Cosmic Ray Acceleration at Quasi-Parallel Plane Shocks

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Abstract

We have studied the CR injection and acceleration efficiencies at cosmic shocks by performing numerical simulation of CR modified, quasi-parallel, shocks in 1D plane-parallel geometry for a wide range of shock Mach numbers and preshock conditions. The shock formation simulation includes a thermal leakage injection model that transfers a small proportion of the thermal proton flux through the shock into low energy CRs. We adopted the Bohm diffusion model for CRs, based on the hypothesis that strong Alfvén waves are self-generated by streaming CRs. Our hydro/CR code is designed to follow in a very cost-effective way the evolution of CR modified shocks by adopting subzone shock-tracking and multi-level adaptive mesh refinement techniques. We found that both injection and acceleration efficiencies increase with shock Mach number, and that CRs can absorb up to 60 % of initial upstream shock kinetic energy in the strong shock limit with an associated CR particle fraction of $10^{-4} - 10^{-3}$.

1. Introduction

According to the diffusive shock acceleration (DSA) theory, populations of cosmic-ray (CR) particles can be injected and accelerated to very high energy by astrophysical shocks in tenuous plasmas [6], and a significant fraction of the kinetic energy of the bulk flow associated with a strong shock can be converted into CR protons [2,3]. We developed a numerical scheme that self-consistently incorporates a "thermal leakage" injection model based on the analytic, nonlinear calculations of Malkov [1,5]. This injection scheme was then implemented into the combined gas dynamics and the CR diffusion-convection code with subzone shock-tracking and multi-level adaptive mesh refinement techniques [4]. We applied this code to study the cosmic ray acceleration at shocks by numerical simulations of CR modified, quasi-parallel shocks in 1D plane-parallel geometry with the physical parameters relevant for the cosmic shocks emerging in the large scale structure formation of the universe [2,3]. In this contribution, we present new simulations with a wide range of physical parameters.

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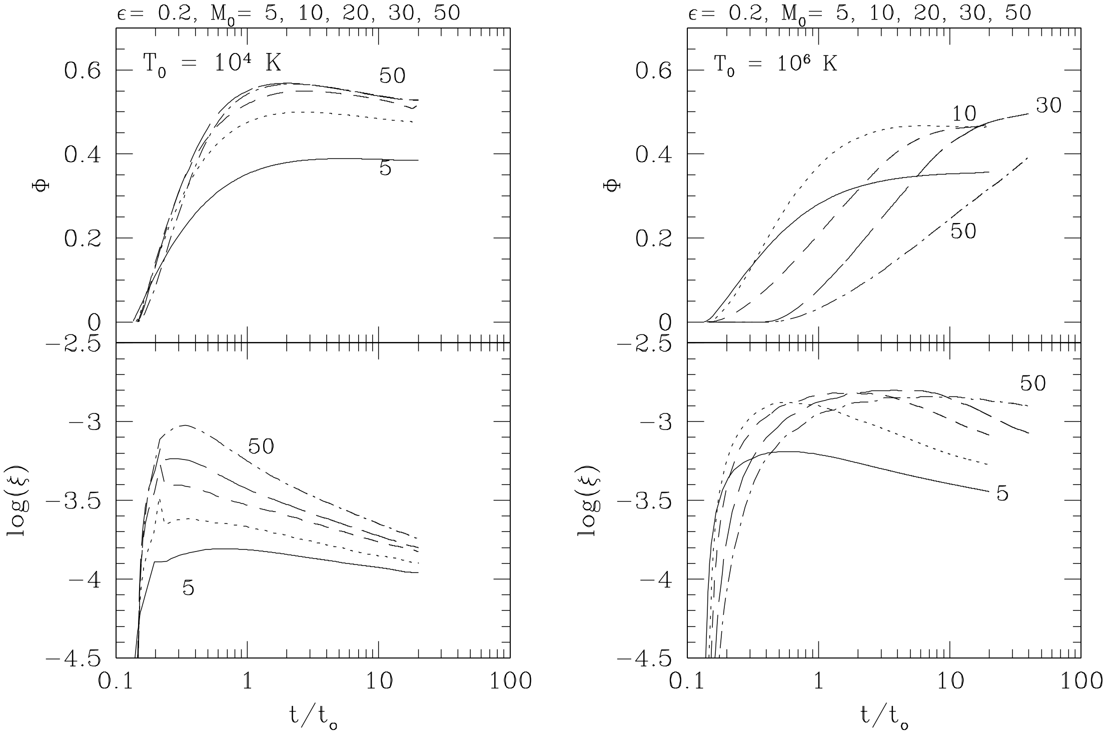

Fig. 1. The CR energy ratio, $\Phi(t)$, and time-averaged injection efficiency, $\xi(t)$ for models with different accretion Mach number M_0. Left panels are for models with $T_0 = 10^4$ K, while right panels for models with $T_0 = 10^6$ K. Accretion speed of each model is given by $u_0 = (15\mathrm{km/s})M_0$ for models with $T_0 = 10^4$ K and by $u_0 = (150\mathrm{km/s})M_0$ for models with $T_0 = 10^6$K. Time is given in terms of the diffusion time, $t_\mathrm{o} = \kappa_\mathrm{o}/u_0^2 \propto M_0^{-2}$.

2. Models: 1D Piston Driven CR Shocks

We calculated the CR acceleration at 1D quasi-parallel shocks that were driven by accretion flows in a plane-parallel geometry. Two sets of models are presented here: 1) $T_0 = 10^4$ K and $u_0 = (15\mathrm{km/s})M_0$ and 2) $T_0 = 10^6$ K and $u_0 = (150\mathrm{km/s})M_0$, where T_0, u_0, and $M_0 = 5-50$ are the temperature, accretion speed, and Mach number of the accretion flow, respectively. We adopted the Bohm diffusion model for CRs, $\kappa(p) = \kappa_\mathrm{o} p^2/(p^2+1)^{1/2}$ where the particle momentum is expressed in units of $m_p c$. In our discussion a choice of κ_o is arbitrary, since we present the results in terms of the diffusion time and length scales defined as $t_\mathrm{o} = \kappa_\mathrm{o}/u_0^2$ and $x_\mathrm{o} = \kappa_\mathrm{o}/u_0$. The gas density normalization constant, ρ_o, is arbitrary as well, but the pressure normalization constant depends on M_0 as $P_\mathrm{o} = \rho_\mathrm{o} u_0^2 \propto M_0^2$. We adopted an injection scheme based on a "thermal leakage" model that transfers a small proportion of the thermal proton flux through the shock into low energy CRs [1,5]. This model has a free parameter, $\epsilon = B_0/B_\perp$, defined

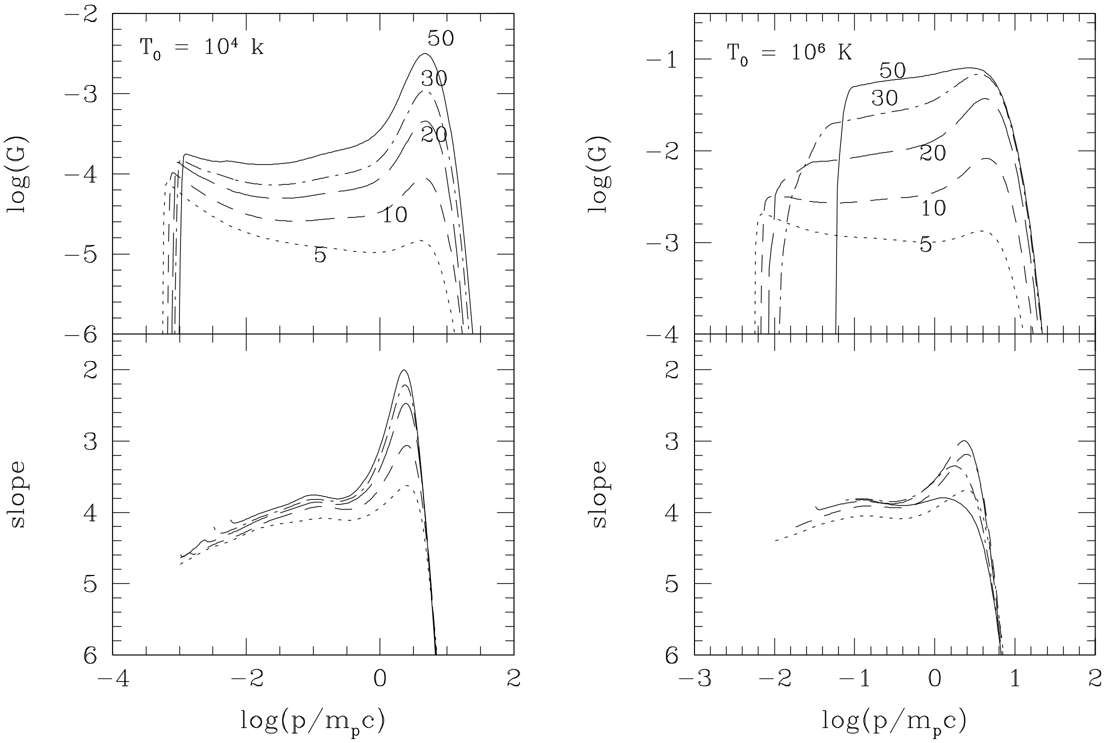

Fig. 2. CR distribution function integrated over the simulation box, $G(p) = \int p^4 f_{\rm cr}(p){\rm dx}$, and its power law slope, $q = -(\partial \ln G/\partial \ln p - 4)$, at $t/t_{\rm o} = 20$. The curves are labeled with the accretion Mach number M_0.

to measure the ratio of the amplitude of the postshock MHD wave turbulence $B_\perp$ to the general magnetic field aligned with the shock normal, B_0 [5]. Here we present models with $\epsilon = 0.2$ only.

3. Injection and Acceleration Efficiencies

We define the injection efficiency as the fraction of particles that have entered the shock from far upstream and then injected into the CR distribution: $\xi(t) = \int {\rm dx} \int 4\pi f_{\rm CR}(p,x,t)p^2 {\rm dp}/(\int n_0 u_s {\rm dt})$, where $f_{\rm CR}$ is the CR distribution function, n_0 is the particle number density far upstream, and u_s is the *instantaneous shock speed*. As a measure of acceleration efficiency, we define the "CR energy ratio"; namely the ratio of the total CR energy within the simulation box to the kinetic energy in the *initial shock frame* that has entered the simulation box from far upstream, $\Phi(t) = \int {\rm dx} E_{\rm CR}(x,t)/(0.5\rho_0 u_{s,0}^3 t)$, where $u_{s,0}$ is the *initial shock speed* before any significant nonlinear CR feedback occurs.

Although the subshock weakens as the CR pressure increases, the injection rate decreases accordingly and the subshock does not disappear. We found that the postshock CR pressure reaches an approximate time-asymptotic value and the evolution of the CR shock becomes "self-similar" due to a balance between fresh injection/acceleration and advection/diffusion of the CR particles away from the shock. So the CR energy ratio, Φ, also asymptotes to a constant value, as shown in Figure 1 (except in the model with $T_0 = 10^6$K and $M_0 = 50$ which has not reached the time-asymptotic state by $t/t_{\rm o} = 40$). Time-asymptotic value of Φ increases with M_0, but it converges to $\Phi \approx 0.5 - 0.6$ for $M_0 \geq 20$. The average injection rate varies $\xi \approx 10^{-4} - 10^{-2.8}$, depending on M_0, u_0 and ϵ. For two models with the same Mach number but different speeds (or different T_0), the injection rate is higher for models with higher speeds, but the CR energy increases more slowly in terms of the normalized time, $t/t_{\rm o}$.

Figure 2 shows the total CR distribution within the simulation box, $G(p) = \int p^4 f_{\rm cr}(p){\rm dx}$ and its power law slope $q = -(\partial \ln G/\partial \ln p - 4)$. For all models shown here, $G(p)$ has an exponential cut-off at the similar momentum ($p_{\rm max} \sim 4$) regardless of values of u_0, since the results are shown at the same values of $t/t_{\rm o} = 20$. The integrated distributions show the characteristic "concave upwards" curves due to nonlinear modification to the shock structures, and this "flattening" trend is stronger for higher M_0 models.

The main conclusions can be summarized as follows: 1) The CR pressure seems to approach a steady-state value and the evolution of CR modified shocks becomes approximately "self-similar". 2) Suprathermal particles can be injected very efficiently into the CR population via the thermal leakage process, so that typically a fraction of $10^{-4} - 10^{-3}$ of the particles passed through the shock become CRs. 3) For a given injection model, the acceleration efficiency increases with the shock Mach number, M_s, but it asymptotes to a limiting value of the CR energy ratio, $\Phi \approx 0.5 - 0.6$, for $M_s > 30$.

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