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From exponential to power-law: Temporal development of energetic ion spectra at quasi-parallel shocks

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Abstract. Diffusive shock acceleration theory predicts ion energy spectrum of power-law form. On the other hand, the energy spectra obtained around terrestrial bow shocks and in hybrid simulations show exponential forms over a wide energy range. Here, we try to reconcile this difference by proposing a spectrum to develop from an exponential to power-law form in time. We have performed hybrid simulations in which we place a non-physical wall in the upstream region. This wall elastically reflect ions in the local fluid frame and drives the classical Fermi process. First we obtain an exponential spectrum which is produced by the injection process from the thermal to the non-thermal ions at the shock front. Later, the effect of the reflections at the wall dominates and increases the characteristic energy of the exponential spectrum, as well as produces a power-law form in the high energy range. Consequently, the well-developed spectrum consists of three populations, the thermal, the non-thermal with the exponential form, and the non-thermal with a power-law form.

1 Introduction

In the region upstream of quasi-parallel shocks non-thermal ions are frequently observed. While the most popular acceleration process is the diffusive shock acceleration mechanism that predicts an energy spectrum of power-law form, the observed energy spectra in the upstream region of earth's bow shocks show exponential forms over a wide energy range (from several keV up to a few hundreds keV). One of the proposed models to explain this discrepancy is loss of ions from the acceleration region. Particles with larger gyro-radii than the acceleration region can be expected to leak from the shock system by cross-field diffusion (e.g. Eichler 1981). However, even in one-dimensional quasi-parallel shock simulations where cross-field diffusion is inhibited, the spectra are still exponentials. Another proposed model invoking a leaking process is a free escape boundary (FEB) model, in which accelerated particles are supposed to escape to the far upstream region along the magnetic field. However, Scholer et al. (1999) have shown that the e-folding energies in the exponential spectra do not depend on the distance of FEB from the shock in one-dimensional simulations. With this result, it was suggested that the discrepancy is because the spectra are still evolving in time. Indeed, the simulation run-time is still smaller than the acceleration time estimated by Giacalone et al. (1997). Giacalone et al. (1992) have shown that in their hybrid simulations the energy spectra in the downstream region shows a power-law in the energy range of $10 \leq E/E_0 \leq 50$ (E_0 is shock ram energy of the thermal ion) when an upstream turbulence is initially superimposed in order to decrease the particle mean-free-path and thus shorten the acceleration time. Here we have taken a different approach to shorten the particle mean-free-path in order to investigate its effect on the time development of the energy spectra. We have performed hybrid simulations in which we place a non-physical wall in the upstream region. This wall elastically reflects non-thermal ions in the local fluid frame and drives the classical Fermi process. The short distance of the wall from the shock surface leads to a more rapid development of the spectrum than in the case of Giacalone et al. (1992). Consequently we can see the evolution of the spectrum within run time.

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2 Simulation model

The hybrid model used in this study treats the ions as macroparticles and the electrons as a charge-neutralizing massless fluid. The simulation allows for one direction (shock normal direction x: positive x directed downstream) and full three-dimensional velocities. A shock wave with Alfvén Mach number $M_A = 5$, upstream plasma beta for protons $\beta = 1$ and for electrons $\beta = 0$ is set up by a conventional way (piston method). A quasi-parallel case $\theta_{BN} = 2^\circ$ is studied. Hereafter, the magnetic field is normalized by the up-

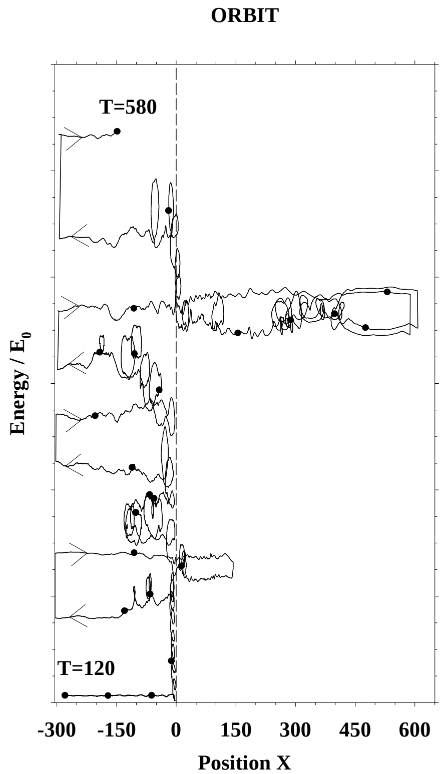

Fig. 1. One of the orbits from the case of W=300. Particle energy is plotted versus position x in the time range from T=120 (left bottom tic) to 580 (left top tic). Dots on the orbit are plotted every 20. Acceleration at the shock front as well as that upon wall reflection is recognized.

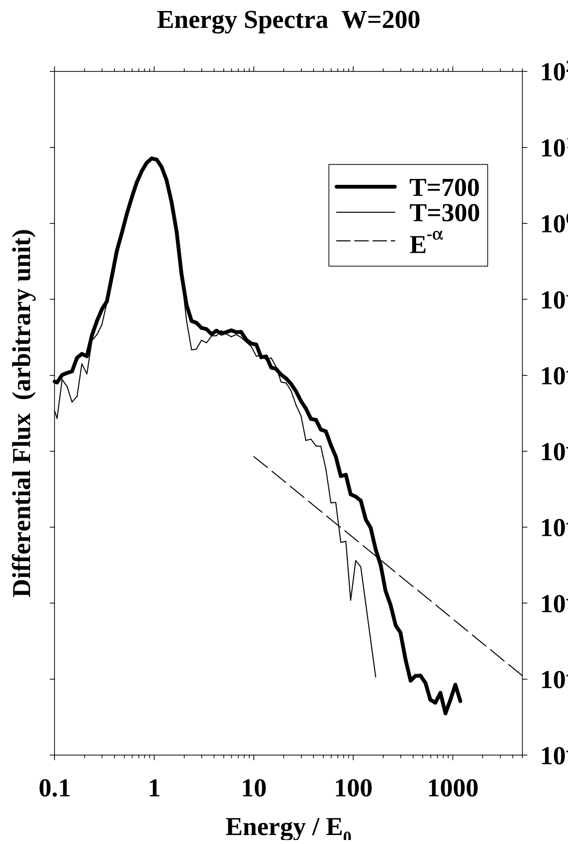

Fig. 2. Upstream energy spectrum for the case of W=200. The spectrum is sampled in the upstream region $-75 \leq x \leq -25$. T = 700 (300) result is shown by thick (thin) curve. The dotted line shows the power-law function.

stream background value B_0: velocity, time, and length, by the Alfvén velocity V_A, the inverse of proton gyro-frequency Ω_i^{-1}, and the ion inertia length $\lambda_i \equiv V_A/\Omega_i$, respectively, based on the upstream parameters. The simulation system size is $2500\lambda_i$ and the grid cell size Δx is $0.5\lambda_i$. The time step size is $0.01{\Omega_i}^{-1}$. 200 particles per cell initially represent upstream unit density. Since only a few percentage of the thermal ions are accelerated, we have applied the particle splitting method to obtain statistically meaningful distributions in the higher energy range. When a particle crosses an energy threshold, it is split into two new particles which contribute half of their mother particle to the field and plasma bulk velocity. The daughters are displaced by $\pm 0.05\Delta x$ from their mother's position. We have chosen 16 energy levels which are evenly spaced on a linear scale in the range 10-460 E_0 (E_0 = shock ram energy of the thermal proton). This allows us to follow the distribution function over ten orders of magnitude. The shock position x=0 used in the analysis of the results is determined by the position where the density exceeds 2.5 times that of the far upstream value. We have placed a non-physical wall in the upstream region with the distance W from the shock surface. This wall elastically reflects non-thermal ions in the local fluid frame which causes the classical Fermi acceleration.

3 Simulation results

Figure 1 shows one of the orbits from the case of W=300. Particle energy is plotted versus position x in the time range from T=120 (left bottom tic) to 580 (left top tic). Dots on the orbit are plotted every 20. Energy is measured in the shock frame and normalized by E_0. The wall in the upstream region reflects the ion which leads to quick acceleration in the present simulation system because the ion is forced to go back to the shock and to cross the shock many times. At the shock surface, the ion is accelerated by the mechanism proposed by Sugiyama et al. (2001), which is different from both the shock-drift and the shock-surfing mechanisms.

Figure 2 shows resultant energy spectra in the case of W = 200. Plotted on the ordinate axis is a differential particle flux dJ/dE in an arbitrary unit. The spectra are sampled in the upstream region $-75 \leq x \leq -25$ at T=300 (thin)

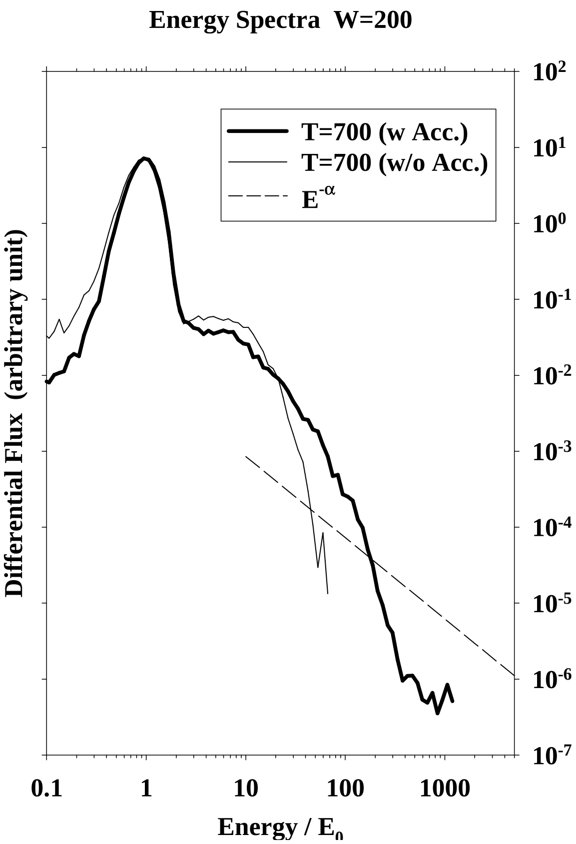

Fig. 3. Upstream energy spectrum for the case of W=200 in the same format as Fig. 2. Thick curve is the same as the thick curve in Fig. 2. Thin curve shows the case where the upstream wall reflects the ion without acceleration in the shock frame.

and 700 (thick). The dotted line indicates the power-law function $E^{-\alpha}$, where $\alpha = (r+2)/2(r-1)$ and r is the density jump at the shock. The Rankine-Hugoniot relations for the present case results in $r \sim 3.6$, and $\alpha \sim 1.07$. At T=300 the spectrum has a non-thermal population above several times E_0 with an exponential form, which is similar to the results of previous works (e.g. Giacalone et al. 1992). On the other hand, at T=700, we can easily see three distinct populations: the thermal population around $E \sim 1$, the non-thermal population with an exponential function in the range $5 \leq E \leq 300$, and another non-thermal population above $E \sim 300$. The third population is not of an exponential form but of a nearly power-law form with the spectrum index α. In addition to the increase in the characteristic energy for the exponential part, the new population (hereafter we refer to it as PL population) is found to be emerging at the highest energy range.

To see whether the emergence of the PL population depends on the acceleration at the wall, we have performed another simulation run where the wall reflects ions without acceleration in the shock frame. Figure 3 shows two energy spectrum from simulation runs with/without acceleration at the wall in the same format as Fig. 2. ¿From the disappearance of the PL population in the case without acceleration (the thin curve) the key role played by the acceleration at the wall to create the PL population is confirmed. In the lower part of the non-thermal ions below about 20 E_0, the two spectra are nearly identical. This is because an acceleration process which is not related to the wall is also present. The acceleration takes place at the shock surface as shown in Fig. 1.

We will investigate how the newly emerging PL population evolves in time. Figure 4 shows the time sequence of the spectrum in the case of W=200. The times are from left to right T=350, 600, and 850. Again, the dotted line shows the power-law function $E^{-\alpha}$. The energy at which a transition from an exponential to a power-law takes place increases with time. The high energy end of the PL population also expands with time to higher energy while the flux level stays almost constant, even though the seed for the PL population (the exponential part) increases.

4 Discussion

Here we have used a different method from the previous studies to shorten the characteristic time for diffusive shock acceleration and have studied its effect on the evolution of the accelerated ions within the limited simulation run time. We have placed a non-physical wall in the upstream region which accelerates ions upon head-on collision, just as the interaction between waves and particles would do. In the case with the reflecting wall, the upstream energy spectrum consists of four distinct populations: (1) the thermal population, (2) the lower energy population with exponential form in which the effect of the upstream wall is small. (3) the higher energy population with exponential form in which the spectrum evolves in time, and (4) the PL population. Here we call the two populations in the exponential region as EX1(lower energy) / EX2(higher energy), respectively, and the energy between EX1 and EX2 as E_1 and that between EX2 and PL as E_2. The existence of E_1 confirms that there is a wall-independent acceleration process at the shock surface as shown in Fig. 1 (for the detail mechanism, see Sugiyama et al. (2001)). The similar spectral form below about 20 E_0 in Fig. 4 suggests that the E_1 is almost constant in time. This is because EX1 is created by the injection process from the thermal population. The presence of the wall not only increases the characteristic energy of EX2 in time but leads to the PL population beyond the energy E_2.

Although we have followed the temporal development of the energy spectrum, the present simulations are still not long enough to show the complete sequence. Indeed we can easily speculate about at least two kinds of scenarios after this. One is that the PL population continues to extend to higher energy as shown in Fig. 4 and becomes the main body of the very energetic component. The other is that if the expansion of the PL population to higher energy is not much faster than that of E_2, the PL population may remain to be a minor at-

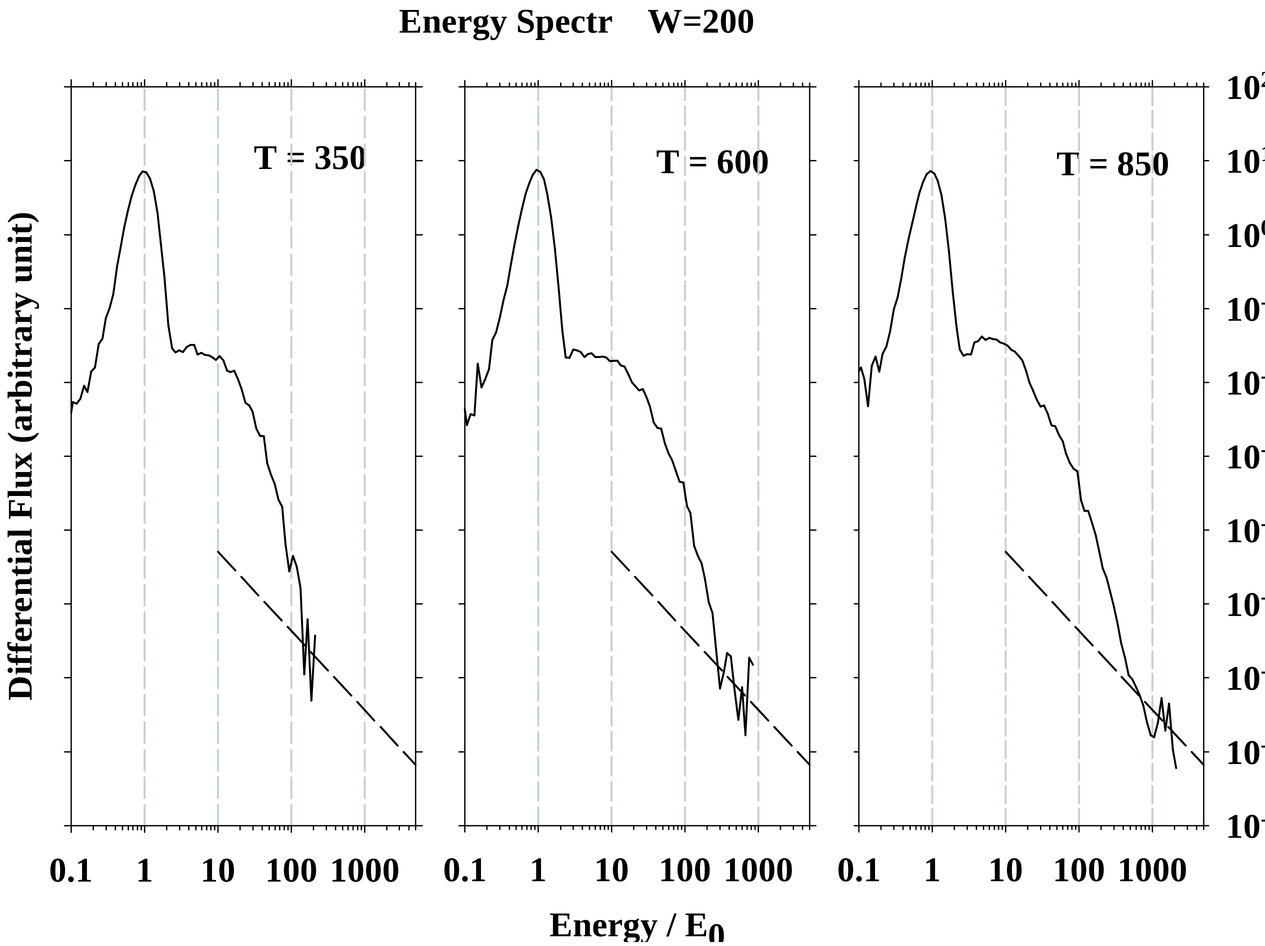

Fig. 4. Time evolving of the PL population at T=350, 600, and 850. The high energy end of the PL population increases with time while keeping the flux level almost constant. The energy at which transition from exponential to power-law takes place (E2) is also increasing with time.

tachment to the major EX2 population (This second scenario has been suggested in previous works.). To determine what kind of a scenario is dominant in the nature, an estimation of the extension speed of E_2 will be most important.

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