Shock Waves and Cosmic Rays in the Large Scale Structure of the Universe

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Abstract

In an N-body/hydrodynamic simulation for large scale structure formation in a universe with cold dark matter and cosmological constant we identified cosmological shock waves and studied their role in the acceleration of cosmic ray particles. Shock waves form around nonlinear structures of mass distribution when gas accretes onto them. Within the nonlinear structures, shock waves are also produced by subsequent gravitational infalls as well as supersonic flow motions. The mean separation between shock surfaces is $\sim 4h^{-1}$ Mpc at present. Shock waves with Mach number of a few are mainly responsible for cosmic ray acceleration. From a nonlinear diffusive shock acceleration model for cosmic ray protons, the ratio of cosmic ray energy to gas thermal energy dissipated at cosmological shock waves was estimated to be $\sim 1/2$ through the history of the universe. Our result supports scenarios in which the intracluster medium contains significant populations of cosmic rays.

1. Introduction

During large scale structure formation, infall of baryonic gas toward sheets, filaments and knots, as well as supersonic flows associated with hierarchical clustering, induce shocks [4]. Those cosmological shock waves, like most astrophysical shocks, are collisionless features mediated by collective, electromagnetic viscosities. Through dissipation the cosmological shock waves convert part of the gravitational energy associated with structure formation into heat. At the same time, due to incomplete plasma thermalization at collisionless shocks, a sizeable portion of the shock energy can be converted into cosmic ray (CR) energy (mostly ionic) via diffusive shock acceleration.

A number of clusters have been found with diffuse synchrotron radio halos or/and radio relic sources, indicating the existence of CR electron populations in the intracluster medium [1]. In addition, some clusters have been reported to possess excess EUV and/or hard X-ray radiation compared to that expected from the hot, thermal X-ray emitting media, due to inverse-Compton scattering of cosmic microwave background radiation photons by CR electrons [3]. If some

pp. 2055–2058

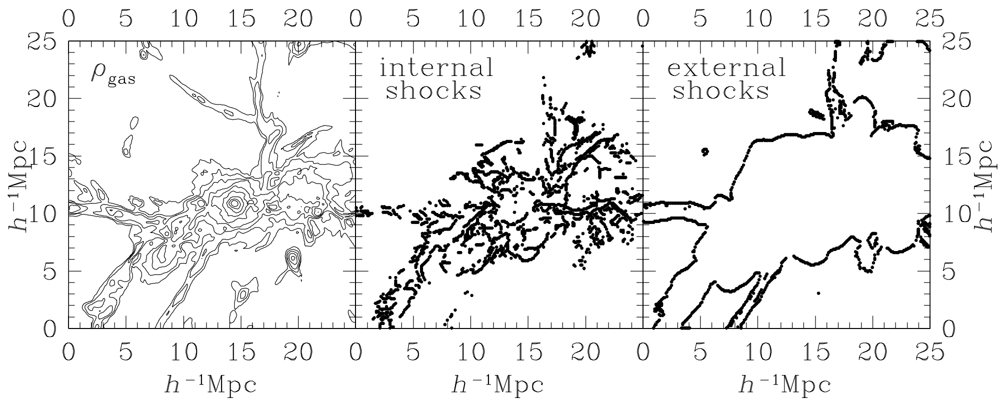

Fig. 1. Two-dimensional slice of a $(25h^{-1}\mathrm{Mpc})^2$ region around a complex at $z = 0$, showing gas density, internal shock and external shock distributions.

of those CR electrons have been energized at cosmological shock waves, the same process should have produced greater CR proton populations.

In this paper, we study cosmological shock waves in a numerical simulation: the ΛCDM cosmology with $\Omega_{BM} = 0.043$, $\Omega_{DM} = 0.227$, and $\Omega_\Lambda = 0.73$, $h \equiv H_0/(100\ \mathrm{km/s/Mpc}) = 0.7$, and $\sigma_8 = 0.8$. A cubic region of comoving size $100h^{-1}$ Mpc was simulated inside a computational box with 1024^3 grid zones for gas and gravity and 512^3 particles for dark matter. Details on cosmological shock waves can be found in [4].

2. Results

Shock waves were identified and their characteristics were quantified. Based on close examination of shock locations and the properties of the shocks and their associated flows in our simulation, we classify cosmological shock waves into two broad populations, *external* and *internal* shocks. External shocks surround sheets, filaments and knots, forming when never-shocked, low density, void gas accretes onto those nonlinear structures. Subsequent, internal shocks are distributed within the regions bounded by external shocks. They are produced by flow motions accompanying hierarchical structure formation inside the bounding shocks. Figure 1 shows a two dimensional slice of $(25h^{-1}\ \mathrm{Mpc})^2$. It plots the distributions of external and internal shocks in a cluster with X-ray emission-weighted temperature, $T_x \approx 3.3$ keV, along with the gas density distribution. External shocks here define an entire "cluster complex" which has dimensions of about $(10 \times 10 \times 20)(h^{-1}\mathrm{Mpc})^3$. Numerous internal shocks were identified inside the complex.

In order to estimate quantitative measures of shock frequency, we computed the surface area of identified shocks per logarithmic Mach number interval, $dS(M, z)/d \log M$, normalized by the volume of the simulation box. Figure 2 shows $dS(M, z)/d \log M$ for external and internal shocks at several epochs. The

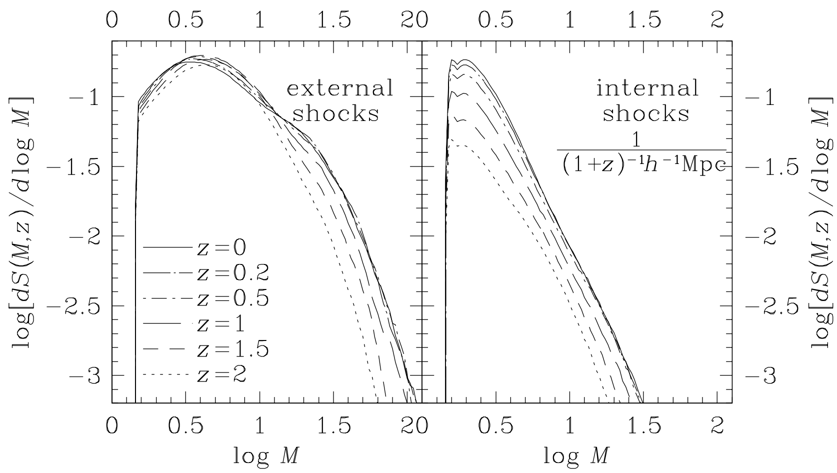

Fig. 2. Shock surface area with Mach number between $\log M$ and $\log M + d(\log M)$ normalized by the volume of the simulation box at different redshifts, $dS(M,z)$, for external shocks and internal shocks.

mean distance between shock surfaces is $\sim 4h^{-1}$ Mpc at present The area distribution of external shock surfaces peaks at $M \approx 3-5$, extending up to $M \sim 100$ or higher. In contrast, the comoving area of internal shocks increases to the weakest shocks we identified in our analysis ($M = 1.5$). Although the mean Mach number is higher for external shocks, the mean shock speed is actually larger for internal shocks. In addition, the preshock gas density is significantly higher for internal shocks.

To get quantitative estimates of the thermal and CR energies from dissipation at cosmological shock waves, we calculated these energy fluxes through shock surfaces: 1) the kinetic energy flux, $f_\phi = (1/2)\rho_1 v_{sh}^3$; 2) the thermal energy flux generated at shocks, f_{th}; 3) the CR energy extracted, "nonthermal dissipation", at shocks, f_{CR}. The thermal energy flux was calculated from the Rankine-Hugoniot jump condition, and the ratio $f_{th}/f_\phi \equiv \delta(M)$ defines the efficiency of shock thermalization. For the similarly defined efficiency of CR acceleration, $\eta(M) \equiv f_{CR}/f_\phi$, we applied a nonlinear numerical model of DSA at quasi-parallel shocks [2]. We calculated proton acceleration and accompanying CR-modified flow evolution for shocks with $v_{sh} = 1500 - 3000$ km s^{-1} propagating into media of $T_1 = 10^4 - 10^8$ K, assuming Bohm-type diffusion for the CRs. The efficiency, $\eta(M)$, was calculated from the time-asymptotic quantities. The left panel of Figure 3 shows $\delta(M)$ and $\eta(M)$. Both $\delta(M)$ and $\eta(M)$ increase with Mach number. In strong, high Mach number shocks, $\eta(M)$ approaches the asymptotic value of $\eta(M) \rightarrow\sim 0.53$.

To provide measures of dissipation at cosmological shocks, we integrated from $z = 2$ to $z = 0$ the kinetic energy that passed through shock surfaces and the gas thermal and CR energies dissipated at shock surfaces, $dY_i(M)/d\log M$, with $i \equiv \phi,\ th$, and CR. We also summed these time-integrated measures to

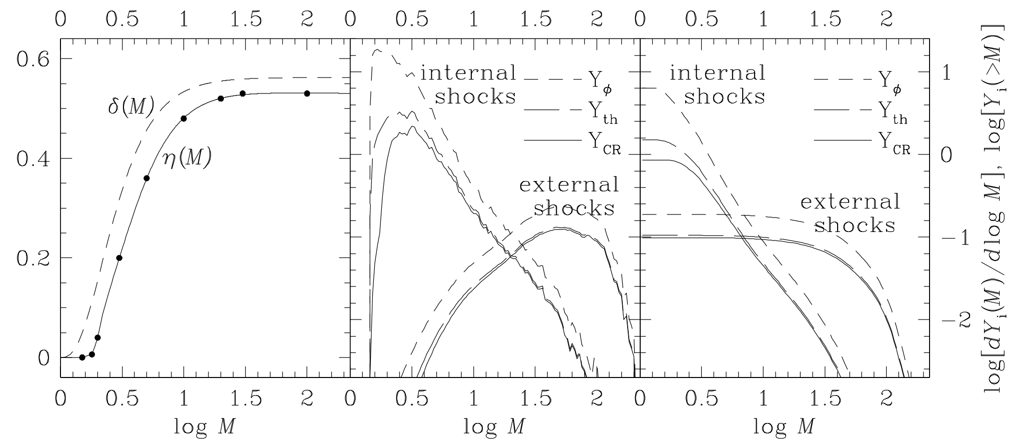

Fig. 3. *Left panel*: Energy conversion efficiencies for gas thermalization, $\delta(M)$, and CR acceleration, $\eta(M)$. Dots for $\eta(M)$ are from numerical simulations and solid line is the fit. *Middle panel*: Kinetic, thermal and CR energies processed through surfaces of external and internal shocks with Mach number between $\log M$ and $\log M + d(\log M)$, from $z = 2$ to $z = 0$. *Right panel*: Same energies processed through surfaces of external and internal shocks with Mach number greater than M, from $z = 2$ to $z = 0$. The energies are normalized to the thermal energy inside simulation box at $z = 0$.

calculate the associated global shock-processed quantities, $Y_i(> M)$. The last two panels of Figure 3 shows $dY_i(M)/d\log M$ and $Y_i(> M)$ for external and internal shocks. The plots indicate that internal shocks play a more important role than external shocks in dissipating energy associated with structure formation. Specifically, internal shocks with $2 \lesssim M \lesssim 4$ account for $\sim 1/2$ of dissipation. With the DSA model we adopted [2], the ratio of the CR to gas thermal energies dissipated at cosmological shock waves with the Mach number greater than 1.5 is $Y_{CR}(\geq 1.5)/Y_{th}(\geq 1.5) \approx 1/2$.

Due to long CR proton trapping times and energy loss lifetimes, they should fill the volumes inside filaments and sheets as well as in clusters and groups. The existence of substantial CR populations could have affected the evolution and the dynamical status of the large scale structure of the universe.

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