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Merger and non-merger galaxy clusters in cosmological AMR simulations

F. Vazza[1,2]

[1] Jacobs University Bremen, Campus Ring 1, 28759, Bremen, Germany
e-mail: f.vazza@jacobs-university.de
[2] INAF/Istituto di Radioastronomia, via Gobetti 101, I-40129 Bologna

Abstract. *Aims*: We discuss the dependence of shocks, cosmic ray acceleration and turbulence on the dynamical state of the host clusters. *Method:* We perform cosmological simulations with the grid code ENZO 1.5, with a mesh refinement scheme tailored to follow shocks and turbulence at high resolution in the clusters volume. *Results:* Sizable differences are found when some important properties, connected to non-thermal activity in clusters, are compared for post-merger, merging and relaxing systems.

Key words. Galaxy: clusters, general – Methods: numerical – Intergalactic medium

1. Introduction

Numerical simulations presently provide a unique way to study the generation and evolution of shock waves, turbulence and chaotic motions following the evolution of large scale cosmic structure over a wide range of scales, and in a fully-time dependent way (Dolag et al. 2008 and references therein). Simulations can also be a very powerful approach to tackle the problem of explaining the occurrence and morphologies of non-thermal emissions in clusters, observed in many systems (e.g. Ferrari et al. 2008 for a review). We recently employed a tailored Adaptive Mesh Refinement (AMR) scheme in the ENZO cosmological code (e.g. O'Shea et al. 2004; Norman et al. 2007) in order to study these phenomena with unprecedented high dynamic range (Vazza et al. 2010a; Vazza et al. 2010d). Here we summarize some of the most important findings of our work, reporting dependences between shocks, CR acceleration and turbulence and the dynamical state of the simulated host clusters.

2. ENZO simulations

The computations presented in this work were performed using the ENZO 1.5 code developed by the Laboratory for Computational Astrophysics at the University of California in San Diego (http://lca.ucsd.edu), see also O'Shea et al. (2004) and Norman et al. (2007).

We performed non-radiative ΛCDM simulations sampling a total cosmological volume with the size of $L_{\rm box} \approx 440$ Mpc/h, in which we re-simulated the evolution of the 20 most massive galaxy clusters, with a DM mass resolution of $m_{\rm DM} = 6.76 \cdot 10^8 M_{\odot}$ and a peak spatial resolution of $\Delta x \approx 25$ kpc/h inside $< 3R_{\rm vir}$ for each cluster (Vazza et al. 2010a). Our Adaptive Mesh Refinement (AMR) strategy was tailored to keep the maximum avail-

Send offprint requests to: F. Vazza

able resolution also at large distances from the cluster centers, tracking the propagation of strong discontinuities in the velocity field associated with shocks or turbulent motions (see Vazza et al. 2009b for a detailed discussion). At $z = 0$ each simulated clusters is sampled with a high number of cells, $N_{\rm grid} \sim 500^3 - 600^3$, allowing a study of the intra cluster medium (ICM) across 2-3 orders of magnitude in spatial scales (see Fig. 1 for a representative example).

Our clusters have total masses in the range $6 \cdot 10^{14} \leq M/M_{\odot} \leq 3 \cdot 10^{15}$; they were divided according to their dynamical state, following in detail their matter accretion history for $z < 1.0$ (see Vazza et al. 2010a for details). According to this definition, our sample contains 10 post-merger systems (i.e. clusters with a merger with a mass ratio larger than 1/3 for $z \leq 1$), 6 merging clusters and 4 relaxed clusters at $z = 0$.

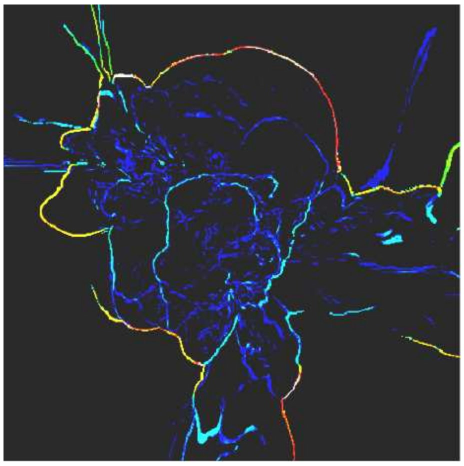

Fig. 2. 2-dimensional slice showing the Mach number of shocks for cluster E1 of our sample. The side of the slice is 13 Mpc/h and the depth along the line of sight is 25 kpc/h.

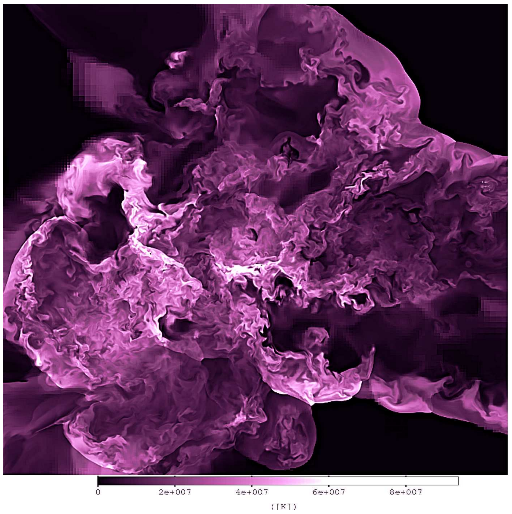

Fig. 1. Map of gas temperature for a major merger at $z \approx 0.6$. The side of the image is 8.8 Mpc/h, the depth along the line of sight is 25 kpc/h.

3. Results

3.1. Shocks and cosmic rays

We identified shocks in the ICM with the same procedure presented in Vazza et al. (2009a), based on the analysis of velocity jumps across close cells (see Fig. 2 for a map of the reconstructed Mach numbers). All clusters show similar shocks frequencies and energy distribution inside $R_{\rm vir}$: the profiles of average Mach numbers are very flat and characterized by very weak shocks, $M < 2$ (top panel of Fig. 3). *Sizable and stronger shocks ($M \sim 2.5 - 3.5$) are detected only in one post-merger systems and in one merging system.* The volume distribution of shocks is very steep ($\alpha \leq -4$ with $\alpha = d \log N(M)/d \log M$), while the distribution of flux of thermal energy through shock surfaces shows a well defined peak of thermalization at $M \sim 2$ (see bottom panel of Fig. 3). In general our distributions are slightly steeper than what was previously reported in the literature (e.g. Ryu et al. 2003; Pfrommer et al. 2006; Skillman et al. 2008), which can be explained as an effect of different resolution, re-ionization models and shocks detection schemes. Only for the few $M > 2$ cases reported above the flux distribution is flatter, with

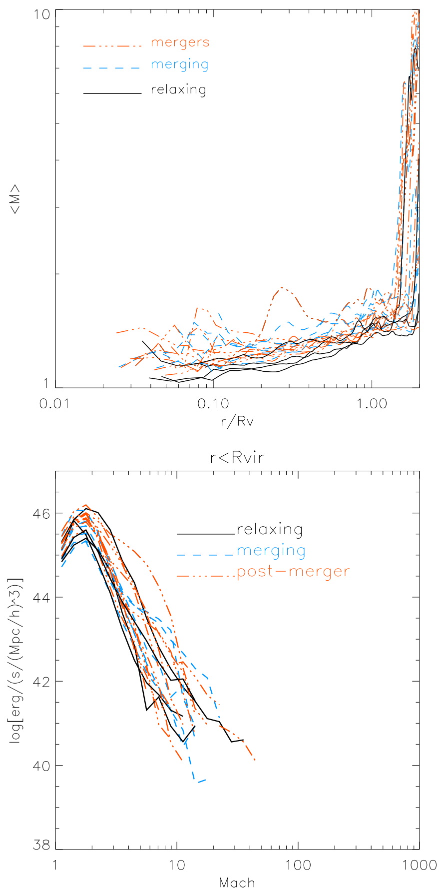

Fig. 3. Top: radial profile of average Mach number for the shocks in our sample. Bottom: distribution of thermal energy flux at shocks in the cluster samples.

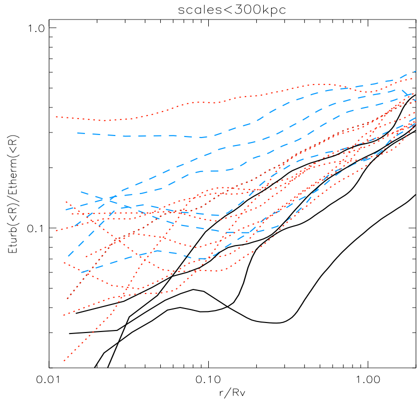

Fig. 4. Radial profile of the ratio between turbulent energy inside a given radius, and the thermal energy. The colors are as in Fig.3.

$\alpha \sim -2$. We investigated the injection of relativistic protons (CR) at shocks applying the efficiency function introduced by Kang & Jones (2007) in the framework of the Diffusive Shock Acceleration model. We found that the ratio between the CR energy flux and the thermal flux is < 0.05 inside $0.2R_{\rm vir}$ and < 0.1 inside $R_{\rm vir}$. *Only in one strong post-merger system we measure a CR injection of* $\sim 0.2 - 0.3$ *of the thermal energy flux.* The estimated amount of CR energy inside clusters implied by our results is well below ~ 0.1, which is presently allowed by observational upper limits coming from the non detection of gamma radiation from secondaries (e.g. Aleksić et al. 2010) and from the non detection of diffuse radio emission in relaxed clusters (Brunetti et al. 2007).

3.2. Turbulence

The turbulence in the ICM is expected to be sustained by the hierarchical process of matter accretion in evolving galaxy clusters (e.g. Norman & Bryan 1999; Dolag et al. 2005; Iapichino & Niemeyer 2008). In Vazza et al. (2010d) we discussed the application of 2 different filtering techniques to disentangle the local mean velocity field of the gas (assuming it is laminar above a certain scale) and the turbulent velocity field. Despite small differences from case to case, the two methods provided consistent estimates of the turbulent energies of our clusters (see Sect. 3.1 of Vazza et al. 2010d). In Fig. 4 we show the radial profile of the turbulent to thermal energy ratio (for the filtering at the scale of $\approx$ 300 kpc) for all clusters in our sample. As expected *turbulent motions are strong in merging and in post-merger systems* ($E_{\rm turb}/E_{\rm therm} \sim 0.1 - 0.3$ for $r < 0.2R_{\rm vir}$), while they are rather weak within the cores of relaxed systems ($E_{\rm turb}/E_{\rm therm} < 0.05$). However, almost all clusters host a sizable amount of turbulence ($\sim 20 - 40 E_{\rm therm}$) within the total virial volume. An interesting

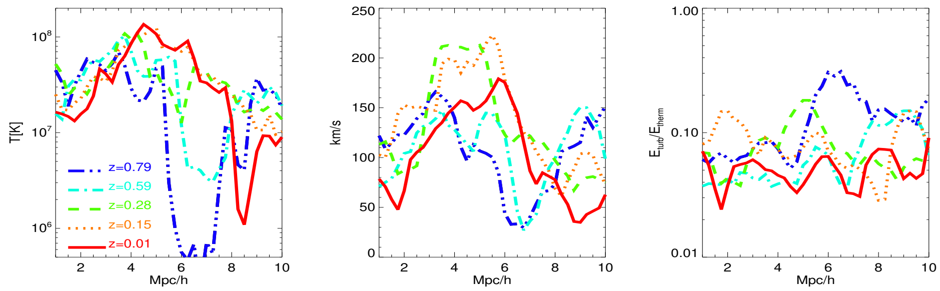

Fig. 5. Evolution of the profiles of gas temperature, turbulent gas velocity and $E_{\rm turb}/E_{\rm therm}$ along the axis of merger of two colliding clusters.

finding of our simulations is that, on average, *the turbulent energy present in merging systems is slightly larger than the turbulent energy of post-merger systems*, when normalized to the thermal energy of the host cluster. This happens because the thermal energy inside the two clusters is initially lowered as an effect of the accretion of cold gas from filaments, while the turbulent energy almost stadely increases (see panels of Fig. 5 and also the discussion in Sect. 3.2 of Vazza et al. 2010d). Our sample is large enough to allow the statistical study of the occurrence of turbulence in cluster cores, and to compare with some basic expectation from the theoretical "turbulent re-acceleration" (e.g. Brunetti et al. 2001), as for instance with the estimated frequency of "turbulent" clusters. We investigated this issue in detail, by considering the typical volumes and turbulent energies needed to produce realistic radio halo emission: at $z \sim 0$, about 1/3 of our simulated clusters host a level of turbulent energy of $\sim 0.25 E_{\rm therm}$ inside a volume of $\sim R_{\rm vir}/3$, in line with existing observations (Fig. 6). Despite these rather large values of turbulence in merging or post-merger clusters, the ICM at the smallest scale is only weakly turbulent, as follows from the general shape of the velocity power spectrum of our simulated ICM (Vazza et al. 2010c; Xu et al. 2009). If turbulence in our clusters is computed for the typical spatial scales of real X-ray observations performed with XMM-Newton (e.g. Sanders et al. 2010), ~ 30 kpc, the simulated turbulent velocities of the ICM within the core region of clusters are much smaller than the upper limits from observations (see Fig. 7).

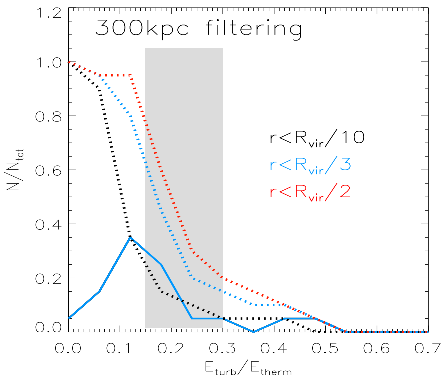

Fig. 6. Cumulative distribution function for $E_{\rm turb}/E_{\rm therm}$ inside $R_{\rm vir}/2$, $R_{\rm vir}/3$ and $R_{\rm vir}/10$ for the simulated clusters assuming $l < 300$ kpc for turbulence. The solid line shows the differential distributions for $R_{\rm vir}/3$. The grey band shows the turbulence required in the turbulent re-acceleration scenario (e.g. Brunetti & Lazarian 2010).

3.3. *Azimuthal scatter of gas profiles*

We investigated the level of intrinsic azimuthal scatter from the center of our clusters, focusing on some important thermodynamical quantities (e.g. density, temperature, entropy and X-

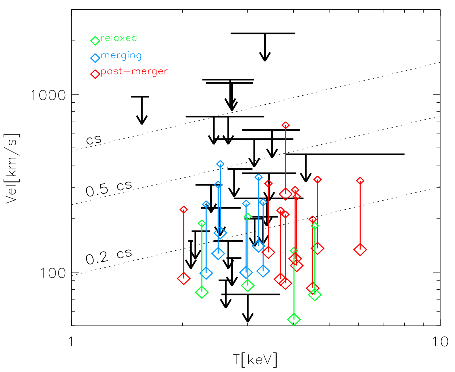

Fig. 7. Relation between temperature and turbulent velocity dispersion (small squares) for our clusters (squares in colors) and for the XMM-Newton observations of Sanders et al. (2010). The thick squares are for turbulent field below < 30 kpc.

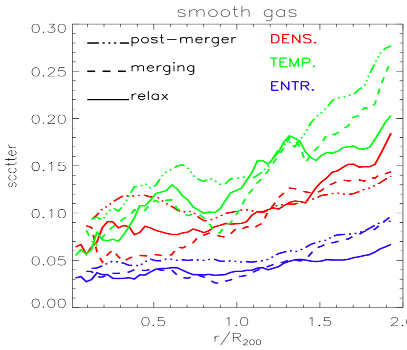

Fig. 8. Azimuthal scatter profile for our sample, after the "99 percent" filtering of the physical fields. The different colors refer to the different physical quantities, the linestyles refer to the dynamical classes of the sample.

ray luminosity). This is interesting because recent long SUZAKU exposures measured sizable differences between the cluster profiles in different sectors from the center (e.g. Bautz et al. 2009; George et al. 2009). The inspection of the radial properties of our simulated data offers a way to assess the need of non-gravitational physics in simulations, such as AGN, cosmic rays, magnetic field, in order to reconcile with observations. In Vazza et al. (2010 c) we tackled this issue by analyzing ENZO and GADGET2 runs of comparable resolution (Dolag et al. 2005). We processed all clusters with the filtering technique introduced in Roncarelli et al. (2006), designed to remove the densest clumpy gas component from each cluster dataset, and computed the cluster profiles in sectors of different angular size. In Fig. 8 we report the azimuthal scatter ($\Delta\alpha = \pi/8$) for the different quantities in the ENZO clusters. *Post-merger clusters present the largest degree of azimuthal scatter at all radii while the relaxed ones have the smallest scatter*. The scatter increases by a factor $\sim$ 2 going from $R_{\rm vir}$ to $2R_{\rm vir}$; the scatter in temperature is always larger than the scatter of the other quantities. Once that the contribution of clumpiness is removed from the datasets, post-merger clusters are the one more affected by an asymmetric distribution of the thermal gas, due to the chaotic pattern induced along mergers and filamentary accretions. The amount of azimuthal scatter is found to be in line with existing observations (see Vazza et al. 2010b for a detailed discussion), even if the presence of a un-removed clumpy component in the observation should be assumed to fit the case of cluster PKS0745-191 (George et al. 2009). These results suggest that non-gravitational processes may be not needed in simulations to model the thermodynamics of the gas in the outer cluster regions (e.g. Burns et al. 2010).

4. Discussion and conclusion

In summary, our AMR simulations with ENZO show that, for all (or most) of clusters:

- the volume and energy flux distributions of shocks in the ICM are steep and most of shocks have $M < 2$;
- the radial distribution of Mach numbers is very flat inside $R_{\rm vir}$;
- the average CR injection efficiency injection is small, $\epsilon_{\rm CR}/\epsilon_{\rm therm} < 0.05$;
- the kinetic energy of turbulent motions is $\sim$ 0.2 – 0.4 of the total thermal energy inside $R_{\rm vir}$;

- the turbulent motions of the ICM at scales < 30 kpc are subsonic $v_{\rm turb} < 0.1c_{\rm c}$;
- the azimuthal scatter of the clusters profiles increases by ~ 2 from $R_{\rm vir}$ to $2R_{\rm vir}$.

We find, however, the following significant dependences on the dynamical state of clusters:

- strong $M \sim 2.5 - 3.5$ shocks are found only inside the central region of clusters in $\sim 1/10$ of cases (never in relaxed clusters);
- in these rare systems, the injection efficiency of CR can be quite large, $\epsilon_{\rm CR} \sim 0.1 - 0.2\epsilon_{\rm therm}$;
- in post-merger system, the turbulent energy inside $R_{\rm vir}/3$ is $E_{\rm turb} \sim 0.25E_{\rm therm}$, while it is $\sim 0.1E_{\rm therm}$ in post-merger systems and $\sim 0.05E_{\rm therm}$ in relaxed ones;
- post-merger systems present a larger volume filling factor of turbulent motions compared to relaxed systems, and host enough turbulent energy to explain radio-halos within the re-acceleration scenario (see Brunetti et al. 2007);
- the azimuthal scatter in merging and post-merger clusters is larger (by a $20 - 50$ percent) compared to the relaxed ones.

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