Large Cosmic Shock Waves as Sites for Particle Acceleration

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Abstract

The properties of cosmic shock waves are studied through numerical simulations in two cosmological scenarios (SCDM and ΛCDM). The scaling relations for the average radius and velocity associated with the accretion shocks are somewhat different, yet qualitatively similar to the self similar solutions for a flat $\Omega_M = 1$ universe. The energy supplied by infalling gas at accretion shock waves is large enough to sustain production of abundant cosmic ray populations if a viable acceleration mechanism can take place there. Finally, in addition to shocks created by the encounter of the merging ICMs of two clusters of galaxies, accretion shocks associated with the merging clusters generate strong "relic" shocks which propagate through the ICM producing additional heating of the ICM, and associated CR acceleration.

1 Introduction:

Cosmic Rays (CRs) acceleration and transport in Galaxy Clusters (GCs) environments is an important topic for several reasons. In fact, being characterized by a huge size ($\sim$ several Mpc) and very large Mach numbers ($\sim 10 - 10^3$, Miniati *et al.* 1999), accretion cosmic shock waves have been proposed as sites for acceleration of high energy CRs up to $10^{18} - 10^{19}$eV. Such energies would be in fact achievable through Jokipii diffusion of the relativistic particles if about 10^{-4} of the kinetic energy associated with the accretion flow can be injected into CRs (Kang, Ryu & Jones 1996; Kang, Rachen & Biermann 1997).

In addition, the recent detection of diffuse excess EUV emission compared to that expected from the X-ray emitting Intra Cluster Medium (ICM) for all GCs observed by the EUVE satellite (Lieu *et al.* 1999, Bowyer, Lieu & Mittaz 1998 and references therein) suggested nonthermal contributions much higher than previously expected. The interpretation of the EUV excess as Inverse Compton (IC) emission due to low energy relativistic electrons scattering off the cosmic microwave background looks preferable to a thermal model for several reasons (Sarazin & Lieu 1998). However, while viable, a correct IC-based model which accounts for the radio emission and the magnetic field data is not straightforward (Sarazin & Lieu 1998; Bowyer & Berghöfer 1998, Ensslin, Lieu & Biermann 1999). From published studies a number of consequences emerge. Most dramatic, the electron component of CRs could amount to a few percent of the thermal energy content in GCs (Sarazin & Lieu 1998). In turn, this implies that proton CRs, due to their much longer cooling time, could contribute a large fraction of the total pressure there (Lieu *et al.* 1999). This result could have a great impact on cosmology, because GCs' mass estimates are usually based on the assumption of hydrostatic equilibrium for the ICM gas in the potential well of the total cluster mass. In general, it is clear that a single population of CRs cannot account for all the observed nonthermal emission and that the relative distribution of CRs and magnetic fields plays a crucial role in a correct interpretation (Ensslin, Lieu & Biermann 1999).

Finally, Ryu, Kang & Biermann (1997) addressed the issue of topological characteristics of cosmic magnetic fields, concluding that since the magnetic flux is strongly aligned along cosmic structures such as "sheets" and "filaments", values $\lesssim 1\mu$G are permitted by current rotational measures (Kronberg 1994). In a follow-up paper the same authors discussed the implications of their results for the transport of Ultra High Energy Cosmic Rays (Biermann, Kang & Ryu 1996).

In this paper we describe the properties of shock waves occurring as a result of accretion flows onto GCs and of cluster mergers with respect to their potential contribution to CRs production.

2 Method

We have studied the properties of shocks formed in numerical simulations of large scale structure in the universe using the hydrodynamic code recently developed by Ryu *et al.* (1993). The simulations involved a cubic region of current epoch size 85 h^{-1} Mpc, inside a computational box with 270^3 cells and 135^3 dark matter particles. This provides a spatial resolution of a few times 0.31 h^{-1} Mpc.

We investigate two particular cases: 1) a standard Cold Dark Matter (SCDM) model (Kang *et al.* 1994) with $h \equiv \mathrm{H}_0/(100\ \ \mathrm{km\,s}^{-1}\ \mathrm{Mpc}^{-1}) = 0.5$, $\Omega_0 = \Omega_M = 1$, baryonic fraction $\Omega_b = 0.06$, and 2) a CDM + Λ model (Cen & Ostriker 1994) with $h = 0.6,\ \Omega_0 = \Omega_M + \Omega_\Lambda = 1, \Omega_M = 0.45,\ \Omega_\Lambda = 0.55,\ \Omega_b = 0.043$ (see Kang *et al.* 1994 and Cen & Ostriker 1994 for more details). Finally, we refer to Miniati *et al.* (1999) for a description of the method used to select clusters and to determine their temperature and accretion shock properties.

3 Results

Fig. 1 illustrates a slice of a typical cosmic structure. It shows contours of compression ($\nabla \cdot v$) corresponding to shock waves, superposed on a grayscale image of X-ray bremsstrahlung emission from the hot ICM (brighter regions correspond to higher emission). The figure shows shock waves forming around clusters and filaments as a result of supersonic accretion flow. Shocks around clusters are responsible for the heating of the ICM and several models have been proposed to describe their properties (Bertschinger 1984, Ryu & Kang 1997). In particular, in self similar solutions for a $\Omega_M = 1$ universe, the following relations between v_a and T_x as well as r_a and T_x are expected for accretion shocks (Bertschinger 1985):

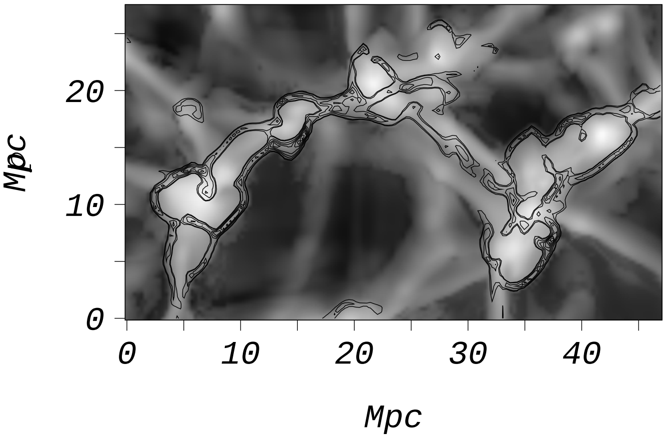

Figure 1: *A typical Cosmic Structure: shock waves contours superposed on grayscale image of X-ray bremsstrahlung emission (text for details).*

$$v_a = K_{v_a} \left(\frac{T_x}{7\times 10^7\mathrm{K}}\right)^{\alpha_{v_a}} = 1.31\times 10^3 \mathrm{Km\,s}^{-1} \left(\frac{T_x}{7\times 10^7\mathrm{K}}\right)^{\frac{1}{2}} \quad (1)$$

$$r_a = K_{r_a} \left(\frac{T_x}{7\times 10^7\mathrm{K}}\right)^{\alpha_{r_a}} = 2.12\ h^{-1}\mathrm{Mpc} \left(\frac{T_x}{7\times 10^7\mathrm{K}}\right)^{\frac{1}{2}} \quad (2)$$

In addition to stationary shocks around GCs, shocks traveling through the ICM are also of great interest for their potential contribution to heating the ICM and/or CR acceleration. Such shocks are commonly produced during a merger event at the interface between two cluster. However, during the merging process the accretion shocks associated with the initial clusters also collide, producing strong “relic” shocks that propagate in the outer regions of the ICM of the new-born cluster. Over the evolutionary history of a cluster, several merging processes occur, creating an ICM rich in shock structures (Miniati *et al.* 1999). Both merging and “relic” shocks are clearly visible in Fig. 1 .

Some quantitative properties of cosmic shocks, as derived from our numerical study, are summarized in Fig. 2. It shows the average accretion shock velocity (top panels) and radius (bottom panels) as a function of the cluster core temperature (one of GCs best measured quantities), defined as the average temperature inside a central region of radius 0.5 h^{-1} Mpc. The trend is qualitatively similar, but quantitatively different from the analytical relations of eq. 1 and 2. In the SCDM model we find best least square fit with $K_{v_a} = 1400$ Km s^{-1}, $\alpha_{v_a} = 0.33$ and $K_{r_a} = 3.4$ Mpc, $\alpha_{r_a} = 0.15$. While numerical errors both in the cosmological simulation and in the data analysis must be considered, such strong deviations from the self similar model should be not too surprising given the highly idealized assumptions for cluster formation under which eq. 1 and 2 were derived.

The larger discrepancy for the accretion radius probably reflects the complex shock structure in the simulation. We mention for completeness that in the ΛCDM case we obtain $K_{v_a} = 1960$ Km s^{-1}, $\alpha_{v_a} = 0.29$ and $K_{r_a} = 2.8$ Mpc, $\alpha_{r_a} = 0.18$. We note that for both the SCDM and ΛCDM, over the range of temperatures of the selected clusters ($T_x \simeq 6 \times 10^6$K - 10^8K), the accretion velocity extends over at least one order of magnitude from a few 10^2 Km s^{-1} to a few 10^3 Km s^{-1}. The shock radius, on the other hand, only varies by a factor of a few. Whereas the shock speeds are comparable to those characterizing young supernova remnants (SNRs), shock sizes associated with GCs are enormously greater. In addition, since the accretion flows around GCs are much colder than the interstellar medium, Mach numbers associated with the accretion shocks are much larger than for SNRs. In this respect we note further that accretion shocks occurring in a ΛCDM scenario have consistently much larger Mach numbers than in the SCDM (Miniati *et al.* 1999).

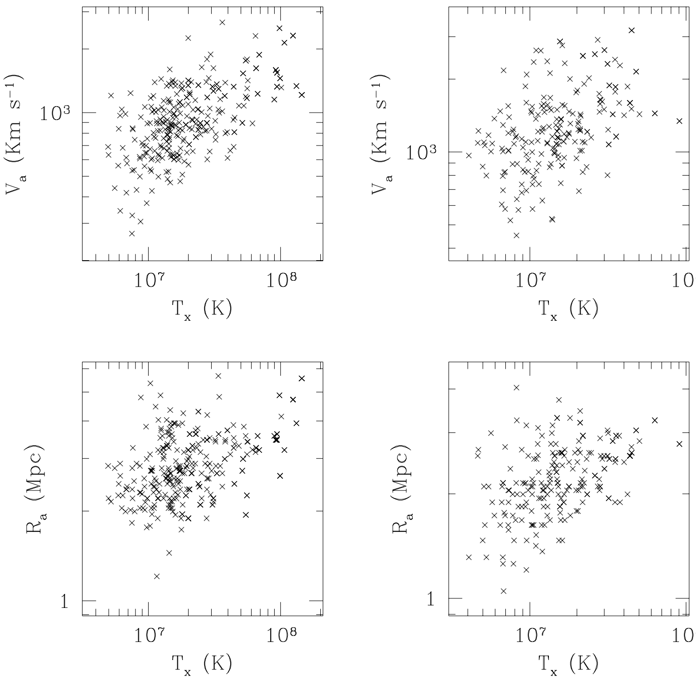

Figure 2: *Properties of accretion shock waves: average velocity (top) and radius (bottom) as a function of average cluster core temperature for SCDM (left) and ΛCDM (right).*

Another quantity of interest is the flux of kinetic energy associated with the gas crossing the shock. This is given by

$$\Phi(E_k) = \frac{1}{2}\,\rho\, v_a^2\, r_a^2\, v_a\,|_{r=r_a}, \tag{3}$$

and is plotted, as a function of cluster core temperature, in Fig. 3. The flux $\Phi(E_k)$ supplies a large amount of energy, not surprisingly, comparable to the cluster X-ray luminosity. It is clear that if a modest fraction of this inflowing kinetic energy can be converted into CRs, those CRs may become important sources of emission and even play a dynamical role. We also point out that $\Phi(E_k)$ is a steep function of cluster temperature ($\propto T^{\alpha}$, $\alpha \sim 1.7$ for SCDM and 1.4 for ΛCDM), spanning several orders of magnitude in the temperature range of the selected clusters. This means that if an acceleration mechanism at accretion shocks around GCs possesses injection mechanism and an efficiency independent on the cluster properties (*e.g.,* mass, temperature), then we would expect hotter clusters to store a relatively larger amount of nonthermal energy in the form of relativistic particles. This should scale with $\Phi(E_k)$ and should produce consequent observational effects.

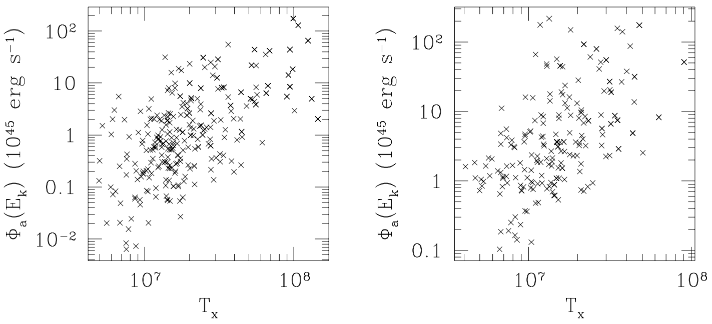

Figure 3: *Average kinetic energy flux at accretion shocks as a function of cluster core temperature for SCDM (left) and ΛCDM (right).*

4 Discussion and Conclusions

Accretion shock waves are the largest shocks in the universe. We have pointed out that they are characterized by a complex structure yet their average properties, such as radius and accretion velocity, show qualitative similarities with theoretical predictions. The energy of accretion flows around GCs are powerful enough to account for the production of copious populations of CRs in the ICM. For energies up to 2 10^{16} eV CRs are efficiently trapped by the cluster magnetic field (for $B \sim$ few μG; Berezinsky, Blasi & Ptuskin 1997). Different spectral components of CRs maybe responsible for the various nonthermal emissions observed from GCs (see §1). In addition, CR protons undergoing p-p collisions could be responsible for a fair fraction of the diffuse gamma-ray background (Colafrancesco & Blasi 1998).

In addition to accretion shocks, we have identified shocks propagating through the ICM and generated during the formation histories of clusters. These shocks could also be important sites of particle acceleration and must be included when a detailed study of the thermal and nonthermal properties of ICM is carried out.

Since there is evidence for a significant magnetic field inside GCs of the order of a μG (Kronberg 1994) shock acceleration should be certainly applicable in the ICM, provided that shocks are present there. However, the question still remains about the magnetic field strength at the accretion shocks and therefore the viability of Fermi acceleration mechanism there. Observations seem to impose a strict upper limit of $10^{-9}\mu$G on both the regular and random component of the magnetic field outside GCs (Vallée 1990, Kronberg 1994), although Biermann *et al.* (1996) suggest higher upper limits ($\lesssim 1\mu$G) at least along cosmic filaments.

We will explore these issues further in planned numerical studies of structure formation in viable cosmological models taking into account explicitly CRs shock acceleration and transport.

5 Acknowledgments

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