Nadia Biava

PhD cycle: XXXIV
PhD tutor: Annalisa Bonafede

Study of new particle acceleration mechanisms in galaxy clusters through low frequency radio observations

Diffuse radio emission, not directly connected with single galaxies, has been observed in galaxy clusters, revealing the presence of cosmic rays and magnetic fields throughout the intracluster medium (ICM). If this emission is located at the cluster center it is classified as giant radio halo (H) or mini halo (MH). Giant radio halos are Mpc-size sources found in massive merging clusters, thought to be powered by re-acceleration of particles by turbulence injected in the ICM during major mergers. Mini halos are typically $\sim 0.1 - 0.5$ Mpc size sources often bounded by X-ray cold fronts, and are located in relaxed cool-core clusters, surrounding the powerful radio source associated with the brightest cluster galaxy. Their origin is still unclear. With the advent of the LOw Frequency ARay (LOFAR) new types of sources have been found, that have the characteristics of giant radio halos, but are located in cool-core clusters that host a central mini halo and show no signs of major mergers. Up to now, only four such cases are known in the literature: A2142, PSZ1G139.61+24, RX J1720.1+2638 and SPT-CL J2031-4037 (Venturi et al. 2017, Savini et al. 2018, 2019, Raja et al. 2020). These new type of sources, bridging the long-standing strict distinction between mini halos and giant radio halos, challenge our understanding of particle acceleration in the ICM. A possible explanation is that minor mergers – while not sufficiently energetic to disrupt the cool-core – could still trigger particle acceleration in the ICM on Mpc-scales (i.e. a giant radio halo), generating steep spectrum emission ($\alpha > 1.5$).

My PhD project consists in the study of a sample of cool-core clusters observed with LOFAR at 144 MHz, to test the occurrence of this hybrid sources and try to understand the processes that trigger the radio emission. The clusters have been selected based on their dynamical state, requiring they host a cool-core and show signs of dynamical interactions on scales larger than the core. Over the three years of my PhD I reduced and analyzed the LOFAR HBA (110 - 240 MHz) data of these sources. We confirmed the presence of a double component (MH+H) in the clusters PSZ1G139.61+24 and RX J1720.1+2638 and we discovered two other candidates: A1068 and MS 1455.0+2232. The radio emission in A1068 extends well beyond the cluster core on a scale of ~ 400 kpc and is not detected at higher frequencies suggesting it has a steep spectrum ($\alpha \geq 1.6$), while MS 1455.0+2232 presents two different components of radio emission, the central one confined inside the sloshing region, and the newly discovered one extending up to 540 kpc. We noticed that all these clusters present cold fronts, associated to the sloshing of the core. For the other clusters in the sample we derived upper limits to giant radio halo power. The results of our observations are summarized in an article almost ready to be submitted.

To increase our understanding on the origin of this type of emission and the physical processes involved, we need to measure the spectral properties of the diffuse emission. For this reason, I asked for LOFAR observations of interesting sources in the lower frequency range (LBA, 30-90 MHz). The source RX J1720.1+2638 was observed last year and I learned how to reduce these data during my period abroad at the Hamburg Observatory working with Prof. De Gasperin. Combining LOFAR LBA (54 MHz) and HBA data (144 MHz) we created a spectral index map of the source. We found a net difference in the spectral properties of the two components: the mini halo has a quite uniform spectral index of $\alpha \sim 1$, while the large-scale diffuse emission has an ultra-steep spectrum $\alpha \sim 3$. We also

compared radio properties with the X-ray surface brightness through point-to-point analysis, founding different trend for the two components. Therefore, the radio emission inside and outside the cluster core have a different nature. We argue that the large-scale diffuse emission is generated by particles re-acceleration after a minor merger, presenting radio-X-ray correlations similar to giant radio halos and excluding it is a remnant of a radio lobe for the absence of an X-ray cavity in correspondence of the radio emission. Our hypothesis is supported by the individuation of a group-scale substructure with optical spectroscopy performed by Owers et al. (2011), that may have perturbed the medium and produced the emission we observe in the radio band. While for the central mini halo we suggest that it could be generated by secondary electrons and positrons from hadronic interactions of relativistic nuclei with the dense cool-core gas, as an alternative to re-acceleration models previously hypothesized.

I have also studied in details the radio source at the center of the cluster MS 0735.6+7421. Although LOFAR data did not show any diffuse emission, this is a famous source deeply studied in the X-ray, but not in the radio band. X-ray observations revealed the presence of two giant cavities and a smaller pair of inner cavities. With LOFAR we found the giant X-ray cavities are perfectly filled by radio lobes, which are wider than in higher frequency detections, and we also found another radio lobe along the south part of the jet not associated to the inner cavities. Re-observing the X-ray data we noticed a depression in correspondence of this radio lobe, indicating the presence of a further phase of the AGN activity, intermediate to the two previously known. The radio lobes associated to the inner cavities instead cannot be reduced at the resolution achieved in our observations. However, this source has been observed with LOFAR international baselines, which allows to reach a sub-arcsecond resolution. It will be interesting in the future to analyze these data to improve the study of this source. By combining archival data with LOFAR data I was able to characterize the spectrum and reconstruct the duty-cycle of this powerful AGN. The source went into three different phases of jet activity interspersed with short periods of quiescence. The particles emitted by the central AGN are probable the seed electrons that are re-accelerated, and/or of the cosmic-ray protons that generate secondary electrons responsible of the origin of mini halos.

WORKSHOPS, CONFERENCES & MEETINGS

- 8 - 12 April 2019 - LAPP, Annecy, France - 3rd ASTERICS-OBELICS International School: "Advanced software programming for astrophysics and astroparticle physics"
- 13 - 24 May 2019 - Ecole de physique des Houches, Les Houches, France - "The multiple approaches to plasma physics from laboratory to astrophysics"
  Poster: "MS 0735.6+7421: new radio data"
- January - June 2019 - Weekly PhD seminars
  Presentation: "Pairing of supermassive black holes in galactic nuclei" (Master thesis work).
- 11 - 14 June 2019 - CNR, Bologna, Italy - The first Italian LOFAR School 2019
- 8 - 13 September 2019 - CNR, Bologna, Italy - X-ray Astronomy 2019: "Current Challenges and New Frontiers in the Next Decade"
- 16 - 18 December 2019 - Torino, Italy - LOFAR SKP meeting
  Presentation: "The cool-core cluster MS 0735.6+7421: Spectral study of the central AGN and cavities"

- January - June 2020 - Weekly PhD seminars
  Presentation: "The cool-core cluster MS 0735.6+7421. Spectral study of the central AGN and cavities".
- 23 - 25 November 2020 - Online Workshop - "Exploiting Archives for Radio Astronomy in the SKA-era"
- 1 - 4 December 2020 - Online Conference - "7th Annual Science At Low Frequencies (SALF) Conference"
- 9 March 2021 - Online Conference - "The LOFAR LBA mini-symposium"
  Presentation: "The ultra-steep diffuse emission observed in the cool-core cluster RXCJ 1720.1+2638 at low frequencies"
- 10 March 2021 - Hamburg Observatory group meeting
  Presentation: "Low frequency observations of a small sample of cool-core galaxy clusters: the case of RXJ 1720.1+2638"
- 15 - 19 March 2021 - Online Conference - "A precursor view of the SKA Sky"
  Poster: "Constraining AGN duty-cycle of the cluster MS 0735.6+7421 with LOFAR data"
- 27 April 2021 - Astrophysics talk
  Presentation: "First study of a small sample of cool-core galaxy clusters at low frequency"
- January - June 2021 - Weekly PhD seminars
  Presentation: "Low frequency observations of a small sample of cool-core galaxy clusters: the case of RXJ 1720.1+2638"
- 28 June - 2 July 2021 - Online Conference - "European Astronomical Society Annual Meeting"
  Poster: "First study of a small sample of cool-core galaxy clusters at low frequency"
- 4 - 8 October - Online Workshop - "The Third National Workshop on the SKA project"
  Presentation: "Ultra-steep diffuse emission outside the cluster core observed with LOFAR at 144 MHz in cool-core galaxy clusters"

INTERNAL COURSES

- 17 - 21 June 2019 - Bologna, Italy - "Statistics for Astrophysics"
- 27/3 - 22/7 2020 - "Virtual Seminar on Multimessenger Astronomy "
- 17 - 22/9 2020 - "Gaia: Great Advances In Astrophysics"
- 30/11 - 2/12 2020 - "The Interstellar Medium"
- 19 - 23 April 2021 - "Gamma Ray Bursts: from observations to physical properties"
- 5 - 14 May 2021 - "Writing, talking and presenting Science"

SEMINARS

- 29 January 2021 - Online seminar - " How to write a scientific paper"
- 5 February 2021 - Online seminar - "How to give a scientific presentation"

ISA LECTURES

- 7 May - "You have to be cool to go to Mars", Lecture by Steven John Swoap, Williams College, USA
- 12 November - "This Turbulent Turbulent World", Lecture by Alexandre Lazarian, University of Wisconsin, USA
- 19 November - "Rigour and aesthetics: Japanese traditional mathematics", Lecture by Emanuele Delucchi, University of Fribourg, Switzerland
- 19 January 2021 - "Extreme events: how to describe and predict them using mathematical theories" Lecture by Sandro Vaienti, University of Toulon, France
- 15 September 2021 - "The Biochemistry of Nickel: Il Buono, Il Brutto, Il Cattivo" Lecture by Michael J. Maroney, University of Massachusetts,USA

RESEARCH PERIOD ABROAD
September - December 2020 - Research collaboration at the Observatory of Hamburg with Prof. F. de Gasperin to work on data reduction and analysis of LOFAR LBA observations of the cool-core cluster RX J1720.1+2638.

PROPOSALS
Accepted:

- as PI - LOFAR, Cycle 12: "LBA observations of the weak halo in the cool-core cluster RXJ1720.1+2638"
- as PI - uGMRT, Cycle 39: "Follow up observations of extended radio mini halo: the case of A1068 & RX J1532.9+3021"
- as PI - VLA, Semester 2021A and 2021B: "Follow up observations of extended radio mini halo: A1068 & RX J1532.9+3021"
- as PI - uGMRT, Cycle 40: "Follow up observations of the weak halo in the cool-core cluster RX J1720.1+2638"
- as Col - uGMRT, Cycle 39: Rajpurohit et al. "Uncovering the origin of an under-luminous relic residing in the low-mass galaxy cluster CIZA J0649.3+1801"
- as Col - uGMRT, Cycle 39: Rajpurohit et al. "Follow up observation of the spectacular radio relic in A2256: spectral and curvature analysis"
- as Col - MeerKAT, Cycle 2: Riseley et al. "A Spectral Census of Mini-Haloes with MeerKAT"

- as Col - LOFAR, Cycle 16: Riseley et al. "A Spectral Census of Mini-Haloes with LOFAR and MeerKAT"

Submitted:

- as PI - LOFAR, Cycle 17: "Exploring the unexpected large-scale diffuse emission in relaxed clusters"

PUBBLICATIONS

- "Constraining the AGN duty cycle in the cool-core cluster MS 0735.6+7421 with LOFAR data" - Biava et al. 2021, published on A&A
- "The ultra-steep diffuse radio emission observed in the cool-core cluster RX J1720.1+2638 with LOFAR at 54 MHz" - Biava et al. 2021, published on MNRAS