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COSMIC RAY ACCELERATION AT COSMOLOGICAL SHOCKS

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ABSTRACT

Cosmological shocks form as an inevitable consequence of gravitational collapse during the large scale structure formation and cosmic-rays (CRs) are known to be accelerated at collisionless shocks via diffusive shock acceleration (DSA). We have calculated the evolution of CR modified shocks for a wide range of shock Mach numbers and shock speeds through numerical simulations of DSA in 1D quasi-parallel plane shocks. The simulations include thermal leakage injection of seed CRs, as well as pre-existing, upstream CR populations. Bohm-like diffusion is assumed. We show that CR modified shocks evolve to time-asymptotic states by the time injected particles are accelerated to moderately relativistic energies ($p/mc \gtrsim 1$), and that two shocks with the same Mach number, but with different shock speeds, evolve qualitatively similarly when the results are presented in terms of a characteristic diffusion length and diffusion time. We find that $10^{-4} - 10^{-3}$ of the particles passed through the shock are accelerated to form the CR population, and the injection rate is higher for shocks with higher Mach number. The CR acceleration efficiency increases with shock Mach number, but it asymptotes to $\sim 50\%$ in high Mach number shocks, regardless of the injection rate and upstream CR pressure. On the other hand, in moderate strength shocks ($M_s \lesssim 5$), the pre-existing CRs increase the overall CR energy. We conclude that the CR acceleration at cosmological shocks is efficient enough to lead to significant nonlinear modifications to the shock structures.

Key words : acceleration of particles – cosmology – cosmic rays – hydrodynamics – methods:numerical

I. INTRODUCTION

Collisionless shocks form ubiquitously in tenuous cosmic plasmas via collective, electromagnetic viscosities. The formation process of such shocks inevitably produces suprathermal particles in addition to thermal particles with Maxwellian velocity distributions (Blandford & Eichler 1987, Malkov & Drury 2001). Here we refer to cosmic rays as nonthermal particles above the Maxwellian distribution in momentum space, so they include nonrelativistic, suprathermal particles as well as relativistic particles. These nonthermal particles can be further accelerated to very high energies through the interactions with resonantly scattering Alfvén waves in the converging flows across a shock (Drury 1983). Detailed nonlinear treatments of DSA predict that a small fraction of incoming thermal particles can be injected into the CR population, and that a significant fraction of the shock kinetic energy can be transferred to CRs (*e.g.,* Berezhko *et al.* 1995; Kang, Jones & Giesler 2002; Kang & Jones 2002; Kang 2003).

On a galactic scale it is well known that the CR energy density is comparable to the gas thermal energy density in the interstellar medium and plays important dynamical roles in the evolution of our Galaxy. Although the Galactic CRs are commonly believed to be accelerated mostly at supernova remnant shocks (Berezhko & Völk 2000), CR acceleration is probably important in all shock-heated cosmic plasmas. CR populations are also indicated by extended, diffuse nonthermal emissions in some galaxy clusters (Giovannini & Feretti 2000, Feretti *et al.* 2001). Recent observations in EUV and hard X-ray have revealed that some clusters possess excess radiation compared to what is expected from the hot, thermal X-ray emitting ICM (*e.g.,* Sarazin & Lieu 1998; Bowyer *et al.* 1999; Fusco-Femiano *et al.* 1999). One mechanism proposed for the origin of this component is the inverse Compton scattering of cosmic background photons by CR electrons accelerated by merger shocks and accretion shocks around the clusters. Also it has been suggested that the diffuse gamma-ray background radiation could originate from the same process (Loeb & Waxman 2000, Miniati 2002). The same mechanisms that are capable of producing CR electrons may have produced CR protons, although the existence of CR protons in the ICM has not yet been directly observed. The existing evidence for substantial CR populations in these environments argues that nonthermal activities in the ICM could be important in understanding the dynamical status and the evolution of clusters of galaxies.

According to hydrodynamic simulations of large scale structure formation in the universe, nonlinear structures such as pancakes, filaments, and knots are surrounded by *external* accretion shocks and contain com-

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plex webs of *internal* flow shocks including accretion shocks around individual clusters and merger shocks inside clusters (Miniati *et al.* 2000). These shocks have a wide range of physical parameters with shock speeds, u_s, up to $\sim$ 3000 km s^{-1}, preshock temperatures of $10^4 < T_0 < 10^8$ K, and Mach numbers up to a few 100 (Ryu *et al.* 2003). In the present universe the mass inside nonlinear structures has been shocked approximately twice on average over cosmic time, and shocks with $2 \lesssim M \lesssim 4$ have contributed $\sim 1/2$ of the total energy dissipated at the shocks. In this contribution we calculate the CR acceleration at such shocks with a wide range of physical parameters suitable for application to cosmic structure formation shocks, and also consider the influence of a pre-existing, upstream CR population.

In the next section we briefly describe our numerical simulations. The simulation results are presented and discussed in §III, followed by a summary in §IV.

II. BASIC PHYSICS

(a) Bohm Diffusion Model

DSA depends on the spatial diffusion coefficient for the CRs. The diffusion coefficient can be expressed in terms of a mean scattering length, λ, as $\kappa(x,p) = \frac{1}{3}\lambda v$, where v is the particle velocity. For Alfvén wave scattering one can write $\lambda \approx r_g(B/\delta B)^2$ (*e.g.,* Skilling 1975), where r_g is the particle gyroradius. The Bohm diffusion model, representing a saturated wave spectrum ($\delta B \sim B$) and the minimum diffusion coefficient, gives $\kappa_{\rm B} = (1/3) r_{\rm g} v$. If we assume "Bohm-like" diffusion with $\lambda = \zeta r_g$ with $\zeta \geq 1$, the diffusion coefficient can be expressed as

$$\kappa(\rho, p) = \kappa_{\rm n} \left(\frac{\rho_0}{\rho}\right) \frac{p^2}{(p^2+1)^{1/2}}, \quad (1)$$

where hereafter momentum, p, is expressed in units of mc and $\kappa_{\rm n} = \zeta(1/3)mc^2/(eB)$, represents the diffusion coefficient far upstream of the shock for CRs with $p \approx 1.3$.

(b) Self-Similar Shock Evolution

In the test-particle limit where the nonlinear CR feedback is not significant, the mean acceleration time scale for a particle to reach momentum p (*e.g.,* Drury 1983) is defined as

$$\tau_{acc}(p) = \frac{3}{u_1 - u_2}\left(\frac{\kappa_1}{u_1} + \frac{\kappa_2}{u_2}\right) \approx \frac{8M_s^2}{M_s^2 - 1} t_d(p) \ , \quad (2)$$

where $t_d(p) = \kappa(p)/u_s^2$ is the diffusion time and u_s is the shock speed. The approximate, Mach-number-based expression in equation (2) is based on the compression through a gasdynamic shock for $\gamma_g = 5/3$ and sets $u_s = u_1$. Thus, the CR acceleration time depends on both the speed and the Mach number (actually compression) of the shock in addition to the diffusion coefficient. In the limit of strong shocks ($M_s \gg 1$), however, it becomes independent of the shock Mach number, and is about an order of magnitude greater than the nominal diffusion time, *i.e.,* $\tau_{acc} \approx 8t_d$.

The ideal gasdynamic equations in 1D planar geometry do not contain any intrinsic time and length scales, but in CR modified shocks the CR acceleration and the precursor growth can be characterized by the diffusion scales, $t_d(p)$ and $x_d(p)$, where $x_{\rm d}(p) = \kappa(p)/u_s$. $\kappa_n = \kappa(p \approx 1.3)$ provides a useful canonical value, since nonlinear feedback from CRs to the underlying flow becomes significant typically by the time transrelativistic CRs are accelerated. Consequently, we normalize our shock evolution times and structure scales by $t_{\rm n} = \kappa_{\rm n}/u_{\rm n}^2$, and $x_{\rm n} = \kappa_{\rm n}/u_{\rm n}$, respectively, where $u_{\rm n}$ is a characteristic flow speed. One expects intrinsic similarities in the dynamic evolution and structure of two CR shock models with the same Mach number, but with different shock speeds, *so long as the results are expressed in terms of* $t_{\rm n}$ *and* $x_{\rm n}$. This approach removes the need for any particular choice in $\kappa_{\rm n}$.

(c) CR/AMR Hydrodynamics Code

We solve the standard gasdynamic equations with CR pressure terms added in the conservative, Eulerian formulation for one dimensional plane-parallel geometry along with the diffusion-convection equation for the CR momentum distribution function, $g(p) = f(p)p^4$. Unlike ordinary gas shocks, the CR shock includes a wide range of length scales associated not only with the dissipation into "thermal plasma", but also with the nonthermal particle diffusion process. Those are characterized by the diffusion lengths (Kang & Jones 1991). To follow the acceleration of highly relativistic CRs from suprathermal energies, all those scales need to be resolved numerically. However, the diffusion and acceleration of the low energy particles are important only close to the shock owing to their small diffusion lengths. Thus it is necessary to resolve numerically the diffusion length of the particles only around the shock. To solve this problem generally we have developed the CRASH (Cosmic-Ray Amr SHock) code by combining a powerful "Adaptive Mesh Refinement" (AMR) technique and a "shock tracking" technique, and implemented them into a hydro/CR code based on the wave-propagation method (Kang *et al.* 2001; Kang *et al.* 2002). The AMR technique allows us to "zoom in" inside the precursor structure with a hierarchy of small, refined grid levels applied around the shock. The shock tracking technique follows hydrodynamical shocks within regular zones and maintains them as true discontinuities, thus allowing us to refine the region around the gas subshock at an arbitrarily fine level.

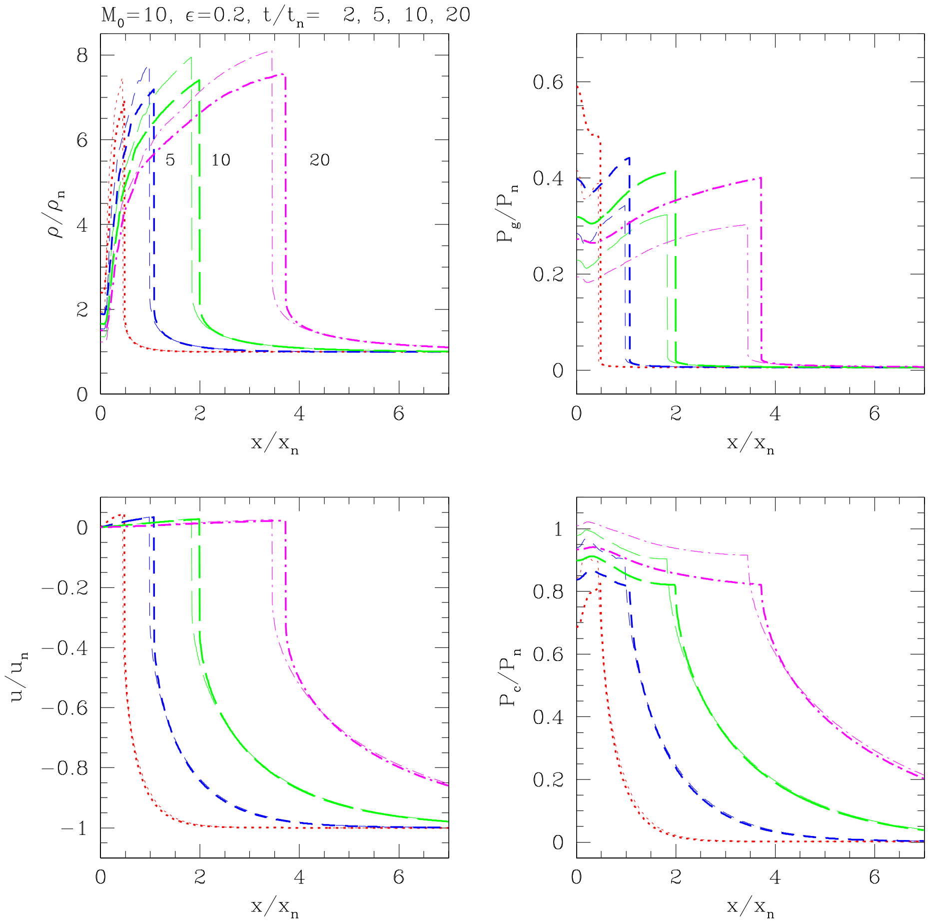

Fig. 1.— Time evolution of the shocks driven by 1D pistons with $M_0 = u_{\rm n}/c_{s,0} = 10$ is shown at normalized times, $t/t_{\rm n} = 2$, 5, 10, and 20. The flows are reflected at $x/x_{\rm n} = 0$ and shocks with $M_s = 13.3$ propagate to the right. The leftmost profile corresponds to the earliest time. Light lines represent the piston with $u_{\rm n} = 150$ km s^{-1}, $T_0 = 10^4$ K, and a pre-existing CR population with $f_{up} \propto (p/p_M)^{-4.7}$. Heavy lines represent the model with $u_{\rm n} = 1500$ km s^{-1}, $T_0 = 10^6$ K, and $f_{up} \propto (p/p_M)^{-4.5}$. For both models the pre-existing upstream CR pressure is $P_{c,0}/P_{g,0} = 0.25$. The normalization diffusion time scale, $t_{\rm n} = \kappa_{\rm n}/u_{\rm n}^2$, and diffusion length, $x_{\rm n} = \kappa_{\rm n}/u_{\rm n}$ are defined by the piston speed of each model. The inverse wave-amplitude parameter $\epsilon = 0.2$ is adopted for both models.

(d) Injection Model

Our discussion will focus on a quasi-parallel shock, in which the direction of propagation is almost parallel to the magnetic field lines. According to plasma simulations of quasi-parallel shocks (Quest 1988), the particle velocity distribution has some residual anisotropy in the local fluid frame due to the incomplete isotropization during the collisionless shock formation process and so some particles can stream back upstream of the shock. Streaming motions of high energy particles against the background fluid generate strong MHD Alfvén waves upstream of the shock, which in turn scatter particles and prevent them from escaping upstream (e.g., Bell 1978;Quest 1988;Lucek & Bell 2000). Due to these self-generated MHD waves thermal particles are confined and advected downstream, while some suprathermal particles in the high energy tail of the Maxwellian velocity distribution may re-cross the shock upstream. Then these particles are scattered back downstream by those same waves and can be accelerated further to higher energies via Fermi first order process. Hence the nonthermal, cosmic-ray particles are extracted from the shock-heated thermal particle distribution (Malkov & Völk 1998, Malkov & Drury 2001).

In order to model this "thermal leakage" injection process in Gieseler *et al.* (2001) we adopted a "transparency function", $\tau_{\rm esc}(\epsilon, \upsilon)$, which expresses the probability that supra-thermal particles at a given velocity can leak upstream through the magnetic waves, based on non-linear particle interactions with self- generated waves (Malkov and Völk 1998). The inverse wave-amplitude parameter, $\epsilon = B_0/B_\perp$, measures 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. The breadth of the thermal velocity distribution relative the downstream flow velocity in

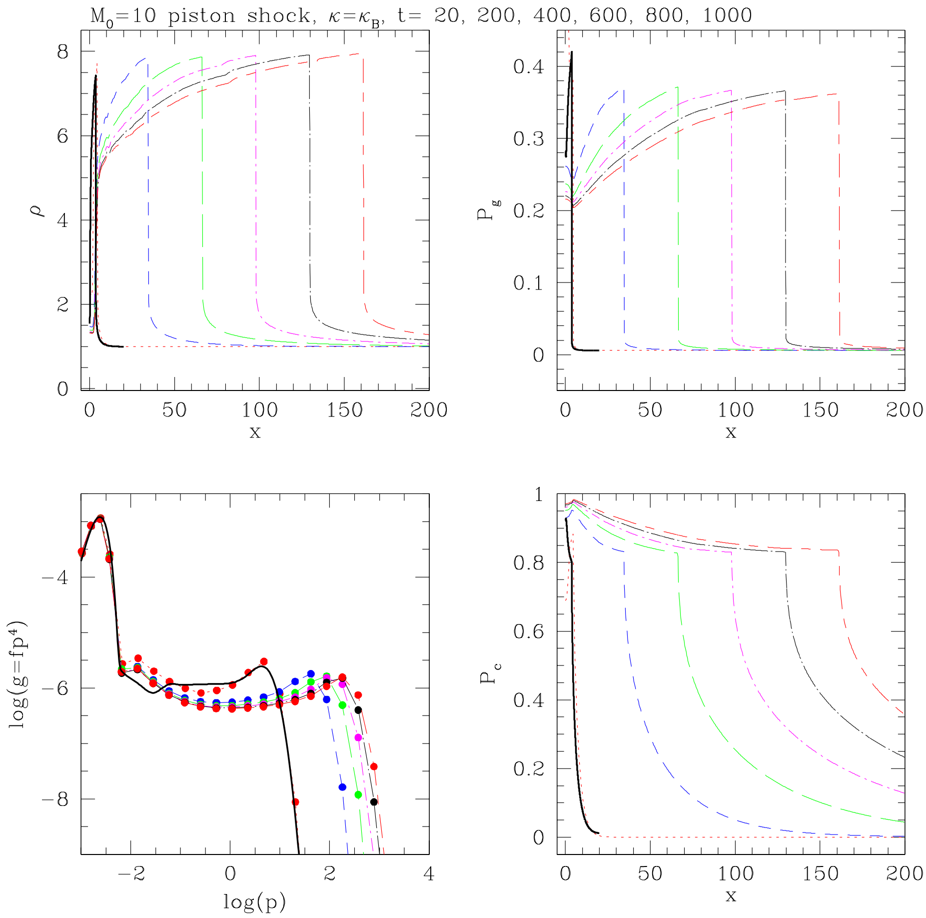

Fig. 2.— Time evolution of the $M_0 = 10$ model without pre-existing CRs calculated with "coarse-Grained Momentum Volume" method is shown up to $t/t_{\rm n}$ =1000. The leftmost profile corresponds to the earliest time, $t/t_{\rm n} = 20$. For comparison, the results of "Fine-Grained Momentum Volume" simulation are shown at the same time by the heavy solid line.

the subshock rest-frame determines the probability of leakage, and so the injection process is sensitive to the velocity jump at the subshock, which depends on the subshock Mach number. The injection rate increases with the subshock Mach number, but becomes independent of M_s in the strong shock limit of $M_s \gtrsim 10$ (Kang *et al.* 2002). The only free parameter of the adopted transparency function is ϵ and it is rather well constrained, since $0.3 \lesssim \epsilon \lesssim 0.4$ is indicated for strong shocks (Malkov & Völk 1998).

III. SIMULATION RESULTS

We have calculated the CR acceleration at 1D quasi-parallel shocks driven by a plane-parallel piston with $u_{\rm n} = 75 - 7500 {\rm kms}^{-1}$ and preshock temperatures of $T_0 = 10^4 - 10^{7.6}$K. The upstream sound speed is given by $c_{s,0} = 15 \;\; {\rm km\ s}^{-1} (T_0/10^4)^{1/2}$. Then the normalization constants are set by two parameters, the piston Mach number, $1.5 \le M_0 \le 100$, and $c_{s,0}$, through $u_{\rm n} = c_{s,0} M_0$. The initial speed (u_s) of the shock driven by the piston is higher than the piston speed, and depends on the compression ratio across the shock. So Mach numbers of the resulting shocks range over $2 \le M_s \le 133$. Due to the nonlinear CR feedback, however, the *instantaneous* shock speed is different from the initial shock speed in CR dominated shocks.

(a) Characteristics of 1D Plane-Parallel CR Shocks

Once shocks develop nonlinear properties in response to CR feedback, there are several important characteristics that distinguish them from more familiar gasdynamic shocks: 1) CR shocks continue to evolve over relatively long times and broaden as they do so. While full thermalization takes place instantaneously at a simple, discontinuous jump in an ideal gasdynamic shock, CR acceleration and the corresponding modifications to the underlying flow depend on suprathermal particles passing back and forth diffusively across the shock structure. These processes develop, therefore, on the diffusion time scale, t_d, and diffusion length scale, x_d. Generally, these scales are expected to be increasing functions of particle momentum, so CR acceleration and shock evolution rates slow over time. 2) CR diffu-

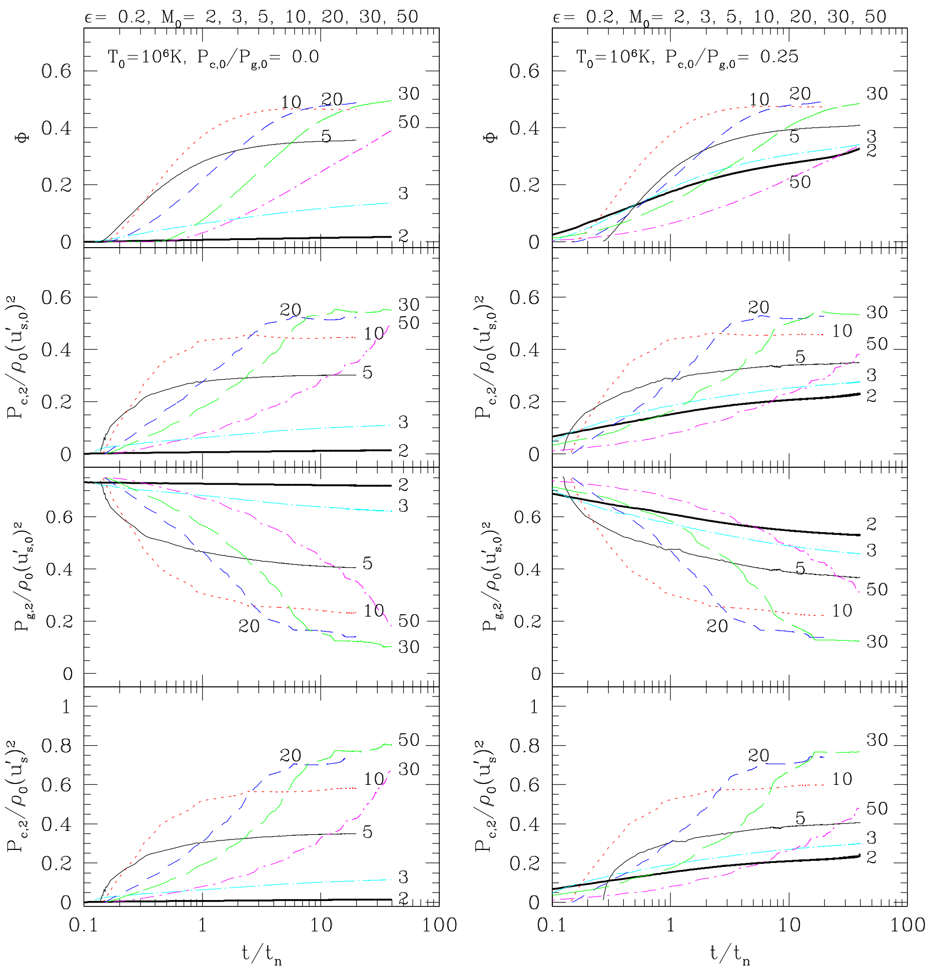

Fig. 3.— The ratio of total CR energy in the simulation box to the kinetic energy in the initial shock rest frame that has entered the simulation box from upstream, $\Phi(t)$, the postshock CR pressure, $P_{c,2}$, and gas pressure, $P_{g,2}$, in units of upstream ram pressure in the *initial* shock frame, $\rho_0 u'^{\,2}_{s,0}$ and the postshock CR pressure in units of upstream ram pressure in the *instantaneous* shock frame, $\rho_0 u'^{\,2}_s$ Left panels show the models with $M_0 = 2-50$ and $T_0 = 10^6$ K but without pre-existing CRs. Right panels for the same models but with the upstream CR pressure of $P_{c,0} = 0.25 P_{g,0}$ and $f_{up} \propto (p/p_M)^{-4.5}$.

sion upstream of the shock discontinuity leads to strong pressure gradients in a shock precursor, enhancing the total compression through the shock transition over that in the viscous subshock. The total compression through a high-Mach-number CR shock can greatly exceed the canonical value $r = (\gamma_g + 1)/(\gamma_g - 1)$ for strong gasdynamical shocks (where γ_g is the gas adiabatic index). 3) Both the effective compressibility of the combined thermal-CR plasmas and the mean CR diffusion coefficient increase over time as relativistic CRs absorb more energy and as escaping CRs remove energy from the shock structure. Details of these properties depend on the CR momentum distribution. Thus, downstream states of the CR modified shock cannot be found from simple shock jump conditions, but rather have to be integrated time-dependently from given initial states or, for steady solutions, found in terms of some predefined limits to the CR spectrum (*e.g.,* an upper momentum cutoff). 4) Energy transfer to the CRs rather than to the thermalized gas in the shock transition reduces the downstream thermal energy of a CR modified shock compared to a gasdynamic shock with the same shock speed and Mach number.

Figure 1 illustrates these characteristics very well. Three key stages of shock evolution in response to CR feed back can be defined: 1) Development of the shock precursor that slows and heats the flow entering the gas subshock, reducing the Mach number of the latter; 2) achievement of an *approximately* time-asymptotic dynamical shock transition, including nearly steady postshock CR and gas pressures; 3) continued, approximately "self-similar" evolution of the shock structure for Bohm-type diffusion, as CRs are accelerated to ever higher momenta. Once stage (3) is reached, there is little change in the dynamical properties of the shocks, and, in particular, little change in the total efficiency

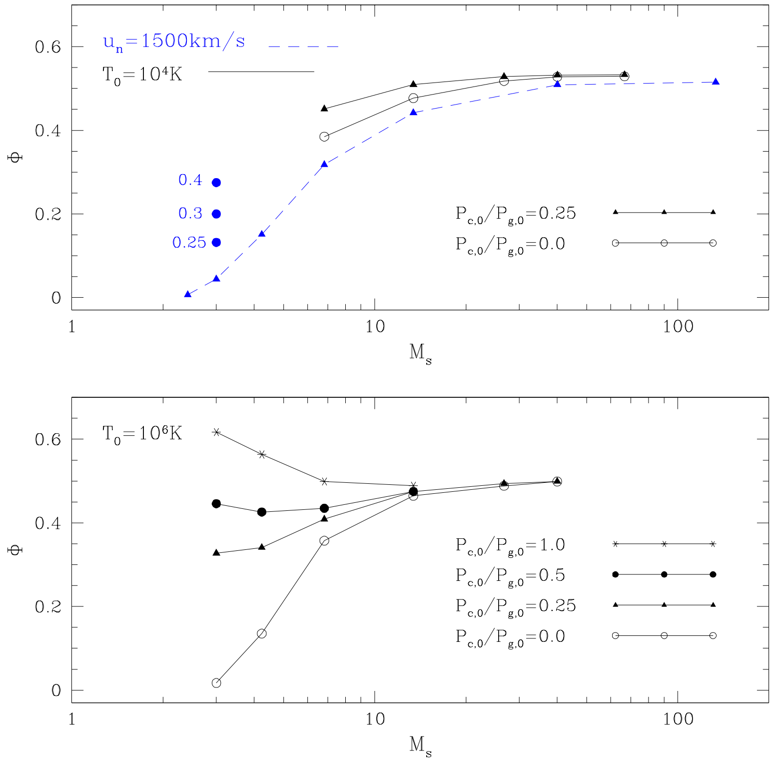

Fig. 4.— The CR energy ratio, Φ, at the simulation termination time of our simulations as a function of the shock Mach number, M_s. *Upper panel*: models with $T_0 = 10^4$ K, $u_s = (15 \text{ km s}^{-1})M_s$, $\epsilon = 0.2$, and no pre-existing CRs (solid line with open circles), models with $T_0 = 10^4$ K, $u_s = (15 \text{ km s}^{-1})M_s$, $\epsilon = 0.2$, and $P_{c,0} = 0.25P_{g,0}$ (solid line with filled triangles). For comparison we also show "constant $u_{\rm n}$ models with $u_{\rm n} = 1500$ km s^{-1}, $T_0 = 10^4$K$(100/M_0)$, $\epsilon = 0.2$, and no pre-existing CRs in the upper panel (dashed line with filled triangles). Three filled circles are labeled with the value of $\epsilon = 0.25$, 0.3, 0.4 and for the models with $M_s = 3$, $T_0 = 5 \times 10^5$K and no pre-existing CRs. *Lower panel*: models with $T_0 = 10^6$ K, $u_s = (150 \text{ km s}^{-1})M_s$, $\epsilon = 0.2$, and a various level of pre-existing CR pressure.

with which kinetic energy is transferred to CRs.

We have further explored these time asymptotic behaviors by performing much longer simulations with a new "Coarse-Grained Momentum Finite Volume" (CGM) numerical scheme under development. CGM utilizes the fact that the distribution function can be approximated as a piecewise power-law within a given broad momentum bin and so only roughly one momentum bin per octave is necessary to follow the CR population numerically (Jones & Kang, 2005). In figure 2, we show the simulation results of $M_0 = 10$ model, which was calculated by this CGM method with 20 momentum bins up to $t/t_{\rm n} = 1000$. The heavy solid lines are for the simulation results at $t/t_{\rm n} = 20$, which was calculated by the "fine-grained momentum" with 240 momentum bins. These figures confirm very firmly the aforementioned "self-similarity" of the shock evolution and the time-asymptotic behaviors.

(b) Cosmic Ray Acceleration Efficiency

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,

$$\Phi(t) = \frac{\int_0^{x_{\rm max}} {\rm d}x E_{\rm CR}(x,t)}{0.5\rho_0 (u'_{s,0})^3 t}, \qquad (3)$$

where $u'_{s,0}$ is the initial shock speed.

Figure 3 shows for the models with $T_0 = 10^6$K the CR energy ratio, Φ, the CR pressure and the gas pressure at the subshock. The left panels illustrate the models without pre-existing CRs, while right panels show the models with the upstream CR pressure, $P_{c,0} = 0.25P_{g,0}$. The postshock P_c for all Mach numbers increases until a balance between injection/acceleration and advection/diffusion of CRs is achieved. After that time the postshock CR pressure remains almost steady. Simultaneously, the CR energy ratio, Φ, also initially increases with time, but then asymptotes to a constant value, once $P_{c,2}$ has reached a quasi-steady value. The presence of pre-existing CRs increases the asymptotic postshock P_c for the weaker shock, $M_0 \leq 5$ model, while it does not affect the strong shock models with $M_0 \geq 10$. Since strong shocks can be mediated mostly by CRs, the postshock gas thermal energy is reduced greatly compared to that in conventional gasdynamic shocks of the same Mach number.

Figure 4 shows the CR energy ratio Φ at the termination time for models with different M_s, $P_{c,0}$, and T_0. We find that time asymptotic values of Φ increase with M_s but approach ~ 0.5 for $M_s > 30$, independent of upstream $P_{c,0}$ and ϵ. In weak to moderate strength shocks with $M_s < 5$, on the other hand, the CR acceleration efficiency increases with the level of pre-existing CRs and ϵ. Most baryonic matter in clusters has been shocked more than once before the current epoch and weak shocks with $2 \lesssim M_s \lesssim 4$ are primarily responsible for energy dissipation during structure formation (Ryu *et al.* 2003). Since magnetic field should tie CRs up to moderately relativistic energies to the thermal plasma over cosmic time scales, those shocks may be substantially more efficient at CR acceleration than one might otherwise expect.

IV. SUMMARY

The main purpose of this study is to explore how the CR acceleration efficiency at cosmic structure shocks depends on the preshock temperature, shock speed and pre-existing CRs as well as shock Mach number. This, in turn, affects the thermal and dynamical history of the shocked-heated baryon gas, since the energy transfer to CRs reduces the thermal energy of the gas and increases the compressibility of the gas flow, much like radiative shocks. Unlike pure gasdynamic shocks, downstream states of the CR modified shocks cannot be found from "shock jump conditions", so they have to be integrated time-dependently from given initial states or found from nonlinear analytical methods. We have performed such time-dependent simulations in order to study the CR acceleration at quasi-parallel astrophysical shocks.

The main results of our simulations can be summarized as follows:

1) The CR pressure approaches a steady-state value in a time scale comparable to the acceleration time scales for mildly relativistic protons after which the evolution of CR modified shocks becomes approximately "self-similar".

2) Two shocks with the same Mach number, but with different shock speeds, evolve qualitatively similarly when the results are presented in terms of a characteristic diffusion length and diffusion time. So the acceleration efficiency is determined mostly by the shock Mach number.

3) Suprathermal particles can be injected efficiently into the CR population at quasi-parallel cosmic shocks via the thermal leakage process. For a given injection parameter defined in the text, ϵ, the fraction of injected CRs increases with the subshock Mach number, but approaches $\xi \sim 10^{-3}$ in the strong shock limit.

4) For a given value of ϵ, the acceleration efficiency increases with the shock Mach number, but approaches a similar value in the strong shock limit. Time asymptotic values of the ratio of CR energy to inflowing kinetic energy, Φ, converge to $\Phi \approx 0.5$ for $M_s \gtrsim 30$ and it is relatively independent of other upstream or injection parameters (see figure 4). Thus, strong cosmic shocks can be mediated mostly by CRs and the gas thermal energy can be up to ~ 10 times smaller than that expected for gasdynamic shocks.

5) For weak shocks, on the other hand, the acceleration efficiency increases with the injection rate (or ϵ) and the pre-exiting P_c (see figure 4). The presence of a pre-existing CR population acts effectively as a higher injection rate than the thermal leakage alone, leading to greatly enhanced CR acceleration efficiency in low Mach number shocks.

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