Shock waves in the large-scale structure of the Universe

Dongsu Ryu · Hyesung Kang

Abstract Cosmological shock waves are induced during hierarchical formation of large-scale structure in the universe. Like most astrophysical shocks, they are collisionless, since they form in the tenuous intergalactic medium through electromagnetic viscosities. The gravitational energy released during structure formation is transferred by these shocks to the intergalactic gas as heat, cosmic-rays, turbulence, and magnetic fields. Here we briefly described the properties and consequences of the shock waves in the context of the large-scale structure of the universe.

Keywords Cosmic-rays · Large-scale structure of universe · Magnetic fields · Shock waves · Turbulence

1 Introduction

Shock waves are ubiquitous in astrophysical environments; from solar winds to the largest scale of the universe (Miniati et al. 2000; Ryu et al. 2003; Furlanetto and Loeb 2004; Pavlidou and Fields 2006). In the current paradigm of the cold dark matter (CDM) cosmology, the large-scale structure of the universe forms through hierarchical clustering of matter. Deepening of gravitational potential wells causes gas to move supersonically. Cosmological shocks form when the gas accretes onto clusters, filaments, and sheets, or as a consequence of the chaotic flow motions of the gas inside the nonlinear structures. The gravitational energy released during the formation of large-scale structure in the universe is transferred by these shocks to the intergalactic medium (IGM).

Cosmological shocks are collisionless shocks which form in a tenuous plasma via collective electromagnetic interactions between baryonic particles and electromagnetic fields (Quest 1988). They play key roles in governing the nature of the IGM through the following processes: in addition to the entropy generation, cosmic-rays (CRs) are produced via diffusive shock acceleration (DSA) (Bell 1978; Blandford and Ostriker 1978), magnetic fields are generated via the Biermann battery mechanism (Kulsrud et al. 1997) and Weibel instability (Medvedev et al. 2006) and also amplified by streaming CRs (Bell 2004), and vorticity is generated at curved shocks (Binney 1974).

Cosmological shocks in the intergalactic space have been studied in details using various hydrodynamic simulations for the cold dark matter cosmology with cosmological constant (ΛCDM) (Ryu et al. 2003; Pfrommer et al. 2006; Kang et al. 2007; Skillman et al. 2008; Vazza et al. 2008). In this contribution, we describe the properties of cosmological shocks and their implications for the intergalactic plasma from a simulation using a PM/Eulerian hydrodynamic cosmology code (Ryu et al. 1993) with the following parameters: Ω_{BM} = 0.043, Ω_{DM} = 0.227, and Ω_{Λ} = 0.73, h \equiv H_0/(100 \text{ km/s/Mpc}) = 0.7, and σ_8 = 0.8. A cubic region of comoving size 100 \ h^{-1} \text{ Mpc} was simulated with 1024^3 grid zones for gas and gravity and 512^3 particles for dark matter, allowing a uniform spatial resolution of Δl = 97.7 \ h^{-1} \text{ kpc}. The simulation is adiabatic in the sense that it does not include radiative cooling, galaxy/star formation, feedbacks from galaxies/stars, and reionization of the
Fig. 1 Two-dimensional images showing X-ray emissivity (top left), locations of shocks with color-coded shock speed $V_s$ (top right), perpendicular component of vorticity (bottom left), and magnitude of vorticity (bottom right) in the region of $(25 \, h^{-1} \, \text{Mpc})^2$ around a galaxy cluster at present ($z = 0$). Color codes $V_s$ from 15 (green) to $1,800 \, \text{km s}^{-1}$ (red).

IGM. A temperature floor was set to be the temperature of cosmic background radiation.

2 Properties of cosmological shocks

As a post-processing step, shocks in the simulated volume were identified. The procedure to identify shocks was described in details in Ryu et al. (2003). A zone was tagged as a shock zone whenever the following criteria are met: 1) the gradients of gas temperature and entropy have the same sign, 2) the local flow is converging with $\nabla \cdot \vec{v} < 0$, and 3) $|\Delta \log T| \geq 0.11$ corresponding to the temperature jump of a shock with $M \geq 1.3$. Typically, a shock is represented by a jump spread over 2–3 tagged zones. Hence, a shock center was identified within the tagged zones, where $\nabla \cdot \vec{v}$ is minimum, and this center was labeled as part of a shock surface. The Mach number of the shock center, $M$, was calculated from the temperature jump across the entire shock zones, and the shock speed, $V_s$, was calculated with the Mach number and the pre-shock sound speed. To avoid confusion, only those portions of shock surfaces with $M \geq 1.5$ were kept and used for the analysis of shocks properties.

In the top panels of Fig. 1, we compare the locations of cosmological shocks with the X-ray emissivity in the region around a cluster of galaxies, both of which are calculated from the simulation data at redshift $z = 0$. External shocks encompass this complex nonlinear structure and define the outermost boundaries up to $\sim 10 \, h^{-1} \, \text{Mpc}$ from the cluster core, far beyond the region observable with X-ray of size $\sim 1 \, h^{-1} \, \text{Mpc}$. Internal shocks are found within the region bounded by external shocks. External shocks have high Mach numbers of up to $M \sim 10^3$ due to the low temperature of the accreting gas in the void region. Internal shocks, on the other hand, have mainly low Mach numbers of $M \lesssim 3$, because the gas inside nonlinear structures has been previously heated by shocks and so has high temperature.

The frequency of cosmological shocks in the simulated volume is represented by the quantity $S$, the area of shock surfaces per unit comoving volume, in other words, the