Authors' response to reviewer#3 comments on manuscript
Dynamics of He++ ions at interplanetary shocks
by Sapunova et al.

Dear Reviewer, Thank you very much for your remark comments in the interactive discussion of our paper. We tried to clarify points raised in your review and apologize if we didn't understand completely some of them.

Remark 1. As I understand, the BMSW instrument does not have a magnetometer onboard and hence magnetic field measurements from other instruments on spatially separated spacecraft are used. These measurements from additional instruments, however, make up a considerable number of the quantities considered including the Mach number, shock normal angle, etc. It is well-known that the turbulent magnetic field evolves over short timescales, and that the magnetic field (and especially fluctuations thereof) varies similarly over small length scales. This can also be seen from Figs. 4 and 5, where the plasma properties are significantly different between different instruments. Thus, I do not think that using magnetic field measurements from a different spacecraft can be used to analyse particles distributions measured on a another spacecraft. Therefore, in my mind, the bulk of the analysis presented in this manuscript cannot be robustly defended. If we then take away the magnetic field measurements, the manuscript contains insufficient new material for publication.

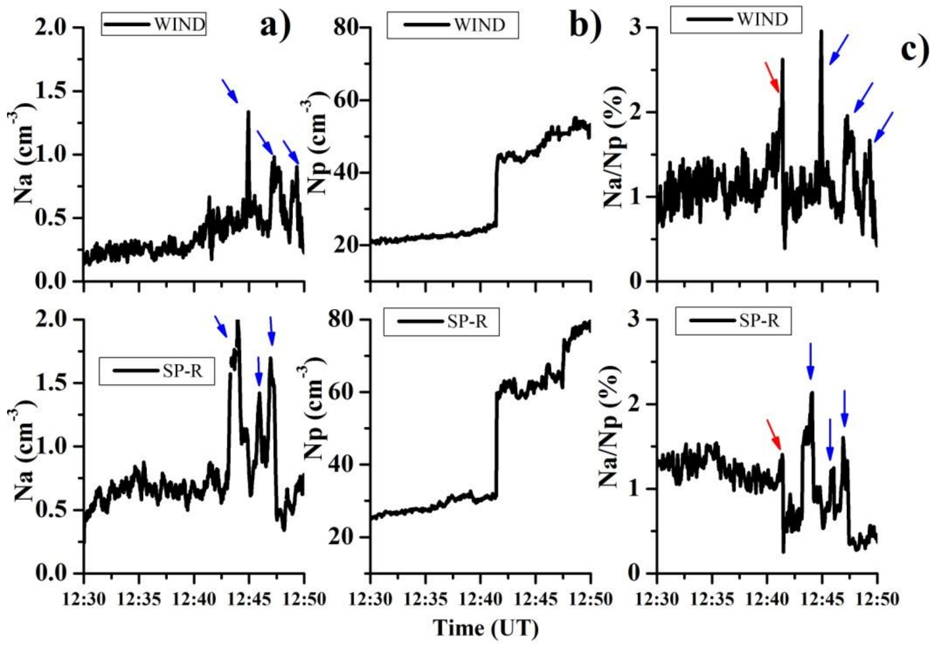
Reply to Remark 1. (This text will be also added to the)

Magnetometer was installed onboard the SPEKTR-R satellite, but, unfortunately, didn't operate. We agree that magnetic field and plasma fluctuations occur in the solar wind and shock front structures observed on the WIND and SPEKTR-R may not be identical. However, as it was shown in (*Weygand, J.M., Matthaeus, W. H., Kivelson, M. G., Dasso S., 2013, Magnetic correlation functions in the slow and fast solar wind in the Eulerian reference frame. Journal of Geophysical Research: Space Physics, 118, 3995–4004. doi:10.1002/jgra.50398)* that the assumption that the IP magnetic field fluctuations are frozen in at distances from the L1 Lagrange point to the Earth is valid, while over large distances, the frozen-in assumption will break down first for the fast solar wind. So the presence of magnetic field fluctuations in the slow solar wind has little effect on its quasi-stationary structure. At the same time, it is known that IP shocks usually propagate in the slow solar wind which has fluctuations in density. Matthaeus et al. *(Matthaeus et al., 2016)* investigated space-time correlation of plasma turbulence in the solar wind and revealed that the plasma frame slow wind correlation persists for larger time separation. Also, there are inhomogeneities along the front itself. In such a case, the collisionless shock front structures measured by SPEKTR-R and WIND might differ noticeably from each other. According to Eselevich and Eselevich, *(Eselevich, M. V., &Eselevich, V. G., 2005, Fractal Structure of the Heliospheric Plasma Sheet in the Earth's Orbit. Geomagnetism and Aeronomy, 45, 3, 326–336.),* the spatial scale at which the solar wind can be considered as uniform in density along the shock front in the ecliptic plane, is about (4 -8) • 10^6 km. This is a fairly large size along the shock front. Taking into account that the properties of He++ ions are investigated on the MHD scales magnetic field measurements onboard WIND can be used for shock analysis.

We took into account your comment about Figures 4 and 5 and expanded the description of Figure 4 (in new version this figure will change the number to 2 due to the revision of the article structure) to present our position:

Figure 4 represents an example of comparing the densities (absolute — both for protons and He++ ions, relative — for He++ ions) obtained on the SPEKTR-R and WIND satellites for the very first IP shock in our database — September 9, 2011.

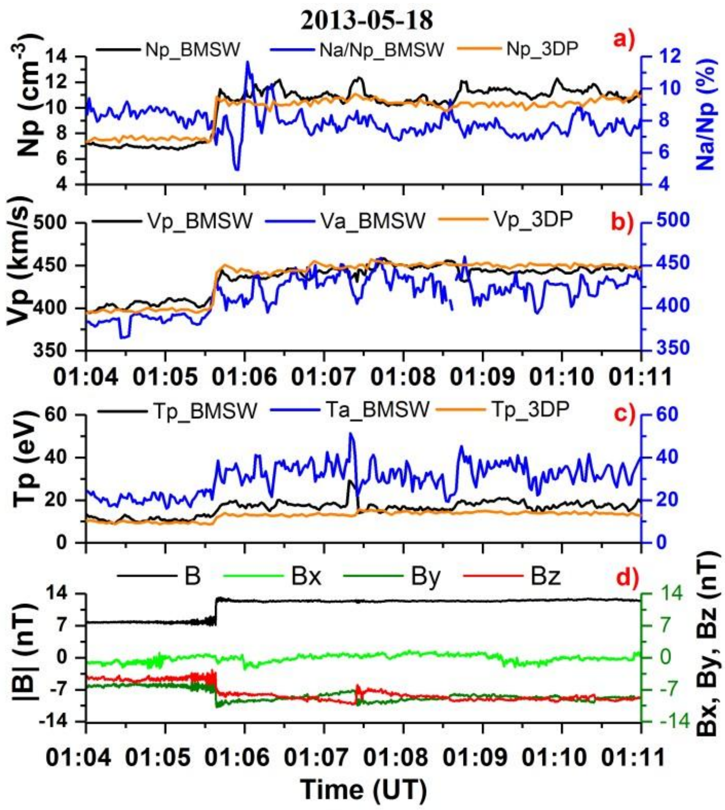
Data of both instruments show structures according to the parameters of the density of He++ ions. In column a), the blue arrows indicate 3 structures with an increased absolute density of He++ ions. They are located downstream, although their position relative to the IP shock ramp is slightly different, the coincidence of the shapes and the number of peaks indicates a good stability of the structures, given that we are talking about a perturbed region. A certain difference in the absolute values of the proton density, which is noticeable in column b), can be explained by the different sensitivity of the sensors of the instruments. Despite this, it should be noted that the relative change in the proton density coincides on both instruments and amounts Np2/Np1 = 1.85. The helium abundance Nα/Np is given in column c), representing three structures corresponding to those shown in column a). Also, the red arrows highlight the increase in the helium abundance Nα/Np immediately before the IP shock ramp, which is clearly visible from the data of the two instruments, as well as a sharp decline after ramp.



We changed Figure 5 by adding the proton density, velocity and temperature of the solar wind measured by the 3DP instrument installed on the WIND spacecraft for comparison.

Figure 5 shows that, despite the small fluctuations in the values, the velocity of the solar wind protons measured at different points in space coincides in numerical values. As for the protons density measured by different spacecraft, it should be taken into account the fact that instruments with sensors based on the Faraday cup measure the density much more accurately than electrostatic analyzers with detectors based on MCP. And for the proton temperature, the situation is opposite.

Thus, a comparison of the parameters of the plasma and the magnetic field measured at different points in space shows that there are both well-matched areas and different ones. Taking into account the fact that the dynamics of the behavior of He++ ions is studied on the MHD scale, the authors believe that it is possible to combine magnetic field measurements on WIND spacecraft with plasma measurements on SPEKTR-R satellite.



We expanded the description of Figure 5 and the following paragraph was inserted into the text of the article:

Figure 5 (panels a-c) shows the plasma data of the SPEKTR-P and WIND satellites measurements. The proton parameters are given in black for BMSW and in orange for the 3DP instruments, respectively. The blue color shows the parameters of alpha-particles according to the data of the BMSW instrument. Panel d of Fig. 5 shows the magnitude and components of the magnetic field according to the MFI instrument of the WIND satellite. There are areas with a good coincidence of parameters, and also areas with some differences in values, but in general, the data of the two instruments are similar in shape. It should be noted that the proton bulk velocity, measured by WIND and SPEKTR-R, are in good agreement with each other, and the slope of the IP ramp are the same for all proton parameters measured by different instruments. This fact confirms IP shock ramp stability on MHD scales during the shock propagation from WIND to SPEKTR-R.

Remark 2. Only a small number of events are considered (a total of 20) and I think this small subset is insufficient for a statistical study. E.g. the results presented in Fig. 6 seem not to be statistically significant.

Remark 3. Given the small number of events (point 2), and the fact that non-local magnetic field measurements are used (point 1), I do not think that the results presented in Fig.7 (and this is the main results of the manuscript) is statistically significant, and therefore not a robust result

Reply to Remark 2 and 3. (This text will be also added to the article) Unfortunately, due to the short period of the SPEKTR-R satellite, we are limited by the available amount of data recorded by the BMSW instrument.

We have increased statistics of events, for which we have processed data of the Earth's bow shock crossings by the SPEKTR-R in the period from 2011 to 2013.

To increase the statistics, we processed data of the Earth's bow shock crossings by the SPEKTR-R during the period from 2011 to 2013 year. The Figure 8 shows obtained results, superimposed with the existing data set. The estimation of the θ_{Bn} angle for the new events was made using the model (Verigin et al., 2003a.) for the shape of the bow shock and data from nearby satellites, including an estimate of the magnetic field direction. The new data set allowed us to supplement the area of quasi-parallel events, with an angle of $\theta_{Bn} < 45^o$. Despite the errors of this definition (shown in the Figure 8), there is a trend - the larger the θ_{Bn} angle is, the more helium abundance Nα/Np will increase after IP shock front. This trend coincides with the one already mentioned in the set of the IP shock fronts crossings - the helium abundance Nα/Np changes less in the quasi-parallel cases.

However, comparisons of the two sets of events show a significant difference in the values of the helium abundance Nα/Np change. At the IP shock front crossings, the helium abundance Nα/Np usually becomes less than in the unperturbed region, but in the case of the Earth's bow shock crossing, this parameter always increases, in some cases - by almost an order of magnitude. The literature usually describes the results of simulations performed for ions reflected from the front, but not for those that have passed beyond the ramp. However, a recent paper (Ofman et al., 2019) showed the possibility of a strong increase in the helium abundance Nα/Np behind the shock front. The data obtained by us are consistent with the results of modeling performed in this work.

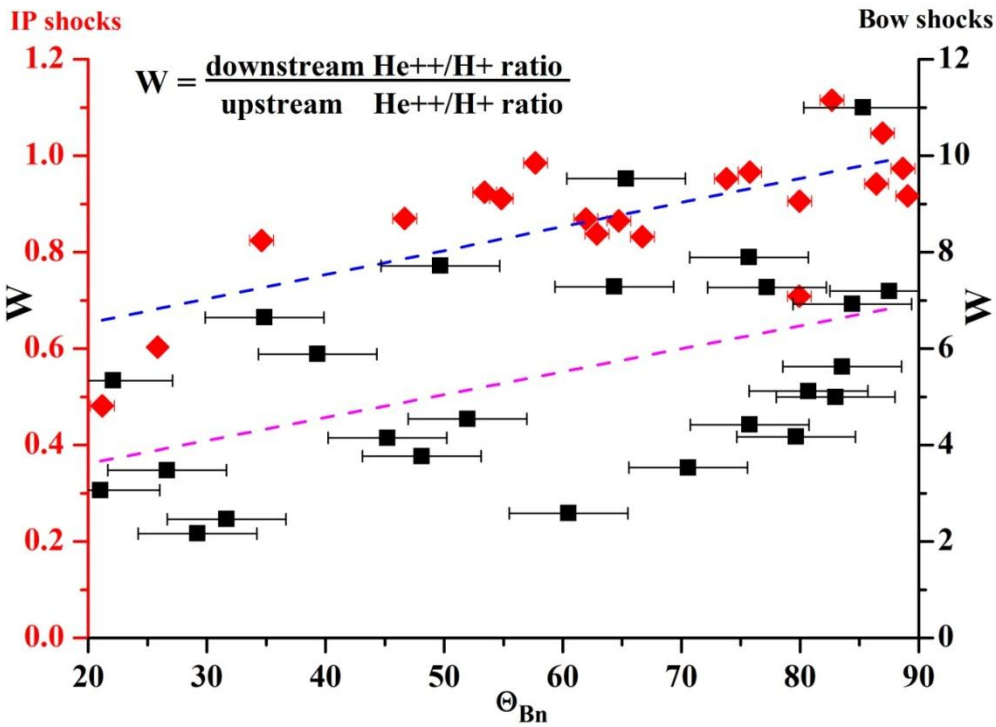


Figure 8 The dependence of the helium abundance Nα/Np change on the θ_{Bn} angle at the intersection of the shock front. Red marks show the events of the IP shock fronts crossings, black marks - the Earth's bow shock front crossings. The blue dashed line shows the trend for the first set, and the purple dashed line shows the trend for the second set. Errors in determining the θ_{Bn} angle are shown by bars.

Smaller issues:

1. The manuscript states that IPs are generated by solar flares, which is definitely not correct.

The interplanetary shocks are generated by fast phenomena of SW plasma (usually by two types pushing like a piston - High Speed Streams or fast ICMEs) when velocity difference between piston and undisturbed solar wind is higher than sound or Alfvenic speeds (e.g. Dryer, 1994; Berdichevsky et al., 2000; and references therein).

We are thankful to the reviewer for his/her indication of the inaccuracy, which was made in the text. We updated this description in the introduction.

2. Although I'm not a native speaker, the language in the manuscript has to be improved, and at several places, I had a hard time figuring out what the authors mean, e.g. "with a wavelength having a time scale of..."

We are grateful to the reviewer for his/her careful reading and comments about incorrect expressions and typos made during the layout of the article. We tried to fix all the errors we noticed.

Best regards,
Olga Sapunova