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Solar wind proton reflection and injection to the ACR regime at the parallel termination shock

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Abstract. Our recent kinetic model for the parallel solar wind termination shock describes the ion shock transit under the influence of a decelerating electrostatic potential and the turbulent wave-particle interaction with electrostatic plasma waves. Due to this diffusive interaction, a certain number of ions are reflected at the shock. These ions propagate with a bulk velocity comparable to the bulk velocity of the incoming solar wind backwards into the inner heliosphere. They undergo strong pitch-angle diffusion as they interact with the interplanetary Alfvénic turbulence similar to freshly ionized pick-up ions (PUIs). Their distribution function is hence isotropized to a shell in velocity space. Since their velocity magnitude in the wind frame is higher (about two times) than the estimated PUI velocity, part of the reflected and isotropized ions can directly enter an acceleration process (diffusive or stochastic, respectively) without the necessity of a pre-acceleration. This means that an additional self-initialized seed population for the injection into the anomalous cosmic ray (ACR) acceleration is shown to appear due to shock reflected solar wind ions.

1 Introduction

Collisionless plasma shock waves (i.e. no binary ion collisions occuring at the shock passage) in magnetized plasmas are characterized by the magnetic field orientation with respect to the shock normal. The two extreme cases are the perpendicular and the parallel shock. The denotation "perpendicular" or "parallel", respectively, refers to the orientation of the magnetic field vector with respect to the shock normal vector. In the parallel case, no Lorentz force acts on the gyroaveraged motion of the plasma particles. Due to the Parker spiral magnetic field, a quasi-perpendicular shock is expected during most of the time at the heliospheric boundary (Parker, 1958). Both VOYAGER crossings are also interpreted to have occured at a quasi-perpendicular magnetic field orientation (Stone et al., 2005; Burlaga et al., 2008; Li et al., 2008). However at the Earth bow shock, quasi-parallel shock crossings are observed, e.g. by CLUSTER (Shevyrev et al., 2007; Lucek et al., 2008). A quasi-parallel field orientation is also expected at the solar wind termination shock during changes in the magnetic sector structure (Fahr et al., 2008) and, more or less permanently, at high heliographic latitudes according to the Parker field geometry. The influence of the magnetic field increases with its angle to the shock normal. At small deviations from the parallel orientation, we expect a similar behavior of the particles to the purely parallel case. Therefore, we also here address to quasi-parallel shocks with our model. Some properties of quasi-parallel shocks are extensively discussed both from the observational and the simulational side (in for example Krasnoselskikh et al., 2002; Treumann and Scholer, 2002; Lucek et al., 2008; Verscharen and Fahr, 2008a).

We present a considerable advancement of our recent model (Verscharen and Fahr, 2008a; Fahr and Verscharen, 2008) by changing to a time-dependent description of the shock crossing, which asymptotically leads to a stationary solution of the handled differential equation. This allows for a kind of a microscopic kinetic analysis of the plasma at each position during the transit. The model assumes an electrostatic field as the source of deceleration because the magnetic field cannot interact with the ion flow at the parallel field orientation. If the electrostatic field has the necessary properties to decelerate the ions, it will–due to their other sign of charge–accelerate the very light electrons. This situation leads to a two-stream instability which drives electrostatic plasma waves to arrange identical bulk velocities for both ions and electrons on the downstream side of the shock.

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There might be other wave-particle interactions also occuring at the shock, like scattering with whistler or Alfvén waves or further instabilities. For a parallel magnetic field orientation, however, we here only take the two-stream instability into account because it turns out to be a very efficient way to yield a quasineutral downstream flow. Also a possible excitation of plasma turbulence and other precursor modifications due to reflected ions in the upstream region are not treated in our model (for a comprehensive overview, see for example Quest, 1988).

The governing Boltzmann-Vlasov equation can be transformed to an equation of Fokker-Planck type that is solved with the aid of Itō's calculus for stochastic differential equations. This method was already succesfully applied in space physics before (Achterberg and Krulls, 1992; Chalov et al., 1995; Dworsky and Fahr, 2000).

In Sect. 2, we go through the kinetic modelling and the governing equations up to a set of integrable stochastic differential equations. Sect. 3 shows the results of the numerical integration. A discussion of the results and a comparison with earlier results and observations is given in Sect. 4. Finally, the conclusions in Sect. 5 summarize the work and give an outlook to possible future investigations.

2 Kinetic modelling

We start with a general Boltzmann-Vlasov equation for the plasma protons in one dimension with the stream line coordinate s and the velocity $w_\parallel$ in parallel direction:

$$\frac{\partial f}{\partial t} + w_\parallel \frac{\partial f}{\partial s} + \frac{\mathrm{d}w_\parallel}{\mathrm{d}t}\frac{\partial f}{\partial w_\parallel} = \mathrm{coll}\, f \tag{1}$$

with the Boltzmann collision term on the right hand side (see e.g., Lifshitz and Pitaevskii, 1981).

The force term is identified with the deceleration due to the electrostatic potential. According to Verscharen and Fahr (2008a), it can be written as

$$\frac{\mathrm{d}w_\parallel}{\mathrm{d}t} = U\frac{\mathrm{d}U}{\mathrm{d}s} \tag{2}$$

with the ion bulk velocity U, which is the first moment of the ion distribution function. This expression was derived from the Euler equation for the case of a high-Mach number shock. Nevertheless, it is also at a lower Mach number a reasonable formulation for the force term in Eq. (1) since it describes the deceleration of a proton as the consequence of a gradient in the bulk velocity profile. This means, a particle with velocity w at position s is decelerated by the same amount as a particle with velocity $U(s)$ at the position s due to the external force. In the Euler equation, a quiet parallel magnetic background field has no influence on the plasma flow. Furtheron, we take only electrostatic plasma waves as a consequence of a two-stream instability into account and, hence, the magnetic field does not play a role (except for its parallel orientation) in our model, which is a difference to other models for parallel shock waves taking into account whistler waves or Alfvén waves as stated above. Since the solar wind is a collisionless plasma, the collision term is not taken in its classical form. The wave-particle interaction with electrostatic plasma waves leads to a temporal change of the distribution function instead of the collision term:

$$\mathrm{coll}\, f \rightarrow \left(\frac{\delta f}{\delta t}\right)_{\mathrm{wp}}, \tag{3}$$

which can be expressed as a diffusion term in velocity space:

$$\left(\frac{\delta f}{\delta t}\right)_{\mathrm{wp}} = \frac{\partial}{\partial w_\parallel} D_\parallel \frac{\partial f}{\partial w_\parallel} \tag{4}$$

(Kadomtsev, 1965) with a diffusion coefficient $D_\parallel$, which can be written as

$$D_\parallel = \frac{\sqrt[3]{\frac{4m_\mathrm{p}}{m_\mathrm{e}}}}{\sqrt{3}}\left(\frac{m_\mathrm{e}}{m_\mathrm{p}}\right)^2 \omega_\mathrm{p}(u_\mathrm{e} - U)^2 \tag{5}$$

in our case (Verscharen and Fahr, 2008a).

Altogether, our Boltzmann equation can be transformed to the conservation law form

$$\frac{\partial f}{\partial t} = -\frac{\partial}{\partial s}\left(w_\parallel f\right) - \frac{\partial}{\partial w_\parallel}\left(U\frac{\mathrm{d}U}{\mathrm{d}s} f\right) + \frac{\partial^2}{\partial w_\parallel^2}\left(D_\parallel f\right), \tag{6}$$

which is also referred to as the Fokker-Planck form. The advantage of a transport equation in this form is the equivalence of this second-order partial differential equation with a system of ordinary differential equations according to Itō's calculus for stochastic differential equations (for an extended discussion see e.g. Gardiner, 1994). In the very general case, such an equation has the form

$$\begin{aligned}\frac{\partial f(\boldsymbol{x},t)}{\partial t} &= -\frac{\partial}{\partial \boldsymbol{x}}\left(\boldsymbol{\mathcal{A}}(\boldsymbol{x},t) f(\boldsymbol{x},t)\right) \\ &\quad + \frac{1}{2}\sum_{i,j}\frac{\partial^2}{\partial x_i \partial x_j}\left(\left[\mathrm{B}(\boldsymbol{x},t)\mathrm{B}^\mathsf{T}(\boldsymbol{x},t)\right]_{ij} f(\boldsymbol{x},t)\right)\end{aligned} \tag{7}$$

with the so-called drift coefficient $\boldsymbol{\mathcal{A}}(\boldsymbol{x},t)$ and the diffusion coefficient matrix $\mathrm{B}_{ij}(\boldsymbol{x},t)$. The corresponding system of integrable equations is then given by

$$\mathrm{d}\boldsymbol{x} = \boldsymbol{\mathcal{A}}(\boldsymbol{x},t)\mathrm{d}t + \mathrm{B}(\boldsymbol{x},t)\mathrm{d}\boldsymbol{W}_t \tag{8}$$

with a determined drift term and a stochastic diffusion term. Its stochastic properties are defined by the Wiener increment $\mathrm{d}W_t$. The Wiener process is a Gaussian distributed Markov process with the probability density

$$p(w,t|w_0,t_0) = \frac{1}{\sqrt{2\pi\,(t-t_0)}}\exp\left(-\frac{1}{2}\frac{(w-w_0)^2}{t-t_0}\right) \tag{9}$$

for the transition from the value w_0 at the time t_0 to the value w at the time t. Its stochastic increment is denoted as $\mathrm{d}W_t$.

According to the Itō formalism, the transport equation (6) corresponds to the integrable set of equations

$$\mathrm{d}s = w_{\|}\mathrm{d}t \tag{10}$$

$$\mathrm{d}w_{\|} = U\frac{\mathrm{d}U}{\mathrm{d}s}\mathrm{d}t + \sqrt{2D_{\|}}\mathrm{d}W_t. \tag{11}$$

We decide not to calculate the bulk velocity profile as the first moment of the distribution function self-consistently. Instead, we choose our Itō trajectories as test-particle paths in a predefined background velocity field. The exact shape of the given profile should not be a crucial factor; however, the boundary values and the spatial spread determine its influence. Therefore, we use a tanh-profile as a simple and reliable choice (see also Lee et al., 1986). The velocity profiles $U(s)$ for the ions and $u_{\mathrm{e}}(s)$ for the electrons are hence given by

$$U(s) = \frac{U_1+U_2}{2} - \frac{U_1-U_2}{2}\tanh\left(\frac{s}{\lambda}\right) \tag{12}$$

$$u_{\mathrm{e}}(s) = u_{\mathrm{e}}^{\mathrm{el}}(s) + u_{\mathrm{e}}^{\mathrm{turb}}(s) \tag{13}$$

$$u_{\mathrm{e}}^{\mathrm{el}} = \sqrt{\frac{m_{\mathrm{p}}}{m_{\mathrm{e}}}}U\sqrt{\frac{U_1^2}{U^2}\left(1+\frac{m_{\mathrm{e}}}{m_{\mathrm{p}}}\right)-1} \tag{14}$$

$$u_{\mathrm{e}}^{\mathrm{turb}}(s) = \frac{U_2-u_{\mathrm{e},2}^{\mathrm{el}}}{2} + \frac{U_2-u_{\mathrm{e},2}^{\mathrm{el}}}{2}\tanh\left(\frac{s-b}{\mu}\right) \tag{15}$$

with $U_1 = 4\times10^7$ cm/s, $U_2 = U_1/\kappa$, $\lambda = 5\times10^5$ cm, $\mu = 5\times10^5$ cm, and $b = 2\times10^6$ cm with the given compression ratio κ (for more details and a discussion on the parameter dependence see Verscharen and Fahr, 2008a).

3 Results

We integrate the Itō increments (Eqs. (10) and (11)) with sufficiently small time steps in such a way that the shock profile is covered properly. We achieve after a certain integration time a stationary distribution of particles. But, the evaluation of the downstream bulk velocity U_2 shows that it is higher than that given by U_1/κ for the profile due to the stochastic velocity increment. Therefore, we use the new downstream value as a boundary value for a second iteration. We iterate the simulation several times until the downstream bulk velocity becomes constant, too. Counting the particles and normalizing to the incoming solar wind flux leads to the distribution function shown in Fig. 1.

In this figure, we can follow the ions starting at the upstream side of the shock (negative s-values) with the upstream solar wind bulk velocity (i.e. $w_{\|} = 1$ after normalization). The width of the upstream beam is determined by the upstream temperature (in our model $T_1 \simeq 10^4$ K). At the shock ($s = 0$), the particles are decelerated down to subsonic bulk velocities and the width of the beam in our diagram increases. This corresponds to the dissipative thermalization of the solar wind plasma. The downstream temperature

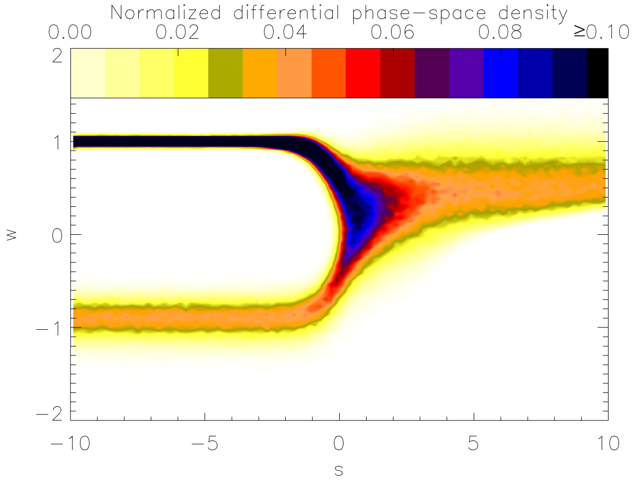

Fig. 1. Normalized differential phase-space density of the solar wind ions. The shock is located at $s = 0$. The lower left branch is the reflected ion beam, the branch on the right hand side is the ion downstream plasma. For a better view, the scale is cut at $f = 0.1$, which has only influence on the upstream beam.

can be calculated by evaluating the second moment of the downstream distribution function leading to $T_2 \simeq 10^6$ K. The wave-particle interaction leads to a higher downstream bulk velocity than given by the compression ratio parameter $\kappa = 4$. The mitigated real compression ratio is $\simeq 2$.

In the shock layer, some ions are brought to negative velocities $w_{\|}$ due to the velocity diffusion representing the wave-particle interaction. If they are not shifted back to a positive velocity in the furthermore occuring diffusion, they can leave the shock with this particular velocity and convect in the first view undisturbed backwards into the inner heliosphere. This means that a certain number of the solar wind ions are reflected (negative s-values and negative $w_{\|}$-values, lower left part of Fig. 1). They are also thermalized but not in such a strong way as the downwind beam.

Interestingly, these reflected ions obtain a velocity of about $w_{\|} = -U_1$, so comparable to the upstream bulk velocity but with the contrary sign. Investigating the amount of solar wind ions that are reflected at the shock yields that about 18% of the incoming particles follow the above described way of reflection.

4 Discussion

Up to now, similar kinetic theories describe the shock in stationarity (Fahr and Siewert, 2007; Siewert and Fahr, 2007; Verscharen and Fahr, 2008a). There are, however, several advantages to change to a time-dependent description. First, the shock should be stationary and, hence, even the time-dependent description should lead to a stationary solution that allows to check for consistency. Furthermore, the mathematical structure of the Itō calculus provides a way to treat the shock transit and the reflection together in one integration instead of an iterative separate calculation (Fahr and Verscharen, 2008). The disadvantage, on the other hand, is a more sophisticated numerical treatment until a stationary shock is established.

In our model, 18% of the incoming solar wind particles are reflected at the shock. Compared with measurements at the Earth bow shock this value appears quite high (Gosling et al., 1982; Meziane et al., 2004). However, in our case the plasma properties are very different to those at the Earth bow shock. The different density and magnetic field strength can lead to very different fractions of reflected ions (e.g., the different importance of pitch-angle scattering). These processes might also have a varied ability to filter particles from the reflection mechanism so that only particles with certain energies can escape into the upstream direction. Reliable and solid measurements of the reflected ions at the termination shock are not yet available. The reflected beam has velocities comparable to the incoming solar wind in the reference frame in which the shock is at rest. In the reference frame that is comoving with the upstream solar wind bulk flow the velocity of the reflected beam is about $2U_1$. Due to the interplanetary magnetohydrodynamic turbulence, the reflected beam is supposed to undergo strong pitch-angle diffusion similar to pick-up ions in the inner heliosphere (see Chalov and Fahr, 1996, 1999). Since the properties of the reflected beam are in very good agreement with earlier results (Verscharen and Fahr, 2008b), our result should be able to lead to the same processes, i.e. a self-initialized injection to the Fermi-1 acceleration process at the shock and a suprathermal part in the spectrum on the downstream side (see Fig. 3 in Verscharen and Fahr, 2008b). After the pitch-angle isotropization, the ions' distribution function has a shell-like form in the three-dimensional velocity space. The radius of the shell is given by the reflected ion bulk velocity in the co-moving reference frame (i.e. $\sim 2U_1$!) and the center of the shell is placed at $w_\parallel = U$ in the shock rest frame. A certain number of these re-distributed particles are not able to overcome the shock potential again. They are trapped in the acceleration mechanism to ACR energies at the termination shock.

The VOYAGER measurements during their shock crossings in 2004 or 2007, respectively, arose new problems for the explanation of ACR acceleration in the heliosphere and set this question again into the center of interest for a wide community. One central observation is that the source of the anomalous cosmic ray component was not found at the position of the shock, at least for the quasi-perpendicular case (Stone et al., 2005; Decker et al., 2005). Several very recent investigations provide possible explanations for this observation (McComas and Schwadron, 2006; Schwadron et al., 2008); however, the problem of an effective injection mechanism is still an open question. Nevertheless, the higher injection efficiency at quasi-parallel magnetic field orientations is confirmed by several other theories (e.g. Chalov and Fahr, 1996; Kallenbach et al., 2005; Fahr et al., 2008).

5 Conclusions

The central results from our kinetic treatment of the parallel solar wind termination shock are a plasma deceleration together with a thermalization on the downstream side and reflection at the shock due to energy diffusion because of the turbulent wave-particle interaction. The assumed processes (i.e. an electrostatic potential for the deceleration leading to a two-stream instability which excites electrostatic plasma waves) are shown to lead to a stationary parallel shock. This type of shock creates a self-initialized seed population of ions for a possible injection into the diffusive shock acceleration mechanism (Fermi-1). The occuring additional injection is not supposed to be the most important source for ACRs since the pick-up ion density also acting as ACR injection seed is higher than the reflected and injected solar wind density.

The different importances of the pick-up ion injection and the self-initialized injection are interesting tasks for further investigations. Since the self-injection process is able to work also for higher-mass ions in the solar wind, this mechanism could explain differences in the abundancies of ACR and LISM particle species. One possibility to observe this correlation directly is given by the charge of the injected ions: pick-up ions are singly charged particles whereas solar wind ions are fully ionized ion species.

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References

Achterberg, A. and Krulls, W. M.: A fast simulation method for particle acceleration, Astron. Astrophys., 265, L13–L16, 1992.

Burlaga, L. F., Ness, N. F., Acuña, M. H., Lepping, R. P., Connerney, J. E. P., and Richardson, J. D.: Magnetic fields at the solar wind termination shock, Nature, 454, 75–77, doi:10.1038/nature07029, 2008.

Chalov, S. V. and Fahr, H. J.: Reflection of Pre-Accelerated Pick-up Ions at the Solar Wind Termination Shock: The Seed for Anomalous Cosmic Rays, Sol. Phys., 168, 389–411, doi:10.1007/BF00148064, 1996.

Chalov, S. V. and Fahr, H. J.: Interplanetary Pick-Up Ion Acceleration A Study of Anisotropic Phase-Space Diffusion, Astrophys. Space Sci., 264, 509–525, 1999.

Chalov, S. V., Fahr, H. J., and Izmodenov, V.: Spectra of energized pick-up ions upstream. of the heliospheric termination shock I. The role of Alfvenic turbulences., Astron. Astrophys., 304, 609–616, 1995.

Decker, R. B., Krimigis, S. M., Roelof, E. C., Hill, M. E., Armstrong, T. P., Gloeckler, G., Hamilton, D. C., and Lanzerotti, L. J.: Voyager 1 in the Foreshock, Termination Shock, and Heliosheath, Sci., 309, 2020–2024, doi:10.1126/science.1117569, 2005.

Dworsky, A. and Fahr, H. J.: Ion acceleration in connection with a modulated solar wind termination shock: phase space propagation and complete energy spectra, Astron. Astrophys., 353, L1–L4, 2000.

Fahr, H.-J. and Siewert, M.: Anisotropic unstable ion distribution functions downstream of the solar wind termination shock, Astrophysics and Space Sciences Transactions, 3, 21–27, 2007.

Fahr, H.-J. and Verscharen, D.: Ion reflections from the parallel MHD termination shock and a possible injection mechanism into the Fermi-1 acceleration, Astron. Astrophys., 487, L21–L24, doi: 10.1051/0004-6361:200810217, 2008.

Fahr, H. J., Scherer, K., Potgieter, M. S., and Ferreira, S. E. S.: Longitudinal variation of the pickup-proton-injection efficiency and rate at the heliospheric termination shock, Astron. Astrophys., 486, L1–L4, doi:10.1051/0004-6361:200809561, 2008.

Gardiner, C. W.: Handbook of stochastic methods for physics, chemistry and the natural sciences, Springer, Berlin, 1994.

Gosling, J. T., Thomsen, M. F., Bame, S. J., Feldman, W. C., Paschmann, G., and Sckopke, N.: Evidence for specularly reflected ions upstream from the quasi-parallel bow shock, Geophys. Res. Lett., 9, 1333–1336, doi:10.1029/GL009i012p01333, 1982.

Kadomtsev, B. B.: Plasma turbulence, New York: Academic Press, 1965, 1965.

Kallenbach, R., Hilchenbach, M., Chalov, S. V., Le Roux, J. A., and Bamert, K.: On the ”injection problem” at the solar wind termination shock, Astron. Astrophys., 439, 1–22, doi:10.1051/0004-6361:20052874, 2005.

Krasnoselskikh, V. V., Lembège, B., Savoini, P., and Lobzin, V. V.: Nonstationarity of strong collisionless quasiperpendicular shocks: Theory and full particle numerical simulations, Phys. Plasmas, 9, 1192–1209, doi:10.1063/1.1457465, 2002.

Lee, L. C., Wu, C. S., and Hu, X. W.: Increase of ion kinetic temperature across a collisionless shock. I - A new mechanism, Geophys. Res. Lett., 13, 209–212, doi:10.1029/GL013i003p00209, 1986.

Li, H., Wang, C., and Richardson, J. D.: Properties of the termination shock observed by Voyager 2, Geophys. Res. Lett., 35, 19 107, doi:10.1029/2008GL034869, 2008.

Lifshitz, E. M. and Pitaevskii, L. P.: Physical kinetics, Course of theoretical physics, Oxford: Pergamon Press, 1981, 1981.

Lucek, E. A., Horbury, T. S., Dandouras, I., and Rème, H.: Cluster observations of the Earth’s quasi-parallel bow shock, J. Geophys. Res., 113, 7, doi:10.1029/2007JA012756, 2008.

McComas, D. J. and Schwadron, N. A.: An explanation of the Voyager paradox: Particle acceleration at a blunt termination shock, Geophys. Res. Lett., 33, 4102, doi:10.1029/2005GL025437, 2006.

Meziane, K., Mazelle, C., Wilber, M., Lequéau, D., Eastwood, J., Rème, H., Dandouras, I., Sauvaud, J., Bosqued, J., Parks, G., Kistler, L., McCarthy, M., Klecker, B., Korth, A., Bavassano-Cattaneo, M., Lundin, R., and Balogh, A.: Bow shock specularly reflected ions in the presence of low-frequency electromagnetic waves: a case study, Ann. Geophys., 22, 2325–2335, 2004.

Parker, E. N.: Dynamics of the Interplanetary Gas and Magnetic Fields., Astrophys. J., 128, 664–676, doi:10.1086/146579, 1958.

Quest, K. B.: Theory and simulation of collisionless parallel shocks, J. Geophys. Res., 93, 9649–9680, doi:10.1029/JA093iA09p09649, 1988.

Schwadron, N. A., Lee, M. A., and McComas, D. J.: Diffusive Acceleration at the Blunt Termination Shock, Astrophys. J., 675, 1584–1600, doi:10.1086/527026, 2008.

Shevyrev, N. N., Zastenker, G. N., and Du, J.: Statistics of low-frequency variations in solar wind, foreshock and magnetosheath: INTERBALL-1 and CLUSTER data, Planet. Space Sci., 55, 2330–2335, doi:10.1016/j.pss.2007.05.014, 2007.

Siewert, M. and Fahr, H.-J.: Full Boltzmann-kinetical treatment of an ion plasma crossing an MHD shock: parallel and non-parallel cases, Astron. Astrophys., 471, 7–15, doi:10.1051/0004-6361:20077413, 2007.

Stone, E. C., Cummings, A. C., McDonald, F. B., Heikkila, B. C., Lal, N., and Webber, W. R.: Voyager 1 Explores the Termination Shock Region and the Heliosheath Beyond, Sci., 309, 2017–2020, doi:10.1126/science.1117684, 2005.

Treumann, R. A. and Scholer, M.: The magnetosphere as a plasma laboratory, p. 1495, The Century of Space Science, Volume I, 2002.

Verscharen, D. and Fahr, H.-J.: A kinetic description of the dissipative quasi-parallel solar wind termination shock, Astron. Astrophys., 487, 723–729, doi:10.1051/0004-6361:200809950, 2008a.

Verscharen, D. and Fahr, H.-J.: Self-initialised Fermi-1 acceleration by pitch-angle re-scattering of solar wind ions reflected from the parallel termination shock, Astrophys. Space Sci. Trans., 4, 51–58, 2008b.