The Heliotail: Theory and Modeling

N. V. Pogorelov
Department of Space Science, University of Alabama in Huntsville, Huntsville, AL 35805, U.S.A.
E-mail: nikolai.pogorelov@uah.edu

Abstract. Physical processes are discussed related to the heliotail which is formed when the solar wind interacts with the local interstellar medium. Although astrotails are commonly observed, the heliotail observations are only indirect. As a consequence, the direct comparison of the observed astrophysical objects and the Sun is impossible. This requires proper theoretical understanding of the heliotail formation and evolution, and numerical simulations in sufficiently large computational boxes. In this paper, we review some previous results related to the heliotail flow and show new simulations which demonstrate that the solar wind collimation inside the Parker spiral field lines diverted by the heliopause toward the heliotail is unrealistic. On the contrary, solar cycle effects ensure that the solar wind density reaches its largest values near the solar equatorial plane. We also argue that a realistic heliotail should be very long to account for the observed anisotropy of 1–10 TeV cosmic rays.

1. Introduction
The heliopause is a tangential discontinuity formed due to the solar wind (SW) interaction with the local interstellar medium (LISM). It is an essential ingredient of the SW–LISM interaction pattern. Mathematically, it can be considered as a component of the solution to the three-dimensional (3D), MHD Riemann problem that is used to generate an initial distribution of quantities in the computational region surrounding the Sun. Physically, this is a surface that is expected to separate the SW and LISM plasma if the effects of finite resistivity and viscosity are ignored. Numerical simulations of the SW–LISM interaction have long history. They started from simplified statements of the problem, e.g., a hypersonic, thin shock layer approximation [1, 2], and further evolved into the full gas dynamics modeling of the upwind part of the interaction pattern [3], where the effect of charge exchange of the SW plasma and LISM neutral atoms was also included. The latter effect is of great importance [4, 5, 6] because the LISM is only partially ionized with the neutral hydrogen density, \( n_\infty \), being about three times greater than the proton density, \( n_\infty \). In principle, the SW–LISM interaction can be interpreted as a combination of blunt-body and supersonic jet flows. Both may be turbulent and experience MHD and kinetic instabilities. As shown in [7], there are similarities in the SW–LISM and comet-SW interactions, but charge exchange is a physical phenomenon that cannot be neglected in the distant heliosphere (beyond 10 AU from the Sun). A simple numerical model aimed to include the charge exchange into consideration was proposed in [8]. However, because of a very large mean free path, the neutral atom transport is essentially a kinetic process and ideally should be described by solving the Boltzmann equation. This approach was used to model the H-atom transport throughout the heliosphere initially neglecting the action of atoms on the plasma [9] and ultimately in a self-consistent fashion by solving the Euler gas
dynamics equations for plasma and kinetic Boltzmann equation for neutrals iteratively [10]. The latter paper followed the approach of [11] to perform numerical simulation in a closed region surrounding the Sun. These papers manifest the first simulations of the heliotail. The axially symmetric Euler–Boltzmann simulations of the SW–LISM interaction were extended to 3D and time-dependence much later [12]. Here multi-fluid models of the heliospheric interface proved to be useful [13, 14, 15, 16] because of their simplicity. In multi-fluid models, different Euler gas dynamics equations are solved for neutral atoms born in thermodynamically different regions of the heliosphere, e.g., in the pristine LISM, in the region where the LISM plasma is modified by the presence of the heliopause, in the inner heliosheath between the heliopause and the heliospheric termination shock, and in the supersonic SW. The multi-fluid approach made it possible to perform serial time-dependent and 3D simulations.

It is now known that the heliospheric and interstellar magnetic fields (HMF and ISMF) affect the heliopause and the heliotail. MHD models of the SW–LISM interaction were used in [17, 18, 19, 20]. The paper of [20], in particular, took into account charge exchange using a simplified approach similar to [8]. Three-dimensional effect of the ISMF orientation on the shape and rotation of the heliopause were addressed in [21] in purely MHD and [22] in multifluid MHD approaches. MHD-kinetic models have been developed and used in [23]–[40], in particular, to analyze the energetic neutral atom ENA fluxes being measured by the Interstellar Boundary Explorer (IBEX) and the effect of the choice of the the BV-plane (the plane formed by the velocity and magnetic field vectors in the unperturbed LISM) on the neutral H deflection discovered and discussed in [41, 42]. In [43, 44, 45], the results of comparison between multi-fluid and MHD-kinetic models have been presented. In principle, a good qualitative agreement has been observed, although it should be understood that hydrodynamic effects are likely to produce artifacts on the neutral atom transport, especially in large computational boxes. Additionally, only MHD-kinetic models can ensure accurate energy distribution of neutral atoms. We are focused on the heliotail flow in this paper and by no means try to provide a comprehensive list of references.

2. Heliotail Theory

In [46], two extreme cases of the SW–LISM interaction have been considered. One of them assumed a subsonic, incompressible flow of the SW beyond the termination shock and a subsonic LISM. Another one, assumed the SW propagation into a magnetized vacuum. The former model is possible only if the ISMF is taken into account [47, 36]. Otherwise, the LISM is now known to be supersonic and a bow shock should, in principle, be expected [1]. The model of the SW expansion into the magnetized vacuum, on the other hand, is an idealization which does not take into account the presence of charge exchange even in a very slow LISM. However, it correctly reproduces the formation of the heliotail. Summarizing, charge exchange is known now to have a profound effect on the SW–LISM interaction and on the heliotail, in particular.

The theory of the heliotail flow was considered in detail more than 30 years ago in [48]. The knowledge of the SW–LISM interaction was very basic then as compared with nowadays, both because of the abundance of new observational data and availability of more detailed models. In [48], the SW flow beyond the termination shock was generated analytically in a way close to that used in [46]. The analysis of the solution showed the collimation of the SW flow inside the Parker spiral field deflected to the heliotail and creating tornado-like structures. The reason of such collimation was attributed to the HMF tension exerted on the SW plasma. It was suggested for this reason that a possibility of the heliotail splitting into two lobes should not be excluded. Additionally, it was acknowledged that according to [49] the parcels of plasma confined within the spiral field line should be subject to the kink instability. One should notice that such instability, as will be shown in the next section (see also [50]), eliminates the reason for the SW to be collimated. The solution similar to [48] have been proposed recently in [51]
with essentially the same conclusions. Neither of those theoretical analyses took into account charge exchange processes.

Another interesting theoretical model has been proposed in [52] where the focus is on the tailward flattening of the heliopause in the direction perpendicular to both the incoming flow and the large-scale interstellar magnetic field (see, e.g., [22], where the effect of the magnetic field strength and the angle between the magnetic field and velocity vectors in the unperturbed LISM has been considered). This analytical model is an improvement over [53, 54] where the heliotail was assumed to have a circular cross-section.

It is understood, however, that the problem is too complicated to be solved analytically, especially taking into account the necessity to accurately describe charge exchange that clearly determines the length of the heliotail.

3. Heliotail Modeling
Simulations of the SW–LISM interaction require an accurate treatment of the boundary conditions at subsonic exit boundaries. This issue is especially complicated for subsonic-supersonic transitions, where solutions to the Riemann problem based on the LISM and SW parameters at the exit produce a shock slowly propagating upwind towards the Sun [55, 17, 56, 57]. It has been shown in [58] that if the LISM is supersonic (and it indeed is, according to our current knowledge, see [59]) the SW in the heliotail will ultimately become supersonic as well at distances of about 4,000 AU. The reason for this is charge exchange which is continuously fed by an inexhaustible reservoir of interstellar neutral atoms. As a result of this charge exchange, hotter SW ions are substituted with cooler secondary ions with properties of the parent neutral atoms. Newly created H atoms are energetic enough to leave the heliotail region.

In [58], a gasdynamic model of the SW–LISM interaction was used. Magnetic fields (both the HMF and the ISMF) are important once we are interested in the shape of the heliopause and its orientation in space. This is done through the magnetic pressure which occurs in the boundary conditions at the heliopause. Magnetic fields also shape the SW and LISM flows. Additionally, the HMF–ISMF coupling may result in magnetic reconnection at the heliopause. In [60, 50], we have performed simulations in the MHD-kinetic approximation assuming the unipolar HMF. Such approximation is sometimes useful if it is impossible to resolve the heliospheric current sheet (HCS), which serves as the magnetic equator for the HMF [61, 62, 63]. Although our results are in general agreement with axially-symmetric simulations without magnetic field [58], there are some differences. Primarily, we found that instability of the heliopause results in substantial mixing of the the SW and LISM plasmas (see Fig. 1). The SW plasma becomes fast magnetosonic at 4,200 AU from the Sun. The computational region was chosen to be 6,000 AU cubed. The number of particles in the Monte Carlo simulation of neutral atoms was $1.5 \times 10^{10}$. The SW quantities at 1 AU were spherically symmetric: the plasma density $n_p = 7.4 \, \text{cm}^{-3}$, temperature $T = 51100 \, \text{K}$, velocity $V_R = 450 \, \text{km/s}$, and the radial component of magnetic field $B_R = 37.5 \, \mu \text{G}$. The SW is of course neither steady nor spherically symmetric. The choice of the LISM properties were the same as in [64]. Notice that the LISM properties have been updated recently using IBEX observations [59] and modeling [40]. The top panel of this figure shows the plasma density distribution in the solar equatorial plane. The solid line is the isoline of the fast magnetosonic Mach number equal to 1. Once the flow at the exit boundary becomes superfast magnetosonic, no boundary conditions are required. This is a substantial positive byproduct of long-tail simulations. The middle panel shows the heliopause, the position of which is strictly determined with a level-set method. Yellow and blue colors correspond to the simulation with $B_{\infty}$ equal to 3 $\mu \text{G}$ and 4 $\mu \text{G}$, respectively. The direction of the field is at $30^\circ$ to the LISM velocity vector and the $BV$-plane coincides with the hydrogen deflection plane defined by the neutral H velocity vectors in the unperturbed LISM and in the inner heliosphere. We note here that our
Figure 1. MHD-plasma/kinetic-neutrals simulation of the SW–LISM interaction. (Top panel) Plasma density distribution in the solar equatorial plane. The black lines outline the fast magnetosonic transition, i.e., the plasma flow is subfast magnetosonic between these lines. (Middle panel) The shape of the heliopause for two different ISMF strengths is shown (yellow and blue for $B_{\infty} = 3 \mu$G and $4 \mu$G, respectively). (Bottom panel) HMF line behavior initially exhibits a Parker spiral, but further tailward it becomes unstable. Also shown are ISMF lines draping around the heliopause. The distribution of the plasma density is shown in the semitransparent equatorial plane. (From [50] with permission of the AAS.)
coordinate system, which we call the heliospheric system, has the \( z \)-axis parallel to the Sun’s rotation axis, while the \( x \)-axis belongs to the plane formed by the \( z \)-axis and \( \mathbf{V}_\infty \), and is oriented upstream the LISM flow. The \( y \)-axis completes the right coordinate system. We clearly see that the heliopause is Kelvin–Helmholtz unstable. The Rayleigh–Taylor instability of its nose is not revealing itself in this simulation because this requires much higher resolution in the upwind region. The heliopause extends to the heliocentric distance of 5,000 AU showing no “croissant” structure reported in multi-fluid simulations [63]. We will return to this subject later. It is worth mentioning at this point is that our own multi-fluid solution of the same problem does not ensure the SW acceleration to superfast magnetosonic speeds. This is in contrast with the MHD-kinetic solution. The reason for this is entirely due to the hydrodynamic artifacts intrinsic to multi-neutral-fluid simulations. In particular, we have found a region inside the helitail (and close to the equatorial plane) which is not crossed by the LISM H streamlines. The absence of (or considerable depression in) charge exchange prevents the natural evolution of the SW flow in the tail. In kinetic simulations, interstellar H atoms easily cross this region due to the chaotic component in their velocity.

The bottom panel of Fig. 1, shows the kink instability in the SW plasma described in [48, 49] and recently rediscovered in [51, 63]. According to [48], this instability is theoretically unconditional. However, numerical simulations are performed on a grid and therefore some wave lengths are inevitably suppressed. We see that the HMF lines initially belonging to the Parker spiral field are suddenly destroyed and become chaotic when the SW temperature decreases. We addressed this phenomenon in [50] and will show some additional details below.

To understand the origin of the very short, croissant-shaped heliotail in [63], we preformed our own simulation using the same set of the LISM and SW parameters. However, for simplicity and to avoid problems with the subfast magnetosonic exit boundary conditions, we assumed \( B_\infty = 0 \). As stated in [63], this assumption cannot eliminate the effect of the heliotail separation into two lobes as proposed in [48]. For completeness, we reproduce our figure from [50] (see Fig. 2). The heliopause is very well seen in panel \( e \), which shows \(|\nabla \times \mathbf{B}|\), which is proportional to the magnitude of the electric current (we used arbitrary units here), and is especially large near the heliopause. Panels \( a–c \) show the line \( B_y = 0 \). It starts at the point where the inner boundary is crossed by the Sun’s rotation axis. Magnetic field vanishes on this line while it belongs to the supersonic SW region. Because we assumed zero tilt between the Sun’s magnetic and rotation axes, this line indicates a singularity where the Parker spiral magnetic field degenerates into a non-magnetic line. On crossing the termination shock, the Parker spiral and the line \( B_y = 0 \) in the figure turn tailward. The HMF strength is not zero any more on this line, but it is still small because the spiral component should be dominant. One can see that the plasma density is enhanced along this line. The nature of this enhancement is described in [48]. In addition to the magnetic field strength becoming larger on the spiral field lines that start at the inner boundary with increasing spherical angle \( \theta \), the spiral field exerts tension collimating the SW flow towards the center of the spiral field (the line \( B_y = 0 \)). Because of the kink instability [49], the spiral field starts to disappear at about 1,000 AU from the Sun along the \( x \)-axis tailward. We also notice that the start of this instability coincides with the decrease in plasma temperature, as was also discussed in [48]. Once the spiral field becomes chaotic, there is no more reason for the solar wind to remain collimated. However, as seen from panels \( e–f \), only a narrow isthmus connects the heliotail lobes. However, the separation of the lobes is much less than it is shown in [63], and the heliotail does not resemble “a croissant.” We also remember that this is exactly the region where the SW flow remains subfast magnetosonic in our multi-fluid simulations mentioned earlier. The shape of the heliotail shown in Fig. 1 is totally different: the flow collimation observed initially inside the spiral field completely disappears if neutral atoms are treated kinetically. It is worth emphasizing that no heliotail lobes are observed in the MHD-kinetic simulation of [65], where the statement of the problem is very close to our kinetic simulation.
Figure 2. Meridional cuts of a multi-fluid simulation of the SW–LISM interaction with the boundary conditions from [63] without ISMF. (a) The distribution of \( B_y \). The black lines show the level \( B_y = 0 \). The HMF is assumed to be unipolar. (b) The distribution of plasma density shows its increase toward the center of the Parker spiral in the tail and eventual destruction of the regular magnetic field due to kink instability. (c) The distribution of the plasma temperature. (d) The distribution of the plasma \( \beta \) (log scale) shows that the flow is weakly affected by the HMF, except the regions identified by the isoline \( \beta = 1 \). (e) The distribution of \( |\nabla \times B| \) shows substantial currents in the lobes. (f) The distribution of the plasma density across the tail \( (x = 200 \mathrm{AU}) \) shows the northern and southern lobes. The solid line outlines the heliopause. (From [50] with permission of the AAS.)
There is another aspect related to the multi-fluid simulation shown in Fig. 2. As shown in [50], the lobes disappear also if the HMF is dipolar while the tilt of the Sun’s magnetic axis with respect to its rotation axis is zero (or small, by continuity). Such statement of the problem is more realistic than the unipolar statement. Besides, there is no difficulty in resolving the HCS in this case. This means, that the two-lobe structure predicted in [48] and shown in [63] is not only an artifact of the multi-fluid treatment of neutral atoms, but also is heavily based on the assumption of the unipolar HMF.

It is argued in [50] that the solar cycle effects related to the latitudinal variations in the boundary between slow and fast SW and the tilt between the Sun’s magnetic and rotation axes (and changes in the HMF polarity every 11 years) substantially modify solutions that assume a spherically-symmetric SW. While this is surely true, it is interesting to see the solar cycle effects remaining in the framework of the unipolar HMF. This solution is shown in Fig. 3. It is immediately seen here that the collimation effects are completely swept away by the solar cycle. As one would have expected, the denser plasma is concentrated around the equatorial plane, because the slow SW is always denser than the fast wind. By choice, \( B_y \) is negative for \( x - x_\odot > 0 \) and positive for \( x - x_\odot < 0 \) in the SW region ahead of the termination shock. The flow carrying the positive polarity hits the heliopause and diverts tailward through the north-
and south-pole axes. Conversely, the SW carrying negative polarity just continues to move to the left. The boundary between these two regions is clearly seen in the figures. It is unstable as in the spherically symmetric SW simulations, but behaves quite differently. The black lines are separating the SW from the LISM. It is seen that the heliopause instability results in the clumps of LISM plasma penetrating into the SW, and vice versa. The “jets” that show up in the simulations ignoring the solar cycle disappear. One of the reasons is that the changes in the latitudinal extent of the slow wind cause changes in the HMF strength and tightening of the spiral field lines. As this frequently happens, a stronger effect made a weaker effect invisible. Another example of this can be found in [66], where the variations of the SW velocity due to the presence of the HCS in the ideal MHD simulation without neutral atoms were completely wiped out by the flow deceleration with the heliocentric distance inside that termination shock because of charge exchange between interstellar atoms and SW protons.

While the solution that takes solar cycle effects into account is a step forward compared with the solutions assuming the unipolar HMF in a spherically symmetric SW, the changes in the angle between the Sun’s rotation and magnetic axes, as well as the dipolar field flipping at solar maxima, are known to have a profound effect on the SW–LISM interaction. Figure 4 shows the same quantities as in Fig. 3 when the tilt is also the function of solar cycle with the HMF polarity changing to the opposite each solar maximum. Although the solutions look quite similar in the upwind LISM, there are noticeable differences in the heliopause shape. In essence, the heliopause is narrower in the latter simulation. First of all, this is due to the change of the HMF polarity every 11 years. The stability and numerical reconnection across the heliopause are therefore different in the dipolar-field case. Besides, clearly there exist certain regions in the heliotail where the HMF is poorly resolved due to its frequent changes of polarity caused by solar rotation. Although the energy and momentum are preserved in those regions, the numerical dissipation is elevated. Additional investigations should be performed to estimate the importance of this. Such a study is complicated by the necessity to perform simulations in computational boxes extending into the tail direction possibly to 18–20 thousand AU. Such distances are necessary if we want to explain flux anisotropy of 1–30 TeV cosmic rays observed in multiple air shower observations [67].

4. Discussion and conclusions

We have discussed very briefly the theoretical results related to the heliotail topology and flow inside it. Because of the complexity of the flow, especially due to highly nonlinear effects related to charge exchange, the applicability of such theoretical studies is limited, although the results themselves are inspiring. In particular, we have shown that the theoretical analyses of [48, 51], however sophisticated and accurate they are, inevitably miss certain details of the heliotail flow. Although some features of the above-mentioned theoretical results are indeed seen in the simplified problem statements similar to those accepted by theorists (see [50, 63]), the reality appears to be much more complicated. We have presented the results of a series of simulations which show that neutral atoms and their charge exchange with ions, as well as the solar cycle effects, turn out to be damaging to analytical solutions. On the other hand, this is not surprising because the physical processes excluded from the theoretical models described above play the major role in the SW–LISM interaction. Our comparison of the numerical models of different level of sophistication is also rather instructive. In particular, the models that try to reproduce the theoretical predictions of [48] by a radical simplification of the statement of the problem, turn out to be sensitive to the choice of the neutral-atom-transport model. We have demonstrated that multi-fluid models of the SW–LISM interaction can produce hydrodynamic artifacts that especially affect the heliotail because of its length. Again, this is not surprising because the differences between kinetic and hydrodynamic models are expected to increase at longer times and distances. It should be remembered that we are talking about collisionless plasma here,
and any multi-fluid model is a simplification of real kinetic processes determining the transport of neutral atoms and their charge exchange with ions. Although good qualitative agreement between the MHD-kinetic and multi-fluid models, as described in [44, 45, 68], is possible, certain adjustments in the boundary conditions are usually necessary to have a quantitative agreement. While such adjustments are plausible if both types of simulations are performed and compared, the difference in the solutions can become large in new simulations, where no “experience” can substitute the accurate treatment of the problem. We have also demonstrated that the solar cycle destroys the flow-collimation effect described in [48, 51] even if the HMF is assumed unipolar. The unipolar assumption, however convenient it is to avoid difficulties in the HCS resolution, may be very dangerous. The MHD equations are invariant with respect to the change of sign of the $B$ vector. However, solutions do depend on the change of sign of the HMF only. This occurs through the coupling between the HMF and ISMF at the heliopause. The positive and negative HMF values are also coupled across the HCS. This can be seen, e.g., in the presented simulations that take into account the flipping of the magnetic dipole of the Sun at solar maxima and the corresponding change of the HMF polarity.

Numerical modeling of the 1–30 TeV galactic cosmic ray flux in [67] requires a long heliotail. Otherwise, very high energy cosmic rays will not be affected noticeably by the presence of the
heliotail. For this reason, a short, croissant-shaped heliosphere is not suitable. We have also shown here that this is incompatible with the realistic SW model. While the heliotail cannot be observed from outside, its features are seen in IBEX measurements [69, 53]. No SW collimation, or two-lobe structure, is necessary to see the observed heliotail features in numerical simulation, as shown, e.g., in [40].

Acknowledgments

This work was supported, in part by NASA grants NNX14AJ53G, NNX14AF41G, NNX14AF43G, NNX15AN72G, and NNX16AG83G, and DOE Grant DE-SC0008334. This work was also partially supported by the IBEX mission as a part of NASA’s Explorer program. We acknowledge NSF PRAC award OCI-1144120 and related computer resources from the Blue Waters sustained-petascale computing project. Supercomputer time allocations were also provided on SGI Pleiades by NASA High-End Computing Program award SMD-15-5860 and on Stampede by NSF XSEDE project MCA07S033.

I highly appreciate discussions at the team meeting “Heliosheath Processes and Structure of the Heliopause: Modeling Energetic Particles, Cosmic Rays, and Magnetic Fields” supported by the International Space Science Institute in Bern, Switzerland.

Bibliography

[1] Baranov V B, Krasnobaev K V and Kulikovskii A G 1971 Soviet Physics Doklady 15 791
[2] Baranov V B and Krasnobaev K V 1971 Cosmic Research 9 568
[3] Baranov V B, Lebedev M G and Ruderman M S 1979 Astrophys. Space Sci. 66 441–451
[4] Blum P W and Fahr H J 1969 Nature 223 936–937
[5] Wallis M K 1975 Nature 254 202
[6] Wallis M 1971 Nature Physical Science 233 23–25
[7] Baranov V B, Ermakov M K and Lebedev M G 1983 Fluid Dynamics 17 754–759
[8] Baranov V B 1983 Fluid Dynamics 17 754–759
[9] Baranov V B, Lebedev M G and Malama I G 1991 Astrophys. J. 375 347–351
[10] Baranov V B and Malama Y G 1993 J. Geophys. Res. Space Phys. 98 15
[11] Matsuda T, Fujimoto Y, Shima E, Sawada K and Inagushi T 1989 Progress of Theoretical Physics 81 810–822
[12] Izmodenov V V and Baranov V B 2006 ISSI Scientific Reports Series 5 67–136
[13] Pauls H L, Zank G P and Williams L L 1995 J. Geophys. Res. Space Phys. 100 21595–21604
[14] Zank G P, Pauls H L, Williams L L and Hall D T 1996 J. Geophys. Res. Space Phys. 101 21639–21656
[15] Pauls H L and Zank G P 1997 J. Geophys. Res. Space Phys. 102 19779–19788
[16] Fahr H J, Kausch T and Scherer H 2000 A&A 357 268–282
[17] Pogorelov N V and Dryer M 1976 Astrophys. J. 205 895–899
[18] Baranov V B, Ermakov M K and Lebedev M G 1983 Fluid Dynamics 17 754–759
[19] Baranov V B, Lebedev M G and Malama I G 1991 Astrophys. J. 375 347–351
[20] Pogorelov N V and semenov A Y 1997 A&A 321 330–337
[21] Pogorelov N V and Matsuda T 1998 J. Geophys. Res. Space Phys. 103 237
[22] Ratkiewicz R, Barnes A, Molvik G A, Spreiter J R, Stahara S S, Vinokur M and Venkateswaran S 1998 A&A 335 363–369
[23] Linde T J, Gombosi T I, Roe P L, Powell K G and Doezema D L 1998 J. Geophys. Res. Space Phys. 103 1889
[24] Pogorelov N V, Zank G P and Ogino T 2004 Astrophys. J. 614 1007–1021
[25] Pogorelov N V, Zank G P and Ogino T 2006 Astrophys. J. 644 1299–1316
[26] Izmodenov V, Alexashov D and Myasnikov A 2005 A&A 437 L35–L38
[27] Heerikhuisen J, Florinski V and Zank G P 2006 Journal of Geophysical Research (Space Physics) 111 A06110
[28] Heerikhuisen J, Pogorelov N V, Zank G P and Florinski V 2007 Astrophys. J. Lett. 655 L53–L56
[29] Pogorelov N V, Heerikhuisen J and Zank G P 2006 Astrophys. J. Lett. 675 L41
[30] McComas D J, Allegri F, Bochsler P and et al 2009 Science 326 959
[31] Schwartzron N A, Bzowski M, Crew G B, Gruntman M, Fahr H, Fichtner H, Frisch P C, Funsten H O, Fasel S, Heerikhuisen J, Izmodenov V, Kucharek H, Lee M, Livadiotis G, McComas D J, Moebius E, Moore T, Mukherjee J, Pogorelov N V, Prested C, Reisenfeld D, Roelof E and Zank G P 2009 Science 326 966
[32] Izmodenov V, Malama Y G, Ruderman M S, Chalov S V, Alexashov D B, Katsushina O A and Provornikova E A 2009 Space Sci. Rev. 146 329–351
[33] Pogorelov N V, Heerikhuisen J, Mitchell J J, Cairns I H and Zank G P 2009 Astrophys. J. Lett. 695 L31–L34
[34] Heerikhuisen J and Pogorelov N V 2009 Astrophys. J. Lett. 695 L58–L61
Heerikhuisen J, Pogorelov N V, Zank G P, Crew G B, Frisch P C, Funsten H O, Janzen P H, McComas D J, Reisenfeld D B and Schwadron N A 2010 Astrophys. J. Lett. 708 L126–L130

Chalov S V, Alexashov D B, McComas D, Izmodenov V V, Malama Y G and Schwadron N 2010 Astrophys. J. Lett. 716 L99–L102

Zank G P, Heerikhuisen J, Pogorelov N V, Burrows R and McComas D 2010 Astrophys. J. 708 1092–1106

Heerikhuisen J and Pogorelov N V 2011 Astrophys. J. 738 29

Pogorelov N V, Heerikhuisen J, Zank G P, Borovikov S N, Frisch P C and McComas D J 2011 Astrophys. J. 742 104

Izmodenov V V, Alexashov D B and Ruderman M S 2014 Astrophys. J. Lett. 795 L7

Katushkina O A, Izmodenov V V and Alexashov D B 2015 Astrophys. J. Lett. 808 L18

Lallement R, Quémerais E, Bertaux J L, Ferron S, Koutroumpa D and Pellinen R 2005 Science 307 1447–1449

Lallement R, Quémerais E, Koutroumpa D, Bertaux J L, Ferron S, Schmidt W and Lamy P 2010 Twelfth International Solar Wind Conference 1216 555–558

Alexashov D and Izmodenov V 2005 A&A 439 1171–1181

Müller H R, Florinski V, Heerikhuisen J, Izmodenov V V, Scherer K, Alexashov D and Fahr H J 2008 A&A 491 43–51

Pogorelov N V, Heerikhuisen J, Zank G P and Borovikov S N 2009 Space Sci. Rev. 143 31–42

Parker E N 1961 Astrophys. J. 134 20

Florinski V, Pogorelov N V, Zank G P, Wood B E and Cox D P 2004 Astrophys. J. 604 700–706

Yu G 1974 Astrophys. J. 194 187–202

Roberts P H 1956 Astrophys. J. 124 430

Pogorelov N V, Borovikov S N, Heerikhuisen J and Zhang M 2015 Astrophys. J. Lett. 812 L6

Drake J F, Swisdak M and Opher M 2015 Astrophys. J. Lett. 808 L44

Kleimann J, Röken C, Fichtner H and Heerikhuisen J 2016 Astrophys. J. 816 29

Schwadron N A, Adams F C, Christian E R, Desiati P, Frisch P, Funsten H O, Jokipii J R, McComas D J, Moebius E and Zank G P 2014 Science 343 988–990

Isenberg P A, Forbes T G and Möbius E 2015 Astrophys. J. 805 153

Pogorelov N V and Semenov A Y 1996 Computational Mathematics and Mathematical Physics 36 395–404

Pogorelov N V 2000 Astrophys. Space Sci. 274 115–122

Kulikovskii A G, Pogorelov N V and Semenov A Y 2001 Mathematical Aspects of Numerical Solution of Hyperbolic Systems (Chapman & Hall/CRC, London, UK/Boca Raton, Florida, USA)

Izmodenov V V and Alexashov D B 2003 Astronomy Letters 29 58–63

McComas D J, Bzowski M, Frisch P, Fuselier S A, Kubiak M A, Kucharek H, Leonard T, Möbius E, Schwadron N A, Sokół J M, Swaczyna P and Witte M 2015 Astrophys. J. 801 28

Pogorelov N V, Borovikov S N, Bedford M C, Heerikhuisen J, Kim T K, Kryukov I A and Zank G P 2013 Modeling Solar Wind Flow with the Multi-Scale Fluid-Kinetic Simulation Suite Numerical Modeling of Space Plasma Flows (ASTRONUM-2012) (Astronomical Society of the Pacific Conference Series vol 474) ed Pogorelov N V, Audit E and Zank G P p 165

Czechowski A, Strumik M, Grygorczuk J, Grzedzielski S, Ratkiewicz R and Scherer K 2010 A&A 516 A17

Borovikov S N, Pogorelov N V, Burlaga L F and Richardson J D 2011 Astrophys. J. Lett. 728 L21

Opher M, Drake J F, Zieger B and Gombosi T I 2015 Astrophys. J. Lett. 800 L28

McComas D J, Alexashov D, Bzowski M, Fahr H, Heerikhuisen J, Izmodenov V, Lee M A, Möbius E, Pogorelov N, Schwadron N A and Zank G P 2012 Science 336 1291

Izmodenov V V and Alexashov D B 2015 Astrophys. J. Suppl. 220 32

Pogorelov N V, Borovikov S N, Zank G P and Ogino T 2009 Astrophys. J. 696 1478–1490

Zhang M, Zuo P and Pogorelov N 2014 Astrophys. J. 790 5

Alouani-Bibi F, Opher M, Alexashov D, Izmodenov V and Toth G 2011 Astrophys. J. 734 45

McComas D J, Dayeh M A, Funsten H O, Livadiotis G and Schwadron N A 2013 Astrophys. J. 771 77