Small scales variations of helium abundance in different large scale solar wind structures

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Motivation:

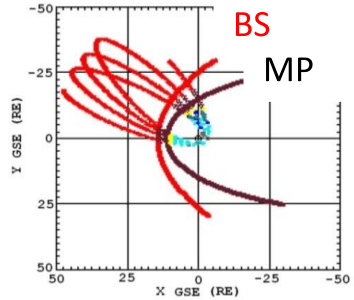
- The boundaries between large scale solar wind streams are often accompanied by sharp changes in helium abundance;
- A high value of the relative abundance N_a/N_p is a sign of some large-scale structures (for example, in magnetic clouds N_a/N_p can increase up to 20%);
- In areas of high helium abundance, the value of N_a/N_p can vary over the wide range.

Main objectives:

- We analyze small-scale variations in the solar wind plasma parameters choosing intervals with a sufficiently high level of correlation of the plasma parameters as a whole;
- For the selected intervals, we study the cross-correlation functions for the SPEKTR-R and WIND measurements to identify local spatial inhomogeneities in the helium abundance, which are observed only at one of the spacecrafts, and also to determine their properties.

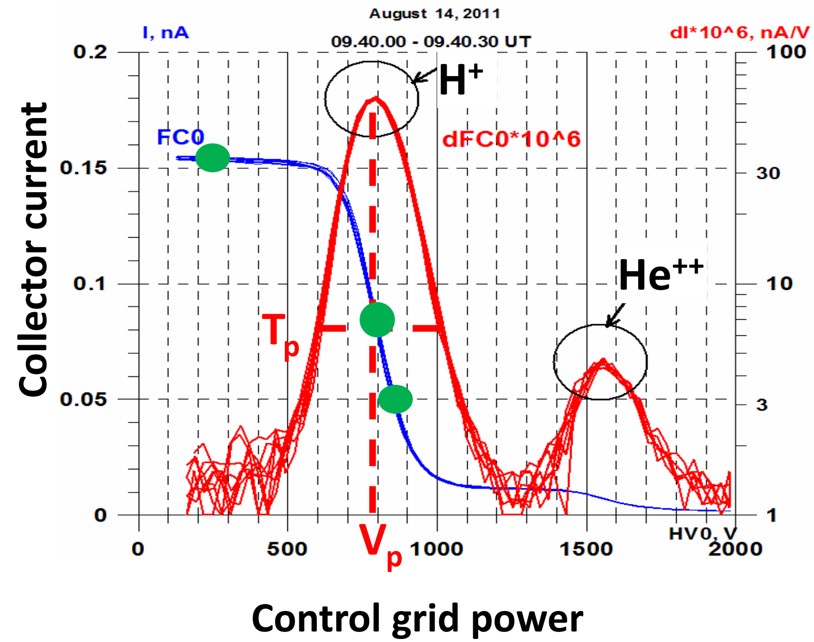
BMSW instrument (experiment PLASMA-F, spacecraft SPEKTR-R)

BMSW instrument

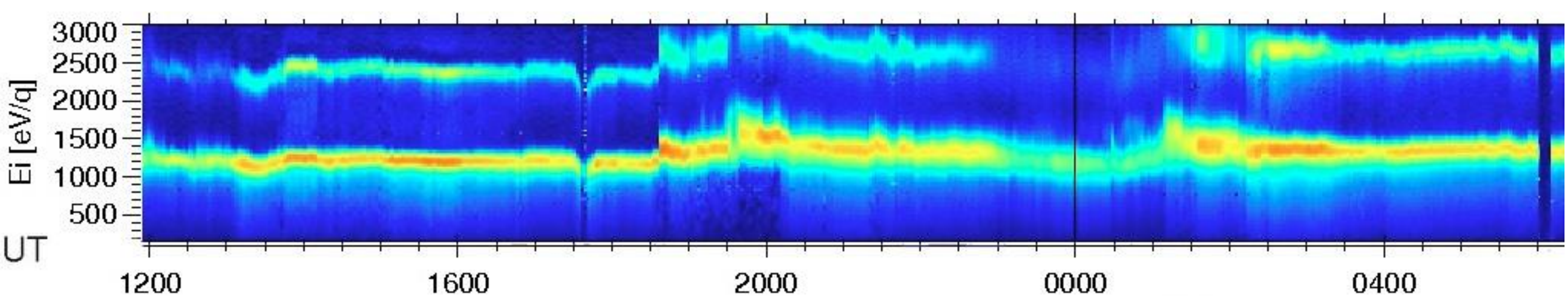


Spektr-R orbit

- Highly elliptical orbit
- Data are available from August 2011 - 2018
- Measurements:
  - -F (ion Flux vector) (31 ms)
  - -N_p, V_p, V_{thp}, N_α, V_α (3 s - sweeping mode)
  - -N_p, V_p, V_{thp} (31 ms –adaptive mode)

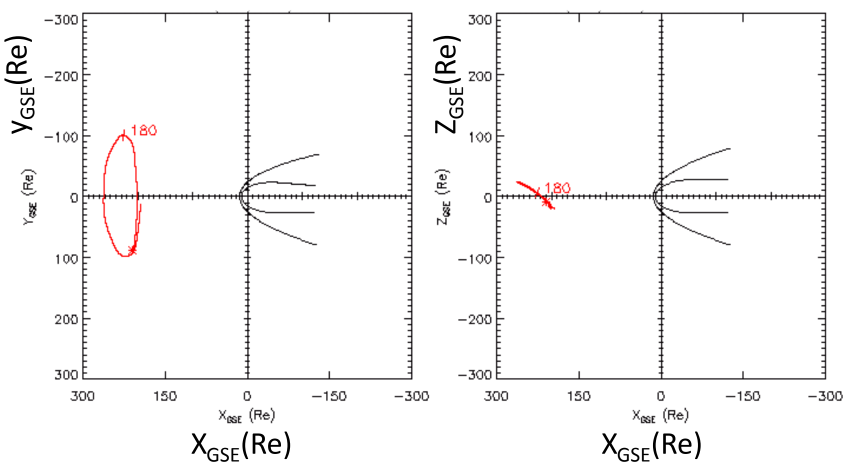


Energy distribution measured by BMSW

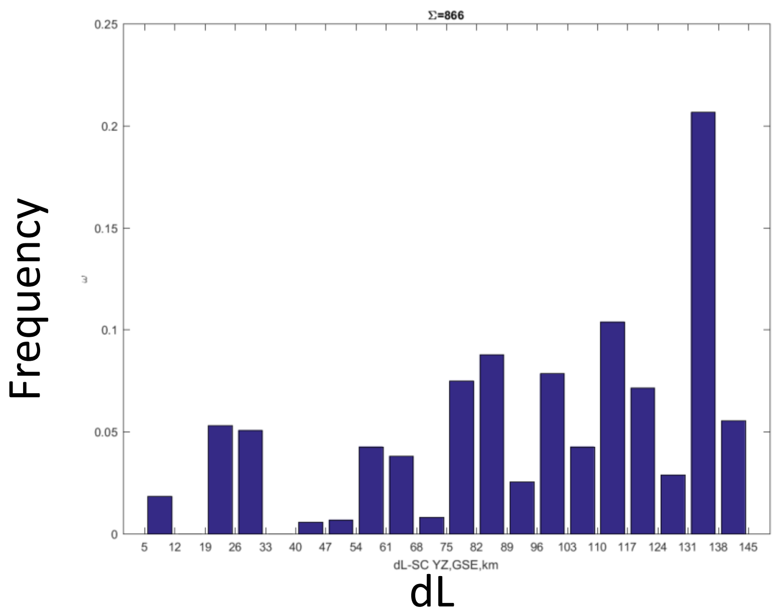


Example of energy spectrogram 19 April 2014 12:00 UT - 20 April 2014 06:00 UT (BMSW)

Data selection



Wind SC orbit



Distance between SC in the YZ plane

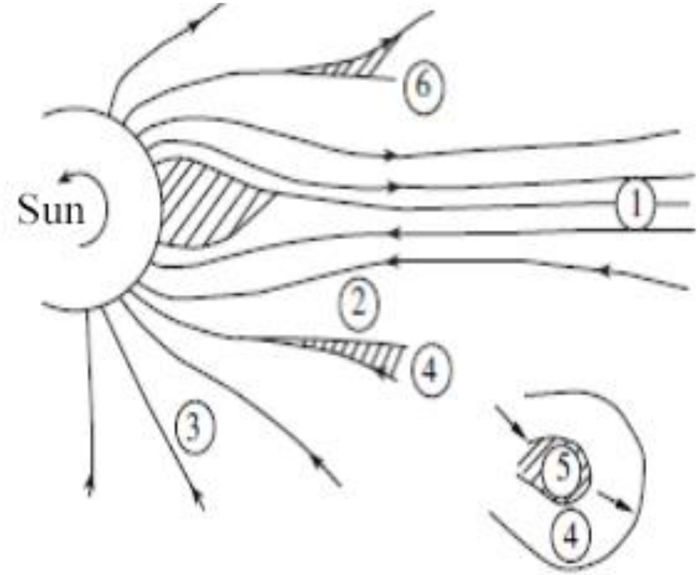
• We examined measurements of BMSW plasma instrument on SPEKTR-R spacecraft in comparison with measurements of SWE and 3DP plasma instruments on WIND spacecraft. We use WIND data from https://cdaweb.sci.gsfc.nasa.gov.

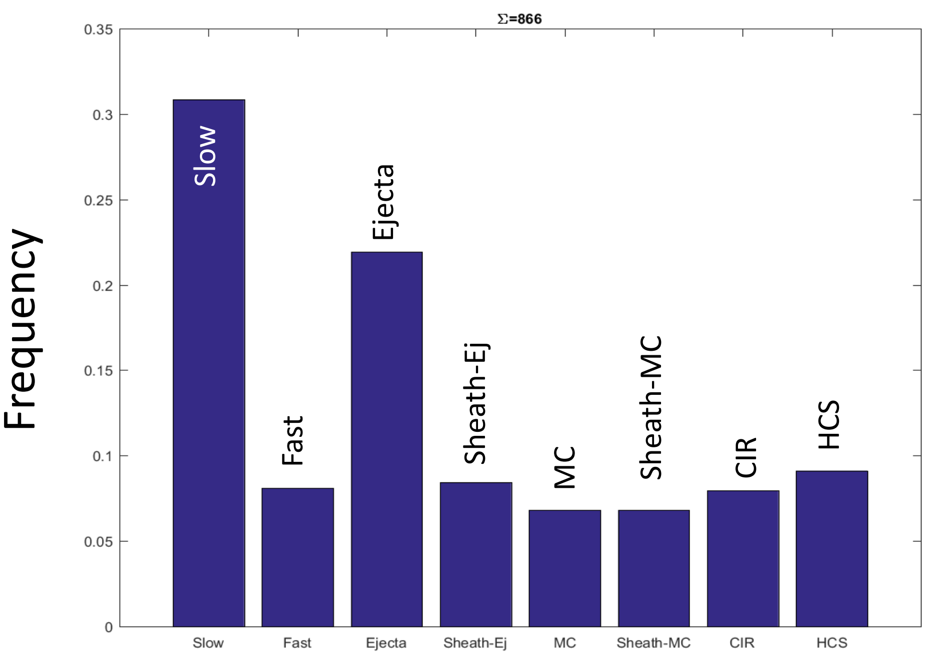
• We selected 43 intervals of simultaneous observations on SPEKTR-R and WIND during 2011 to 2016. The duration of these intervals is from few hours to one day.

• The selected intervals were divided into smaller intervals of one hour duration. There were observed 866 such intervals in total.

• The following parameters are used for the comparison and analysis: Np, Na, Na/Np, Tp, Vp and also the information about spacecrafts position in space.

Data selection



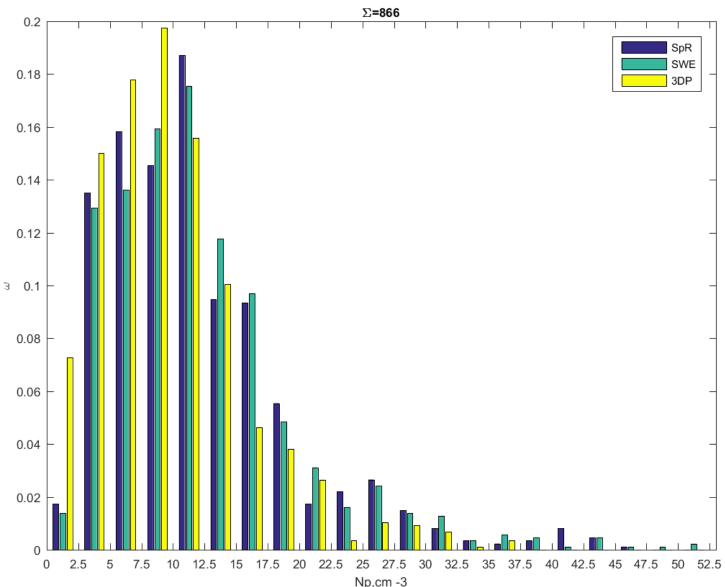


- (1) HCS - heliospheric current sheet,
- (2) Slow stream,
- (3) Fast stream,
- (4) Compressed plasma:
  CIR - Corotating Interaction Region and
  Sheath – in the front of the piston,
- (5) ICME:
  MC – magnetic clouds and Ejecta – pistons,
- (6) Rare - rarefied plasma.

Intervals were sorted by different large scale solar wind types based on a catalog of large-scale solar wind phenomena **ftp://ftp.iki.rssi.ru/pub/omni/catalog/** **(Yermolaev *et al.*, 2009)**.

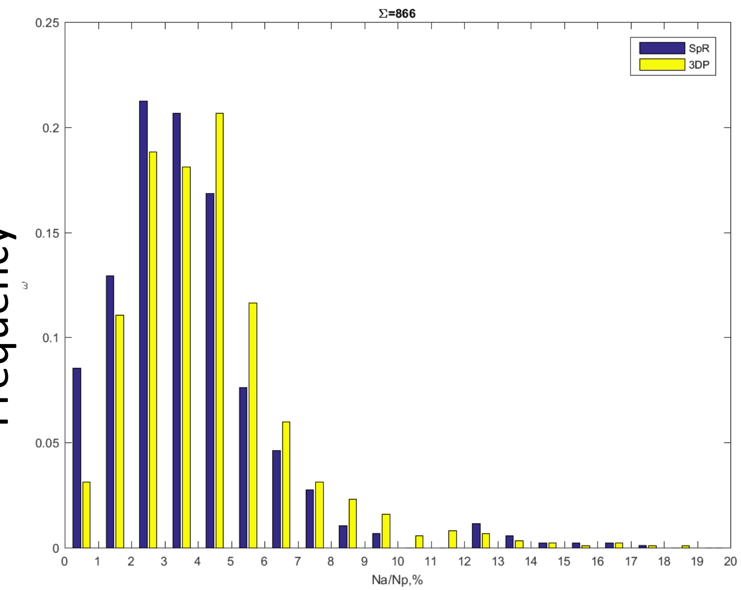
Data selection

Frequency



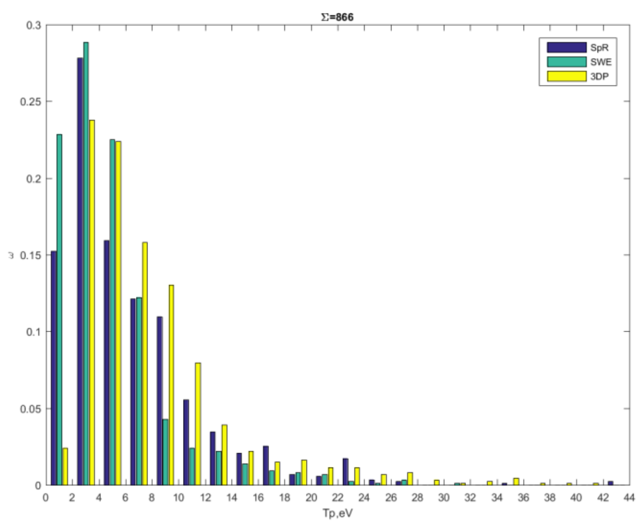
Np, cm^{-3}

Frequency



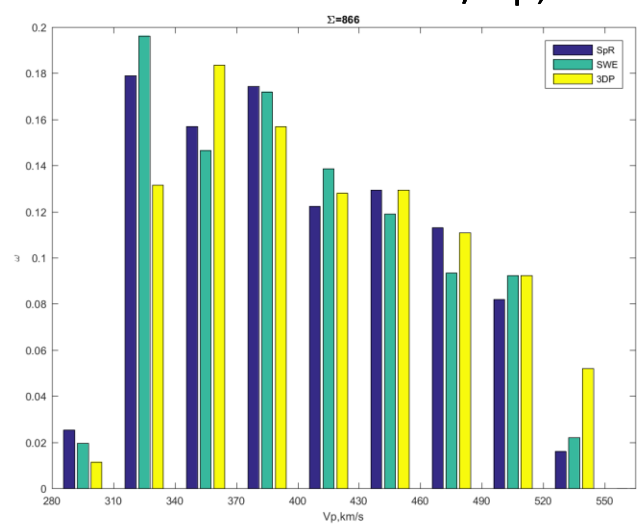
Na/Np, %

Frequency



Tp, eV

Frequency



Vp, km/s

Histograms of solar wind parameters for all events under consideration.

The distributions of plasma parameters in the observed intervals are rather typical.

Data selection

	Np, cm^{-3}	Na, cm^{-3}	Na/Np, %	Tp, eV	Vp, km/s
BMSW, mean	11.98	0.42	3.68	6.56	400
BMSW, median	10.61	0.31	3.29	4.79	391
BMSW, SD	7.65	0.37	2.44	5.85	61
SWE, mean	12.25			4.92	401
SWE, median	11.04			3.84	393
SWE, SD	7.72			4.16	62
3DP, mean	9.66	0.39	4.32	7.80	412
3DP, median	8.65	0.31	3.97	6.26	401
3DP, SD	6.02	0.30	2.61	5.88	63

← Mean, median and standard deviation of solar wind plasma parameters.

Bases on statistical results at the previous slide, we consider that among the devices of the WIND SC, SWE is more reliable in measuring proton parameters, and device 3DP in measuring helium abundance parameters.

WIND-SpR	Np, cm^{-3}	Na, cm^{-3}	Na/Np, %	Tp, eV	Vp, km/s
Mean	0.29	-0.03	0.64	-1.63	0.76
Median	0.25	-0.01	0.44	-0.96	1.64
SD	1.34	0.14	1.06	2.79	7.80

← Mean, median and standard deviation of differences between plasma parameter values at SPEKTR-R and WIND SC.

The difference between observations on WIND and SPEKTR-R is on average close to zero for all plasma parameters.

Methods of analysis

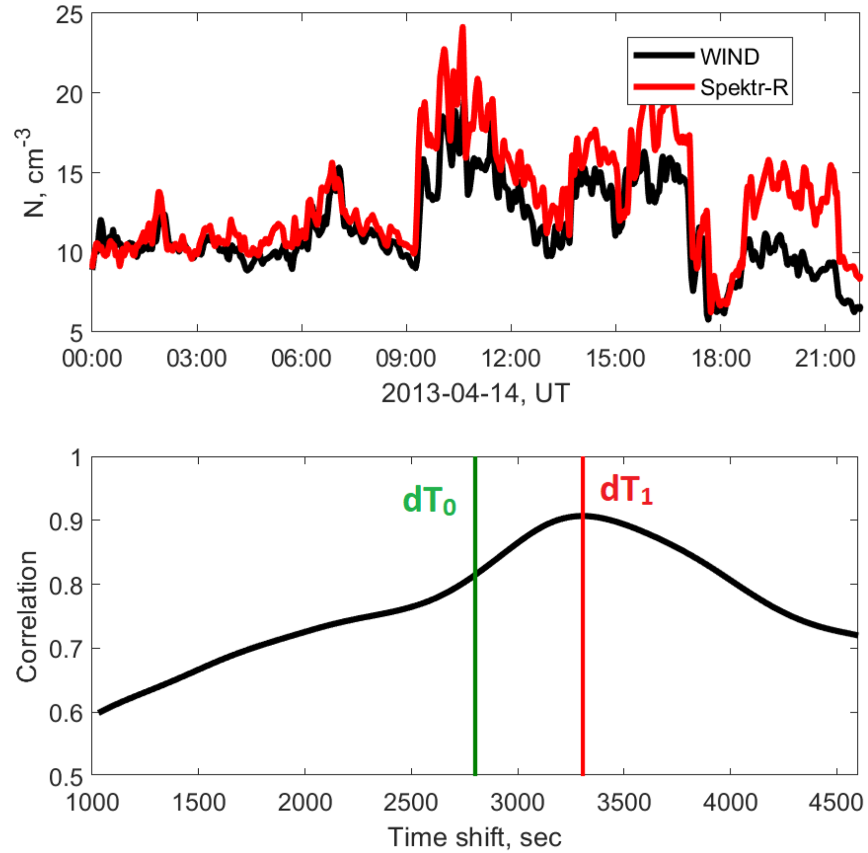
Methodic to determine propagation time of small-scale structures

1. Determining large-scale propagation time via distance between two s/c **r** and solar wind speed **V**:

$$dT_0 = r/V$$

2. Correcting large-scale propagation time via cross-correlation analysis:

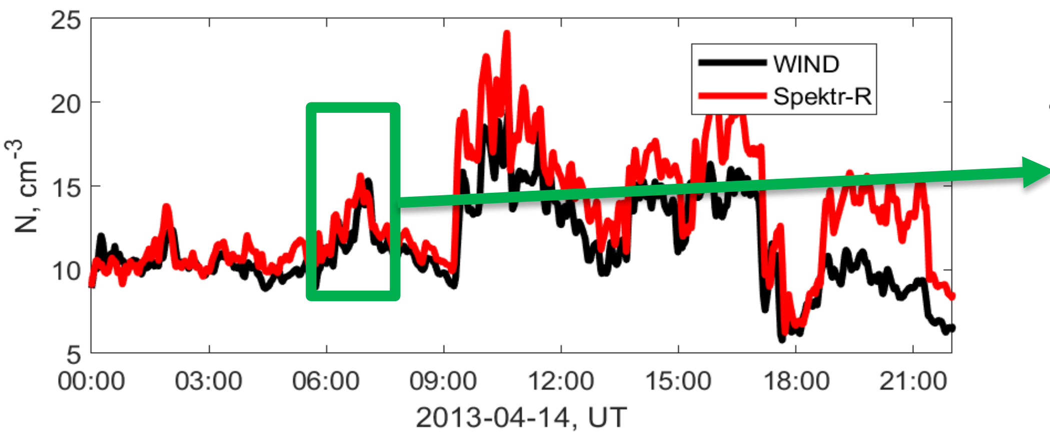
$$dT_1 = \mathit{max}\,(R(N_{s/c1}(t+dt), N_{s/c2}(t)),$$
$$dT_0 - 30\text{ min} < dt < dT_0 + 30\text{ min}$$

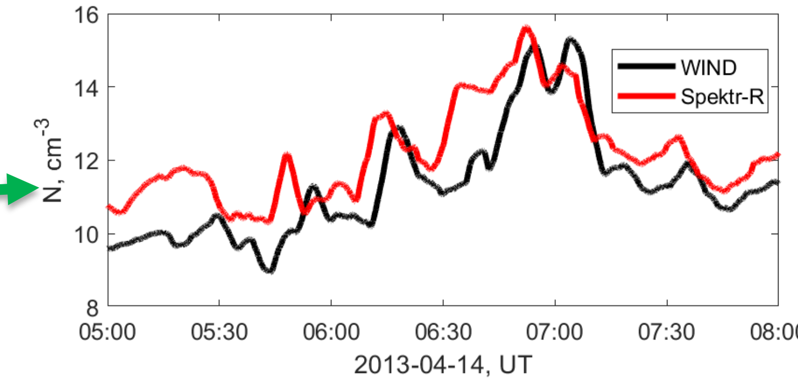


***Top panel**: measurements of proton density by WIND (black line) and SPEKTR-R (red line), WIND data are shifted in time by dT_1; **bottom panel**: Correlation coefficient between time series of density measurements, presented in top panel, as a function of time shift between the time series*

Methods of analysis

Methodic to determine propagation time of small-scale structures





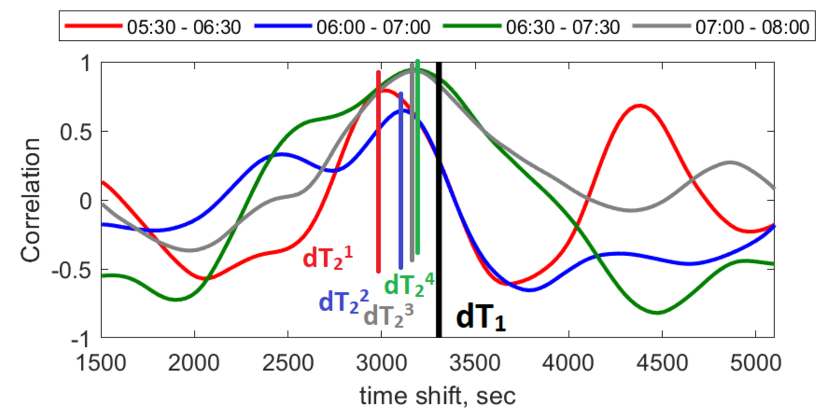
3. Long time interval is divided into sub-intervals with **1 hour** duration, overlapping by **30 min;**

   For each sub-interval propagations time dT_1 is correcting via cross-correlation analysis:

$$\mathbf{dT_2} = \mathit{max}\,(R(\mathbf{N_{s/c1}(t_{sub\text{-}int}+dt)},\ N_{s/c2}(\mathbf{t_{sub\text{-}int}})),$$

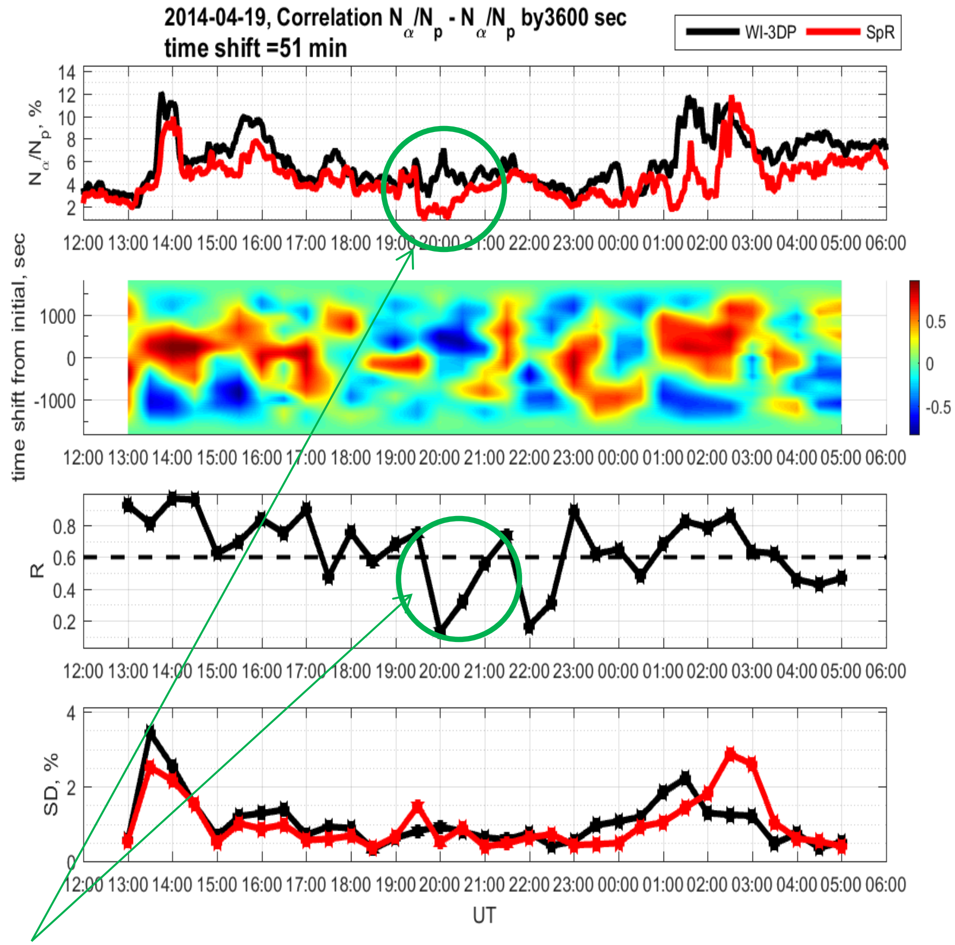
$$\underline{dT_1} - 30\text{ min} < \mathbf{dt} < \underline{dT_1} + 30\text{ min}$$

4. Repeat for N_α and N_α/N



***Top panel**: same as at previous slide;*
***bottom panel**: Correlation coefficient between time series of density measurements for 1 hour sub-intervals*

Methods of analysis



Despite the fact that the level of correlation on the interval as a whole is high on the average, there are areas with dips of local correlation coefficient where local inhomogeneities in helium relative abundance are observed.

large-scale correlation Np: BMSW-SWE	0.86
large-scale correlation Na: BMSW-3DP	0.68
large-scale correlation Na/Np: BMSW-3DP	0.65
large-scale shift, min	51
Distance between SC along the axis X	262 Re
Distance between SC in the YZ plane	77 Re
Estimated speed delay, min	57
Na/Np, %	2.9
Tp, eV	12.2
Vp, km/s	482

Table of plasma parameter values, spacecrafts positions and large scale correlation coefficients for proton and helium density, and relative helium abundance for 19 April 2014 12:00 - 20 April 2014 06:00 UT.

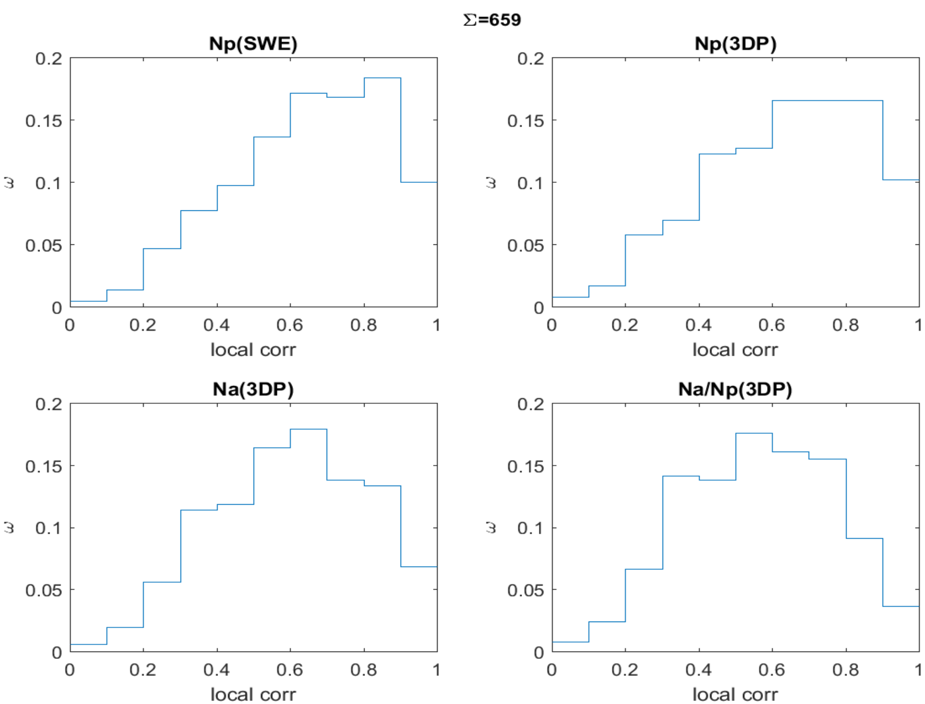
Correlation analysis

The mean values of plasma parameters for good large-scale correlation >0.7. Total events: 659.

	BMSW	SWE	3DP
Np, cm^{-3}	12.8	13.1	10.3
Na/Np,%	3.6		4.4
Tp, eV	7.2	5.5	8.7
Vp, km/s	406	40	417

The mean values of plasma parameters for bad large-scale correlation <0.6. Total events: 156.

	BMSW	SWE	3DP
Np, cm^{-3}	9.9	10.0	8.1
Na/Np,%	3.9		4.3
Tp,eV	3.8	2.9	4.8
Vp, km/s	394	394	404



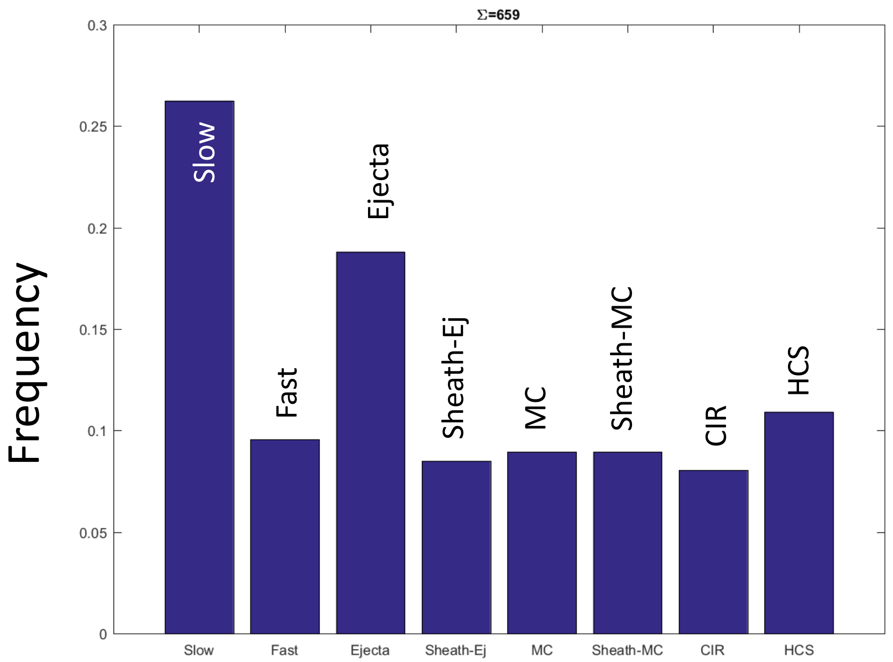
Histogram of local correlation coefficients.

Statistical values of local correlations R_{loc} of SPEKTR-R and WIND with good large-scale correlations >0.7.

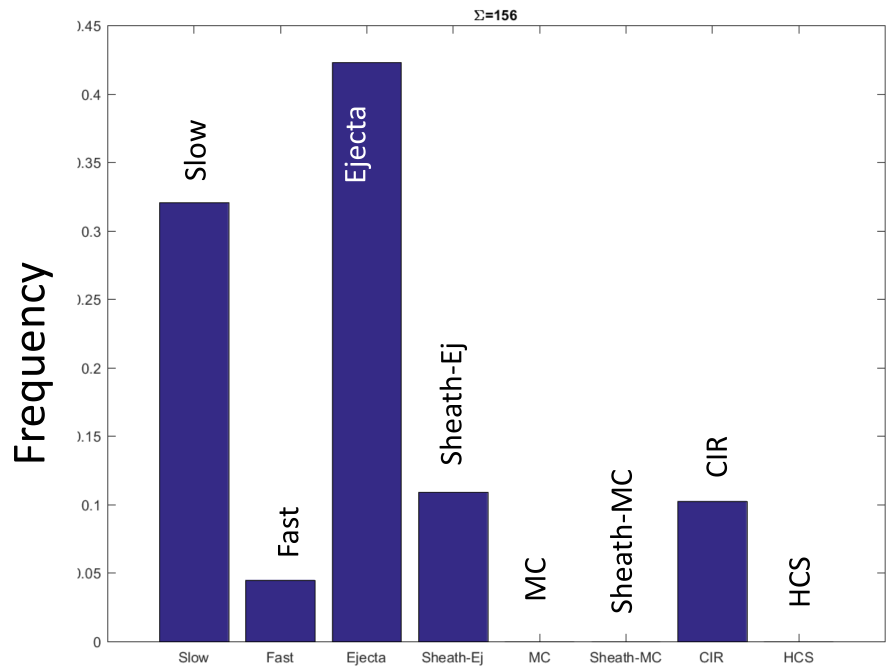
	Np (SWE)	Np (3DP)	Na (3DP)	Na/Np (3DP)
Mean	0.65	0.64	0.60	0.57
Median	0.68	0.67	0.61	0.57
SD	0.21	0.21	0.21	0.20

Correlation analysis

Distribution of solar wind types with good large-scale correlation >0.7.



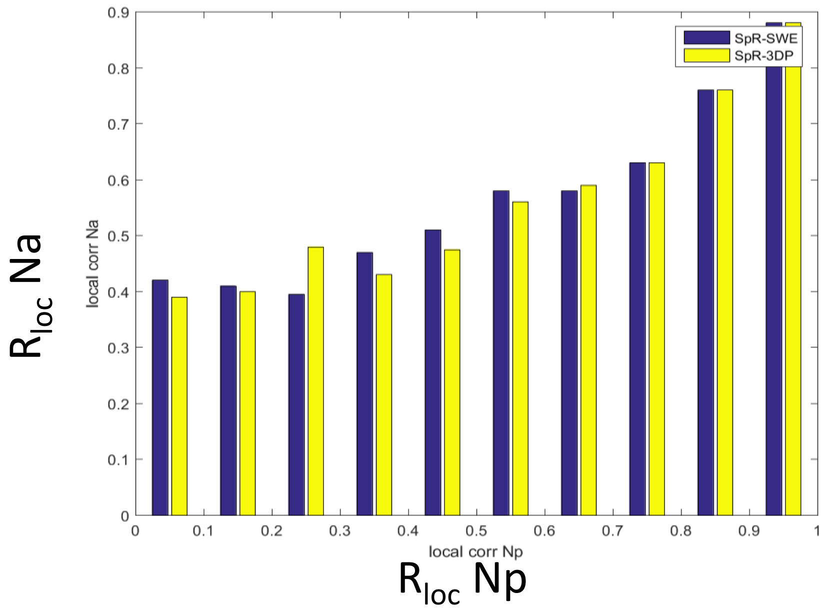
Distribution of solar wind types with bad large-scale correlation <0.6.

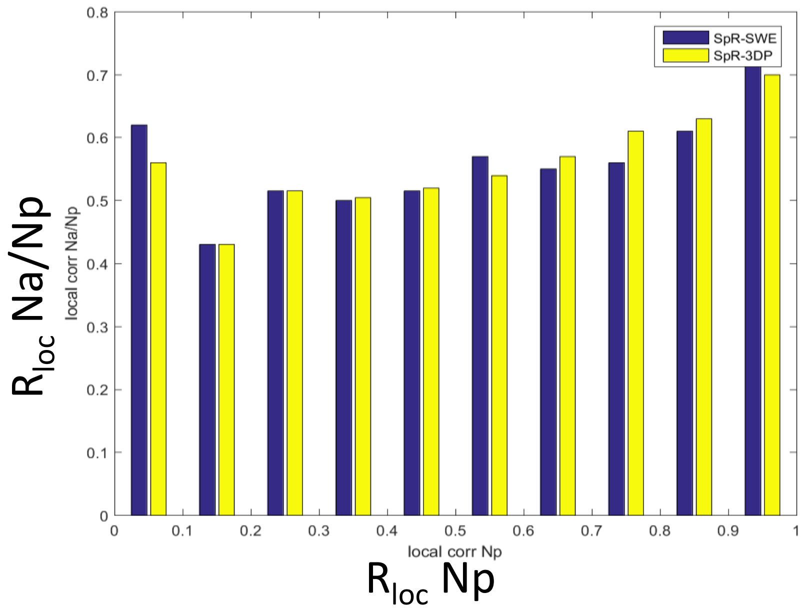


The bad large scale correlation <0.6 is often observed in Ejecta.

Below large-scale poor correlations are not considered and all further statistics are selected for good large scale correlations >0.7.

Correlation analysis



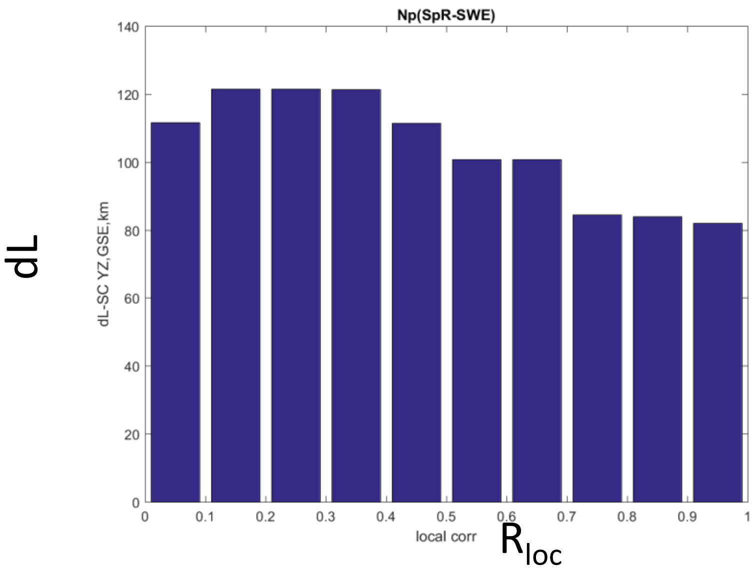


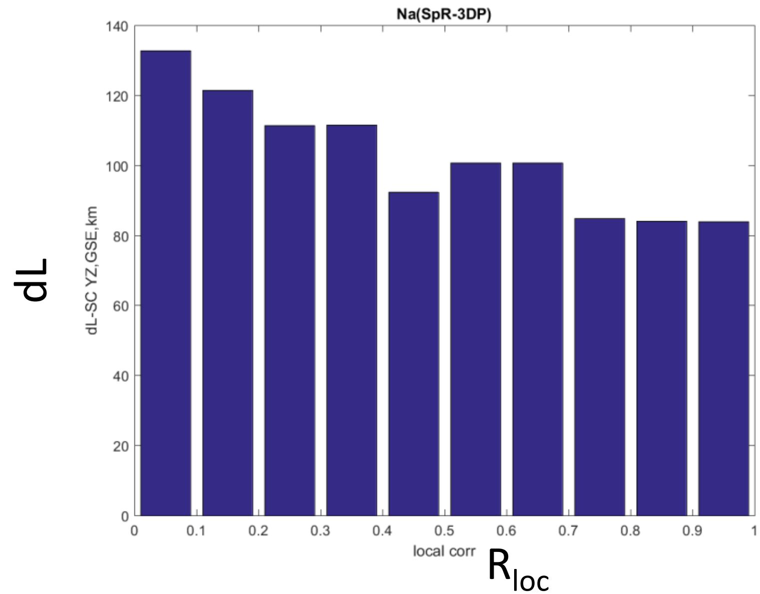
The relation of local correlation coefficients of different plasma parameters for intervals with large-scale correlation >0.7.

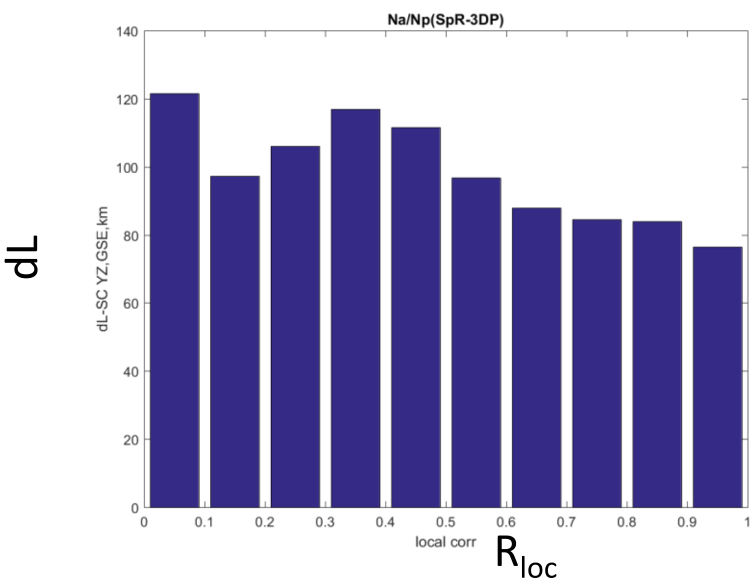
	All events	**Good proton correlation >0.7, bad helium correlation <0.6**	**Bad proton correlation <0.6, good helium correlation >0.7**
Total events	659	47	23
Np, cm^{-3}	12.8	12.7	14.1
Na/Np, %	3.6	3.4	3.0
Tp, eV	7.24	7.47	8.95
Vp, km/s	406	400	404

Table of mean values of plasma parameters for different selections of intervals on SPEKTR-R.

The relation of the correlation coefficient with the distance between spacecraft's



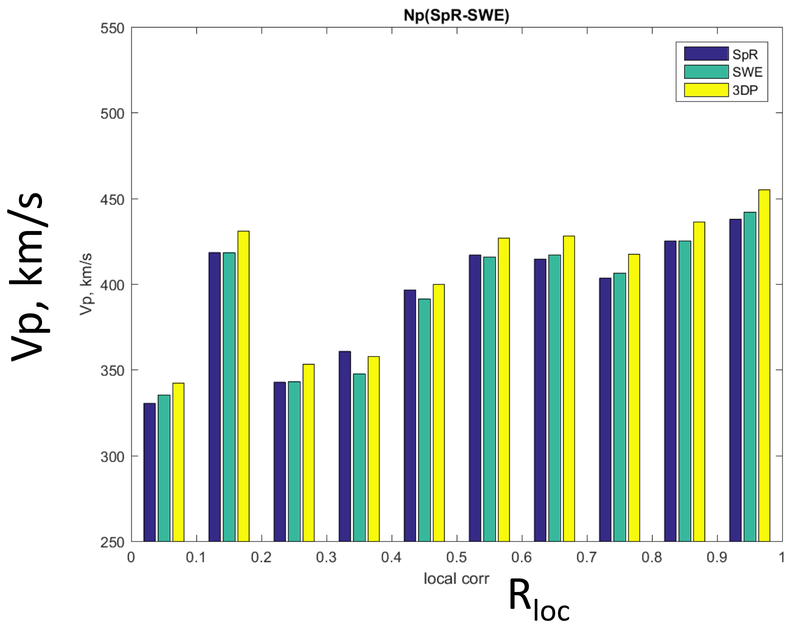


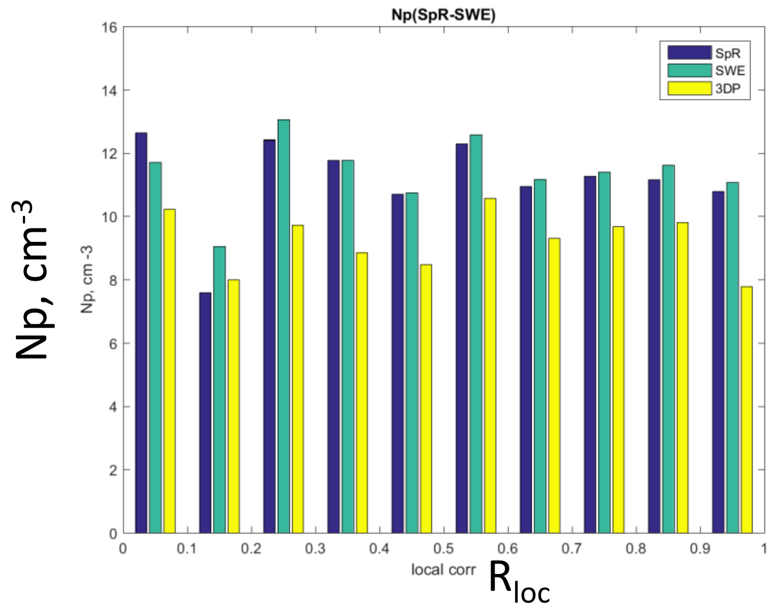


- High value of correlation coefficient >0,7 for Np, Na and Na/Np is observed often for average distance between spacecrafts in YZ plane ~ 80 Re.

- The increasing of the distance leads to the decreasing of the level of correlation.

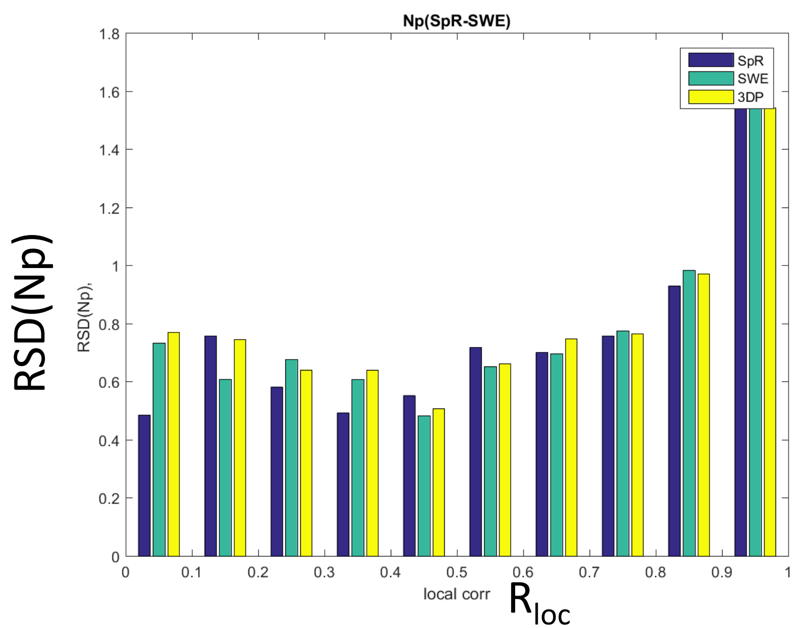
The relation of the correlation coefficient for Np with values of SW plasma parameters



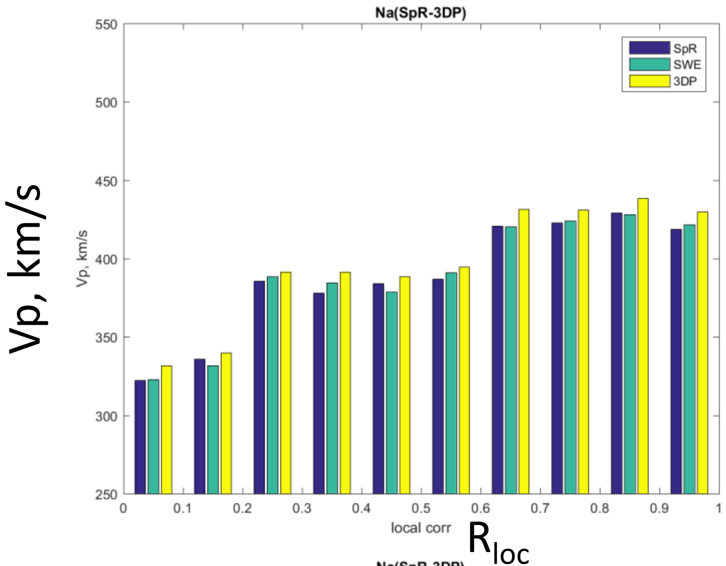


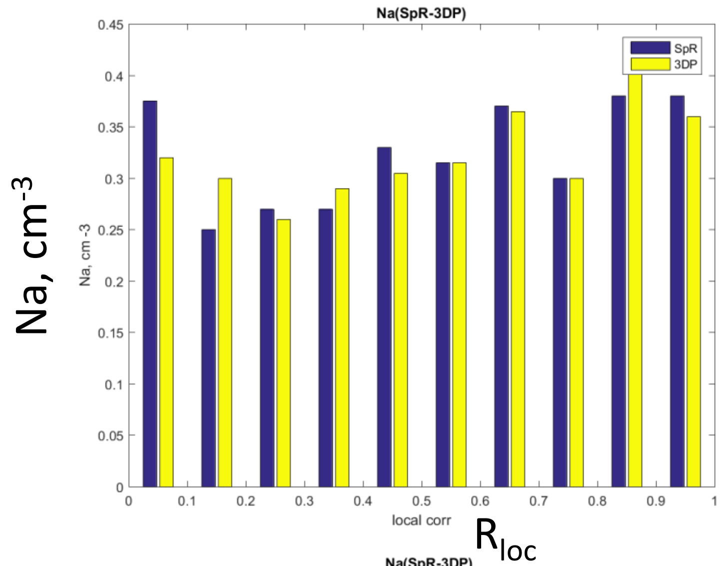
- The significant dependence between local correlation level and Vp, RSD(Np) is observed.

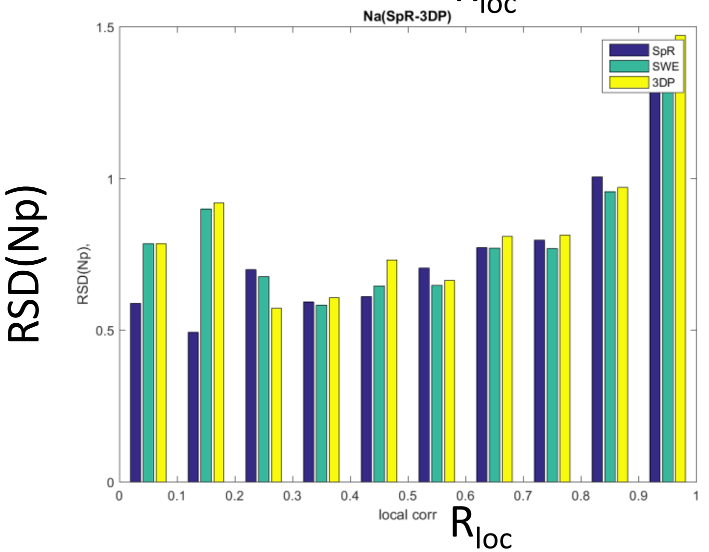
- It was not find any dependence between local correlation level and Np, Tp.

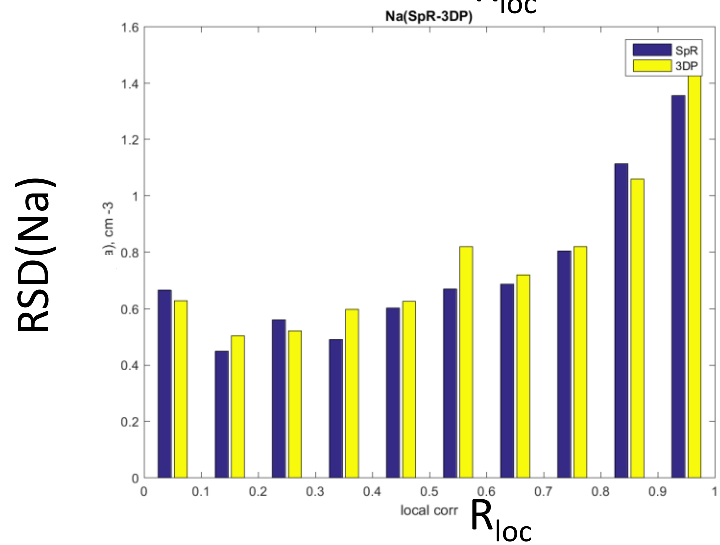


The relation of the correlation coefficient for Na with value of SW plasma parameters



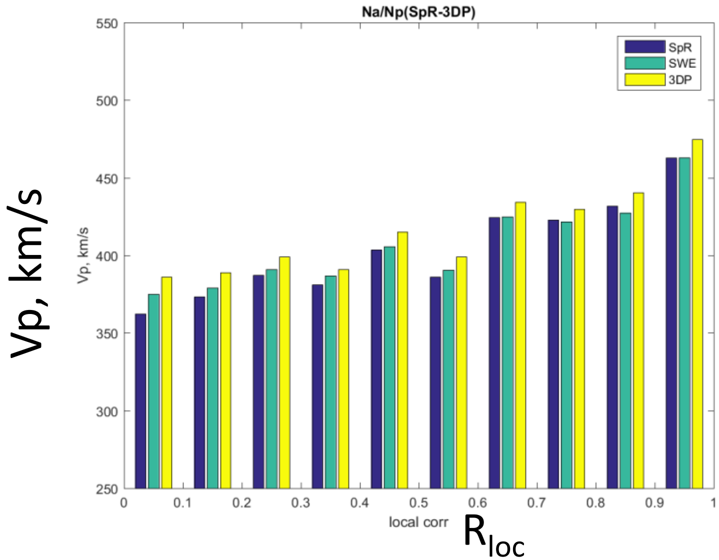


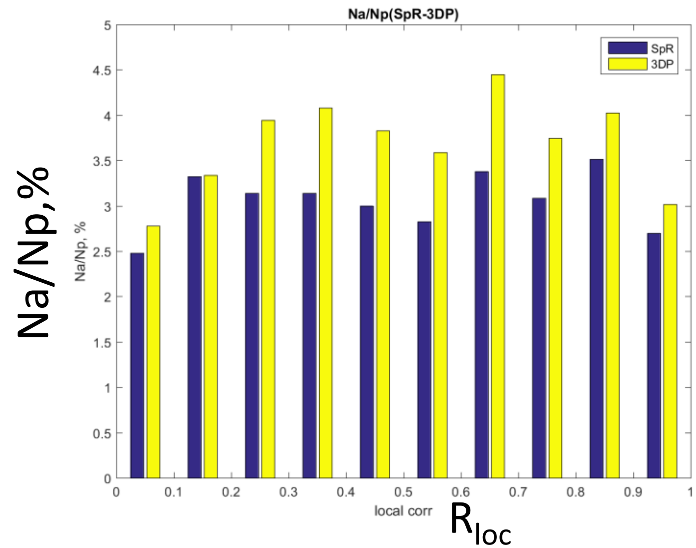


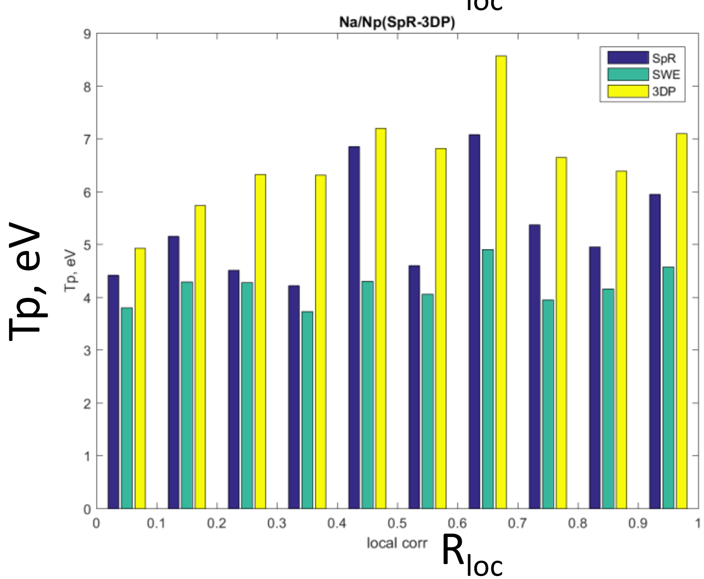


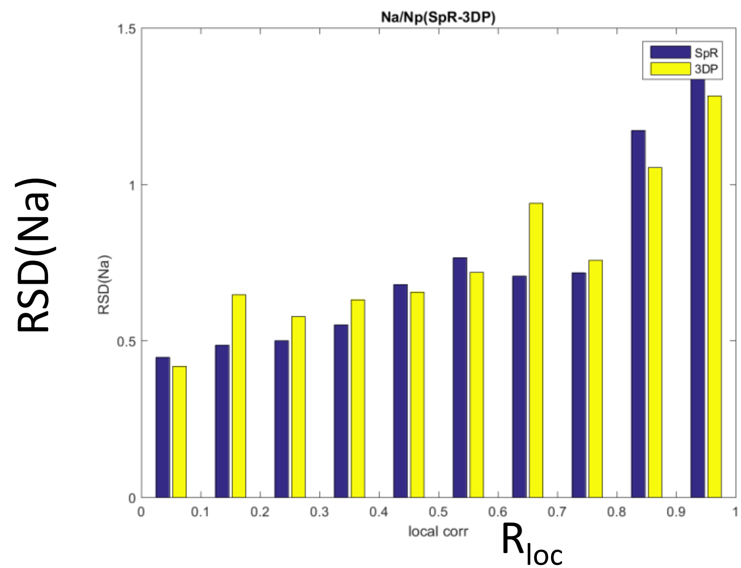
- The significant dependence - between local correlation level and Vp, RSD(Np), RSD(Na).
- No dependence - between local correlation level and Na, Np, Tp.

The relation of the correlation coefficient for Na/Np with value of SW plasma parameters



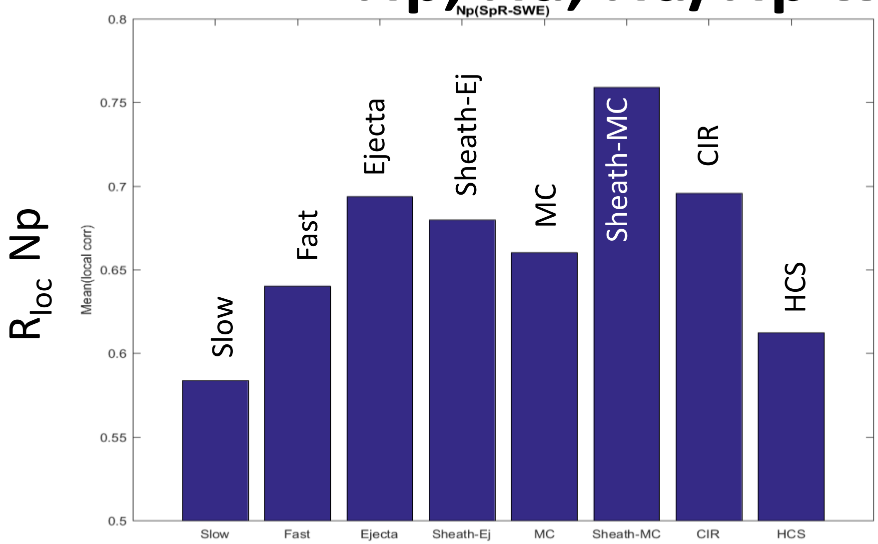




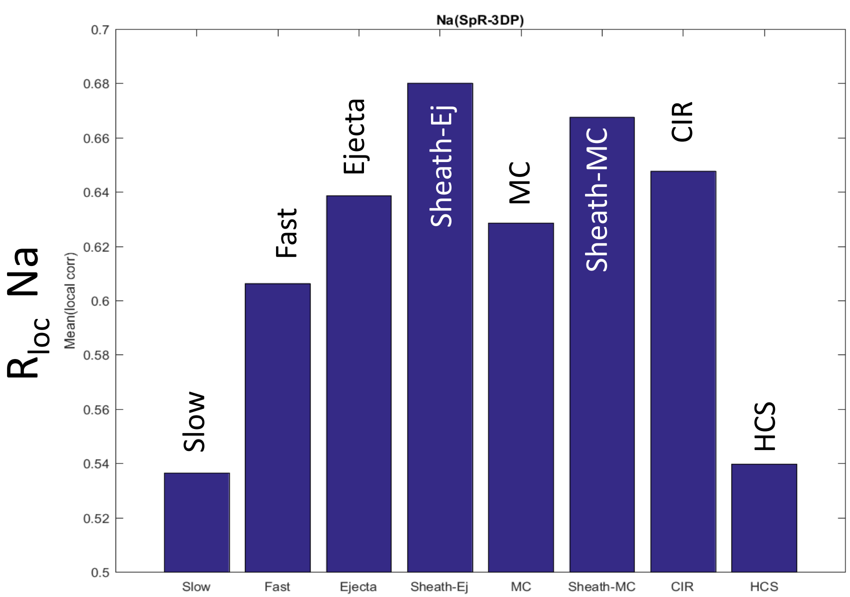


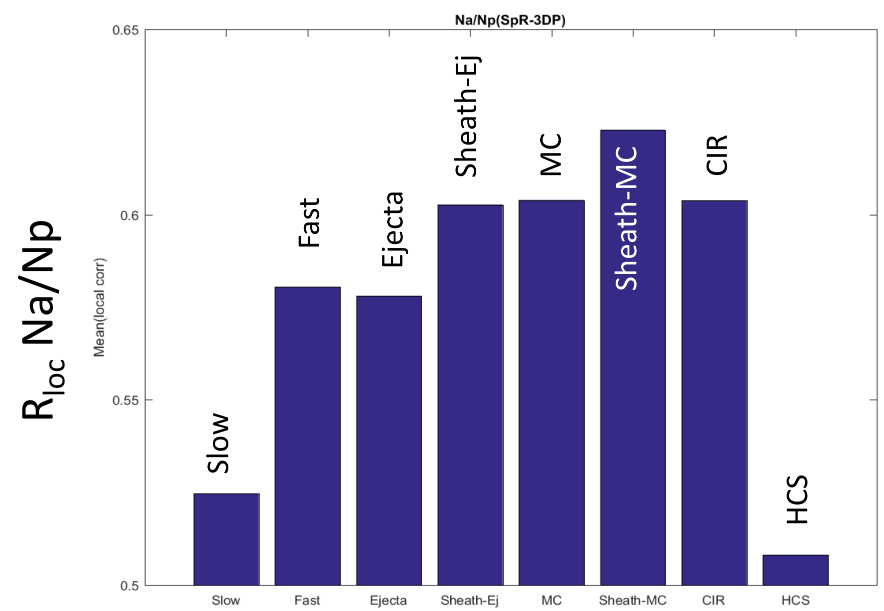
- The significant dependence - between local correlation level and Vp, RSD(Na), Tp.
- No dependence - between local correlation level and Na, Np, Na/Np.

The relation of the correlation coefficient for Np, Na, Na/Np with different SW types

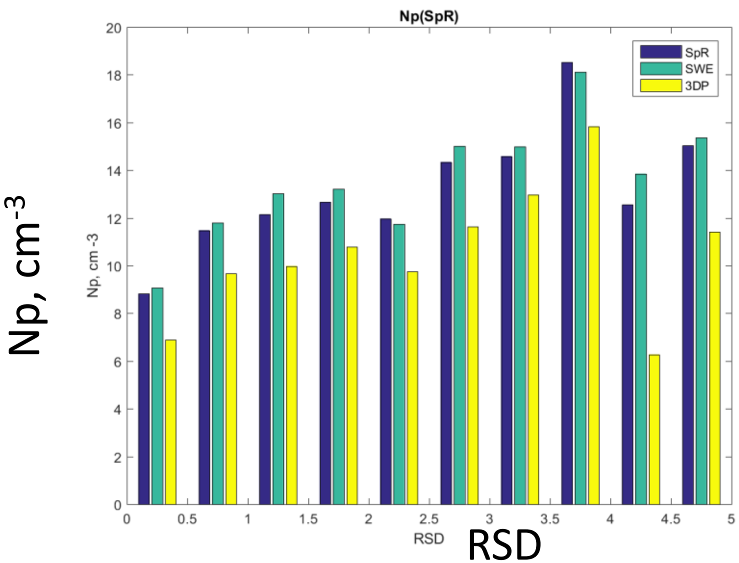


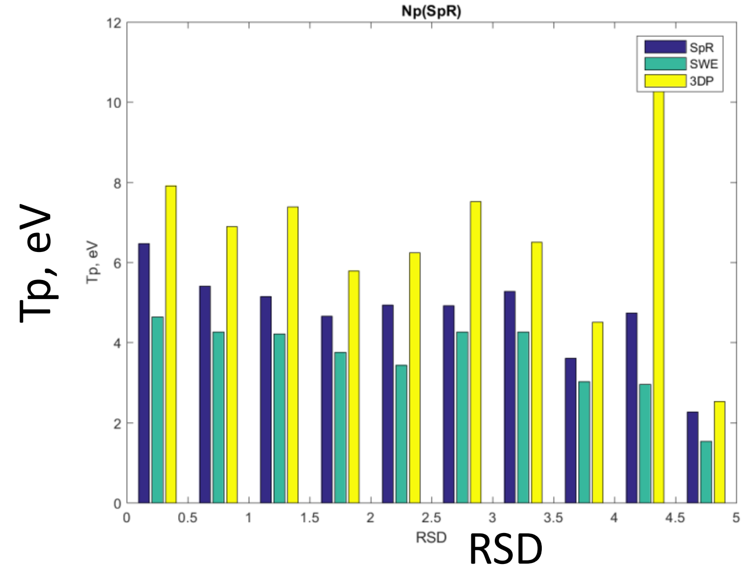
For correlation of all considered parameters, the minimal correlation is observed in slow streams and heliospheric current sheet, maximum correlation in compressed plasma in the front of the piston.

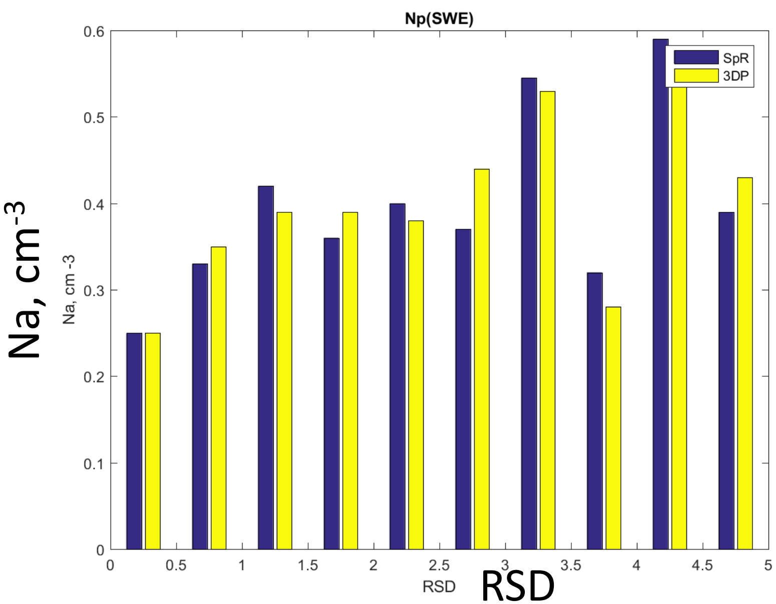




The relation of the RSD for Np with value of SW plasma parameters



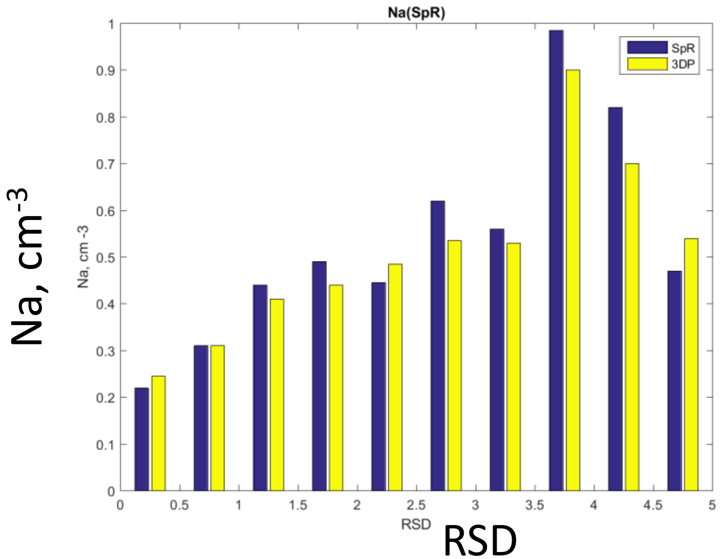


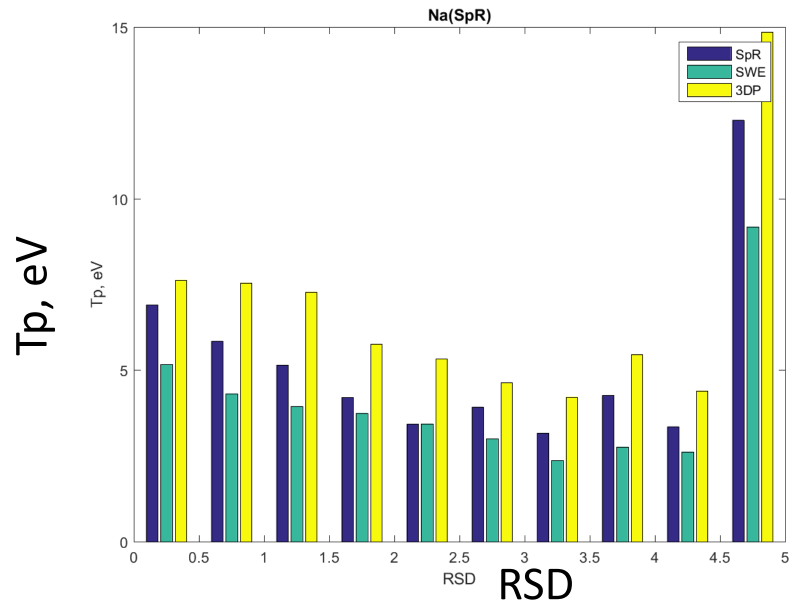


- The noticeable dependence between RSD (Np) and Np and Tp. The same situation for RSD (Na) and RSD (Na/Np) (next slide).

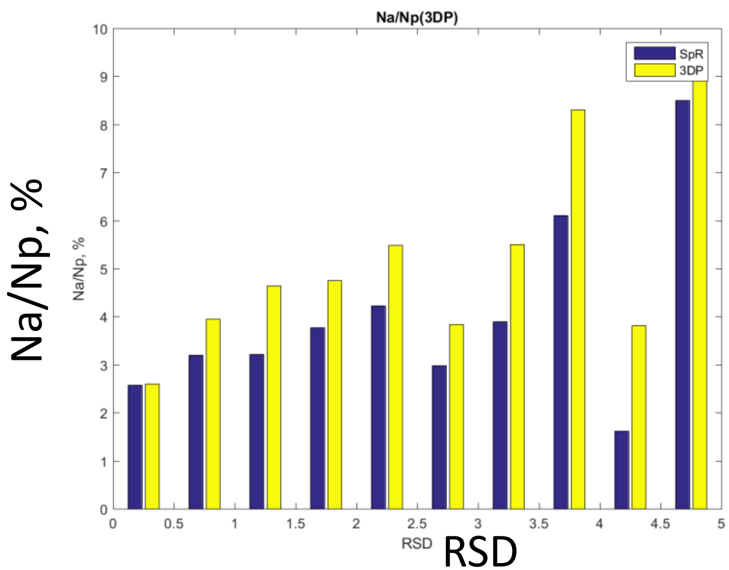
- Weak dependence between RSD (Np) and Na.

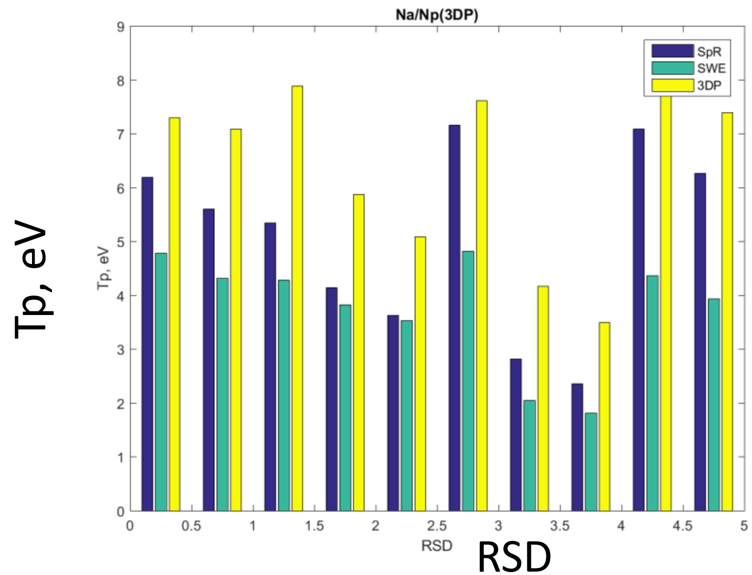
The relation of the RSD for Na with value of SW plasma parameters



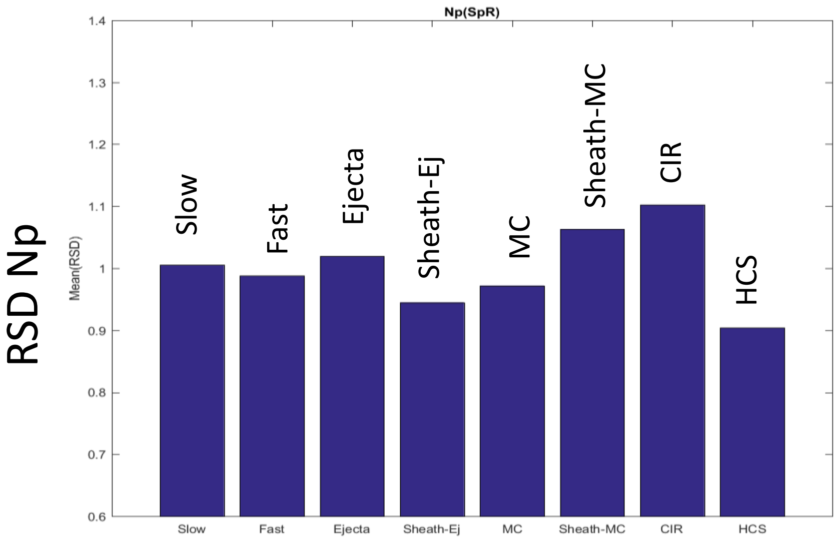


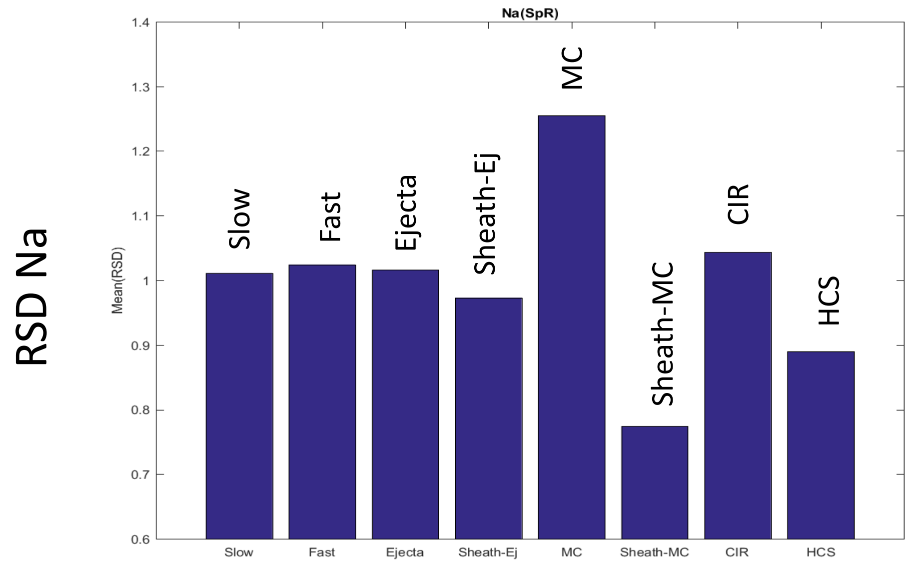
The relation of the RSD for Na/Np with value of SW plasma parameters

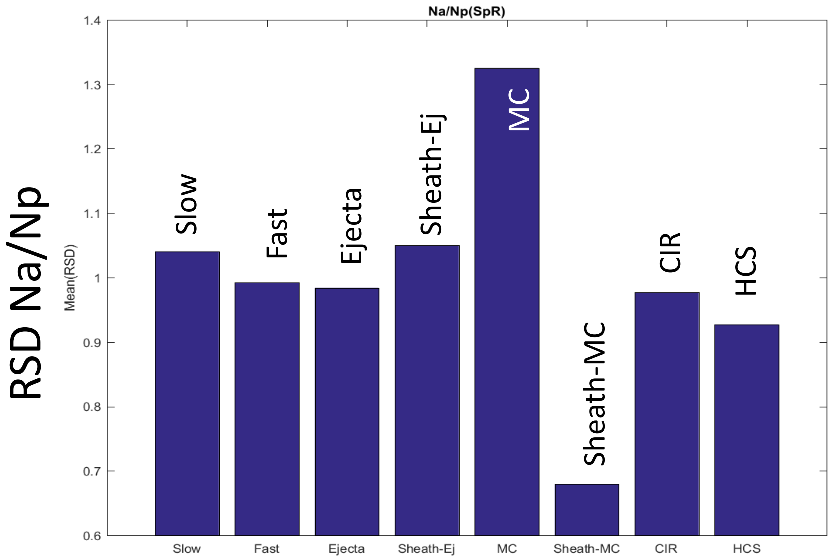




The relation of the RSD for Np, Na, Na/Np of different types of SW streams







Weak dependence between RSD (Np) and type of large-scale structures: the average value is approximately the same for all types of streams. A noticeable peak is observed in magnetic clouds for RSD(Na) and RSD(Na/Np).

Distributions according to WIND data are similar.

Conclusions 1

- Bad large-scale correlation <0.6 can be observed both in protons and in helium abundance. The reason for this is because some large- and medium-sized structures are registered by one spacecraft and pass by the second. More often this situation is observed in streams with lower density and higher temperature.
- Even in the case of good large-scale correlation >0.7, dips of the local correlation of the parameter under consideration can be observed (about 15% of cases). This may be explained by the fact that one of the spacecraft register locally plasma inhomogeneities, when the other did not register.
- Bad local correlations <0.6 are usually more often observed at large distances in the YZ plane> 100 Re, and good correlations >0.7 have a distance of not more than 80 Re. From this, one can estimate the size of local inhomogeneities along the YZ axis ~ 80 Re.
- In most cases, there is a relation between proton density correlation and helium density correlation. However, there are approximately 10% of cases where there is a good correlation of Np and bad of Na, and 5% of cases when there is a bad correlation of Np with a good correlation of Na.

Conclusions 2

- Good local correlations >0.7 for protons and helium abundance are characterized by high RSD and velocities. Densities and temperature, in turn, have no explicit relation with local correlation.
- The local correlation can be quite different depending on the type of large-scale structure. It takes the smallest values in slow streams and in the heliospheric current sheet for all considered parameters. The highest values is observed in compressed plasma before magnetic clouds.
- An increase in the RSD values is observed with decreasing temperature. RSD also takes on large values at high densities, but these values have a less obvious relationship.
- The RSD for proton density has approximately the same values for all types of solar wind streams, however, the picture changes for helium density and relative helium abundance: a sharp peak is observed for magnetic clouds, as well as a sharp decrease for compressed plasma in front of magnetic clouds.