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PhD Cycle: XXXIV
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RESEARCH PROJECT: Macroscopic and microscopic aspects of the acceleration of non-thermal particles by cosmic shocks

My PhD project, started in november 2018, is part of the MAGCOW project funded by the EU and it is aimed at the study of the macroscopic and microscopic aspects of the acceleration of cosmic rays by shocks, by means of magnetohydrodynamics (MHD) simulations with the code ENZO (Bryan et al. 2014) and particle-in-cell (PIC) simulations with the code TRISTAN-MP (Spitkovsky 2005).

Main project

Scientific case

Shocks in the large scale structure of the universe can be generated by accretion of cold gas or merger of subhalos, which convert a fraction of kinetic energy into 1) thermal energy, 2) amplification of magnetic fields and 3) acceleration of energetic particles. Cosmic rays can undergo different levels of acceleration as a function of plasma parameters and the pre-existing magnetic field topology. Direct evidence of the occurrence of non-thermal processes involving electrons can be found in radio observations of the Mpc-size synchrotron emission in clusters of galaxies (e.g. Van Weeren et al. 2019 for a review). On the other hand, cosmic-ray protons would be expected to produce hadronic gamma rays, but the lack of their detection by FERMI (e.g. Ackermann et al. 2010) sets upper limits for the acceleration efficiency that are too low to be consistent with radio observations of relativistic electrons. Recent PIC simulations (e.g. Guo et al. 2014) have shown that cosmic rays undergo diffusive shock acceleration (DSA), possibly assisted by shock drift acceleration (SDA) in the case of electrons, and quantified the acceleration efficiency as a function of the Mach number and the obliquity, i.e. the angle between shock normal and up-stream magnetic field vector. These simulations suggest that cosmic ray electrons are more easily accelerated in perpendicular shocks, while protons are more easily accelerated in parallel shocks. For this reason the expected flux of gamma rays linked to protons may be significantly lower and in agreement with the lack of detection by FERMI.

Results (arXiv:2006.10063)

In this work, we analyzed both uniform and adaptive mesh resolution simulations of large-scale structures with the magnetohydrodynamical grid code Enzo, studying the dependence of shock obliquity with different realistic scenarios of cosmic magnetism. We found that shock obliquities are more often perpendicular than what would be expected from a random three-dimensional distribution of vectors, and that this effect is particularly prominent in the proximity of filaments, due to the action of local shear motions. By coupling these results to recent works from particle-in-cell simulations, we estimated the flux of cosmic-ray protons in galaxy clusters, and showed that in principle the riddle of the missed detection of hadronic gamma-ray emission by the Fermi-LAT can be explained if only quasi-parallel shocks accelerate protons. On the other hand, for most of the cosmic web the acceleration of cosmic-ray electrons is still allowed, due to the abundance of quasi-perpendicular shocks. Differences between the analyzed models of magnetization of cosmic structures become more significant at low cosmic overdensities, indicating that different cosmic environments may be characterized by systematically different regimes of shock obliquity and local plasma parameters.

Side projects

1. Simulations of primordial magnetic fields constrained by PLANCK

We produced cosmological simulations of primordial magnetic fields directly derived from the constraints from the CMB observations, based on the fields' gravitational effect on cosmological perturbations. We evolved different primordial magnetic field models and compared their observable signatures (and relative differences) in galaxy clusters, filaments and voids. The differences in synchrotron radio powers and Faraday Rotation measure from galaxy clusters are generally too small to be detected, whereas differences present in filaments can only be investigated with the higher sensitivity afforded by the Square Kilometre Array. However, several statistical full-sky analyses, such as the cross-correlation between galaxies and diffuse synchrotron power, the Faraday Rotation structure functions from background radio galaxies, or the analysis of arrival direction of Ultra-High-Energy Cosmic Rays, may already be used to detect currently constrained fields.

2. Spin, filament and magnetic field alignment

We analyze Enzo simulations of different magnetogenesis scenarios and reconstruct the cosmic web to study the reciprocal alignment of halos, filaments and magnetic field lines. Our preliminary results suggest that filaments cause magnetic field lines to bend along them, up to several hundreds of kpc away. This effect appears to be stronger for fields of primordial origin, rather dynamo/AGN-enhanced ones.

PhD SCHOOLS

- November 19-28, 2019 La Laguna, Tenerife, Spain – XXXI Canary Islands Winter School of Astrophysics: “Computational Fluid Dynamics in Astrophysics” + poster presentation

COURSES

- May-June, 2020: “Neutrinos and Dark Matter in Astro- and Particle Physics”
- September, 2020: “Gaia: Great advances in Astrophysics”

ISA LECTURES

- May 19, 2020: “Exploration of small bodies of the Solar System: focus on comets”, Lecture by Dr. Maria Cristina De Sanctis

PUBBLICATIONS

- Banfi et al. 2020: “*Shock waves in the magnetized cosmic web: the role of obliquity and cosmic ray acceleration”,* MNRAS, Volume 496, Issue 3, August 2020, Pages 3648–3667, https://doi.org/10.1093/mnras/staa1810, Published: 23 June 2020
- Vazza, Paoletti, Banfi et al. submittted to MNRAS: *"Simulations and observational tests of primordial magnetic fields from Cosmic Microwave Background constraints"*
- Banfi et al. in prep: paper on spin, filament and magnetic field alignment