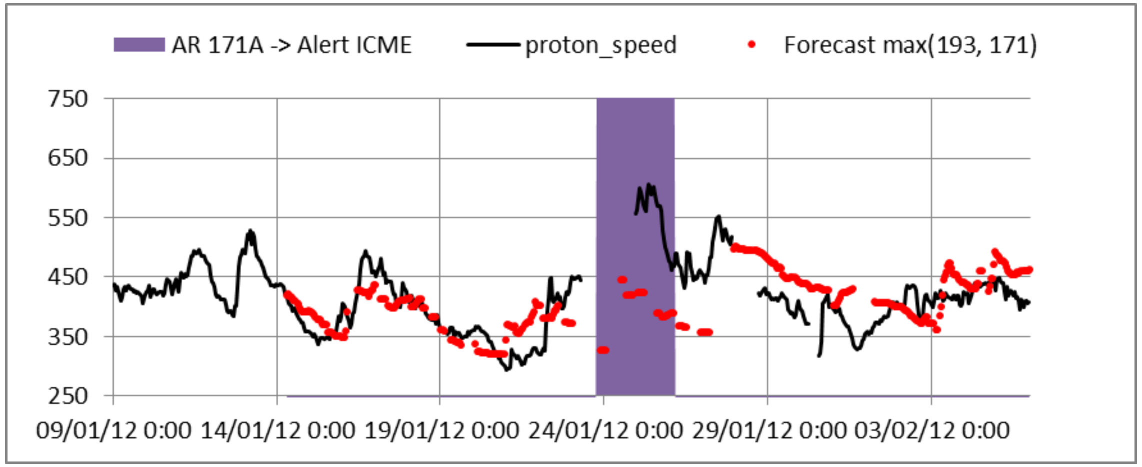
Conclusion

- Coronal sources of solar wind at rising solar activity in 2010 and 2012 were investigated using the SDO/AIA images in 193 and 171 Å bands.
- Non streamer-stalk sources (large CHs) of dominating high-speed SW are better identified in 193 Å , whereas the sources of dominating slow SW (small CHs, ARs) are better disclosed in 171 Å. The source regions for both wavelengths partly overlap.
- In 2012 in comparison with 2010 the relative contribution of the sources identified in 171Å increased almost twice
- Difference in distributions of SW parameters for 2010 and 2012 reflects evolution of the coronal SW source identified from 171 and 193Å with growing solar activity
- Modeling of the SW speed can be improved by combination of empirical relationships for both bands in the framework of the hierarchical approach
- Identification of CME-productive ARs from areas of enhanced brightness in 171 Å allows predicting of ICMEs with probability >30%

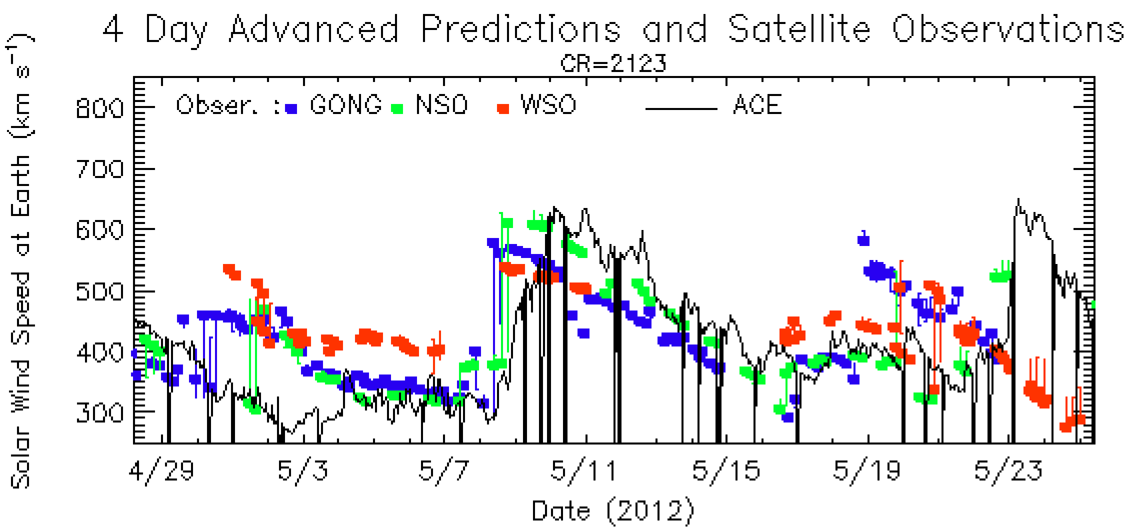
Hierarchical SW model in comparison with the models based on magnetic field extrapolations



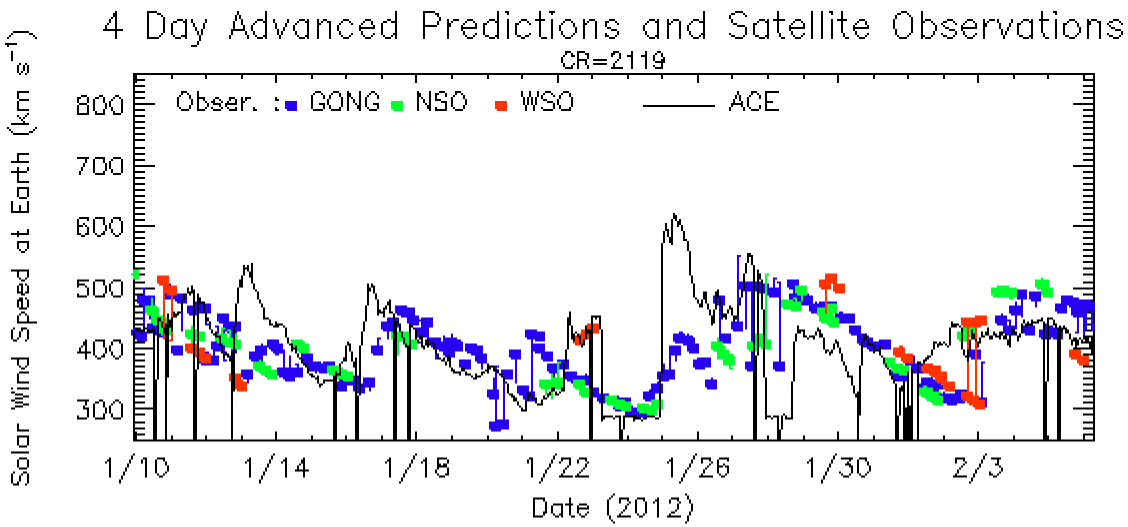
Hierarchical SW model



Hierarchical SW model



WSA model



WSA model