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Letter to the Editor

Supersonic solar wind ion flows downstream of the termination shock explained by a two-fluid shock model

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ABSTRACT

In the view of classic magnetohydrodynamics, it is generally expected that at a shock the supersonic upstream flow is converted into the subsonic downstream flow whereby the increased entropy appears in the increased downstream temperature. In the solar wind termination shock, it is expected that the supersonic upstream solar wind ion flow changes into a subsonic downstream ion flow. The Voyager-2 passage over this shock, however, demonstrated that the downstream solar wind ion flow still has a supersonic signature. In this paper, we present straightforward solution to this unexpected phenomenon by applying a two-fluid model to describe the passage of the solar wind over the termination shock. The two dynamically dependent, but thermodynamically independent fluids are the normal solar wind ions and the comoving suprathermal ions, or so-called pick-up ions. As we can show, the downstream solar wind ion flow can be either subsonic or supersonic depending on the upstream effective Mach number of the flow or the pick-up ion pressure. This is because most of the kinetic energy of the upstream flow is converted into thermal energy of the suprathermal ions, while the normal solar wind ions are heated only ineffectively, so that they can retain a supersonic signature even further downstream. With this two-fluid model, we can explain the main features of the shock structure observed by Voyager-2.

Key words. hydrodynamics – shock waves – solar wind

1. Introduction: the multi-fluid character of the solar wind

The solar wind plasma in principle needs to be described by at least three different fluids, i.e. thermal ions, electrons, and suprathermal ions. Suprathermal ions, picked-up by the supersonic solar wind flow as ionized neutral atoms, are known as pick-up ions (PUIs) and are produced all over the heliosphere. Their production is due to photoionization and charge exchange of interstellar H-atoms (see e.g. Rucinski & Fahr 1991; Fahr & Rucinski 1999; Rucinski et al. 2003). While their spatial distribution is understood well, the PUI phase-space transport has been far less clear. In particular, there exists an ongoing debate about how efficiently PUIs are accelerated just after the pick-up process to higher energies due to nonlinear wave-particle interactions (see e.g. Isenberg 1987; Bogdan et al. 1991; Chalov & Fahr 1996, 1998; and Chalov et al. 2004) and whether energy diffusion can play at all an effective role in this transport.

Primarily injected PUIs represent keV-energetic protons comoving with the supersonic solar wind. Their velocity distribution, however, is toroidal and unstable with respect to wave excitations (see Lee & Ip 1987; Fahr & Ziemkiewicz 1988). With the free energy of this unstable distribution, these ions drive Alfvenic wave power enforcing pitch-angle isotropization of the initial velocity distribution (see Chalov & Fahr 1998, 1999). Due to wave-wave coupling, the wave energy generated by primary PUIs is transported diffusively in wave-vector space both to shorter wavelengths, where it can be absorbed by solar wind protons, and to longer wavelengths, where it is reabsorbed by all PUIs (Chashei et al. 2003; Chalov et al. 2006). It turns out that only a small fraction of about 5 percent of the PUI-generated wave energy reappears in the observed proton temperatures, while about 50 percent is reabsorbed by PUIs.

This explains why PUI temperatures do not decrease at large solar distances, while normal solar wind ion temperatures do. At their arrivals at the termination shock, it is therefore to be expected that two different fluids undergo a shock there, namely one relatively hot and one other, relatively cool fluid. The hot one, the PUI fluid, serves as the seed population for the generation of anomalous cosmic ray (ACR) ions by means of the Fermi-1 acceleration process, i.e. creating an additional high energy fluid, the ACR fluid (Chalov & Fahr 1994, 1997; Fichtner 2001). In principle, these three fluids are dynamically and thermodynamically coupled to each other, and an adequate description of the structure of the termination shock should therefore take into account these three fluids in self-consistent form. We show below that a two-fluid approach to describing the solar wind passage over the termination shock provides an adequate explanation for the downstream supersonicity of the normal solar wind ion plasma observed with Voyager-2 (Richardson et al. 2008).

Evidently any fluid description of the properties of the termination shock, which is collisionless in its nature, is only an approximation. In the framework of this approach, many physical phenomena are lost, although the hydrodynamic theory, based on general conservation laws, can provide important information on plasma-flow properties in the vicinity of the shock. We refer to results of kinetic numerical simulations of the

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termination shock in the presence of pick-up ions (Kucharek & Scholer 1995; Scholer et al. 2003; Lembege et al. 2004; Chapman et al. 2005; Lee et al. 2005), which reveal many interesting features such as reformation and the variability in its structure.

2. Two-fluid model of shock transition

We consider a mixture of thermal solar wind plasma and suprathermal ions (PUIs), which are comoving at speed U. In planar geometry, the conservation laws of mass, momentum, and energy flows for the mixture can be written in the form:

$$\rho U = \text{const.}, \tag{1}$$

$$\rho U^2 + p_{\rm SW} + p_{\rm PUI} = \text{const.}, \tag{2}$$

$$\frac{U^2}{2} + \frac{\gamma}{\gamma - 1}\,\frac{p_{\rm SW} + p_{\rm PUI}}{\rho} = \text{const.}, \tag{3}$$

where ρ is the density of the mixture, and $p_{\rm SW}$ and $p_{\rm PUI}$ are the pressures of the thermal plasma and the pick-up ions, respectively. The pressure $p_{\rm SW}$ includes the pressures of thermal ions and electrons. We do not consider suprathermal electrons, but if present we are able to include their pressure as part $p_{\rm PUI}$. It is clear that Eqs. (1)–(3) are valid both at the smooth parts of plasma flows and at discontinuities. Dynamical effects of the magnetic field are ignored, although it can have an influence on the kinematics of charged energetic particles as discussed below.

The system of Eqs. (1)–(3) is not closed and some additional relation connecting upstream with unknown downstream values is required. To derive this additional relation, we consider two different "scenarios" of pick-up ion behavior at the termination shock. Since the pick-up ions are a hot population of charged particles in the solar wind, the Mach number of which is close to 1 (Chalov & Fahr 1997), we assume that their transition through the shock is adiabatic. In other words, we consider that the magnetic moment of the particles is an adiabatic invariant. This assumption is valid for energetic particles at quasi-perpendicular shocks, if the gyroradii of the particles are larger than the shock thickness, and pitch-angle scattering during the front crossing of their Larmor circles can be ignored (e.g. Decker 1988). The measurements of the magnetic field at Voyager-2 indicate that the thickness of the ramp of the termination shock is ~6000 km (Burlaga et al. 2008). This value is an order of magnitude smaller than the gyroradius of a typical pick-up proton in this region. Effective pitch-angle scattering can violate conservation of the magnetic moment. However, observations of the anisotropy of energetic charged particles close to the termination shock (Decker et al. 2005; Stone et al. 2005, 2008) imply that scattering in the outer heliosphere is weak.

For a perpendicular shock, the jumps in density and magnetic field magnitude are equivalent: $s = \rho_2/\rho_1 = B_2/B_1$. Due to the conservation of the magnetic moment of PUIs passing over the shock, there is a jump in the energy characterized by $\upsilon^2_{\perp 2} = s\upsilon^2_{\perp 2}$, where υ is the thermal speed of the particles. We now consider two cases depending on the efficiency of pitch-angle scattering:

1) Strong scattering occurs when the velocity distribution is isotropic just behind the shock front. In this case, $\upsilon^2_{\perp 2} = (2/3)\upsilon^2_2$ and $\upsilon^2_2 = s\upsilon^2_1$. Due to the differential, phase-space, flow-conservation over the shock (Liouville theorem),

$$f_{\rm PUI,1}\,(\upsilon_1)\,{\rm d}^3\upsilon_1 U_1 = f_{\rm PUI,2}\,(\upsilon_2)\,{\rm d}^3\upsilon_2 U_2, \tag{4}$$

we obtain (Fahr & Lay 2000):

$$f_{\rm PUI,2}(\upsilon) = s^{-1/2} f_{\rm PUI,1}\left(\upsilon/s^{1/2}\right). \tag{5}$$

In Eqs. (4) and (5), f_i is the velocity distribution function of PUIs in front of (index 1) and behind of (index 2) the shock. From Eq. (5), we derive the relation between the downstream and upstream pressures of the pick-up ions:

$$p_{\rm PUI,2} = s^2 p_{\rm PUI,1}. \tag{6}$$

2) Weak scattering occurs when the velocity distribution function becomes isotropic only after passage over some distance downstream of the shock front. In this case, we suppose that $\upsilon_{\parallel 2} = \upsilon_{\parallel 1}$ just behind the front. Then $\upsilon^2_2 = (2s+1)/3\,\upsilon^2_1$. Assuming that at a small distance from the shock (small compared with the shock curvature) distribution is isotropic and applying Liouville theorem (4) we then find:

$$f_{\rm PUI,2}(\upsilon) = \left(\frac{2s+1}{3}\right)^{-3/2} s f_{\rm PUI,1}\left(\upsilon/\sqrt{(2s+1)/3}\right), \tag{7}$$

and correspondingly

$$p_{\rm PUI,2} = \frac{s(2s+1)}{3} p_{\rm PUI,1}. \tag{8}$$

We consider the conditions imposed by Eqs. (6) and (8) to be additional relations that close the system of Eqs. (1)–(3). We introduce the Mach numbers for thermal solar wind plasma and pick-up ions with the formulae:

$$M_{\rm SW} = \left(\frac{\rho_{\rm SW} U^2}{\gamma p_{\rm SW}}\right)^{1/2}, \qquad M_{\rm PUI} = \left(\frac{\rho_{\rm PUI} U^2}{\gamma p_{\rm PUI}}\right)^{1/2}. \tag{9}$$

The relative abundance of pick-up ions is denoted by $\chi = \rho_{\rm PUI}/\rho_{\rm SW}$. Figures 1 and 2 show the downstream Mach number of the thermal solar wind $M_{\rm SW,2}$ and compression at the shock s as functions of the upstream Mach number of PUIs $M_{\rm PUI,1}$ in the case of strong pitch-angle scattering when the jump of the pick-up ion pressure through the shock is given by Eq. (6). The upstream value of the solar wind Mach number $M_{\rm SW,1}$ equals 10. This value is very close to the Mach number given by Richardson et al. (2008). We should emphasize here that even a twofold increase in $M_{\rm SW,1}$ has practically no effect on the results presented in the figures. We consider a narrow range of $M_{\rm PUI,1}$ in the vicinity of unity since the PUIs form an extremely hot population in the solar wind, which is slightly sub- or supersonic (Chalov & Fahr 1997). Different curves in the figures correspond to different values of the relative abundance of PUIs χ. It is evident from Fig. 1 that the flow of the solar wind downstream of the termination shock is supersonic at relatively small values of $M_{\rm PUI,1}$ in accordance with measurements by Voyager-2 (Richardson et al. 2008). Obviously the downstream flow of the mixture of the thermal plasma and suprathermal pick-up ions is subsonic and the entropy in the mixture therefore increases through the shock. We note that, in the framework of this two-fluid model, the Mach number $M_{\rm SW,2}$ at fixed value of χ increases to infinity as $M_{\rm PUI,1}$ decreases. Under special conditions, this implies that pick-up ions can acquire all possible upstream kinetic energy of the solar wind as they pass through the shock.

The shock compression ratio presented in Fig. 2 is, however, higher than that observed by Voyager-2 during the shock crossing (the latter is in the range 2.3–2.4). Figures 3 and 4 indicate the downstream Mach number $M_{\rm SW,2}$ and compression s in the case of weak pitch-angle scattering when the jump in the pick-up ion pressure through the shock is given by Eq. (8). It is evident

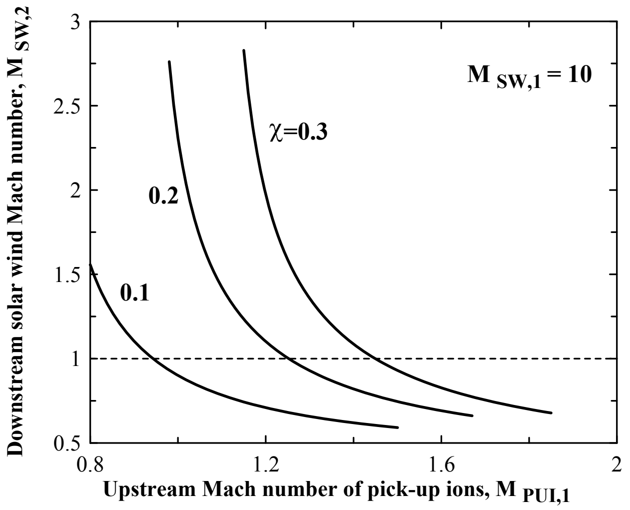

Fig. 1. Downstream Mach number of the thermal solar wind $M_{\mathrm{SW},2}$ as a function of the upstream Mach number of suprathermal pick-up ions in the case of strong pitch-angle scattering when the jump in the pick-up ion pressure through the shock is given by Eq. (6). The numbers show relative abundances of pick-up ions χ.

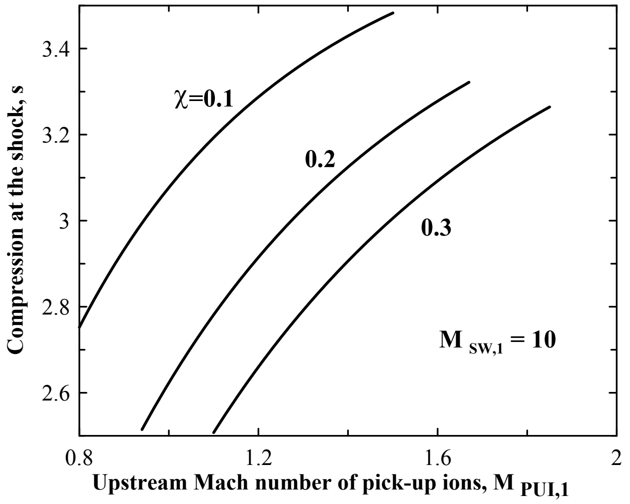

Fig. 2. Compression ratio s through the shock as a function of the upstream Mach number of suprathermal pick-up ions in the case of strong pitch-angle scattering.

that in this case pick-up ions absorb a smaller amount of the solar wind kinetic energy during the shock crossing than in the case of strong scattering, since it is always true that $s^2 > s(2s+1)/3$. There are both subsonic and supersonic regimes in the downstream flow of the thermal solar wind in Fig. 3 depending on the upstream Mach number of pick-up ions. The relative abundance χ of pick-up ions in the outer parts of the heliosphere near the termination shock is close to 0.3. The solar wind flow behind the shock is then supersonic at upstream conditions characterized by $M_{\mathrm{PUI},1} \lesssim 1.2$, which corresponds to fairly probable values of the Mach number for the pick-up ions. We note that the model with weak scattering (Eq. (8)) allows the observed values of shock compression (see Richardson et al. 2008), as is evident from Fig. 4. At $\chi = 0.3$, the compression ratio in the range 2.3−2.4 is realized when $M_{\mathrm{PUI},1}$ is close to 1. From Fig. 3 it follows then that under these conditions the downstream Mach number is $M_{\mathrm{SW},2} \approx 1.4$. This value corresponds to a mixture of thermal ions and electrons. The Mach number of thermal ions alone is therefore even larger.

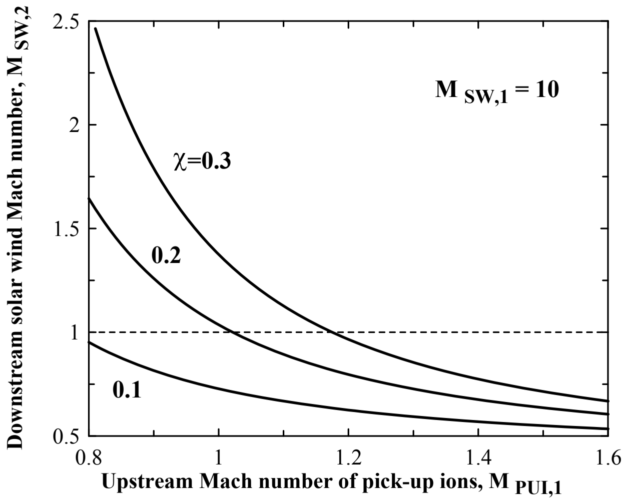

Fig. 3. Same as Fig. 1 but for the case of weak pitch-angle scattering when the jump in the pick-up ion pressure through the shock is given by Eq. (8).

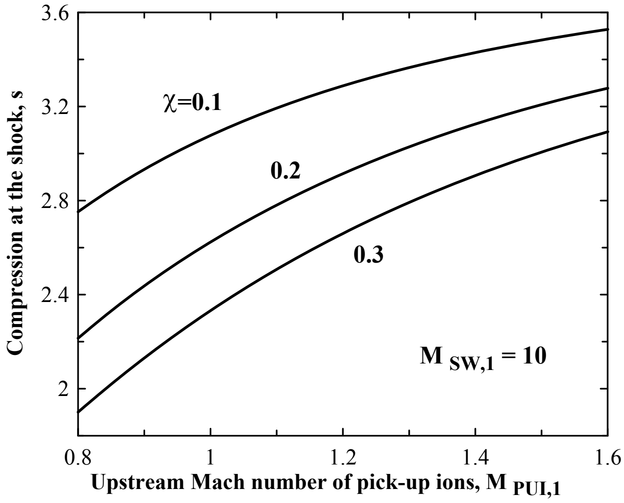

Fig. 4. Same as Fig. 2 but for the case of weak pitch-angle scattering.

3. Conclusions

The data obtained during the passage of spacecraft Voyager-2 through the solar wind termination shock (see Richardson et al. 2008; Decker et al. 2008) was a large surprise to the theoretical plasma physics community, because with these data it became evident that the downstream solar wind ions are still supersonic. Normally at shocks, a supersonic upstream flow is converted into a subsonic downstream flow, but, in case of the Voyager-2 passage, it turned out that the solar wind ion plasma, although substantially decelerated over the shock, is only ineffectively heated sufficiently to retain a supersonic signature in the downstream flow. This clearly indicates that the differential kinetic energy between upstream and downstream ion flows does not reappear adequately in the thermal energy of the downstream solar wind ions. We must therefore ask the question of where this energy is going, which appears to have an answer of more energetic or suprathermal ions (see also Decker et al. 2008).

As suprathermal ions, we consider ions picked up by the upstream supersonic solar wind as ionized neutral atoms. These ions constitute a suprathermal fluid, which on the basis of fluid theories needs to be treated as a separate energetic fluid from the background solar wind ion (SW's) fluid. On the basis of the temperature of SW, a fairly high upstream Mach number $M_{\mathrm{SW},1} \geq 10$

prevails (in fact found with a value of $M_{\mathrm{SW},1} \simeq 10$ by Richardson et al. 2008). On the basis of the PUIs, however, which remain hot until reaching the shock, a far smaller Mach number for the PUI fluid can be calculated, which is of the order of $M_{\mathrm{PUI},1} \simeq 1$, so that the effective two-fluid Mach number attains a value of about $M_1 \simeq 2$.

As we can show, the presence of suprathermal ions, under conservation of the ion magnetic moments at the shock passage, then easily explains why most of the upstream kinetic energy is absorbed in the thermal energy of the downstream PUIs, since the change in the thermal energy of the fluids from upstream to downstream is given by (in the case of strong scattering)

$$\Delta E_{\mathrm{PUI}} = p_{\mathrm{PUI},1}\left(s^2 - 1\right)/(\gamma - 1),$$

which implies that the change increases as the upstream pressure of suprathermal particles increases. If there are practically no PUIs present, as in the case of the bowshock of Earth or Neptune, then the SW ion passage over this shock occurs more or less in full accordance with classical expectations. If, however, there are PUIs of sufficient abundances, then most of the upstream kinetic energy reappears in the downstream thermal energy of these PUIs, while the downstream SW ions remain supersonic. From the data presented by Richardson et al. (2008), it can also be seen that the downstream temperatures of SW ions as well as SW electrons are both about 10^5 K, while classically they should be higher, i.e. about 10^6 K. This means that both SW ions and SW electrons are ineffectively heated only in analogous manner at the multi-fluid shock transition, meaning that the downstream Mach number $M_{\mathrm{SW},2}$ displayed in our Figs. 1 and 3 can be transcribed into the downstream SW ion Mach number by use of the simple relation

$$M_{\mathrm{SW},2} = \frac{U_2}{\sqrt{\gamma\left(p^i_{\mathrm{SW},2} + p^e_{\mathrm{SW},2}\right)/\rho_{\mathrm{SW},2}}} \simeq \frac{1}{\sqrt{2}} M^i_{\mathrm{SW},2}.$$

Taking into account the results presented at the end of Sect. 2, we then obtain $M^i_{\mathrm{SW},2} \approx 2$. This value exactly equals the observed value (Richardson et al. 2008).

Since our theoretical approach above developed strictly applies only to the case of a perpendicular shock, we can discuss shortly possible deviations when the shock is not perpendicular. As inferred from Voyager-2 data (Richardson et al. 2008; Burlaga et al. 2008), the upstream magnetic field has a tilt of 82° with respect to the local shock normal. Assuming that the frozen-in magnetic field at the shock is purely azimuthal, this also implies that the upstream bulk flow has an inclination of about $\alpha_1 = 8°$ with respect to the shock normal. Hence, the upstream and downstream bulk velocities given by $U_1 = U_1^n/\cos\alpha_1$ and $U_2 = U_2^n/\cos\alpha_2$ are related to each other by

$$\frac{U_1}{U_2} = \frac{s}{\sqrt{\cos^2\alpha_1 + s^2\sin^2\alpha_1}},$$

which in the given case of $\alpha_1 = 8°$ would result in $U_1/U_2 = (U_1^n/U_2^n)/\sqrt{1.1} \simeq 0.95\, s$.

A phenomenon of the shock precursor, also observed in the Voyager data, is not explained in the framework of our two-fluid model of the shock passage presented in this paper. This phenomenon is, however, explained in a straightforward manner by a three-fluid model that also includes the shock-generated anomalous cosmic-ray ion population as a third separate fluid (see Chalov & Fahr 1997). Modulated anomalous cosmic-ray ions establish an ACR pressure gradient orientated in the solar direction and, since dynamically coupling to the background solar wind ion flow, starts decelerating the upstream supersonic SW flow at some distance ahead of the termination shock, as observed (Richardson et al. 2008). We shall quantitatively investigate this three-fluid phenomenon in a forthcoming paper.

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