ISSN 0016-7932, Geomagnetism and Aeronomy, 2018, Vol. 58, No. 7, pp. 905–909. © Pleiades Publishing, Ltd., 2018.

Features of the Solar Wind Plasma Flow around the Earth's Magnetosphere

S. A. Grib*, †

Central Astronomical Observatory of RAS at Pulkovo, St. Petersburg, Russia

**e-mail: sagrib@gmail.com*

Received February 16, 2018; in final form, March 11, 2018

Abstract—The change in the properties of the solar wind flow as it crosses the bow shock wave front and moves in the Earth's magnetosheath are discussed. Solar wind data are used to study the refraction of magnetohydrodynamic (MHD) shock waves and the stationary tangential discontinuity of the solar wind into the magnetosheath. It is shown that the refraction of the solar-wind rotational discontinuity into the magnetosheath is accompanied by the emergence of a plateau-type plasma inhomogeneity with respect to the density of charged particles, with a simultaneous decrease in the magnetic field intensity. Moreover, the breaking of the secondary MHD contraction wave, reflected from the magnetopause, may be accompanied by the emergence of a fast reverse shock wave.

DOI: 10.1134/S0016793218070071

1. INTRODUCTION

Today, a multitude of space data on MHD-strong discontinuities in the solar corona and in the solar wind flow has produced different types of models to describe the formation of MHD shock waves in the collisionless solar-wind plasma. For example, these waves arise due to a sudden ejection of coronal plasma and in the pursuit interaction between fast and slow solar-wind quasi-flows, which originate from coronal holes and streamer belts, respectively (Figs. 1a and 1b).

In addition, solar fibers are observed near the Earth's orbit, which have a diamagnetic structure (Parkhomov et al., 2017) showing a negative correlation between the magnetic field and the density of charged particles.

Solar shock waves are known to induce a perturbation in the Earth's magnetosphere and cause a sudden onset of a geomagnetic storm. A perturbation of the same type causes a stationary tangential discontinuity (TD), which is transferred by the solar wind and accompanied by a jump in the plasma density during passage through the discontinuity and by the absence of an interplanetary magnetic field (IMF) component normal to the discontinuity surface. It should be noted that strong MHD discontinuities and combined discontinuous structures, as well as MHD waves, are constantly observed in the solar wind with instruments onboard interplanetary spacecraft.

† Deceased.

2. PROBLEM STATEMENT

The problem has a real, physical meaning that can be formulated as follows. It is assumed that a fast solar shock wave propagates along a stationary solar-wind flow with a speed depending on distance and time or that a structure with constant total pressure (pbs) is transferred by a cosmic plasma flux. In this case, the plasma structure is usually limited by the front and rear MHD discontinuity in the TD, and contact discontinuities arising from the decay of an arbitrary discontinuity in the presence of an oblique IMF are assumed to disappear rapidly due to the diffusion occurring perpendicular to the discontinuity. A question arises: what kind of MHD-heterogeneous structures will appear in the magnetosheath behind the bow shock wave under the influence of these solar wind perturbations before the Earth's magnetosphere?

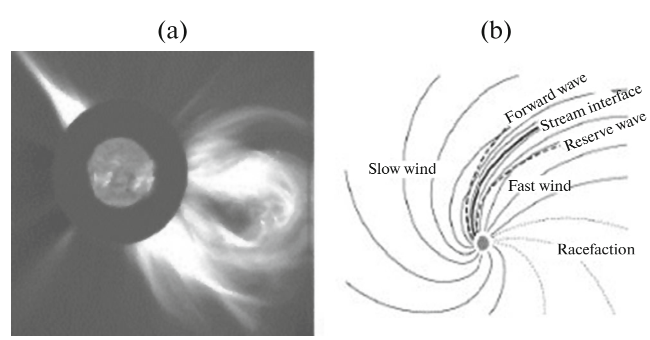

Fig. 1. Examples of the appearance of solar shock waves (a) in the corona and (b) in the free solar-wind flow.

We apply a system of MHD differential equations using five integral invariants (Grib et al., 1996) in a characteristic form for five unknowns: density ρ, speed-hodograph variables V and δ, magnetic-field induction $B = H$, and gas–kinetic pressure P:

$$I_{1,2} = \delta \pm \int_{V^*}^{V} \frac{\sqrt{(V^2 - a^2)(\alpha(V^2 - a^2) + a^2)}}{a^2\sqrt{(1-\alpha)}} \frac{dV}{V} = \text{const}$$

along the characteristics directed at angles of $+\mu$ to the line of flow;

$$I_3 = \frac{H}{\rho V} = \text{const} = C_1 \quad (1)$$

everywhere in the flow range;

$$I_4 = \frac{p}{\rho^\gamma} = \text{const} = C \text{ along the lines of flow;}$$

$I_5 = C_2$ is the Bernoulli integral along the line of flow.

along the characteristics The integral invariants make it possible to describe the continuous flow outside the discontinuities; however, we describe the shock and rarefaction waves using MHD relations expressing the conservation laws, together with the conditions of existence of a TD. Solving the problem of the decay of an arbitrary discontinuity in the interaction of a TD (with increasing density on it) with the head front, we obtain an effective Mach number greater than 1 for a fast MHD shock wave arising in the magnetosheath ($M_e = 3.5$ for a TD with a density jump of 3 in the solar wind), and for a TD with decreasing density, a smooth decrease in the plasma parameters in the magnetosheath on a fast rarefaction wave. Then, in the first case, the fast shock wave is reflected from the magnetopause as a fast rarefaction wave and is refracted into the magnetosphere as a weak fast shock contraction wave. In the second case, a rapid rarefaction wave penetrates the magnetosphere.

The parameters of the flow behind the incident solar-wind wave and behind the bow shock wave for fast S_+ and slow shock waves S_- are taken from experimental data. For the shock wave front, we assume that the Rankine–Hugoniot MHD conditions are satisfied. Then the flow parameters behind the incident solar-wind wave and behind the bow shock wave can be found by the method and formulas in the literature (Grib et al., 1996; Kulikovskii and Lyubimov, 2005). For fast S_+ and slow shock waves S_-, we have:

$$\begin{aligned} S_+ &: \Delta U = U_2 - U_1 = \pm f_+, \\ \Delta V &= V_2 - V_1 = \pm\varphi_+ \operatorname{sgn} h, \\ S_- &: \Delta U = U_2 - U_1 = \pm f_-, \\ \Delta V &= V_2 - V_1 = \pm\varphi_- \operatorname{sgn} h, \end{aligned} \quad (2)$$

where $f_\pm = \frac{h_2 - h_1}{\sqrt{1 + h_2 z}} z V_{a1}$, $\varphi_\pm = \left|\frac{h_2 - h_1}{\sqrt{1 + h_2 z}} V_{a1}\right|$, $h_i = \frac{B_{yi}}{B_x}$, $z = \frac{P_2 - P_1}{h_2 - h_1} + \frac{1}{2}(h_2 + h_1)$, U and V are the velocity vector components. The upper sign in the formulas corresponds to an upflowing wave; the lower sign corresponds to a downflowing one. For the fast (R_+) or slow (R_-) rarefaction wave, we have other relations with continuous functions (Kulikovskii and Lyubimov, 2005).

Thus, we have for the fast MHD wave:

$$R_+ : U_2 - U_1 = \mp\psi_+,$$

$$\psi_\pm = \frac{V_{a1}}{\gamma\rho_1^{\frac{1}{2}}} \int_{P_2}^{P_1} \left(\frac{P}{\rho_1}\right)^{-\frac{\gamma+1}{2\gamma}} q_\pm^{\frac{1}{2}} dP, \quad (3)$$

$$\chi_\pm = \frac{V_{a1}}{\gamma\rho_1^{\frac{1}{2}}} \int_{P_2}^{P_1} \left(\frac{P}{\rho_1}\right)^{-\frac{\gamma+1}{2\gamma}} \left(\frac{1 - q_\pm}{1 - Pq_\pm}\right)^{\frac{1}{2}} dP,$$

where γ is the polytropic coefficient; R_+ is the fast rarefaction wave; R_- is a slow one; $q_\pm$ is the solution of the differential equation:

$$\frac{dP}{dq} + \frac{\theta P}{1 - qq^2} \frac{\theta}{(1-q)} = 0, \quad \theta = \frac{\gamma}{z - \gamma}. \quad (4)$$

3. SOLUTION METHOD

Strong discontinuities are described by the Rankine–Hugoniot dynamical compatibility relations or conditions. We also use integral invariants (1) for plasma regions described by continuous parameters. However, we consider the collision of strong discontinuities (shock waves, TDs, and rotational discontinuities) of the solar wind as a breakup of an arbitrary discontinuity in the presence of a transverse IMF, and the solution of the arbitrary discontinuity breakup problem (the Riemann–Kochin problem) is found numerically by the trial calculation method, taking into account the evolutionary conditions.

In the magnetosheath, secondary MHD waves arise that take away some of the energy from the incoming solar-wind shock waves and equalize the parameters of the stationary plasma flow in the magnetosheath.

The rapid rarefaction wave arising in the magnetosheath is approximately described by the generalized Riemann solution and by formulas (3)–(4).

The wave will be reflected from the rear of the bow shock wave as a direct fast rarefaction wave, which in turn affects the magnetopause, forcing it to move back to the Sun to restore the stationary state.

The secondary rarefaction wave coming from the rear of the bow shock wave front will be reflected from the magnetopause as an MHD compression wave, which, due to nonlinearity, may break, forming a strong discontinuity (Grib, 2011). It should be emphasized that the interaction of the MHD compression waves and the rarefaction waves with the bow shock wave leads not only to the modification of the interacting waves but also to the emergence of a chain of new secondary waves in the magnetosheath plasma (Fig. 2).

In this case, the secondary waves contribute to the equalization of parameters of plasma flows in the magnetosheath.

Observations onboard spacecraft recently recorded isolated magnetic structures with an increase in plasma density in the Mercury's magnetosheath, or diamagnetic plasmoids similar to magnetic holes in the solar wind. Plasma inhomogeneities with a decrease in the IMF and a plateau-type increase in plasma density arise (Grib et al., 2016) with the fall of the plane front of a rotational discontinuity (Pushkar', 2008), moving from the Sun with the solar wind flow, in which there can be no plasmoids or coronal ejections (Eselevich et al., 2017). In this case, we use the solution of the Riemann–Kochin problem and consider the oblique counter interaction of the Alfven discontinuity with a fast MHD shock wave (Barmin and Pushkar', 1997).

Summarizing the results of observations and numerical simulations, we can construct a general scheme of the plateau by density, ($\rho\uparrow$, $P_b\downarrow$) with an indication of the effect of slow shock waves moving in opposite directions (Grib and Leora, 2017).

There is evidence of a plateau that appears due to the action of a diamagnetic plasmoid (Karlsson et al., 2015, 2016) or a magnetic hole in the magnetosheath. The mechanism that actually works is described by the collision of the rotational MHD discontinuity from the solar wind with the bow shock wave and its refraction into the magnetosheath and generation of slow shock waves. The proton density increases; the magnitude of the magnetic field decreases; and the boundaries of the inhomogeneity are maintained by slow shock waves.

4. ASSESSING THE POSSIBILITY OF A SECONDARY REVERSE SHOCK WAVE IN THE MAGNETOSHEATH

The law of motion of the magnetopause in a fixed coordinate system can approximately be expressed as follows:

$$r = (u - c_2)\,t + (c_1 + c_2)\,t\left(\frac{\Delta t}{t}\right)^{c_1(c_1+c_2)} - c_1\Delta t, \qquad (5)$$

where $\Delta t = t_2 - t_1$; c_1 and c_2 are the fast magnetosonic speed in the magnetosheath and before the magnetopause.

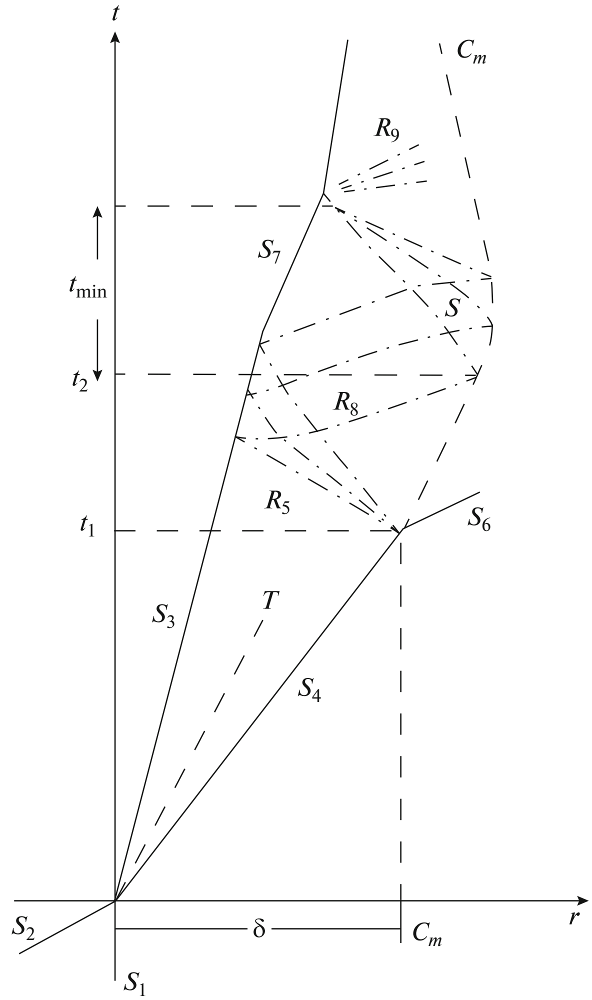

Fig. 2. Scheme of appearance of secondary waves in the magnetosheath.

We search for an envelope curve for the family of characteristics of the MHD equations as a limit line at which isentropicity is violated and a strong discontinuity is formed. We apply the classical analytical method along with the use of Riemann invariants (Kulikovskii and Lyubimov, 2005).

In this case, the inequality expressing the necessary condition for the breaking of the reflected contraction wave can be written as

$$\delta - |x_{\min}| + U\,(\Delta t + t_{\min}) \geq U_1(t_1 + \Delta t + t_{\min}). \qquad (6)$$

Here, $\delta = 3.05R_E$ is the original width of the magnetosheath; U is the flow speed in the neighborhood of the magnetopause; U_1 is the speed of shifting of the bow shock wave front towards the Earth; Δt is the time of contraction of the magnetosphere; t_1 is the time during which the nonstationary shock wave crosses the magnetosheath; $t_{\min}$ is the minimum time from the beginning of rarefaction of the Earth's magnetosphere to the beginning of a reverse passage of the bow shock

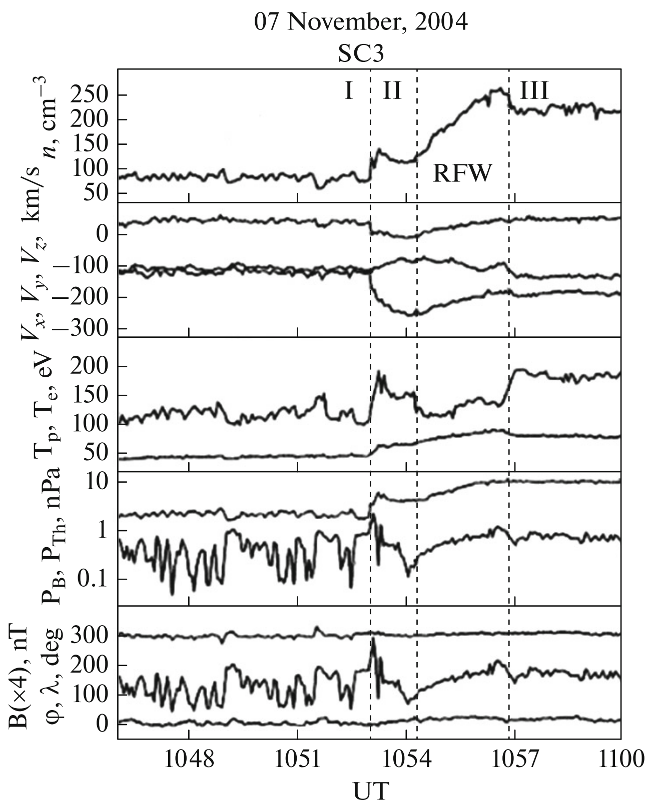

Fig. 3. Behavior of the density, velocity, temperature, and magnitude of magnetic pressure and IMF from the *Cluster SC3* data.

wave; x_{min} is the corresponding shift in space. The solid line in Fig. 2 shows the motion of the shock wave; hence, S_1, S_3, and S_7 indicate the motion of the bow shock wave front and R_5, R_8, and R_9, the rarefaction wave front. Inequality (6) is not satisfied in the interaction of the reflected nonshock contraction wave with the rear of the bow shock wave.

Figure 3 shows the data from the *Cluster* spacecraft (Pallocchia, 2013) as of November 7, 2004; dashed lines I, II, and III indicate the presence of strong MHD discontinuities in the regions under consideration; *RFW* is the reverse fast wave of contraction; *S* is the secondary fast shock wave, or the limiting state of the contraction wave.

One should also pay attention to the existence of vortices of various types in the solar wind flow and in the magnetospheric plasma (Zhao et al., 2016; Alexandrova et al., 2006; Alexandrova, 2008), which are largely due to the curvature of the MHD shock front.

5. CONCLUSIONS

(1) With an increase in the plasma density upon passage through the discontinuity, solar fast shock waves and TDs cause the appearance of secondary MHD waves of various types inside the magnetosheath before the Earth's magnetosphere.

(2) Secondary waves cause the experimentally observed sunward motion of the bow shock wave front.

(3) It is proven that the reverse fast MHD contraction wave can break with the formation of a reverse shock wave in the magnetosheath before the Earth's magnetosphere.

(4) A plateau-type plasma inhomogeneity with respect to density arises in the magnetosheath upon the fall of the solar rotational discontinuity onto the system of the bow shock wave—the Earth's magnetosphere.

The main physical conclusion from the study is as follows: plasma instabilities, MHD waves, discontinuous structures, and various types of magnetic-field and plasma perturbations serve to create the stationary state of a plasma flow around the Earth's magnetosphere in the magnetosheath.

ACKNOWLEDGMENTS

This work was supported in part by the Presidium of the Russian Academy of Sciences, program no. P28.

REFERENCES

Alexandrova, O., Solar wind vs magnetosheath turbulence and the Alfvén vortices, *Nonlinear Processes Geophys.*, 2008, vol. 15, pp. 95–108.

Alexandrova, O., Mangeney, A., Maksimovich, M., et al., Alfvén vortex filaments observed in magnetosheath downstream of a quasiperpendicular bow shock, *J. Geophys. Res.: Space Phys.*, 2006, vol. 111, A121.

Barmin, A.A. and Pushkar', E.A., Nonregular interaction of shock waves in magnetohydrodynamics, *Fluid Dyn.*, 1993, vol. 28, no. 4, pp. 575–585.

Barmin, A.A. and Pushkar', E.A., Oblique interaction of an Alfvén discontinuity and a fast magnetohydrodynamic shock wave propagating in opposite directions, *Fluid Dyn.*, 1997, vol. 32, no. 6, pp. 857–869.

Eselevich, V.G., Eselevich, M.V., Zimovets, I.V. and Sharykin, I.N., Evidence for shock generation in the solar corona in the absence of coronal mass ejections, *Astron. Rep.*, 2017, vol. 61, no. 9, pp. 805–819.

Grib, S.A., On one mechanism for the generation of a reverse solar wind shock in the magnetosheath in front of the Earth's magnetosphere, *Astron. Lett.*, 2011, vol. 37, no. 12, pp. 888–893.

Grib, S.A. and Leora, S.N., Features in the behavior of the solar wind behind the bow shock front near the boundary of the Earth's magnetosphere, *Geomagn. Aeron. (Engl. Transl.)*, 2017, vol. 57, no. 8, pp. 1073–1076.

Grib, S.A., Koutchmy, S., and Sazonova, V.N., MHD shock interactions in coronal structures, *Sol. Phys.*, 1996, vol. 168, pp. 151–166.

Grib, S.A., Pushkar, E.A., and Leora, S.N., Some sources of plasma inhomogeneities in the solar wind in front of the Earth's magnetosphere, *Geomagn. Aeron. (Engl. Transl.)*, 2016, vol. 56, no. 7, pp. 45–49.

Karlsson, T., Kullen, A., Liljeblad, E., et al., On the origin of magnetosheath plasmoids and their relation to magnetosheath jets, *J. Geophys. Res.*, 2015, vol. 120, no. 9, pp. 7390–7403.

Karlsson, T., Liljeblad, E., Kullen, A., et al., Isolated magnetic field structures in Mercury's magnetosheath as possible analogues for terrestrial magnetosheath plasmoids and jets, *Planet. Space Sci.*, 2016, vol. 129, pp. 61–73.

Kulikovskii, G.A. and Lyubimov, A., *Magnitnaya gidrodinamika* (Magnetohydrodynamics), Moscow: *Logos*, 2005.

Pallocchia, G., A sunward propagating fast wave in the magnetosheath observed after the passage of an interplanetary shock, *J. Geophys. Res.*, 2013, vol. 118, pp. 331–339.

Parkhomov, V.F., Borodkova, N.L., Eselevich, V.G., Eselevich, M.V., Dmitriev, A.V., and Chilikin, V.E., Features of the impact of the solar wind diamagnetic structure on Earth's magnetosphere, *Sol-Terr. Phys.*, 2017, vol. 3, no. 4, pp. 44–57. doi 10.12737/stp-34201705

Pushkar', E.A., Collision of solar wind shock wave and near-Earth bow shock in a strong IMF: a three-dimensional MHD model, *Izv. MGIU, Inf. Tekh. Model.*, 2008, no. 1, pp. 46–74.

Roberts, O.W., Li, X., and Li, B., Observations of Alfvén vortices in the fast solar wind, *UK Sol. Phys.*, June 23, 2013.

Zhao, H.Y., Shen, X.C., Tang, B.B., et al., Magnetosphere vortices and their global effect after a solar wind dynamic pressure decrease, *J. Geophys. Res.*, 2016, vol. 121, no. 2, pp. 1071–1077.

Translated by A. Kobkova