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Cosmological shocks in Eulerian simulations: main properties and cosmic rays acceleration

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Abstract. *Aims*: morpholgies, number and energy distributions of Cosmological Shock Waves from a set of ENZO cosmological simulations are produced, along with a study of the connection with Cosmic Rays processes in different environments. *Method:* we perform cosmological simulations with the public release of the PPM code ENZO, adopt a simple and physically motivated numerical setup to follow the evolution of cosmic structures at the resolution of $125kpc$ per cell, and characterise shocks with a new post processing scheme. *Results:* we estimate the efficency of the acceleration of Cosmic Ray particles and present the first comparison of our results with existing limits from observations of galaxy clusters.

Key words. galaxy: clusters, general – methods: numerical – intergalactic medium

1. Introduction

Galaxy clusters store up to several 10^{63} ergs in the form of hot baryonic matter, due to the action of shock-heating processes in large scale structures formation (Zel'Dovich, 1970). Detecting shocks in Large Scale Structures (LSS) is still observationally challenging since they should more frequently develop in peripheral, low X emitting regions of clusters, due to the drop in the sound speed there (e.g. Markevitch & Vikhlinin 2007). Shocks are important not only to understand the heating of the ICM but also because they are expected to be efficient accelerators of supra–thermal particles (e.g. Sarazin 1999), which can then be advected and accumulated inside galaxy clusters (e.g. Völk et al. 1996, Berezinsky et al. 1997).

Non thermal activity in galaxy clusters related to the presence of Cosmic Ray (CR) electrons and $\sim \mu G$ magnetic field is proved by radio observations, which show synchrotron emission in a fraction of merging clusters (e.g. Feretti 2005), in form of Radio Haloes (at the cluster center) and Radio Relics (elongated and at the cluster periphery). CR protons are expected to give γ–Ray emissions from galaxy clusters via the decay of π^0 generated during proton–proton collisions in the intra galactic medium. Still, only upper limits of this γ–Ray emissions have been obtained so far (e.g. Reimer et al. 2003). Recent numerical works claimed that an efficient CR protons acceleration can occur in large scale shocks (Miniati et al., 2001; Ryu et al., 2003; Pfrommer et al., 2006). However, the identification and characterisation of shocks, as well

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as the calculation of the energy injected in the form of CR, remain challenging due to the uncertainties in the numerical schemes and due to our ignorance of the efficency of the acceleration of CRs at relatively weak shocks.

In this paper we follow the approach of the seminal paper by Ryu et al. (2003), studying the shock wave patterns in LSS. Shocks are characterised in a post–processing phase with a new scheme, which evaluates shocks Mach number by analysing the jumps in the velocity varaible. Estimates of the level of CR injections at these shocks are provided and compared to present day observational upper limits. More detailed discussions and presentations of the results can be found in Vazza, Brunetti & Gheller (2008 submitted to MNRAS, hereafter VBG).

2. Numerical Code - ENZO.

The simulations described in this paper were performed with the cosmological code ENZO (e.g. O'Shea et al. 2004). ENZO couples an N-body particle-mesh solver for Dark Matter with an adaptive mesh method for ideal fluidynamics. The hydrodynamical solver is based on the the Piecewise Parabolic Method (PPM, Colella & Woodward 1984), which is a higher order extension of Godunov's shock capturing method. It is at least second–order accurate in space (up to the fourth–order, in the case of smooth flows and small timesteps) and second–order accurate in time, and it is thus a highly suitable hydro method to study shock pattern.

3. Cosmological Simulations.

We adopt the "Concordance" model, with density parameters $\Omega_0 = 1.0$, $\Omega_{BM} = 0.044$, $\Omega_{DM} = 0.226$, $\Omega_\Lambda = 0.73$, Hubble parameter $h = 0.71$, a power spectrum produced according to the Eisenstein & Hu (1999) fitting formulas with a primordial spectrum normalization $\sigma_8 = 0.94$, and an initial redshift of $z = 50$. In order to have a large number stastics of massive galaxy clusters, we collect several boxes in order to produce a final equivalent volume of $\approx (100Mpc/h)^3$ at the fixed numerical resolution of 125 kpc, Our fiducial model here is an ensamble of non-radiative simulations with a a post-processing treatment of cosmic reionizaation, designed to reproduce the Haardt & Madau (1996) model.

4. The Velocity–Jump Method

The crossing of a shock in a simulated volume leaves its imprint as a jump in all the thermodynamical variables, which can be inverted to evaluate the shock Mach number, M, by means of the standard Rankine–Hugoniot jump conditions. The relationship between the jumps in the velocity field, Δv, and M for an idealized shock wave running in an imperturbed medium follows from the conservation of momentum and density across the shock, and transforming the velocities from the shock frame to the Lab frame we get:

$$\Delta v = \frac{3}{4} v_s \frac{1 - M^2}{M^2}. \tag{1}$$

where $v_s = Mc_s$ and c_s is the sound velocity computed in pre–shocked cells.

The procedure adopted is the following: 1) we consider only "candidate" shocked cells with a negative 3–D velocity divergence; 2) in the case of two adiacent candidate shocked cells, the one with the minimum 3–D divergence is considered as the post–shock region; 3) we perfrom 1–D scan along each axes measuring all $\Delta v_{x,y,z}$ jumps across neighbours cells; 4) we measure the shock Mach number along each coordinate according to Eq.1, where v_s is calculated from the temperature of the pre–shock cell; 5) the total Mach number for the shocked cell is finally calculated as $M = (M_x^2 + M_y^2 + M_z^2)^{1/2}$.

As in other methods relying on a post-processing of the simulated output, this method has its major source of uncertainty in the assumption of an unperturbed velocity field prior to the passage of the shock. However, in the case of cosmological simulations the situation is more complex due to the chaotic pattern of velocity and temperature fluctuations which develops during LSS formation (e.g.

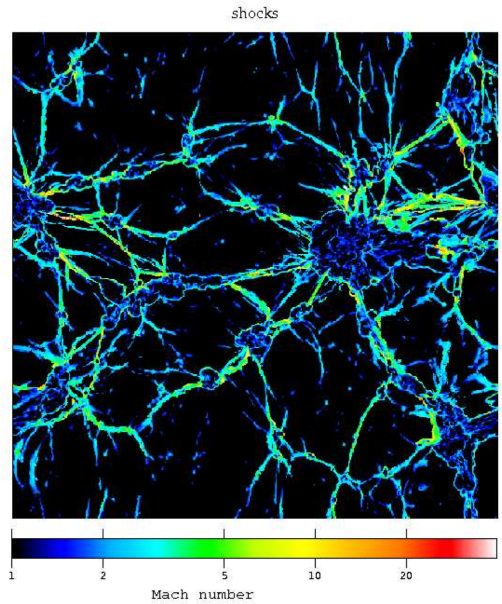

Fig. 1. 2–dimensional slice of the reconstructed Mach numbers of shocks for a box of side $80 Mpc$.

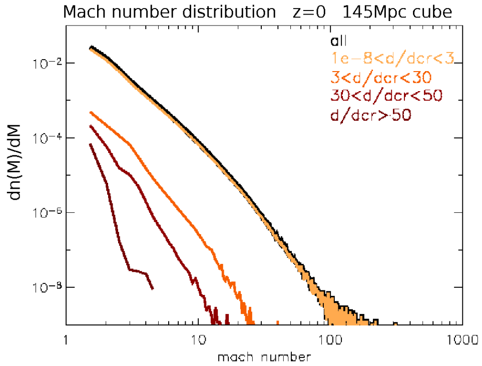

Fig. 2. Distribution of shocks Mach number for the whole fiducial data–set (black line) and distributions for subsamples in the cosmic environment (colour lines).

Dolag et al. 2005). The uncertainties deriving from that are discussed in VBG, where we claim that in the case of dense cosmological regions the efficency of the Velocity Jump (VJ) method in characterising shocks is similar to that of methods based on temperature jumps across cells within clusters, and becomes better in lower density regions (i.e. filaments and voids).

5. Results

In this Section we present the main results obtained for shocks in LSS at $z = 0$ with the VJ method. Additional results concerning the time evolution of shocks in the cosmological volume can be found in VBG.

5.1. Maps and Number distributions.

Fig.1 shows the distribution of detected shocks in a $125 kpc$ cut of a region of side $80 Mpc$, taken at $z = 0$. Roughly a $\sim$ 15 per cent of the simulated volume hosts shocks at present epoch, with the percentage of shocked cells increasing in denser environments. Overall, the picture is pretty similar to early results by Miniati et al. (2000), whith filamentary and sheet–like shocks developing at the interfaces of cosmic filaments and sheets, and with shocks surrounding galaxy clusters showing spherically shaped boundaries at a typical distance of about $1 - 2R_{vir}$ from clusters center. Internal merger shocks are more irregular and weak, $M \leq 2$, while slightly stronger shocks are only episodically found within clusters in case of merger events. An issue which is still poorly addressed in the literature is the Mach number distribution of shocks in numerical simulations. Fig.2 shows the distribution of shocked cells found with the VJ method at $z = 0$, for the total volume and in different cosmic environments. All distributions are steep, with $\alpha \sim -3.5$ ($\alpha = d \log N(M)/d \log M$) for the whole volume, and $\alpha < -6$ inside the virial radius of galaxy clusters. The majority of shocks are weak, with their distribution showing everywhere a peak at $M \sim 1.5$ and a monotonic decrease at larger M.

5.2. Thermal Energy Flux in Shocks.

A shock wave thermalises the post–shock region according to Rankine–Hugoniot jumps conditions, which relate the flux of the kinetic

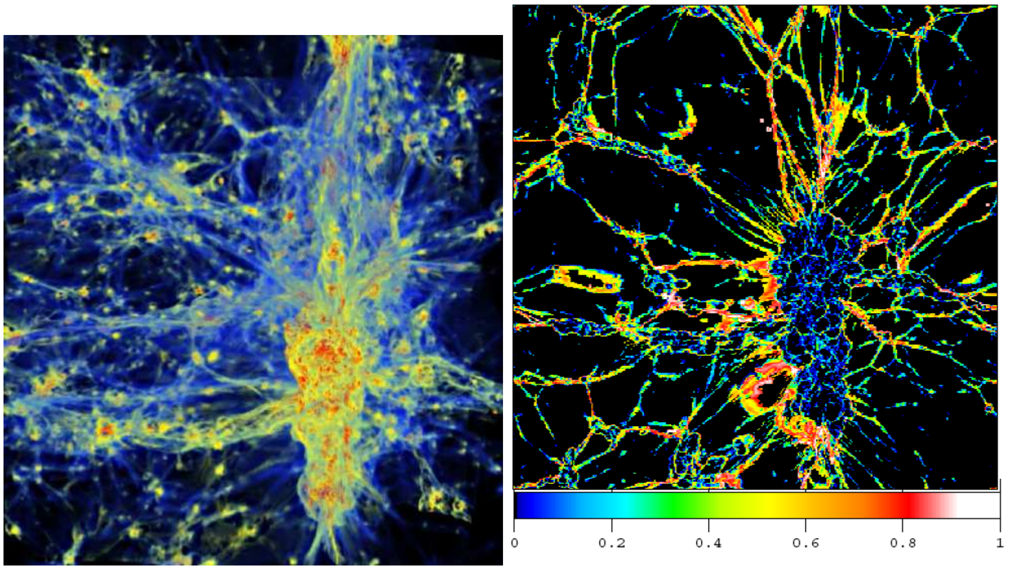

Fig. 3. *Left:*3–D rendering of the dissipated energy flux for a region of 80Mpc per side. Color coding goes from *blue* ($f_{th} \sim 10^{33} erg/s$) to *yellow* ($f_{th} \sim 10^{38} erg/s$) to *red* ($f_{th} > 10^{41} erg/s$). *Right:* energy ratio between injected CR energy flux and thermal energy flux in shock waves, for a slice crossing the center of the same two clusters in left panel.

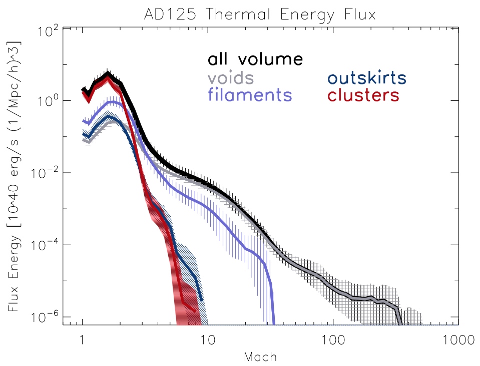

Fig. 4. Distribution of the thermalised energy flux at different overdensity bins, for the whole *AD125* and normalized to a comoving volume of $(1 Mpc/h)^3$.

energy crossing the shock and the resulting thermal flux in the post–shock region, f_{th}. We follow the formalism of Ryu et al. (2003) and Kang et al. (2007) to calculate f_{th} at a given M.

Left panel in Fig.3 shows a 3–D rendering of the thermal energy flux through shocks [1], while Fig.4 depicts the distribution of f_{th} at shocked cells, for different cosmic environments.

About 70 per cent of the total thermal energy flux from shocks comes from the virial region of galaxy clusters and the bulk of the thermalisation is done by shocks with $M \approx 1.8 - 2$. These relatively weak shocks are also responsible for the thermalisation in lower density environments, but in these regions a sizeable fraction of the thermal energy flux is injected at larger Mach numbers.

We find that although the total thermalised energy per cubic Mpc/h in our simulations is consistent with previous finding, our distribution of f_{th} is steeper: we find $\alpha_{th} \approx -3$ (with α_{th} taken as $f_{th}(M)M \propto M^{\alpha_{th}}$), which should be compared to $\alpha_{th} \approx -1.5$ to -2 in Ryu et al.

[1] The 3–D rendering is generated with of the visualization tool VISIVO (Becciani et al. 2007, http://visivo.cineca.it)

(2003) and to $\alpha_{th} \approx -2.5$ in Pfrommer et al. (2007).

5.3. Cosmic Rays acceleration.

The injection and acceleration of Cosmic Rays at shocks is a complex process, where several still unknown quantities play a major role (e.g. Blasi 2004 for a review). In the case of a low level of energy in form of CR, it is customary to describe the acceleration according to the diffusive shock acceleration (DSA) theory (e.g. Drury & Voelk 1981; Blandford & Ostriker 1978). This theory applies when particles can be described by a diffusion–convection equation across the shock, but it fails in case of strong shocks, where the pressure in the accelerated CR back reacts on the shock itself (e.g., Ellison et al. 1995).

In order to have a straightforward comparison with other numerical papers on the issue, we estimate the ratio between the energy flux trough a shock and the energy flux which is channelled into CR acceleration, f_{CR}, by means of a simple parameter, $\eta(M) = f_{CR}/f_{\phi}$ (Kang et al. 2007 for an analytical expression of $\eta(M)$), which depends on the Mach number only. Fig.3 (it right panel) shows the spatial distribution of f_{CR}/f_{th} at shocks for a cut taken across the same region of the left panel. The highest values of f_{CR}/f_{th} are found at the interface layers of filaments or in the outermost regions of galaxy clusters, where a substantial population of relatively strong shocks is present. On the other hand the lower values are typically found inside galaxy clusters, where the Mach number distribution is steep and strong shocks are extremely rare; here $f_{CR}/f_{th} \leq 0.10$ is measured.

As in the case of the thermal energy, we find that the distribution of the energy in CR at shocks is steeper than that reported in other works, with the bulk of the CR injection taking place at $M \sim 2 - 2.5$, at all cosmic environments. Since we use an approach equivalent to that in Ryu et al. (2003) to evaluate the CR acceleration, this difference is likely related to our different shock detecting scheme, and expecially to our modeling of the re-ionization process in the simulations (see VBG for a detailed discussion).

A comparison with the results in Pfrommer et al. (2006) is more difficult since these authors use a Lagrangian Smoothed Particles Hydrodynamics code which also include a different approach in the calculation of CR dynamics. The overall distribution of the energy flux injected in CR reported in Pfrommer et al. (2006) has a slope $\alpha_{CR} \approx -1.8$ which has to be compared with the value of $\alpha_{CR} \approx -2.2$ that we find in our simulations.

5.4. Shocks in Galaxy Clusters.

In this Section we studied shocks in four representative galaxy clusters with masses above $5 \cdot 10^{14} M_{\odot}$ and with different dynamical states: a cluster in a relaxed state, a system with an ongoin merger with a smaller subclump, a system approaching a major merger, and a post–merger system (2 Gyr after the close encounter).

Fig.5 reports the distribution of f_{th} with M in shocked cells within $1R_{vir}$ from the cluster centers; the distributions in the four clusters were normalized to the volume of the most massive system (a sphere of radius $\sim 3Mpc$). A very steep distribution of the energy flux trough shocks is found in the relaxed and in the minor merger case, while in the case of the ongoing merger and in the post merger case the distributions also show tail of higher Mach numbers. Inside R_{vir} no shocks with $M > 3$ are detected, except for a few in the case of the post–merger system, and this is in line with X–ray observations of real merging clusters (e.g. Markevitch & Vikhlinin 2007). We remark that our findings are in line with expectations from semi–analytical treatment of shocks in virialzied merging galaxy clusters (Gabici & Blasi, 2003). On the other hand, we find significantly less strong shocks than in Pfrommer et al. (2007). In this case the differences are due to the different numerical scheme and to the procedure adopted to characterise shocks, and highlight the level of present ucertainty in this issue.

The radial behaviour of the f_{CR}/f_{th} for these four clusters is reported in Fig.6, where

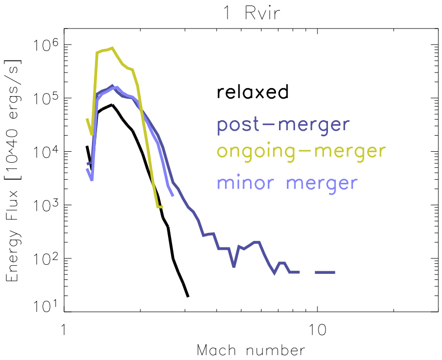

Fig. 5. Distribution of thermalised fluxes for the four different galaxy clusters presented in the text.

we adopted the Kang et al. (2007) formulation. Inside the virial radius we do not find any relevant difference among our clusters, and an average value of $f_{CR}/f_{th} < 10$ is found. This is because shocks crossing the innermost regions are weak, independently of the dynamical status of the clusters. Although we do not follow the advection of CR with cosmic time, and this makes a comparison with observations more challenging, our estimates appear in line with existing upper limits from Radio observations for μG magnetic field in galaxy clusters (Brunetti et al., 2007), as in our case the spectrum of CR is steeper than previous work (with an average slope of $\delta \sim -3.5$, see VBG for a detailed discussion).

6. Discussion and conclusion.

In this paper we have investigated the properties of shock waves in LSS simulations produced with the cosmological code ENZO and by means of a new detection scheme to measure the shocks, based on velocity jumps.

In the following we summarize the main results obtained:

- we detect morphologies of LSS shock–patterns which are qualitatively in agreement with previous numerical works (e.g. Miniati et al. 2001), with strong shocks enveloping filaments and sheets of matter, and weaker shocks hosted inside galaxy clusters.
- We measure the number distribution of shocks as a function of the Mach in all cosmological environments. The bulk of cosmological shocks is made by weak $M \leq 2$ shocks and their distribution can be grossly described by a steep power law $N(M) \propto M^{\alpha}$, with $\alpha \approx -3.5$. In the case of galaxy clusters $\alpha \approx -6$, demonstrating the increasing rarity of strong shocks in these denser (and hotter) regions.
- Following Ryu et al. (2003) and Kang et al. (2007) we calculate the energy rate dissipated in thermal energy at shocks, finding that roughly a 70 percent of the thermal dissipation in the whole volume happens inside galaxy clusters, at an average Mach number of $M \approx 2$. Although in qualitative agreement with previous studies, the energy distributions we measure in all environments are steeper than those obtained by Ryu et al. (2003) and by Pfrommer et al. (2006).
- We calculate the efficeny of CR acceleration for our simulations. Also in this case our results are in qualitatively in line with previous findings, although our energy distributions with M are sistematically steeper than those in Ryu et al. (2003) and slightly steeper than those in Pfrommer et al. (2006).

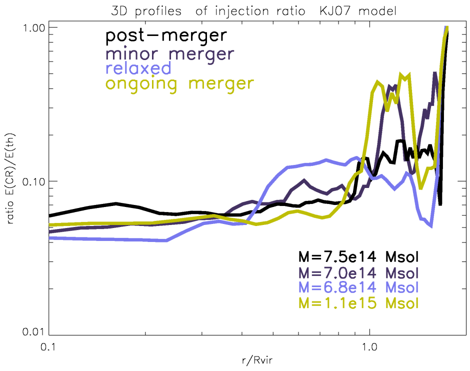

Fig. 6. Volume averaged profiles of the injection efficency, f_{CR}/f_{th}, for the four galaxy clusters.

– We report on the properties of shocked cells propagating in four representative galaxy clusters of our sample. The average Mach number of shocks within $1R_{vir}$ is $M \approx 1.5$ and this is in line with semi–analytical studies dealing with mergers of virialised systems (Gabici & Blasi, 2003). Also, the rariry of stronger shocks ($M > 2-3$) is found in line with the the rarity of shocks detected so far by X–ray observations (e.g. Markevitch & Vikhlinin 2007).

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