A Spectral Cosmic Ray Model for Cosmological Simulations

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Motivation

Cosmic Rays (CRs) are the most likely source of non-thermal emission in galaxy clusters. These emissions are found at merger shocks where they can be observed as highly polarized radio relics, in jets of AGNs and sometimes as a diffuse radio halo across the entire galaxy cluster. As most physical processes of CRs are energy dependent, such as energy loss processes, or diffusion processes, it can be limiting to treat CRs as a single fluid component in simulations. We therefore represent the CR component in our simulation as a distribution function in momentum space, following the `COSMOCR` implementation by Miniati (2001).

The Model

The time evolution of a momentum distribution of CRs is described by the diffusion-convection equation. We evolve this function in our simulations via an on-the-fly Fokker-Planck solver. This is then used to calculate the CR pressure component using the equation of state of an ideal relativistic gas, which contributes to the total pressure and with that the hydro-acceleration in our code. Here present our method for modelling acceleration of CRs at merger- and accretion shocks, as well as radiative losses of electrons due to synchrotron emission and inverse Compton scattering off CMB photons.

Tests

To test the accuracy of our CR acceleration model we ran a series of shocktube tests. We find generally good agreement with the analytic solution with low numerical noise. For the radiative cooling model we compare to the solution by Kardashev (1962) where we also find good agreement.

Cluster Merger

To test our model in a more realistic scenario we ran a number of idealized galaxy cluster mergers with a mass resolution of $M_{Gas} = 6.7 \cdot 10^7 M_\odot$ and $M_{DM} = 4.5 \cdot 10^8 M_\odot$ as well as a spectral resolution of 96 CR bins ranging over 6 orders of magnitude in momentum. We found that our spectra remain stable over the course of the simulation and that the electrons show smooth cooling behaviour. This allowed us to make a first try at calculating the synchrotron spectra of the electrons accelerated at merger shocks. We self-consistently reproduce the expected spectral steepening over the shock, as observed in radio relics. These results are currently limited by resolution, so we aim to re-run these simulations once all other tests are completed.

Outlook

We aim to use this solver in cosmological zoom-in simulations to study the effect of CRs on the formation of galaxy clusters and self-consistently obtain observables.