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Propagation of cosmic rays and their secondaries in the intracluster medium

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Abstract. We present results of the propagation of high-energy cosmic rays (CRs) in the intracluster medium (ICM). To this end, we employ three-dimensional cosmological magnetohydrodynamical simulations of the turbulent intergalactic medium to explore the propagation of CRs with energies between 10^{14} and 10^{19} eV. We study the interaction of test particles with this environment and compute the associated fluxes of CRs and neutrinos using Monte Carlo simulations.

Resumo. Nós apresentamos resultados da propagação de raios cósmicos (CRs) de alta energia no meio intra-aglomerado (ICM). Para isso, utilizamos simulações magnetohidrodinâmicas cosmológicas tridimensionais do meio intergaláctico para investigar a propagação de CRs com energias entre 10^{14} e 10^{19} eV. Nós estudamos a interação de partículas de teste com este meio e calculamos os fluxos associados de CRs e neutrinos empregando simulações de Monte Carlo.

Keywords. Cosmic rays, Gamma Rays, Neutrinos, Magnetic fields and Intracluster Medium

1. Introduction

CRs are produced via shocks and turbulent acceleration processes inside galaxies and re-accelerated by similar processes in the intracluster medium (ICM), in particular in shocks induced by cluster mergers, filaments and haloes. CRs of energies $E \gtrsim 5\times10^{18}$ eV likely have an extragalactic origin (Alves Batista et al. 2019b). However, it is not clear at which energy there is a transition between galactic and extragalactic CRs. CRs with energy $E \lesssim 10^{17}$ eV are believed to have a galactic origin, since their Larmor radii are comparable with the size of the Milky Way. At these energies CRs may also be confined within clusters; that is the topic of our investigation. The energy-loss time of CRs in the ICM makes clusters efficient sites for their storage and production of neutrinos and gamma rays (Berezinsky et al. 1997; Rordorf et al. 2004; Fang & Olinto 2016). So, we are studying propagation of CRs in the energy interval $\sim 10^{14}$–10^{19} eV and the production of secondary particles during their confinement in the ICM.

In this article we perform detailed simulations of CR propagation in the ICM. It is structured as follows: In section 2 we present the three dimensional (3D) magnetohydrodynamical (MHD) simulations of structure formation employed by Dolag et al. (2005). In section 3 we describe the methods used to perform the CR propagation in the ICM and the results are also discussed in that section as well.

2. Simulation setup

We are studying the propagation of CRs in the ICM. For that, we use the large scale cosmological simulations performed by Dolag et al. (2005), shown in Figure1. These 3D-MHD simulations were obtained using the SPH (smooth particle hydrodynamics) code GADGET. They cover a volume of a sphere of radius $\sim$ (110 Mpc)^3. We obtain the magnetic field, gas density, and temperature distributions of two clusters choosen from this large volume. The whole analysis is done for those two clusters.

We inject test particles in the turbulent environments of two clusters, and employ the code CRPropa3 (Alves Batista et al. 2016). We consider all relevant CR interactions, namely, photopion production, photodisintegration, and Bethe-Heitler pair production with the background photon field CMB and extragalactic background light (EBL). We also considered the intercation of CRs with the X-ray radiation from clusters of galaxies primarily due to the thermal bremsstrahlung emission of hot plasma with temperature range $\sim 10^6 - 10^8$ K. Regarding the interaction of CRs in the ICM with the background photon fields, we found that the EBL is dominant at infrared and optical but at X-rays the bremsstrahlung field is more important only near the center of the clusters.

Photon density is not constant in different regions of the cluster. So, we divide the cluster in five shells of different radii: $0 < r < 100$ kpc, $100 < r < 500$ kpc, $500 < r < 1000$ kpc, $1000 < r < 1500$ kpc, $1500 < r < 2000$ kpc. We then calculate the photon density distribution in each one of them.

3. Results and discussion

We first study how the CRs spectrum depends on the position. This is shown in Figure3 for different composition of primaries, namely, proton, nitrogen, and iron.

The injected spectrum (E^{-1}) is clearly modified, due to the interactions with thermal photons in the clusters. We found a significant suppression in the flux of CRs at an energy around $\sim 10^{16}$ eV, which indicates the trapping of CRs within the clusters. The suppression in the flux is apparent as the Larmor radius of a 10^{16} CR in a magnetic field $B \sim \mu$ G is $R_L = 0.01$ kpc, which is much smalller than the cluster size $\sim$ 2 Mpc. Due to magnetic field of the ICM, CRs can be confined in the very large volume of galaxy clusters for a period of time comparable to the age of clusters themselves. This magnetic horizon can limit the energy of CRs that can escape clusters, suppressing the contribution of the lower-energy CRs.

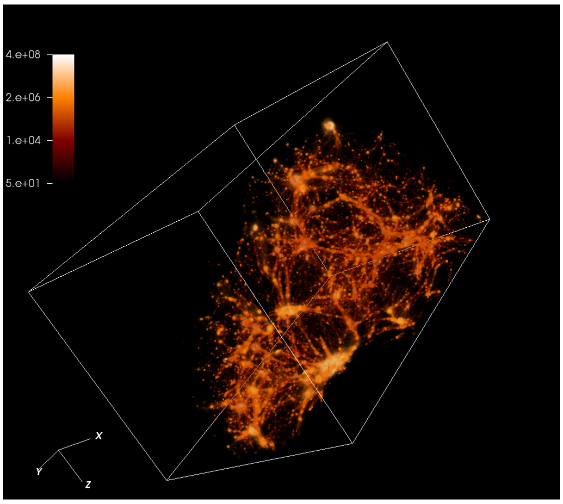

Figure 1. Large-scale distribution of matter, including filaments and clusters (Dolag et al. 2005).

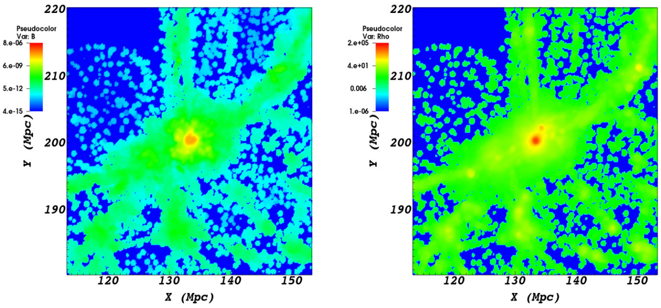

Figure 2. This figure shows a slice from the Figure.1 for the maps of gas density (left panel) and magnetic field (right panel) for one of the clusters.

Clusters are unique environments. Due to their magnetic field configuration, the confinement of CRs for long periods of time enhances the interaction rates, increasing the production of secondary particles including neutrinos and gamma rays (Brunetti & Jones 2014; Blasi 2013; Amato & Blasi 2018; CTA Consortium 2019). In this work, we only calculate the flux of neutrinos generated by the propagation of CRs (Figure. 4) from the two clusters assuming different composition of CRs primaries. These neutrinos production are mainly due to photo-pion production and photodisintegration. However, CRs produce secondary particles like pions during their confinement in the ICM, which decay into photons and electrons. Thus, significant amount of gamma rays can be produced by ICM. We have not studied the production of gamma rays, and the synchrotron emission in the ICM. CR interactions with the gas in the cluster is a well known channel for the production of secondary particles including neutrinos and gamma rays, but we have not considered this interaction in this research work.

Hence, the confinement of CRs for long periods of time enhances the probability of interactions, increasing the production rate of secondaries. The combined contribution of all clusters in the universe may thus respond for a sizeable fraction of the diffuse gamma-ray and neutrino backgrounds. Experiments such as the IceCube Neutrino Observatory IceCube Collab. (2018), and the planned Giant Radio Array for Neutrino Detection (GRAND) GRAND Collab. (2020) may be able to measure the diffuse neutrino flux due to clusters.

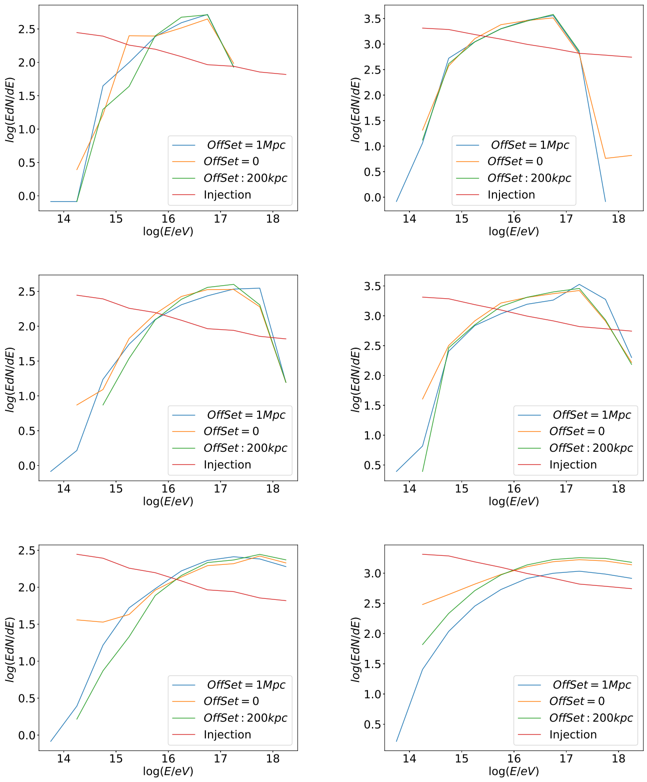

Figure 3. Spectrum (in arbitrary units) of CRs for cluster 1 (left column) and cluster 2 (right column). We assume different compositions at injection: iron (upper panels), nitrogen (middle), and proton (lower). The lines in each plot correspond to: the injected spectrum (red), the flux for a CR source in the centre of the cluster (orange), at 200 kpc (green) and 1 Mpc (blue) away from the centre.

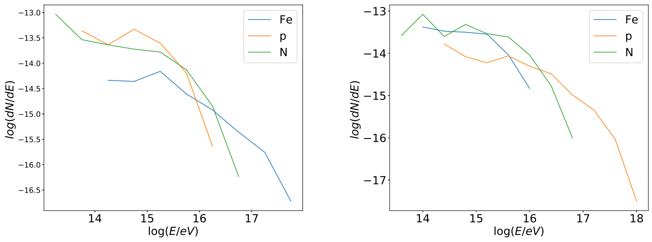

Figure 4. Spectrum of neutrinos (in arbitrary units) for cluster 1 (left) and cluster 2 (right panel), for different assumptions on the composition of cosmic-ray primaries.

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