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Self-initialised Fermi-1 acceleration by pitch-angle re-scattering of solar wind ions reflected from the parallel termination shock

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Abstract. In a recent kinetic calculation a rather high amount of reflected ions was shown to occur at the solar wind termination shock under a parallel magnetic field orientation. The fate of these reflected ions is analysed within the scope of this paper. In the inner heliosphere their further transport is expected to be mainly influenced by pitch-angle scattering similar to the process governing pick-up ions (PUIs). This diffusive scattering isotropises the ions on a shell-like distribution in the comoving upstream solar wind reference frame. The resulting distribution is calculated and the result is applied on our earlier kinetic model. The isotropised ions, when again convected into the shock, tend to attenuate the shock a little and lead to an additional energetic tail population in the downstream distribution function. A consistent incorporation of the reflected ions into the model is iteratively possible. It turns out that a part of the reflected and isotropised ions offer properties which allow for the acceleration to the anomalous cosmic ray (ACR) regime as an additional contribution to the injection by pick-up ions (i.e. we propose a self-injection mechanism to the Fermi-1 acceleration process).

1 Introduction

Magnetohydrodynamic shock waves are known to offer an efficient reflection mechanism for plasmas (Potgieter and Moraal, 1988; Donohue and Zank, 1993). The mainly acting process is the Fermi-1 acceleration mechanism, which describes the kinetic energy transfer from a shocked magnetised background plasma to individual charged particles. Necessary ingredients for this acceleration process are particle and wave motions relative to the plasma background flow. Detailed and quantitative analyses of Fermi-1 acceleration can be found at Drury (1983) and Gaisser (1990), a shorter introductive excerpt in Fichtner (2000).

Our recent kinetical model calculations (Verscharen and Fahr, 2008) describe the solar wind termination shock under a parallel magnetic field orientation. In this model, the decelerating force, which acts on the plasma flow, is assumed to be given by a stationary electric potential. The ions run against this potential and are decelerated. On the other hand the electrons of the quasi-neutral solar wind plasma are strongly accelerated. This situation represents a two-stream-instability, which excites turbulent interaction with electrostatic plasma waves. The transport equation for this problem can be solved by using Itō's calculus of stochastic differential equations (SDEs). The resulting downstream ion distribution function (see Fig. 1) shows a characteristic double-hump structure with a negative particular velocity branch. This means that particles are reflected by the shock structure and penetrate backwards into the upstream regime, i.e. the inner heliosphere. Further calculations show that the amount of reflected solar wind ions due to stochastic wave-particle interactions is rather high (about 18 percent of the incident solar wind) and that this reflected beam is equipped with a velocity comparable in magnitude to the incident solar wind velocity but with opposite direction (Fahr and Verscharen, 2008).

Although the recent VOYAGER-2 shock transit shows evidence for a quasi-perpendicular shock (Richardson et al., 2008; Burlaga et al., 2008), the quasi-parallel configuration is not as rare as one could expect. The latter magnetic field orienation predominantly appears at high heliographic latitudes. Additionally, the convection of magnetic sheath polarity changes over the termination shock leads to a period of about 1.5 days of polarity change within 10 days of constant magnetic polarity. For this time period of about 1.5 days, a nearly parallel shock configuration is occuring and the considerations given in our paper become relevant (see Fahr et al., 2008).

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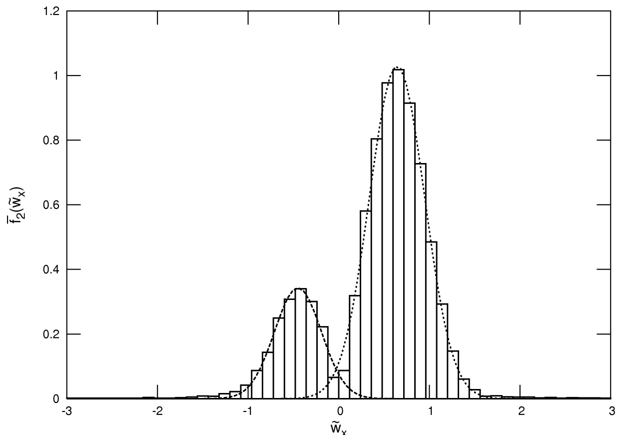

Fig. 1. Normalised ion distribution function in one-dimensional velocity space on the downstream side of the solar wind termination shock. The velocity $\tilde{w}_x$ in the direction of the shock normal is scaled in units of the upstream solar wind bulk velocity $U_1 = 400\,\mathrm{km/s}$. From Verscharen and Fahr (2008).

An observational hint to the existence of such a reflected particle species is provided by VOYAGER measurements, which have been at first misinterpreted as the termination shock transit in 2003 (see Krimigis et al., 2003; McDonald et al., 2003; Burlaga et al., 2003). Later, however, it turned out that these early data have shown the precursor region of the solar wind termination shock, whereas the real shock transit happened in December 2004 (Fisk, 2005). This reflected beam is subject to several interactions with the incoming solar wind and its co-convected MHD turbulences. Similar to the behaviour of newly generated pick-up ions (PUIs) in the outer heliosheath (see e.g. Chalov and Fahr, 1996; Chalov et al., 1995), the reflected solar wind ions are expected to undergo very effective and rapid pitch-angle scattering (cf. Schlickeiser, 1989). The MHD turbulence in the inner heliosheath is responsible for this fact. For example ion-selfgenerated magnetoacoustic turbulence (Chashei et al., 2003) or Alfvén turbulence leads to this behaviour (see for an extensive review Decker, 1988). This likewise called pitch-angle diffusion isotropises the distribution function till it reaches a shell-like distribution in the solar wind rest frame.

The abundance of certain elements in the cosmic ray spectrum below 100 MeV (later referred to as 'anomalous cosmic rays (ACRs)') was found to be higher than expected on the basis of galactic cosmic ray (GCR) extrapolation from the higher energy range by Garcia-Munoz et al. (1973) for the first time. The first observation of anomalous hydrogen took more than a decade since this early date (Christian et al., 1988). Very soon after the detection of anomalous cosmic rays (ACRs), the paradigmatic interpretation of these low-energy particles in cosmic ray observations by Fisk et al. (1974) connected PUIs directly with the origin of ACRs. The details of the mechanisms which are responsible for the acceleration of pick-up ions to ACRs are still an open question in space physics (Zank and Matthaeus, 2001). Different approaches try to explain the injection and pre-acceleration by the interaction with propagating or co-rotating shocks in the inner heliosphere (Jokipii and Giacalone, 1998). The injection efficiency of PUIs and even the acceleration itself strongly depend on the magnetic field orientation (Jokipii, 1987; Chalov and Fahr, 1996; Fahr et al., 2008), but nevertheless for the parallel case it is not sufficiently studied. Here one should remark that the pick-up ion injection efficiency is hitherto a not consistently achieveable crucial factor for these calculations. The literature provides a very wide range for this parameter between 0.0003 and 0.9 (Le Roux and Fichtner, 1997).

Serious hints towards PUIs as really being the seed of ACRs always came from considerations of the elemental abundances. The elemental abundances that appear in the local interstellar medium (LISM) should also reasonably well characterise the elemental abundances of PUIs – besides of heliosheath filtering effects(see Rucinski et al., 1993) – and originate from LISM neutral atoms penetrating into the inner heliosphere. The elemental composition indeed appears to be fairly consistent with that of the neutral component of the LISM (see Cummings and Stone, 1990, 1995). One should, however, bear in mind that the ionisation degree of the LISM and filtration functions for the neutral LISM species in fact even nowadays are not well known. This is because the ionisation state of the LISM neither is characterised as a thermodynamical equilibrium nor perhaps even a quasistationary state (see Frisch, 1990; Reynolds, 1990; Frisch and Slavin, 2006; Breitschwerdt and de Avillez, 2006).

That means to fix the LISM neutral abundances needs the knowledge of its poorly known ionisation state, otherwise relative abundances with respect to hydrogen are a widely open number due to unknown LISM ionisation degrees. This somehow seems to open up the look for ACR seed particle candidates a little and may let it appear worthwhile to also consider contributors to the ACR population different from PUIs.

2 Theoretical approach

The shock-reflected ions (Fahr and Verscharen, 2008) first propagate into the inner heliosphere. Under the influence of MHD turbulence (e.g. Alfvén turbulence) the reflected beam, which is moving opposite to the solar wind flow, is influenced by several processes. The dominating process is assumed to be violent pitch-angle diffusion (Isenberg, 1987). Other possible effects, which could be taken into account additionally, are for example energy diffusion (Fermi-2 scattering) in the ambient medium or adiabatic heating. By means of energy-conserving pitch-angle diffusion the distribution function is isotropised to a shell-like distribution in the reference frame which is co-moving with the solar wind bulk velocity (Chalov and Fahr, 1996, 1999). In the following consideration we calculate the corresponding distribution function and attain the possibility to incorporate these ions consistently into the model.

In a general form the diffusive temporal change of the distribution function due to pitch-angle scattering is given by

$$\left.\frac{\delta f(\boldsymbol{x},\boldsymbol{w},t)}{\delta t}\right|_{\mathrm{PA}} = \frac{\partial}{\partial\mu} D_{\mu\mu} \frac{\partial f(\boldsymbol{x},\boldsymbol{w},t)}{\partial\mu}, \tag{1}$$

where μ indicates the pitch-angle cosine and $(\boldsymbol{x},\boldsymbol{w})$ the phase-space coordinates. The coordinate system is chosen in a way, that the x-direction is parallel to the shock normal. Therefore, the velocity component w_x is parallel to the bulk flow with the ion bulk velocity $U(x)$. Due to the assumption of locally planar geometry of the shock, the distribution is expected to be axially symmetric with respect to the x-axis. The model calculations take place in the shock frame, i.e. the reference frame in which the shock is at rest. However, for the first considerations the solar wind bulk frame (i.e. the frame which is comoving with the ion bulk velocity U) appears more convenient because pitch-angle diffusion can be better described in this frame. In the solar wind bulk frame the reflected ions have a bulk velocity of $U_1+U_1^{\mathrm{refl}}$.

2.1 The mean-free-path for pitch-angle scattering

The quantity $\lambda_\parallel$ is denoted as the mean free path for particles moving parallel to the magnetic field in a supersonic and super-Alfvénic background plasma and is given by (see Hasselmann and Wibberenz, 1970)

$$\lambda_\parallel = \frac{3v}{8}\int_{-1}^{+1}\frac{(1-\mu^2)^2\mathrm{d}\mu}{D_{\mu\mu}} \tag{2}$$

Here $D_{\mu\mu}$ denotes the pitch-angle diffusion coefficient ($\mu=\cos\vartheta$ denoting the pitch-angle cosine) describing the effect of quasilinear ion interactions with Alfvénic MHD turbulences corresponding to Eq. (1). This diffusion process was extensively studied by Schlickeiser (1989). Hereby the ion velocity v is measured in the reference frame of the background plasma flow (solar wind bulk frame). The pitch-angle diffusion coefficient $D_{\mu\mu}$ is related to the velocity diffusion coefficient and can be evaluated for the inner heliosphere in the form given by Chalov and Fahr (1998, 1999)

$$D_{\mu\mu} \sim D_{vv,0} V_{\mathrm{A}}^{-2}\left(\frac{U^3}{r_{\mathrm{E}}}\right)\left(\frac{v}{U}\right)\left(\frac{r_{\mathrm{E}}}{r}\right)^{3/4} \tag{3}$$

with V_{A} being the Alfvén velocity which due to $V_{\mathrm{A}}\sim B/\sqrt{\rho}$ at distances $r\geq r_0$ with $B\sim r^{-1}$ and $\rho\sim r^{-2}$ can be taken as fairly constant. This clearly shows that $\lambda_\parallel$ is independent of the particle velocity and roughly is given by

$$\lambda_\parallel = \frac{3v}{8}\int_{-1}^{+1}\frac{(1-\mu^2)^2\mathrm{d}\mu}{D_{vv,0}V_A^{-2}\left(\frac{U^3}{r_{\mathrm{E}}}\right)\left(\frac{v}{U}\right)\left(\frac{r_{\mathrm{E}}}{r}\right)^{3/4}} \tag{4}$$

$$= \frac{3V_{\mathrm{A}}^2 r}{8U^2\left(\frac{r_{\mathrm{E}}}{r}\right)^{-1/4}}\int_{-1}^{+1}\frac{(1-\mu^2)^2\mathrm{d}\mu}{D_{vv,0}} \tag{5}$$

simply yielding

$$\lambda_\parallel = \frac{3r_{\mathrm{E}}}{8}\frac{V_{\mathrm{A}}^2}{U^2}\left(\frac{r}{r_{\mathrm{E}}}\right)^{3/4}\int_{-1}^{+1}\frac{(1-\mu^2)^2\mathrm{d}\mu}{D_{vv,0}} = \lambda_{\parallel,\mathrm{E}}\left(\frac{r}{r_{\mathrm{E}}}\right)^{3/4} \tag{6}$$

and reminding that the reference value $\lambda_{\parallel,\mathrm{E}}$ for average MHD turbulence levels at $r=r_{\mathrm{E}}$ has been found with $\lambda_{\parallel,\mathrm{E}}\simeq 0.3\,\mathrm{AU}$ (see Chalov and Fahr, 1999) then leads us to the result that at the termination shock distance of $r_{\mathrm{TS}}\simeq 90\,\mathrm{AU}$ one finds the mean free path for the average pitch-angle scattering process given by:

$$\lambda_{\parallel,\mathrm{TS}} = \lambda_{\parallel,\mathrm{E}}\left(\frac{r_{\mathrm{TS}}}{r_{\mathrm{E}}}\right)^{3/4} \simeq 8.77\ \mathrm{AU} \tag{7}$$

We should mention at this position that the validity of the velocity-independence of the velocity diffusion coefficient is restricted to medium energy ions ($1\,\mathrm{keV}\leq E\leq 50\,\mathrm{keV}$). In this range under the assumptions made by Chalov and Fahr (1996) for the the MHD turbulence in the solar wind on the basis of calculations carried out by Schlickeiser (1989), one obtains a velocity diffusion coefficient D_{vv} that is proportional to the velocity and mean scattering free pathes which are essentially velocity-independent.

2.2 Distribution of reflected ions after pitch-angle scattering

After pitch-angle scattering the distribution function is assumed to represent a shell with a Gaussian cut-profile. This takes into consideration that the underlying shape of the Gaussian beam profile of reflected ions is conserved (energy-conserving pitch-angle scattering). The isotropisation takes place in the frame which is comoving with the upstream solar wind (i.e. the wind frame). Therefore, the radius of the shell is $R=U_1+U_1^{\mathrm{refl}}$. In the shock frame the distribution centre is shifted to $w_x=U_1$. This distribution $\tilde{f}(w_x,w_y,w_z)$ hence is given by

$$\tilde{f} = \frac{1}{a}\exp\left\{-\frac{1}{2}\left[\frac{\sqrt{(w_x-U_1)^2+w_y^2+w_z^2}-R}{\sigma}\right]^2\right\}. \tag{8}$$

σ is the width of the reflected ion beam on the upstream side and also the width of the Gaussian shell. It is connected with the beam temperature T by

$$\sigma = \sqrt{k_{\mathrm{B}}T}. \tag{9}$$

The normalisation factor a can be obtained by several integrations in spherical coordinates (the shift can be switched

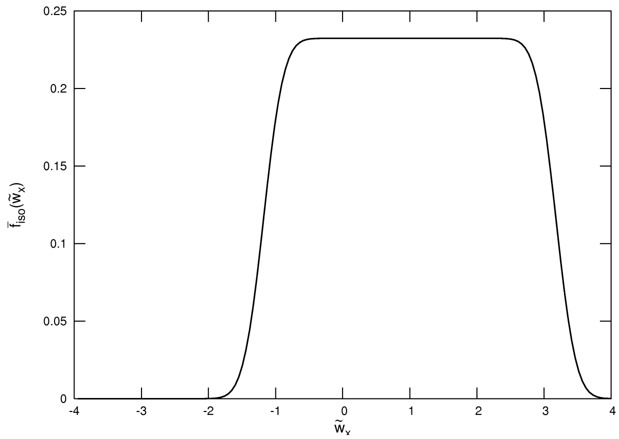

Fig. 2. Result of the integration of the Gauss shell over two velocity space coordinates. The isotropised distribution function is normalised to one.

off by $(w_x - U_1) \rightarrow w_x$ without loss of generality during integration over the full velocity space). It turns out that it is given by

$$a = 12\pi\sigma^2 R \cdot \mathrm{e}^{-\frac{1}{2}\frac{R^2}{\sigma^2}} + \sqrt{32\pi^3}\sigma \cdot \left(\sigma^2 + R^2\right) \cdot \Phi\left(\frac{R}{\sigma}\right), \quad (10)$$

where Φ denotes the Gauss error integral which is related to the error function by

$$\Phi\left(\frac{R}{\sigma}\right) \equiv \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\frac{R}{\sigma}} \mathrm{e}^{-\frac{1}{2}z^2}\mathrm{d}z = \frac{\operatorname{erf}\left(\frac{R}{\sqrt{2}\sigma}\right) + 1}{2}. \quad (11)$$

This result can be confirmed by melting the shell to a three-dimensional Gaussian distribution (i.e. $R \rightarrow 0$). Obviously, Eq. (8) changes to the correct form. Then, with $\Phi(0) = 1/2$, the normalisation factor changes to

$$a = \sqrt{8\pi^3}\sigma^3, \quad (12)$$

which is the correct value for a standard Gauss distribution in three dimensions.

For large values of $R \gg \sigma$ the left part of Eq. (10) becomes small and negligible and $\Phi(\frac{R}{\sigma})$ becomes 1. Under these conditions, the factor a can be simplified to

$$a \approx \sqrt{32\pi^3}\sigma R^2. \quad (13)$$

This takes into account that for a larger shell, due to the larger shell surface, the norm of the distribution function must be smaller to satisfy normalisation to 1.

To obtain the one-dimensional isotropised distribution function $f_{\text{iso}}(w_x)$, the Gauss shell is integrated over w_y and w_z:

$$f_{\text{iso}}(w_x) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \tilde{f}(w_x, w_y, w_z)\mathrm{d}w_y\mathrm{d}w_z \quad (14)$$

The result of this integration is shown in Fig. 2.

Evidently, f_{iso} is a rather constant distribution over a wide velocity range. After isotropisation due to pitch-angle diffusion there is a certain amount of ions with a velocity up to about three times the solar wind bulk velocity in the shock rest frame, which have been provided again with a velocity into the shock direction on the upstream side. This means that the parallel shock configuration with reflection and pitch-angle diffusion of selected ions presents an effective acceleration mechanism for ions.

For the detailed calculation the thermal upstream solar wind distribution f_{SW} is added to the isotropised distribution f_{iso} with the correct proportion:

$$\bar{f}_1 = p_{\text{r}} \cdot f_{\text{iso}} + (1 - p_{\text{r}}) \cdot f_{\text{SW}} \quad (15)$$

Both distribution functions and $\bar{f}_1$ are normalised to 1. $p_{\text{r}} \simeq 0.18$ is the amount of the reflected ions. The resulting $\bar{f}_1$ consists of the flat base f_{iso} with a superimposed Maxwellian hat (from f_{SW}) in the middle at $w_x = U_1$ with the temperature T_1.

Single test particles with a velocity corresponding to this complete distribution $\bar{f}_1$ are obtained by applying von Neumann's method of rejection sampling (see Knuth, 1981, p. 120–121). With this Monte Carlo method, a random variable X, which obeys the probability density function $p(t)$, can be derived from computer-generated, uniformly distributed pseudo random numbers and a given probability density function $g(t)$. Let u_i be uniformly distributed random numbers. v_i are random numbers which are distributed according to $g(t)$. Then one chooses a real k with $p(t) \leq k \cdot g(t)$ for every t. If $k \cdot u_i \cdot g(v_i) < p(v_i)$, the random variable X_i is set to v_i. Otherwise the set (u_i, v_i) is rejected. After several executions the random variables X_i are distributed according to p.

In this special case p is given by the initial distribution $\bar{f}_1$, g is a Gaussian normal distribution, which envelops the distribution function $\bar{f}_1$, and, with this choice, the random variable X_i corresponds to the initial velocity w_x of one test particle.

After isotropisation a small amount of ions has got negative velocities (see Fig. 2). We do not expect a further influence of these ions on the shock. Thus, the distribution function $\bar{f}_1$ is cut at $w_x = 0$ and only the ions with a motion into the shock direction are taken into account. Of course, a new re-normalisation is then necessary.

The shock parameters (even the shock compression ratio) are kept as before to realise that the shock is mainly established by the bulk flow of the solar wind ions and to treat the small amount of isotropised particles as additional test-particles. Therefore, only one iteration with a fixed $U_2 = U_1/r$ is necessary. The particle species, which is a result of the pitch-angle scattering, is hence treated like test-particles. Therefore, it is not necessary to update the downstream bulk velocity U_2 iteratively because it should be set to a constant value by the bulk flow.

3 Results

A newly distributed set of 30 000 ions is sent over the shock under a typical parameter choice (upstream bulk velocity $U_1 = 4\times10^7$ cm/s, compression ratio $r = 2.5$, upstream ion density $n_1 = 5\times10^{-4}$ cm^{-3}, upstream ion and electron temperature $T_1 = 1\times10^4$ K, size of the electric field region $\lambda = 5\times10^5$ cm and size of the turbulent interaction region $b = 2\times10^6$ cm (see Verscharen and Fahr, 2008)). In the first execution, the reflected particle properties are taken from the results in Fahr and Verscharen (2008). Their amount is given by $p_\mathrm{r} = 0.18$ and the bulk velocity of the reflected ions is taken as $U_1^\mathrm{refl} = -4.6\times10^7$ cm/s. The parameter σ is taken from the value of the reflected ion temperature $T_1^\mathrm{refl} = 1.1\times10^6$ K on the upstream side. The result of this treatment is shown in Fig. 3.

Additionally to the known behaviour (broadening, double-hump), a tail distribution at high downstream velocities occurs. At the primary model the highest velocities were in the range of about 1.5 times the solar wind upstream bulk velocity. Now after pitch-angle diffusion of the reflected ions, the positive velocity tail reaches values up to 3 times U_1. This means that reflection and subsequent pitch-angle diffusion leads to the occurence of high particle velocities on the downstream side. The width of the reflected branch, however, does not change significantly. In comparison to the primordial distribution function, which is represented by the dotted lines in Fig. 3, the level of the reflected ions is smaller, whereas the amount of ions with positive proper velocities is higher.

As one can see in comparison with the first calculations, the amount of reflected ions was over-estimated. Thus, there are less reflected ions, which are able to become an isotropised ion population after pitch-angle scattering. This means that the true downstream ion distribution must lie somewhere between both extreme cases: the one without incorporation of the reflected and isotropised ions and the other as given by the first calculation (Fig. 3). A stable description of the shock situation can be obtained by changing the amount of reflected ions till, after several iterations, no further change of the downstream distribution function (respectively, the compression ratio and the area of the hump with negative velocity) occurs. The artifical reduction of the reflected ions in the model code will essentialy lead to an immediate shrinking of the high-velocity tail of the downstream distribution function connected with a lower value U_2 after evaluation of the first moment of the distribution function. The shock is stable if the reflected ions reproduce themselves after isotropisation. The stable self-reproducing downstream distribution function essentially describes the consistent solution of the shock. This situation is found, if the amount of the reflected ions is reduced to $p_\mathrm{r} = 0.15$ and the reflected bulk velocity on the upstream side is set to $U_1^\mathrm{refl} = -1.15\cdot U_1 = -4.6\times10^7$ cm/s.

Concluding, we want to remind here that these particles are not assumed to replace the pick-up ions; but, they must be taken into consideration as an additional particle species in the inner heliosheath.

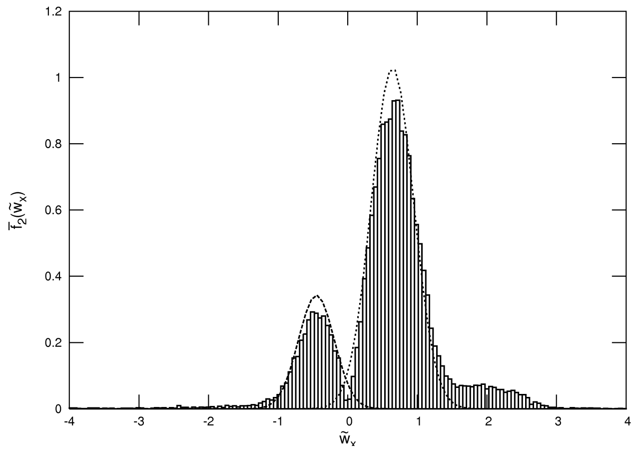

Fig. 3. Distribution function on the downstream side of the shock. A remarkable result is the high-velocity tail on the right hand side. The primordial distribution function on the downstream side without the treatment of the reflected ions after pitch-angle diffusion is plotted with the dotted lines for a better comparison (cf. Fig. 1).

4 Discussion

4.1 Dissipative Entropisation

The appearence of a high-energy tail in the distribution of the downstream ions is the most conspicuous result of our extended model. These tail ions possess higher than sonic particular velocity in the downstream regime. Because of the difference between their velocity and the bulk flow, a further interaction will take place on the downstream side of the shock. For example, a certain set of different wave modes will be excited, which brings the distribution to a higher entropy. By the H-theorem, the entropy S can be calculated by

$$S = Nk_\mathrm{B}\int f\ln f\,\mathrm{d}^3w \approx Nk_\mathrm{B}\sum_i p_i \ln p_i\,, \qquad (16)$$

where N denotes the number of particles and p_i the probability for a particle in the velocity cell i (i.e. $p_i = \bar{f}(w_x)\Delta w_x$) (see e.g. Landau and Lifshitz, 1980). Evaluation of this expression shows that during the shock transit the entropy grows by a factor of about three from the initial ion distribution $\bar{f}_1$ to the downstream distribution $\bar{f}_2$. This shows the dissipative nature of this process and legitimates the approach from a thermodynamical point of view.

4.2 Particle injection into the Fermi-1 acceleration process

A certain amount of the isotropised ions has got a parallel velocity component w_x which is too small to overcome the shock potential. They must be reflected again. The constance of the total energy and the fact that both particle species are affected by the same potential Φ

$$\frac{1}{2}m_\mathrm{p}U_1^2 = \frac{1}{2}m_\mathrm{p}U_2^2 + e\Phi \tag{17}$$

$$\frac{1}{2}m_\mathrm{p}w_1^2 = \frac{1}{2}m_\mathrm{p}w_2^2 + e\Phi \tag{18}$$

leads to

$$w_2^2 = w_1^2 + U_2^2 - U_1^2. \tag{19}$$

The particle velocity w_2 is expected to be negative (i.e. reflection at the potential) if w_1 is small enough but greater than zero. This corresponds to the necessary condition

$$0 < w_1 < \sqrt{U_1^2 - U_2^2} \tag{20}$$

for the injected ions. With $U_1 = 4\times 10^7$ cm/s and a compression ratio of $r = 2.5$ this leads to $0 < w_1 < 3.67\times 10^7$ cm/s, which corresponds to $0.91\cdot U_1$. Because of their isotropisation, the particles with a small value of w_x (close to 0) have a rather high tangential velocity component.

These particles undergo a successively accelerating process with subsequent reflection and diffusion, whereby they climb-up to systematically higher kinetic energies. This mechanism provides the possibility to reach a sufficient high energy level for diffusive shock acceleration (Fermi-1 acceleration) for anomalous cosmic rays (Pesses et al., 1981; Fichtner et al., 1996). This can be seen as a new kind of a self-initialised Fermi-1 acceleration process.

The amount of the reflected ions which can undergo the first acceleration process after isotropisation can be estimated. On the first view, the isotropised distribution function can be treated like a rectangular distribution with a width of about $a_\mathrm{tot} = 4.5$ (see Fig. 2) in scaled units (i.e. a range of $4.5\cdot U_1 = 1800$ km/s). The ions with $0 < w_1 < 3.67\times 10^7$ cm/s correspond to a rectangle with a width of $a_\mathrm{acc} = 0.91$ (i.e. a range of $0.91\cdot U_1 = 364$ km/s). Due to the correct normalisation of f_iso, this leads to an estimation for the trapped ions of

$$p_\mathrm{acc} = p_\mathrm{r}\cdot\frac{a_\mathrm{acc}}{a_\mathrm{tot}} = 0.15\cdot\frac{0.91}{4.5} = 0.03. \tag{21}$$

This means that 3% of the incoming solar wind ions are able to undergo the acceleration mechanism as it is described above. Converted into particle density, this corresponds to $n_\mathrm{acc} = p_\mathrm{acc}\cdot n_\mathrm{SW} = 0.03\cdot 5\times 10^{-4}\,\mathrm{cm}^{-3} = 1.5\times 10^{-5}\,\mathrm{cm}^{-3}$. One can compare this density with a pick-up ion injection efficiency, if the same number of ions was injected by pick-up ions.

If a pick-up ion population with this number density n_acc occured in the velocity range of 0 to $0.91\cdot U_1$, this would correspond to a mean pick-up ion flux of $\mathcal{F}_\mathrm{iPUI} = n_\mathrm{acc}\cdot\frac{1}{2}364$ km/s for injected PUIs. The flux of incoming neutrals from the local interstellar medium can be estimated with $\mathcal{F}_{H_\mathrm{n}} = n_{H_\mathrm{n}}\cdot u_\mathrm{HS}$ with the neutral hydrogen number density $n_{H_\mathrm{n}} = 0.14\,\mathrm{cm}^{-3}$ and the relative velocity $u_\mathrm{HS} = 25$ km/s of the heliosphere with respect to the LISM. The corresponding pick-up ion efficiency can be defined by the ratio of these fluxes. This means that – in our case – the injected solar wind particles would correspond to a pick-up ion efficiency of

$$\eta = \frac{\mathcal{F}_\mathrm{iPUI}}{\mathcal{F}_{H_\mathrm{n}}} = \frac{n_\mathrm{acc}\cdot\frac{1}{2}364\ \mathrm{km/s}}{n_{H_\mathrm{n}}\cdot u_\mathrm{HS}} = 0.0008 \tag{22}$$

in the classical understanding. This shows that the flux of the isotropised ions is rather low in comparison to the usually assumed PUI fluxes. However, it lies sufficiently within the possible range of values as mentioned above (Le Roux and Fichtner, 1997). Therefore, we do not interpret the herein proposed mechanism as the dominant acceleration effect for ACRs but rather as an additional possibility, especially for the case of the parallel MHD shock.

5 Conclusions

Hitherto, a partially neutral interstellar medium for the generation of pick-up ions was necessary to produce ACRs. In our model a self-generation of ACRs by solar wind particles and their interaction with the shock is shown to be possible. This means that the parallel termination shock is able to produce particles with a high kinetic energy similar to ACR particles analogous to the contribution by PUIs. The injection is a result of subsequent diffusive acceleration by wave-particle interaction and pitch-angle scattering on the upstream side.

For the classical pick-up ion acceleration process it is known that the injection efficiency strongly depends on the magnetic field orientation at the shock (Chalov and Fahr, 1996; Kucharek and Scholer, 1995; Fahr et al., 2008). Therefore, it is of great interest to study the dependence of the new injection process on the magnetic field orientation. For this investigation, the primary model should be extended for a more general magnetic field configuration. Even though the solar wind termination shock for the largest region is assumed to be quasi-perpendicular, the study of oblique shocks is important to provide a higher generality (see also Liewer et al., 1993).

A further point of interest is given by the unexpected element abundances in the ACR component (Cummings and Stone, 1995). Up to now, they used to be explained by PUI injection (e.g. Steenkamp and Moraal, 1993; Cummings and Stone, 1996). The effect of the elementary composition on shock-generated high energy solar wind particles should be the task for further considerations. If the shock itself does not filter the less abundant elements, maybe another selective process will become necessary.

For further studies this model should be applied on other astrophysical shocks. The interplanetary shock waves behave rather similar to the termination shock. Maybe even relativistic shock waves with high compression ratios – for example like supernova shocks – show a similar self-initialised acceleration process. Then this mechanism could contribute to the energisation of galactic cosmic rays (see also Scherer et al., 2008).

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