Project title: High-Resolution Study of the Topology of Radio Relics

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Principal investigator:
Dr. Denis Wittor - University of Hamburg, Germany & University of Bologna, Italy

Project contributors:
Matthias Hoeft - Thüringer Landessternwarte Tautenburg
Kamlesh Rajpurohit - University of Bologna, Italy & Center for Astrophysics-Harvard & Smithsonian, Cambridge, MA, USA
Francesco de Gasperin - University of Hamburg, Germany & IRA-INAF, Bologna, Italy

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Abstract

The shock acceleration of cosmic-rays occurs at all scales in the Universe, ranging from the small scales of Supernova to the large scales of galaxy clusters and beyond. In galaxy clusters, shock acceleration of cosmic-ray electrons is seen in form of radio relics – clouds of diffuse radio emission. Radio relics probe both the shock acceleration and the magnetic fields in galaxy clusters. The recent technological advances in radio astronomy have provided pictures of radio relics with unprecedented details. To connect these observations to the underlying theory cosmological simulations are unambiguous. This project targeted the production of high-resolution simulations of radio relics to provide new insights in the physics of shock acceleration in the Universe.

Essay

Introduction

On its largest scales, the Universe is permeated by filaments, forming the cosmic web. The intersection of these filaments are inhabited by galaxy clusters – large assemblies of matter in form of galaxies, dark matter and the intracluster medium, a hot and ionized plasma that fills the space in between the galaxies. The intracluster medium is filled with a variety of exciting and fascinating physical phenomena. One of these are radio relics, elongated clouds of diffuse radio emission that live in the periphery of galaxy clusters.
The radio emission of radio relics is synchrotron emission, i.e. it is emitted by high energetic cosmic-ray electrons that spiral around the cluster magnetic fields. Yet, what is the origin of both the magnetic fields and the cosmic-ray electrons?
It is commonly accepted that shock waves in the intracluster medium shock accelerate the cosmic-ray electrons to the high energies. The co-observation of shock waves at the relics' locations supports these theory. The origin of the cluster magnetic fields is less constrained. It has been proposed that their origin is either primordial, i.e. they have been formed close the big bang, or astrophysical, i.e. they are produced inside galaxies and transported to the larger scales of galaxy clusters. Though, the two scenarios do not exclude each other and the truth could be a combination of both.

Radio relics are perfect objects to study both the shock acceleration and the physics of the cluster magnetic fields. However, radio relics are very large. Normally, they extend over 1 to 2 mega-parsecs, i.e. they are 40 to 80 times longer than the diameter of the Milky Way. Moreover, the properties of the intracluster medium are not reproducible in any laboratory on earth, e.g. temperatures of 10 millions degrees. Hence, radio observations are our only way to study radio relics. Yet, we only observe a very tiny fraction of a relics lifetime. Their formation and evolution takes several 10 to 100 million years. Hence, it is impossible to observe the shock acceleration in real time.
To connect the observations to the underlying theoretical models, computer simulations of radio relics are unambiguous. These cosmological simulations can be thought of numerical laboratories, in which various theoretical models for the formation and evolution of radio relics are recreated. A detailed comparison of the simulations’ outputs and observations allows to either confirm or discard theoretical models.
In the recent years, the technology of radio telescopes has significantly improved, providing a never before seen detail of radio relics. As simulation must keep up with these advances, the goal of this computing project was to produce a set of high-resolution cosmological simulations of radio relics to aid the interpretation of observations and to provide new insights on the physics of radio relics.

Simulations

In this project, cosmological simulations were produced with the ENZO-code [A]. Such cosmological simulations model the temporal and spatial evolution of a cutout of the Universe. Hence, they model the formation of the cosmic web, of galaxy clusters and of radio relics. However, modeling radio relics in cosmological is challenging for two reasons.
First, the volume that is simulated must be large enough to contain massive galaxy clusters that are capable of hosting bright radio relics. However, these simulations must have a high spatial and temporal resolution to properly model the small-scale physics of radio relics. However using a high spatial resolution, as required, for the entire simulations is impractical as they computation time would become infinitely large. A work around to this problem, is the usage of adaptive mesh refinement. In adaptive mesh refinement, the spatial resolution is locally increased in the region of interest, e.g. in a region where a galaxy cluster forms.
Second, the cosmic-ray electrons that are shock accelerated and form the radio relics must be included in the simulation as well. Here, the method of choice are Lagrangian tracer particles that were simulated with the CRaTer-code [B]. In this approach, passive tracer particles are injected into the simulation. These tracer particles record the evolution of the cosmic-rays.

Results

Through the combination of cosmological simulations and Lagrangian tracer particles, this project produced the most detailed simulations of radio relics to-date. These simulations provided new insights on the formation of radio relics, and, hence, on the physics of shock acceleration and magnetic fields in the intracluster medium. Moreover, these simulations helped with the interpretation of observations and, hence, to ultimately provide a better understanding of our Universe. In total, the simulations produced in this project contributed to a total of 14 scientific publications in various research journals.

The first research highlight of this project was the study of the polarized emission of radio relics [1]. In this work, the downstream cooling of cosmic-ray electrons has been included for the first time in the modeling of radio relics. Herewith, it could be shown that the topology of the polarized emission depends highly on the host environment of the relic.

With a second set of simulations obtained within this project, two long standing questions could be answered. First, it was shown that the shocks that produce radio relics are not able to accelerate the protons of the intracluster medium [2]. This finding could explain, why shock accelerated cosmic-ray protons have never been observed in the intracluster medium. Second, the problem of the “Mach number discrepancy” was solved [3]. The Mach number is a characteristic for the strength of the relic producing shock. There is a frequent discrepancy between the Mach number estimates from radio observations and X-ray observations. This project showed that this discrepancy occurs naturally and does not impose any problem for the underlying theoretical models.

New high resolution radio observations revealed that the surfaces of radio relics consist of threads and filaments, whose origin is still unknown. Within this project it was show, that these substructures are not produced via adiabatic compression [4]. Furthermore, a morphological analysis showed that these substructures are indeed three dimensional filaments seen in projection [5].

The radio relics simulated in this project significantly contributed to the interpretation of several observations. This included interpretation of the relics in the Toothbrush relic [6], and the relics observed in the galaxy clusters RXC J1314.4-2515 [7] , MACS J0717.5+3745 [8,9] and Abell 3667 [10]. Finally, these simulations were used to study the evolution of cosmic-rays in the intracluster medium [11,12] and shock acceleration in the filaments of the cosmic web [13,14].

Publications produced within this project:

[1] Polarization of radio relics in galaxy clusters
Wittor D., Hoeft M., Vazza F., Brüggen M., Domínguez-Fernández P., 2019, MNRAS, 490, 3987. doi:10.1093/mnras/stz2715

[2] Limiting the shock acceleration of cosmic ray protons in the ICM
Wittor D., Vazza F., Ryu D., Kang H., 2020, MNRAS, 495, L112. doi:10.1093/mnrasl/slaa066
On the Challenges of Cosmic-Ray Proton Shock Acceleration in the Intracluster Medium
Wittor D., 2021, NewA, 85, 101550. doi:10.1016/j.newast.2020.101550

[3] Exploring the spectral properties of radio relics - I: integrated spectral index and Mach number
Wittor D., Ettori S., Vazza F., Rajpurohit K., Hoeft M., Domínguez-Fernández P., 2021, MNRAS, 506, 396. doi:10.1093/mnras/stab1735

[4] Modelling the Energy Spectra of Radio Relics
Wittor D., Hoeft M., Brüggen M., 2021, Galaxies, 9, 4, doi:10.3390/galaxies9040111

[5] A morphological analysis of the substructures in radio relics
Wittor D., Brüggen M., Grete P., Rajpurohit K., 2023, arXiv, arXiv:2305.07046. doi:10.48550/arXiv.2305.07046

[6] New mysteries and challenges from the Toothbrush relic: wideband observations from 550 MHz to 8 GHz
Rajpurohit K., Hoeft M., Vazza F., Rudnick L., van Weeren R. J., Wittor D., Drabent A., et al., 2020, A&A, 636, A30. Doi:10.1051/0004-6361/201937139

[7] Particle re-acceleration and Faraday-complex structures in the RXC J1314.4-2515 galaxy cluster
Stuardi C., Bonafede A., Wittor D., Vazza F., Botteon A., Locatelli N., Dallacasa D., et al., 2019, MNRAS, 489, 3905. doi:10.1093/mnras/stz2408

[8] Understanding the radio relic emission in the galaxy cluster MACS J0717.5+3745: Spectral analysis
Rajpurohit K., Wittor D., van Weeren R. J., Vazza F., Hoeft M., Rudnick L., Locatelli N., et al., 2021, A&A, 646, A56. Doi:10.1051/0004-6361/202039428

[9] Turbulent magnetic fields in the merging galaxy cluster MACS J0717.5+3745
Rajpurohit K., Hoeft M., Wittor D., van Weeren R. J., Vazza F., Rudnick L., Rajpurohit S., et al., 2022, A&A, 657, A2. Doi:10.1051/0004-6361/202142340

[10] MeerKAT view of the diffuse radio sources in Abell 3667 and their interactions with the thermal plasma
de Gasperin F., Rudnick L., Finoguenov A., Wittor D., Akamatsu H., Brüggen 14M., Chibueze J. O., et al., 2022, A&A, 659, A146. doi:10.1051/0004-6361/202142658

[11] Ultra-steep-spectrum Radio ”Jellyfish” Uncovered in A2877
Hodgson T., Bartalucci I., Johnston-Hollitt M., McKinley B., Vazza F., Wittor D., 2021, ApJ, 909, 198. doi:10.3847/1538-4357/abe384

[12] Simulating the transport of relativistic electrons and magnetic fields injected by radio galaxies in the intracluster medium
Vazza F., Wittor D., Brunetti G., Brüggen M., 2021, A&A, 653, A23. Doi:10.1051/0004-6361/202140513

[13] Shock waves in the magnetized cosmic web: the role of obliquity and cosmic-ray acceleration
Banfi S., Vazza F., Wittor D., 2020, MNRAS, 496, 3648. doi:10.1093/mnras/staa1810

[14] Polarized accretion shocks from the cosmic web
Vernstrom T., West J., Vazza F., Wittor D., Riseley C. J., Heald G., 2023, SciA, 9, eade7233. doi:10.1126/sciadv.ade7233

Other References:

[A] Bryan, G. L., Norman, M. L., O’Shea, B. W., et al. 2014, ApJS, 211, 19
[B] Wittor, D., Vazza, F., & Brüggen, M. 2017, MNRAS, 464, 4448

Caption figure1.png

The figure shows a 3D rendering if the cosmic web. Filaments of matter permeate the space. Empty regions between the filaments are called cosmic voids. Galaxy clusters are located at the intersection of the filaments, e.g. bright central region. Galaxy clusters host a variety of fascinating physical phenomena.

Caption figure2.png

The figure shows the rendering of a simulated radio relic. Radio relics are produced by cosmic-ray electrons that have been shock accelerated to the high energies. To connect the observations to the underlying theory, simulations of radio relics are required. As the observations become more and more detailed, also the simulations have to model radio relics with more details.