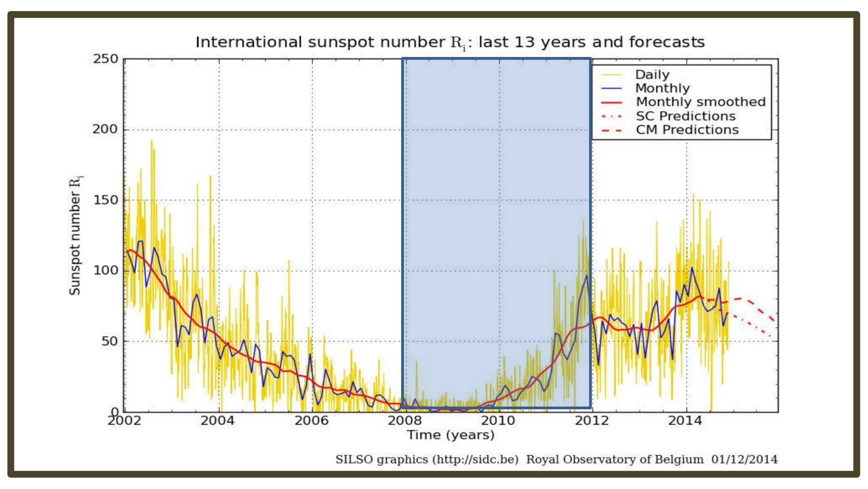
Structure and sources of solar wind in the growing phase of 24th solar cycle

V. Slemzin[1], F. Goryaev[1], Yu. Shugay[2], D. Rodkin[2], I. Veselovsky[2]
[1] P.N. Lebedev Physical Institute, Moscow, Russia
[2] Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

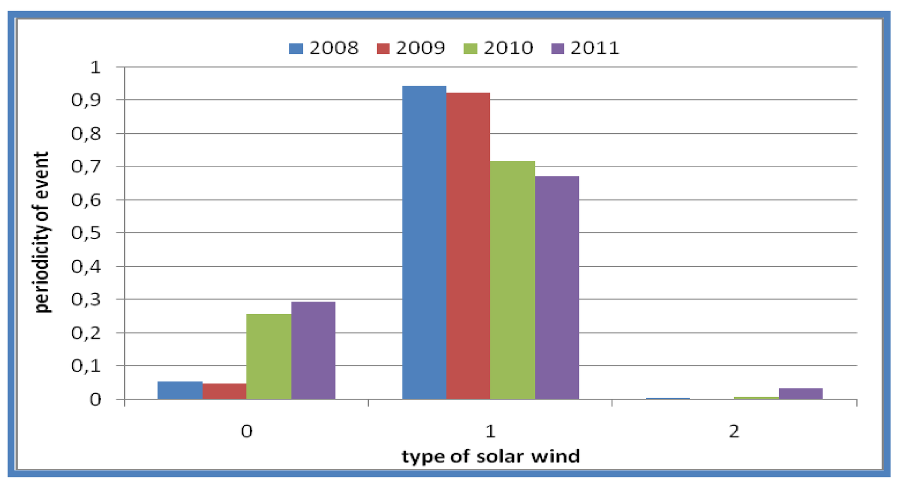
Abstract

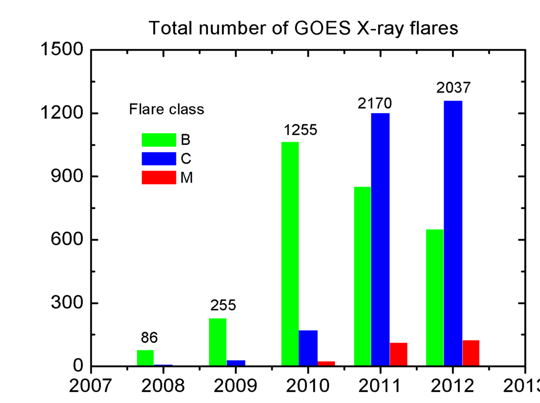
We present analysis of the solar wind (SW) structure and its association with coronal sources during the minimum and rising phase of 24th solar cycle (2008-2012). The coronal sources prominent in this period - coronal holes, small areas of open magnetic fields near active regions and transient sources associated with small-scale solar activity have been investigated using EUV solar images and soft X-ray fluxes obtained by the CORONAS-Photon/TESIS/Sphinx, PROBA2/SWAP, Hinode/EIS and AIA/SDO instruments as well as the magnetograms obtained by HMI/SDO. It was found that at solar minimum (2009) velocity and magnetic field strength of high speed wind (HSW) and transient SW from small-scale flares did not differ significantly from those of the background slow speed wind (SSW). The major difference between parameters of different SW components was seen in the ion composition represented by the C^6/C^5, O^7/O^6, Fe/O ratios and the mean charge of Fe ions. With growing solar activity, the speed of HSW increased due to transformation of its sources – small-size low-latitude coronal holes into equatorial extensions of large polar holes. At that period, the ion composition of transient SW changed from low-temperature to high-temperature values, which was caused by variation of the source conditions and change of the recombination/ionization rates during passage of the plasma flow through the low corona. However, we conclude that criteria of separation of the SW components based on the ion ratios established earlier by Zhao&Fisk (2011) for higher solar activity are not applicable to the extremely weak beginning of 24th cycle.

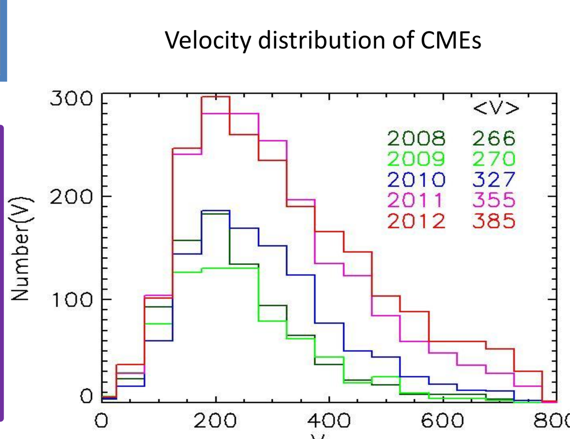
Sunspot numbers



Solar wind composition







Separation of solar wind flows into three types: slow flows, high-speed recurrent flows, sporadic flows in relation with the O^{7+}/O^{6+} ratio :

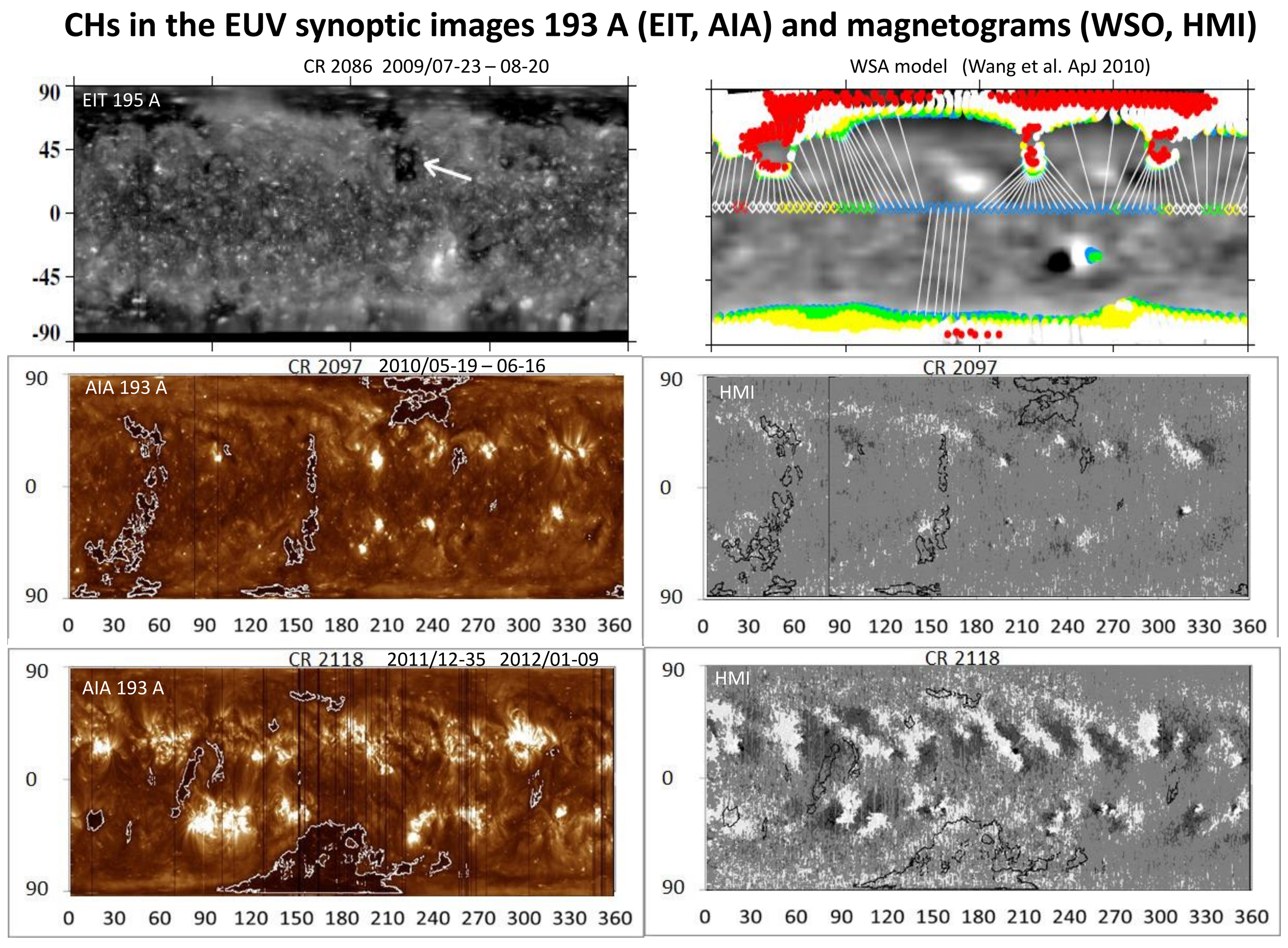
0 *slow flows (streamers)* $0.145 < O^{7+}/O^{6+} < 6.008\exp(-0.00578 V_{sw})$
1 Non-streamer-stalk wind (CHs) $O^{7+}/O^{6+} \leq 0.145$
2 Sporadic flows (ICMEs) $O^{7+}/O^{6+} \geq 6.008\exp(-0.00578 V_{sw})$

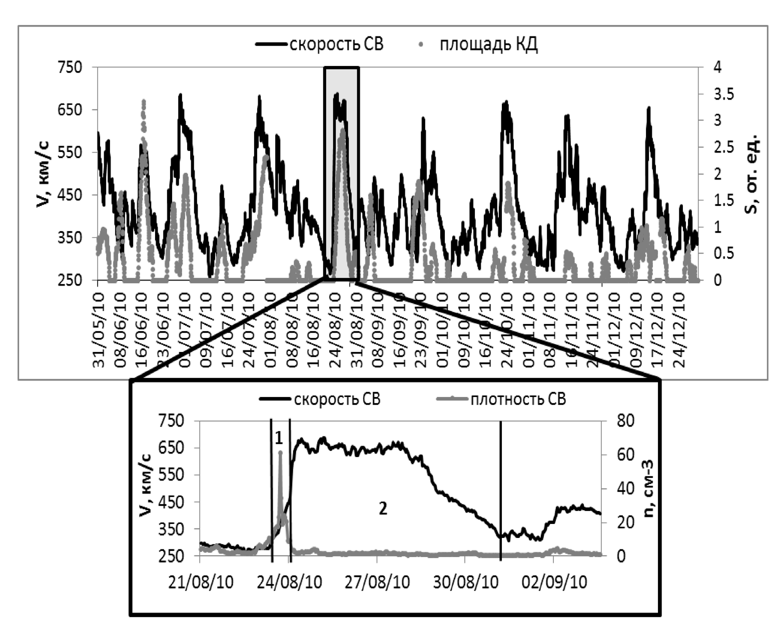
Richardson&Cane (2004), Zhao, Zurbuchen and Fisk (2011)

Types of SW and their sources	Parameters of SW flows
High-speed recurrent SW (coronal holes)	• high speed (V мах > 500 km/sec) • low proton density (< 5 sm^{-3}) • high correlation between temperature and proton speed • IMF: |B| = 1-5 nT • polarity of the IMF radial component the corresponds to the polarity of CH
Slow SW (coronal streamers)	• low speed (< 450 km/sec) • plasma parameters and IMF vary widely (depending on the location of the source) • high density (~10 sm^{-3}) • Strong IMF
Sporadic SW (CMEs)	• speed varies in wide range • strong magnetic field (IMF > 10nT) • low plasma beta (< 0.1) • low proton temperature (T/Texp < 0.5)

Types of coronal SW sources and their evolution in the ascending phase of cycle 24

CHs in the EUV synoptic images 193 A (EIT, AIA) and magnetograms (WSO, HMI)

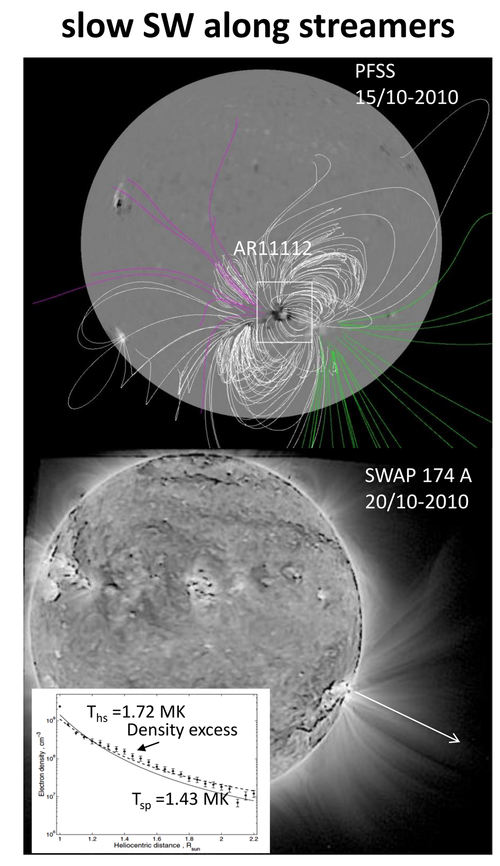




In solar minimum(2009): only polar CHs and small mid-latitude CHs and single Ars presented.
Small-scale solar activity (flares+CMEs) produced transient SW flows with velocity similar to background SW, decreased Tp and enhanced ionic O^7/O^6 and C^6/C^5 ratios.

At growing solar activity (2010-2012): large-scale equatorial CHs and extensions of polar CHs preceding magnetic field polarity reversal dominated. Numerous ARs, some producing SW outflows at the base of streamers, contributed to slow SW.

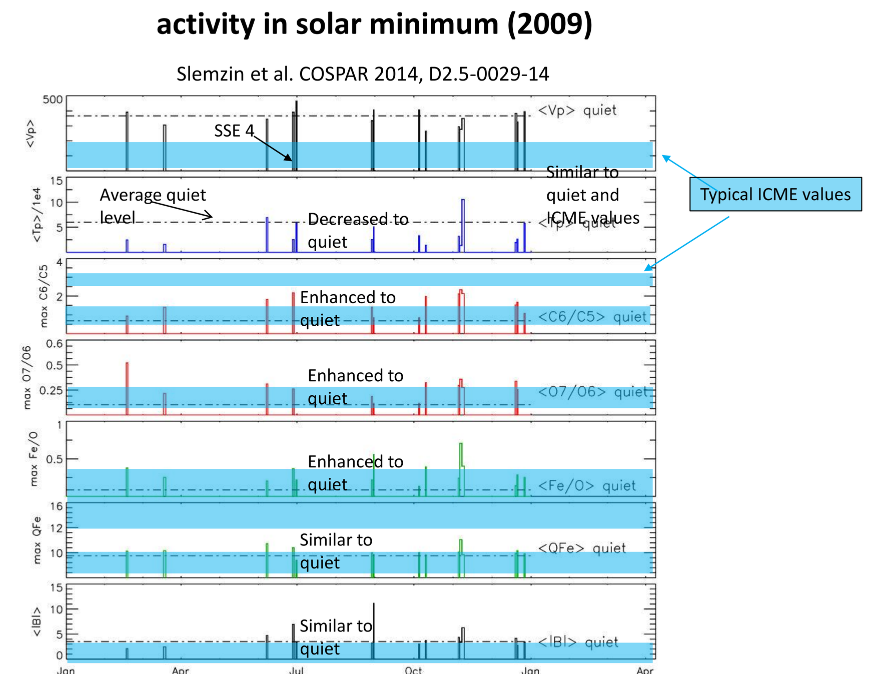
Outflows from Ars produce slow SW along streamers



F. Goryaev, V. Slemzin. ApJ 2014
V.Slemzin, Yu. Shugai. *Cosmic Research, 2015*

SW transients associated with small-scale solar activity in solar minimum (2009)

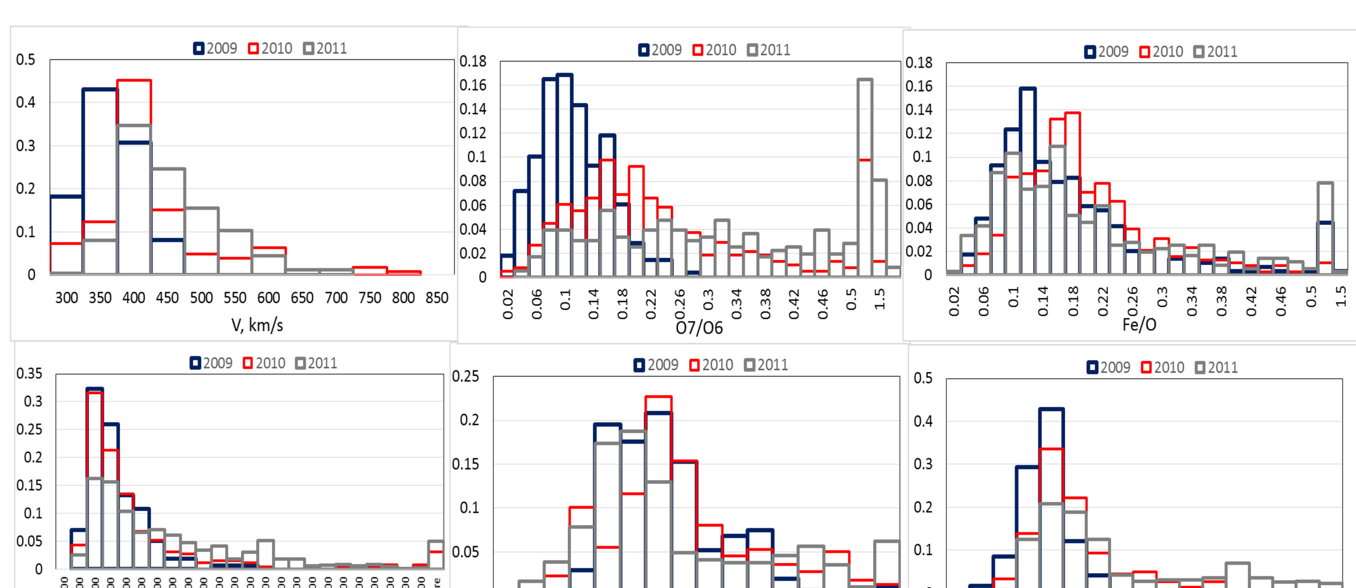
Slemzin et al. COSPAR 2014, D2.5-0029-14



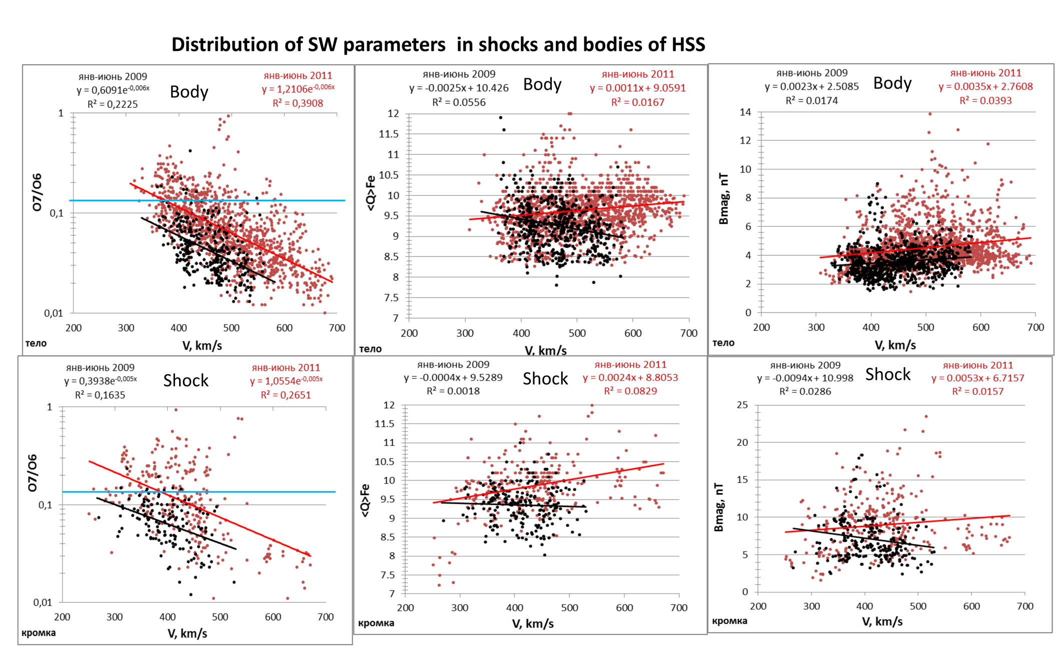
SW parameters	ICME trans., min-max	Quiet periods, mean	Typical ICME
Vp, km/s	264 - 360	367	360-490 [1]
Tp, 10^4K	1.3 – 6.9	6.1	2.85 -4.87 [4]
C6/C5	0.847-2.34	0.691	3 – 12 [2,3]
O7/O6	0.092 – 0.416	0.083	0.59 – 1.19 [2]
Fe/O	0.134 – 0.706	0.086	>0.235 [1]
QFe	8.5 – 12.6	9.4	>12 [2]
Bm, nT	2.1 – 11.1	3.5	8.8 – 12.9 [1]

[1]Cane&Richardson JGR 2003
[2]Gopalswamy et al. Sol.Ph. 2013
[3]von Steiger Springer book, 2008
[4] Richardson&Cane Sol.Ph. 2010

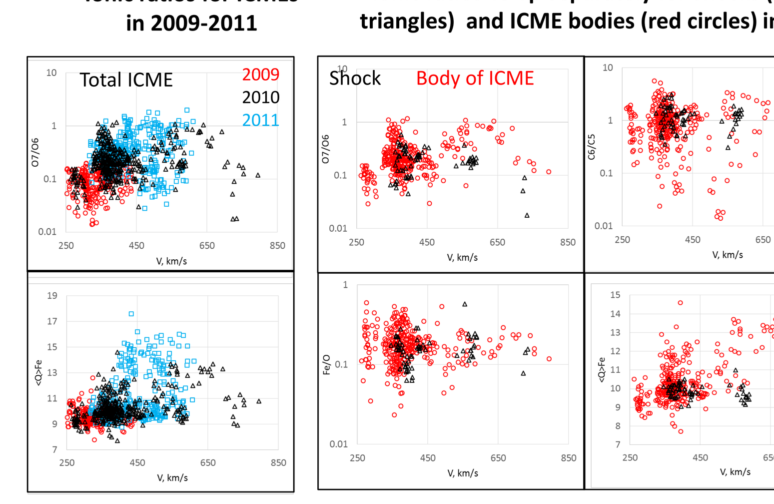
Distributions of the SW parameters in 2009 - 2011



Distribution of SW parameters in shocks and bodies of HSS



Ionic ratios for ICMEs in 2009-2011 / Ionic ratios vs Vp separately for shocks (black triangles) and ICME bodies (red circles) in 2010



Mean values for ICME parameters (from the list of Richardson&Cane 2010)

Date	Np	Tp	He4/p	Vp	Bmag	C6to5	O7to6	avqFe	FetoO
2009	11.0	2.86E+04	0.009	337	6.8	0.86	0.10	9.63	0.17
2010	5.8	4.90E+04	0.031	407	7.5	1.10	0.26	10.27	0.19
2011	6.3	7.73E+04	0.034	428	7.8	1.65	0.42	11.21	0.21

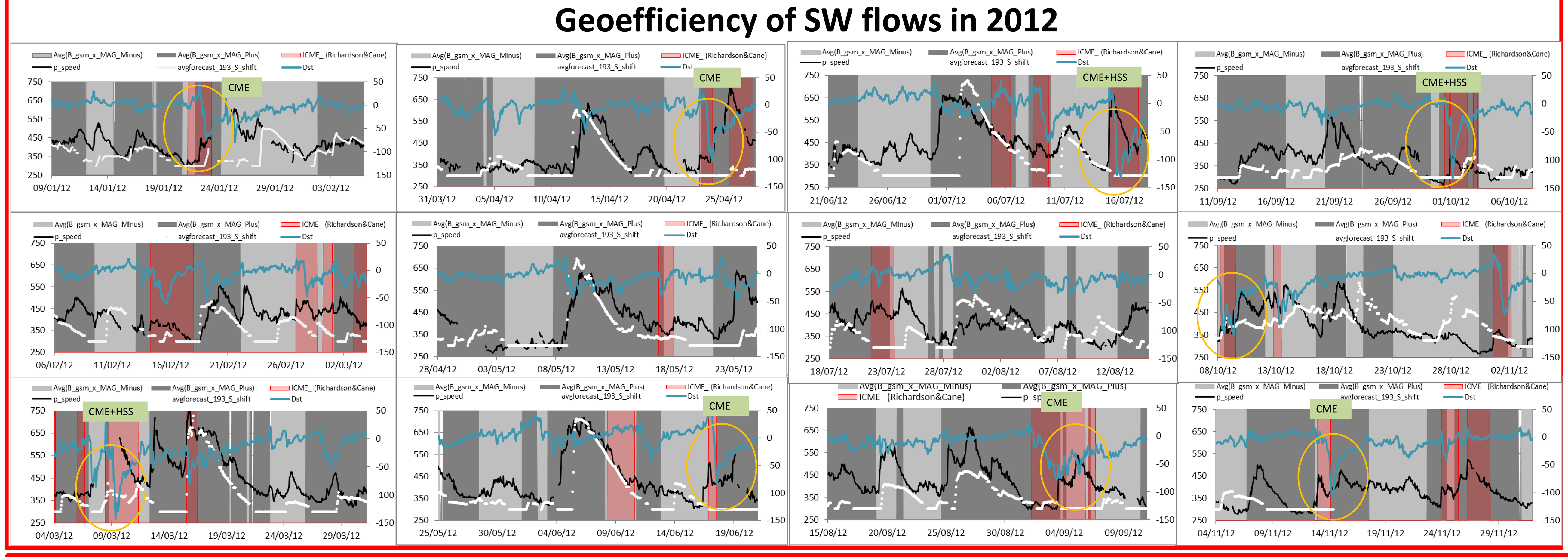
Mean values for parameters of slow solar wind (V<450 km/s)

Date	Np	Tp	He4/p	Vp	Bmag	C6to5	O7to6	avqFe	FetoO
2009	3.1	2.79E+04	0.014	49	1.8	0.46	0.08	0.06	0.01
2010	3.3	3.32E+04	0.021	46	1.9	0.61	0.08	0.13	0.01
2011	3.9	3.54E+04	0.018	45	2.1	0.67	0.09	0.13	0.01

- At the minimum of cycle 24 (2008-2009) flows from low-latitude coronal holes (CH) dominated
- At the ascending phase of cycle 24 (2010 – 2011) contribution of slow SW and sporadic flows increased as it follows from the ionic composition
- Growing contribution of sporadic flows associated with spontaneous solar activity

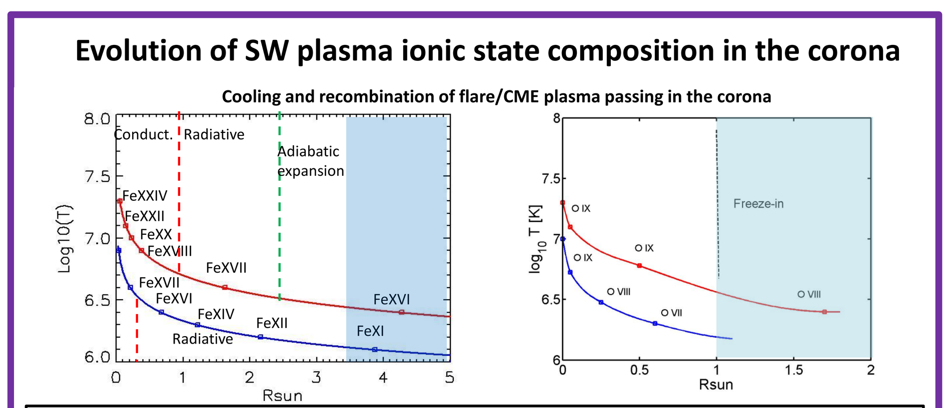
- 2009 – no CH contribution observed based on velocity; increase of the slow SW flows (V_{max} < 400 km/sec)
- 2010 - 2011 – increasing frequency of SW flows with V > 550 km/sec due to CMEs, and emerged CH
- 2008-2009 - distribution of values of O^7/O^6 primarily in the interval of < 0.16 , indicating CH contribution
- 2010-2011 - increase the contribution of values of O^7/O^6 > 0.16, indicating ICME contribution

Geoefficiency of SW flows in 2012



Evolution of SW plasma ionic state composition in the corona

Cooling and recombination of flare/CME plasma passing in the corona



1) Standard flare+ CME (solar max)
T_{max}=20 MK, $N_{e\ max}=10^{11}cm^{-3}$, V_{CME}=0 - 500 km/s
2) Small-scale flare+ CME (solar min)
T_{max}=10 MK, $N_{e\ max}=10^{11}cm^{-3}$, V_{CME}=0 - 100 km/s

Model relationships

$\tau_{recomb} < \tau_{cooling}$

$N_e \sim 1/R^2$

$t_{exp} \approx L_{freeze-in} / \langle V_{CME} \rangle$

Cooling processes:

Thermoconductivity: $T(t)=T_1(1+t/\tau_{cond})^{-2/5}$, $\tau_{cond} \sim Ne/T^{5/2}$

Emission: $T(t)=T_1(1-t/\tau_{rad})^{3/5}$, $\tau_{rad} \sim T^{5/3}/Ne$

Adiabatic expansion: $T \sim N_e^{\gamma-1} = 1/R^2 = (\int V(t)dt)^{2(1-\gamma)}$

Results
▪ Ionic state composition of the plasma is determined by initial temperature at the flare site and its cooling / recombination during expansion in the corona till the freeze-in region
▪ At solar max the modeled "frozen" charge <Qfe>Fe = 15
▪ At solar min the modeled <Qfe> = 10
▪ The dominating oxygen ions at solar max are O^{+7} , at solar min - O^{+6}.

Conclusions

The results of analyses of SW composition and associated coronal sources in the ascending phase of Solar Cycle 24 (2008 – 2012) can be summarized as follows:

- According to the O^7/O^6 criterion, (Richardson&Cane, 2004; Zhao, Zurbuchen&Fisk 2011), the contributions of HSW from CHs, SSW from streamers and ICME transients changed from NN/NN/NN in 2008 to MM/MM/MM in 2011.
- In solar minimum (2008-2009) the flows from polar and small mid-latitude CHs dominated in SW producing slow SW with V<450 km/s. ARs did not give sizeable contribution. Parameters of transient SW flows from small-scale solar activity, except T_p, O^{7+}/O^{6+} and C^6/C^5 ratios, and outflows from ARs, were not distinguished from the background SW. At the ascending phase of Cycle 24 (2010 – 2011) Vp and Tp of HSW increased as a result of transformation of small mid-latitude CHs into large equatorial extensions of polar CHs.
- In shocks and main bodies of HSW, the O^7/O^6 ratio linearly fell down with growing Vp, the values in shocks being higher than in the HSW bodies, as well as in 2011 as compared with 2011. The <QFe> values weakly grew with Vp both in shocks a n bodies of HSS, but practically did not depend on solar activity.
- The O^7/O^6 and Fe/O ratios in ICMEs increased with Vp up to 500 km/s and then fell down. This dependence was similar in shocks and main bodies of ICMEs for temperature-dependent ratios O^{7+}/O^{6+} and C^6/C^5 and <QFe>, but the values in shocks were systematically smaller than in bodies. It suggests that shocks contain the compressed slow SW rather than the hot CME matter.
- It was shown that ion charge states of O and Fe in the freeze-in region and their variation with solar activity can be estimated from parameters of flare plasma in a process of recombination taking into account the initial temperature and density and their variation during the plasma expanding in the corona.
- Analysis of geoefficiency of the SW flows from different sources in 2012 has shown that the strongest storms with Dst <-50 nT were produced by the overlapping HSW and ICMEs. HSW flows alone produced storms with Dst <-50 nT or did not produce them at all, ICMEs alone produced storms with Dst up to -50 ÷ -70 nT.
- We conclude that criteria of separation of the SW components based on the ion ratios established earlier by Zhao&Fisk (2011) for higher solar activity are not applicable to the extremely weak beginning of 24th cycle.

The research leading to these results has received funding from the European Commission's Seventh Framework Programme (FP7/2007-2013) under the grant agreement eHeroes (project n° 284461, www.eheroes.eu).