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Cosmological shock waves

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Abstract

Cosmological shock waves, developed during the formation and evolution of cosmic structures, encode crucial information on the hierarchical formation of the Universe as well on its thermalization. They also play an essential role in galaxy cluster properties, contributing very efficiently to the virialization of haloes. In this contribution, we analyse an Eulerian adaptive mesh refinement (AMR) hydrodynamical and N-body simulation in a ΛCDM cosmology especially developed for the study of cosmological shock waves. The simulation incorporates common cooling and heating processes for a primordial gas. The combination of a new shock-capturing algorithm together with a halo finder allows us to study in detail some of the main features of the cosmological shock waves developed during the hierarchical evolution of the simulated Universe. We pay especial attention to discuss the spatial and morphological distribution of shocks within the computational box as well as the correlations between the shock Mach numbers and some of the main halo properties. We also analyse the connexion between the formation and evolution of shocks with the dynamical history of the cluster haloes.

1 Introduction

The cosmological shock waves develop as a consequence of the hierarchical formation of structures in the Universe and, therefore, they are crucial ingredients in a unified picture of the formation of cosmological structures. In a first phase, gravitational energy associated to the collapse of dark matter haloes corresponding to galaxy clusters and galaxies is transformed into internal energy of the intra cluster medium (ICM) and inter galactic medium (IGM) gaseous components. In the following phases, the evolution of those structures also produces mergers and accretion phenomena that modify the energetic balance of the gas through shock waves. Therefore, the shocks associated to cosmic structure formation and evolution encode information about the formation of the structures and their thermal impact on the gas.

The role of shocks in cosmological structures has been studied from observational, theoretical, and numerical approaches. However, in spite of all previous works, the identification and characterisation of shocks is still challenging due to the complex dynamics involved in the formation and evolution of cosmological structures and to the large dynamical range needed to describe all the scales involved by shocks.

Our purpose is to pursue the analyses of the main properties of the shock waves developed during the evolution of a high resolution hydrodynamical and N-body simulation of a large cosmological volume performed with an AMR cosmological code. In addition, we will put especial emphasis in analysing the existing connection between the cosmological shock waves and the population of haloes. In order to do so, we have developed a numerical algorithm able of detecting and characterising shocks in 3-D AMR simulations. The use of AMR hydro codes turns out to be crucial so as to obtain good dynamical ranges with an advanced hydrodynamical algorithm that is able to capture shocks very accurately.

2 Simulation details and halo identification

The simulation used in this work was performed with the Eulerian-AMR cosmological code MASCLET [6]. The simulation assumes a spatially flat ΛCDM cosmology with cosmological parameters: $\Omega_{\rm m} = 0.25$, $\Omega_\Lambda = \Lambda/3H_0^2 = 0.75$, $\Omega_{\rm b} = 0.045$, $h = H_0/100$ km s^{-1} Mpc^{-1} $= 0.73$, $n_{\rm s} = 1$, $\sigma_8 = 0.8$. The initial conditions were set up at $z = 50$, using a CDM transfer function from [2], for a cube of comoving side length 64 Mpc discretised in 512^3 cubical cells. A maximum of six levels of refinement have been used, which gives a peak physical spatial resolution of ~ 4 kpc. For the dark matter we consider two particles species being the best mass resolution $\sim 2.7 \times 10^8\, h^{-1}\,{\rm M}_\odot$. The simulation includes cooling and heating processes which take into account inverse Compton and free-free cooling, UV heating, atomic and molecular cooling for a primordial gas, and star formation.

The population of dark matter haloes has been identified with the ASOHF halo finder [4]. The sample used for this work consists in ~ 260 haloes at $z \sim 0$ within a range of virial masses[1] between $1.0 \times 10^{12}\,{\rm M}_\odot$ and $8.0 \times 10^{14}\,{\rm M}_\odot$.

For further details on the simulation, its initial conditions or its analysis see [5].

3 Detecting shock waves

Shocks produce irreversible changes in the gas of the cosmic structures. As a consequence, the evolution of a shock in a cosmological volume produces a jump in all the thermodynamical quantities. If we assume that the pre-shocked medium is at rest and in thermal and pressure

[1] The virial mass of a halo, $M_{\rm vir}$, is defined as the mass enclosed in a spherical region of radius $R_{\rm vir}$ with an average density $\Delta_c = 18\pi^2 + 82x - 39x^2$ times the critical density of the Universe, being $x = \Omega(z) - 1$ and $\Omega(z) = [\Omega_m(1+z)^3]/[\Omega_m(1+z)^3 + \Omega_\Lambda]$ [1].

equilibrium, the pre-shock and post-shock values for any of the hydrodynamical variables are unambiguously related to the shock Mach number, $\mathcal{M} = v_s/c_s$, which characterises the strength of a shock, and where v_s is the shock speed and c_s is the sound speed ahead of the shock. All the information needed to evaluate $\mathcal{M}$ is contained in the Rankine-Hugoniot jump conditions for the density (ρ), the temperature (T), and the entropy ($S = T/\rho^{\gamma-1}$) of the gas, e.g. [3]. Therefore, the Mach number can be obtained from the jumps in any of these hydrodynamical variables or from a combination of them.

Following a similar approach to that presented by [8], our shock-finding algorithm is based on temperature jumps (see [5] for further details on this algorithm). The whole procedure identifies all the shocked cells within the computational box and obtains their Mach number. The assembly of all these shocked cells defines the characteristic shock surfaces associated to shock waves. When this procedure is applied to an AMR simulation, the analysis is carried out in a hierarchical fashion, first on the most highly refined grids, moving down to progressively coarser levels of resolution. Given that this procedure is applied, independently, at each level of refinement of the simulation, the algorithm is able to find, in a natural way, shock waves related to different spatial scales provided by the simulation itself.

4 Results

4.1 Shock waves and cosmic structures

Cosmological shocks derived from the formation and evolution of cosmic structures have to present some correlations with the main features of the distribution of such structures. In order to deepen in this connection, we analyse the correlation between the distribution of cosmological shock waves and the halo population (galaxies and galaxy clusters). The first analysis one can think about is to compare the shock pattern with the density distribution of the different components forming the haloes in the simulation. Thus, Fig. 1 shows a 2-D projection along the z axis of the Mach number distribution to compare with the gas, dark matter and stellar overdensities at $z = 0$. Each panel represents a thin slice of 0.2 Mpc thickness and 64 Mpc side length centred at the position of the most massive halo found in the computational box. All the plotted quantities are in logarithmic scale. In all these panels, the contours of the strong shock waves —with high Mach numbers ($\mathcal{M} > 20$)— are overplotted. From Fig. 1 we can see how the shock pattern perfectly traces the cosmic web [7]. Nevertheless, this shock pattern has two clearly separated regimes. The first of these regimes gathers the high-$\mathcal{M}$ shocks —overplotted as contour lines in Fig. 1— that wrap filaments, sheets, and haloes. As these shocks are located out of the virial radius of the structures, they are classified as external shocks. These shocks have quasi-spherical geometries and can be located at distances of several virial radius from the centre of the structure where they were created [8]. Although for the sake of clarity the low-Mach number shocks are not plotted in Fig. 1, moving inwards the virial radius of haloes, more irregular and weaker shocks ($\mathcal{M} \leq 5$) are formed, in line with results from previous studies, e.g. [8]. This second regime corresponds to the internal shocks which are mainly associated to random flow motions and merger events within the haloes.

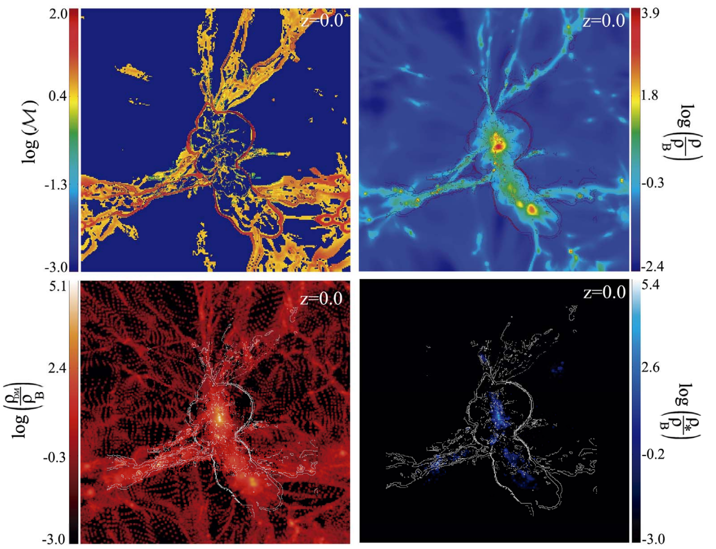

Figure 1: Distribution of shock Mach numbers compared with dark matter ($\rho_{\rm DM}/\rho_B$), gas (ρ/ρ_B) and stellar (ρ_*/ρ_B) overdensities at $z = 0$. Each panel is a thin slice of 0.2 Mpc thickness and 64 Mpc side length. In all the panels, the contours of the shock waves with high Mach numbers are overplotted.

4.2 The Mach number scaling relation

In this Section we introduce what we call the Mach number scaling relation. In order to build this relation we compute an average volume-weighted Mach number within the virial radius of each halo in our sample, representing, therefore, a virial Mach number. After that, we bin individual haloes into a two-dimensional grid of Mach number versus virial mass in order to have information on the number of haloes within a certain range of Mach numbers and viral masses. The obtained scaling relation is displayed in Fig. 2 in which we show different contour lines in order to highlight the shape of the 2-D distribution. Four different epochs corresponding to $z \simeq 2, 1, 0.4$, and 0, are shown.

The analysis of Fig. 2 revels some striking features. Let us focus first on the analysis of the distribution at $z = 0$ (lower right panel), where there are two well-differentiated trends. On the one hand, there is an almost constant region for low Mach numbers ($\mathcal{M} \lesssim 5$) which seems to be no-dependant on the mass of the haloes. On the other hand, a steeper trend along all the range of Mach numbers seems to be correlated with halo masses. Our explanation for this distribution is that the first trend is occupied by haloes which started their evolution in a relatively smooth way, with no mergers or a few minor mergers. The shocks within the virial radius producing the average Mach numbers associated with these haloes are related with smooth accretion flows of gas falling into the objects during this quiescence evolution. Therefore, haloes that have been quietly set up since early phases of their evolution have low $\mathcal{M}$ an tend to be located at the bottom of the plane $\mathcal{M} - M_{\rm vir}$ independently of their virial masses. Complementary, haloes that initially were involved in merger events and in

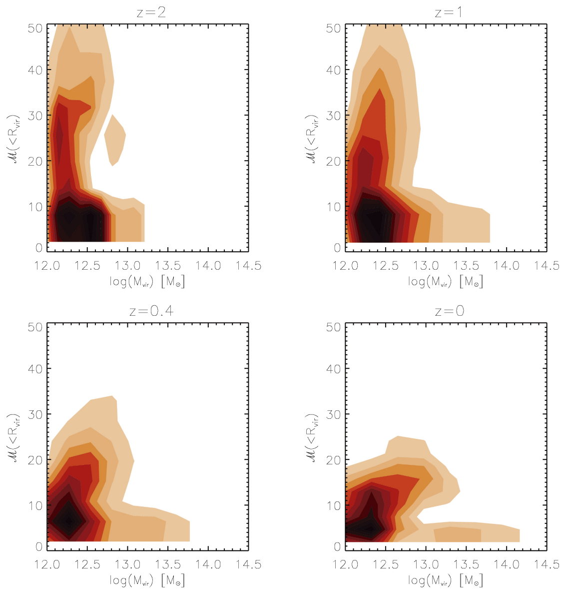

Figure 2: Halo distribution in the Mach number – virial mass plane. Results at $z \simeq 2, 1, 0.4$, and 0, are shown. The shaded regions have been computed by binning individual haloes into a two-dimensional grid in the plane $\mathcal{M} - M_{\rm vir}$. Six contour lines equally spaced are plotted to highlight the two-dimensional distributions.

active phases of their evolution suffer violent events that produce stronger shocks compared with those in the previous region. In this branch of the $\mathcal{M} - M_{\rm vir}$ plot, there is a strong dependence on the virial masses of haloes.

Therefore, the evolutionary history of each halo explains the bimodal segregation shown in Fig. 2, which is also observed through the temporal evolution. At early epochs, corresponding to the formation time of large galaxies and small groups of galaxies ($z \sim 2$), an L–like pattern in the plane $\mathcal{M} - M_{\rm vir}$ appears. These times correspond to highly non-linear epochs of the evolution of the haloes, with high rates of merger events and interaction among the structures at different spatial and mass scales. When advancing in time, the initial L–pattern trend progressively bends over to higher masses —corresponding to big galactic haloes and galaxy clusters— but lower Mach numbers, reaching the bimodal distribution, previously discussed, at $z \sim 0$.

In order to understand this behaviour, we have followed the global evolution of individual haloes looking at their overall drifts along the plane $\mathcal{M} - M_{\rm vir}$. We have studied this evolution for the 22 more massive haloes in the simulation which, indeed, are the best numerically resolved. The haloes in this subsample evolve according to two different behaviours. Roughly the 50% of this subsample of haloes begin, at high redshift, with a relatively high Mach number and evolve to progressively lower Mach numbers while increasing their mass. The remaining percentage of haloes depart from low-Mach number states ($\mathcal{M} < 5$) and tend to move, during their evolution, almost parallel to the x-axis while augmenting their masses. Since our sample of haloes is far from being statistically complete we can not make a robust conclusion. However, our hypothesis to explain this behaviour is that the evolution of haloes along the plane $\mathcal{M} - M_{\rm vir}$ is intimately related with their dynamical history. Like a gross trend, those haloes suffering important merger events (major mergers) early in their evolution only can evolve towards lower Mach numbers while reaching an equilibrium state producing, therefore, the decline of the initial L–like pattern into the flatter final distribution. On the other hand, haloes with a relatively quiet beginning show very low initial Mach numbers and evolve without significant changes in their virial Mach number and, consequently, they move almost parallel to the $M_{\rm vir}$–axis while increasing their mass.

5 Summary and conclusions

Our main conclusion is that shock waves play a crucial role in the formation and evolution of galaxies and galaxy clusters. Despite this general and obvious statement, direct evidence of shocks, both from the cosmic web formation processes (large scales) and those due to cluster merging events (small scales), has been found only in a relatively small number of clusters thanks to observations of radio relics and temperature maps in X-rays. Therefore, we believe that it is necessary to pursue the study of the role of shocks in cosmological context as they are fundamental players in the paradigm of structure formation in the Universe. Their complete theoretical description together with their detection and observation are still a challenge.

Acknowledgments

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