DETECTING SHOCK WAVES IN COSMOLOGICAL SMOOTHED PARTICLE HYDRODYNAMICS SIMULATIONS

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Shock waves during cosmological structure formation not only play a decisive role for the thermalization of gas in virializing structures but also for the acceleration of relativistic cosmic rays through diffusive shock acceleration. We present a novel formalism of identifying and measuring the shock strength on the fly in smoothed particle hydrodynamics simulations. Our formalism is applicable both to non-relativistic thermal gas, and to plasmas composed of cosmic rays and thermal gas. We apply our methods to study the properties of structure formation shocks in high-resolution hydrodynamic simulations of the Lambda cold dark matter model. We find that most of the energy is dissipated in weak shocks internal to galaxy clusters with low Mach numbers. Collapsed cosmological structures are surrounded by external shocks with higher Mach numbers up to 1000, but they play only a minor role in the energy balance of thermalization. This finding has important consequences for our understanding of the spatial distribution of relativistic particles in the cosmic large-scale structure, since it suggests that the ratio of the energy density of the cosmic ray proton population to the thermal gas within galaxy clusters increases with the cluster radius. Such an increase is required to explain the huge extended radio synchrotron halos of galaxy clusters by the injection of relativistic electrons through hadronic interactions of the cosmic ray protons with the ambient gas.

1 Motivation

Cosmological shock waves form abundantly in the course of structure formation, both due to infalling cosmic plasma which accretes onto filaments, sheets and halos, as well as due to supersonic flows associated with merging substructures. Additionally, shock waves in the interstellar and intracluster media can be powered by non-gravitational energy sources, e.g. as a result of supernova explosions.

Cosmologically, shocks are important in several respects and connected to the following interesting questions. (1) Shock waves dissipate gravitational energy associated with hierarchical clustering into thermal energy of the gas contained in dark matter halos, thus supplying the intrahalo medium with entropy and thermal pressure support: where and when is the gas heated to its present temperatures, and which shocks are mainly responsible for it? (2) Shocks also occur around moderately overdense filaments, heating the intragalactic medium. Sheets and filaments are predicted to host a warm-hot intergalactic medium with temperatures in the range $10^5\,\mathrm{K} < T < 10^7\,\mathrm{K}$ whose evolution is primarily driven by shock heating from gravitational perturbations developing into mildly nonlinear, non-equilibrium structures. Thus, the shock-dissipated energy traces the large scale structure and contains information about its dynamical history. (3) Besides thermalization, collisionless shocks are also able to accelerate ions through diffusive shock acceleration. These energetic ions are reflected at magnetic irregularities through

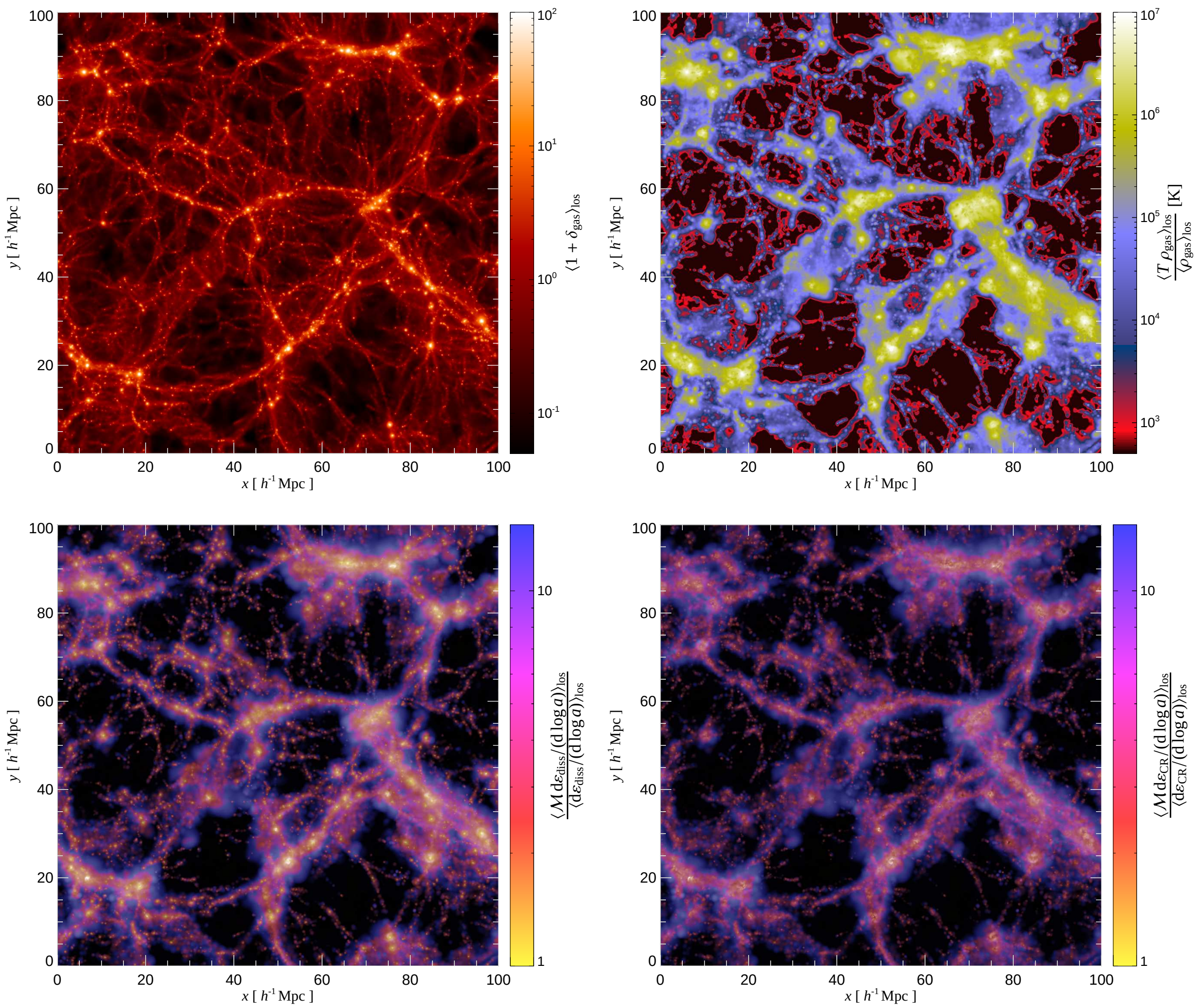

Figure 1: Visualization of a non-radiative cosmological simulation at redshift $z = 0$ where the cosmic ray (CR) energy injection was only computed while the effect of the CR pressure on the dynamical evolution was not taken into account. The **top panels** show the overdensity of the gas and the mass weighted temperature of the simulation. The **bottom panels** show a visualization of the strength of structure formation shocks. The color hue of the map on the left-hand side encodes the spatial Mach number distribution weighted by the rate of energy dissipation at the shocks. The map on the right-hand side shows the Mach number distribution weighted by the rate of CR energy injection above the momentum threshold of hadronic CRp-p interactions. The brightness of each pixel is determined by the respective weights, i.e. by the energy production density. Most of the energy is dissipated in weak shocks which are situated in the internal regions of groups or clusters, while collapsed cosmological structures are surrounded by strong external shocks (shown in blue). Since strong shocks are more efficient in accelerating CRs, the CR injection rate is more extended than the dissipation rate of thermal energy.

magnetic resonances between the gyro-motion and waves in the magnetized plasma and are able to gain energy in moving back and forth through the shock front: what are the cosmological implications of such a CR component, and does this influence the cosmic thermal history? (4) Simulating realistic CR distributions within galaxy clusters will provide detailed predictions for the expected radio synchrotron and γ-ray emission. What are the observational signatures of this radiation that is predicted to be observed with the upcoming new generation of γ-ray instruments and radio telescopes?

2 Structure formation shock waves and cosmic rays

We develop a formalism that is able to measure the shock strength instantaneously during an SPH simulation (Pfrommer et al. 2006). The method is applicable both to non-relativistic gas, and to plasmas composed of CRs and thermal gas. We apply our methods to study the properties of structure formation shocks in high-resolution hydrodynamic simulations of the Lambda cold dark matter (ΛCDM) model using an extended version of the distributed-memory parallel TreeSPH code GADGET-2 (Springel, 2005) which includes self-consistent CR physics (Enßlin et al. (2006), Jubelgas et al. (2006)). Fig. 1 shows the spatial distribution of structure formation shocks in comparison to the density and temperature distribution while Fig. 2 shows the cosmological Mach number distribution at different redshifts.

The main results are as follows. (1) Most of the energy is dissipated in weak shocks internal to collapsed structures while collapsed cosmological structures are surrounded by external shocks with much higher Mach numbers, up to $\mathcal{M} \sim 1000$. Although these external shocks play a major role locally, they contribute only a small fraction to the global energy balance of thermalization. (2) More energy per logarithmic scale factor and volume is dissipated at later times while the mean Mach number decreases with time. This is because of the higher pre-shock gas densities within non-linear structures, and the significant increase of the mean shock speed as the characteristic halo mass grows with cosmic time. (3) A reionisation epoch at $z_{\mathrm{reion}} = 10$ suppresses efficiently strong shocks at $z < z_{\mathrm{reion}}$ due to the associated increase of the sound speed after reionisation. (4) Strong accretion shocks efficiently inject CRs at the cluster boundary. This implies that the dynamical importance of shock-injected CRs is comparatively large in the low-density, peripheral halo regions, but is less important for the weaker flow shocks occurring in central high-density regions of halos. Zoomed simulations of individual galaxy clusters support this picture (cf. Fig. 3).

3 Conclusions

We studied the properties of cosmological shock waves using a technique that allows us to identify and measure the shock strength on-the-fly during a smoothed particle hydrodynamics simulation. Invoking a model for CR acceleration in shock waves, we have carried out the first self-consistent hydrodynamical simulations that follows the CR physics self-consistently. The resulting pressure distribution of CRs within galaxy clusters matches the required distribution of CRs to explain the huge extended radio synchrotron halos of galaxy clusters by the injection of relativistic electrons through hadronic interactions of the CR protons with the ambient gas.

References

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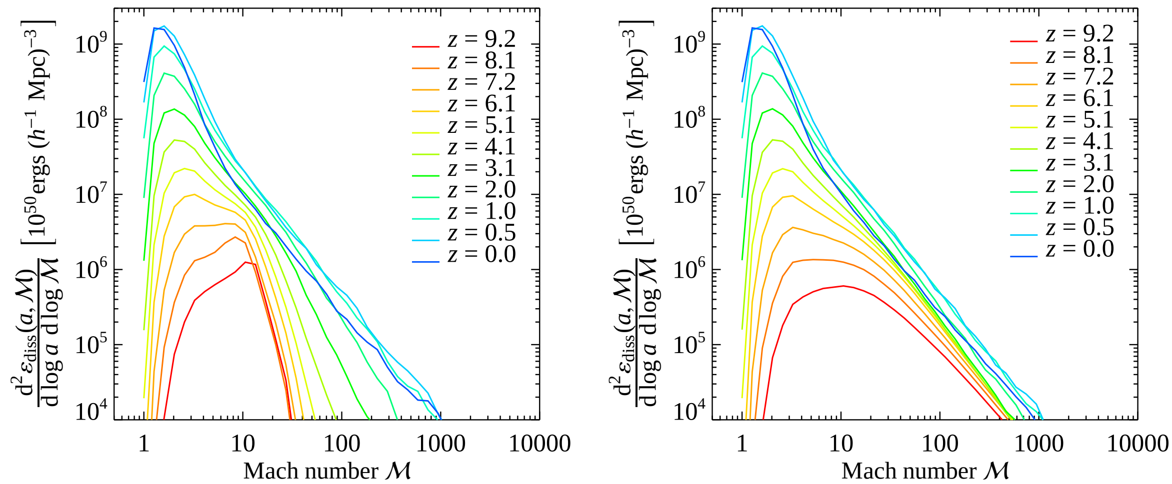

Figure 2: Influence of reionisation (at redshift $z = 10$) on the Mach number statistics of non-radiative cosmological simulations. The figure on the **left-hand side** shows the differential Mach number distribution $\mathrm{d}^2\varepsilon_{\mathrm{diss}}(a,\mathcal{M})/(\mathrm{d}\log a\,\mathrm{d}\log\mathcal{M})$ for our simulation with reionisation while the figure on the **right-hand side** shows this distribution for the simulation without reionisation. Strong shocks are effectively suppressed due to an increase of the sound velocity after reionisation.

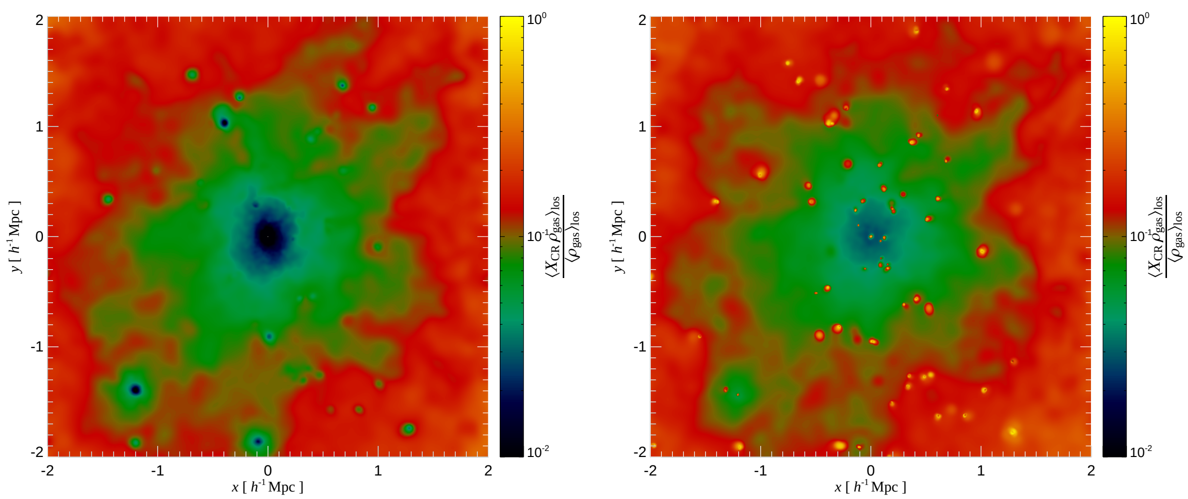

Figure 3: Visualization of the pressure contained in CRs relative to the total pressure $X_{\mathrm{CR}} = P_{\mathrm{CR}}/(P_{\mathrm{CR}} + P_{\mathrm{th}})$ in a zoomed simulation of an individual galaxy cluster with mass $M = 10^{14} h^{-1} M_{\odot}$. The map on the **left-hand side** shows a non-radiative simulation with CRs accelerated at structure formation shock waves while the map on the **right-hand side** is from a simulation with dissipative gas physics including cooling, star formation, supernova feedback, and structure formation CRs. The relative CR pressure X_{CR} declines towards a low central value of $X_{\mathrm{CR}} \simeq 10^{-4}$ in the non-radiative simulation due to a combination of the following effects: CR acceleration is more efficient at the peripheral strong accretion shocks compared to weak central flow shocks, adiabatic compression of a composite of CRs and thermal gas disfavors the CR pressure relative to the thermal pressure due to the softer equation of state of CRs, and CR loss processes are more important at the dense centers. Interestingly, X_{CR} reaches high values at the center of the parent halo and each galactic substructure in our radiative simulation due to the fast cooling gas which transforms into stars in the densest regions while diminishing thermal pressure support relative to that in CRs. This additional CR pressure support has important consequences for the thermal gas distribution at cluster centers and alters the resulting Sunyaev-Zel'dovich effect significantly.