PhD name: Luca Bruno
PhD Cycle: XXXV
Tutor: Gianfranco Brunetti (INAF-IRA), Daniele Dallacasa (UNIBO)
RESEARCH PROJECT: "Non-thermal phenomena in galaxy clusters: the LOFAR revolution"

The presence of relativistic particles and magnetic fields mixed with the thermal particles of the intra-cluster medium (ICM) is probed by diffuse synchrotron radio emission in form of radio halos and relics found in a fraction of galaxy clusters on Mpc-scales. While radio halos are centrally located and their radio surface brightness is spatially correlated with the X-ray distribution of the ICM, relics are peripheral and elongated. The origin of relics and halos is associated with shocks and turbulence, respectively, induced into the ICM by cluster mergers, which can re-accelerate particles and amplify magnetic fields. The study of diffuse cluster sources is fundamental to investigate the energy transfer mechanisms from cosmological (Mpc) to microscopic scales. Owing to the steep synchrotron spectra ($\alpha > 1$, $S \propto \nu^{-\alpha}$) of halos and relics, they are brighter at low frequencies; in this regime, the unprecedented sensitivity and resolution reached by LOFAR (Low Frequency Array) at 150 MHz are providing high advances on this field of research.
My PhD project aims to investigate the radio diffuse emission with new LOFAR data. As a member of the LOFAR *Survey Key Project* (SKP) collaboration, I have access to the data and pipelines. A summary of the activities carried out in 2020-2021 is reported below.

1. During my 1st year, I studied the high redshift ($z \sim 0.5$) and very steep spectrum ($\alpha = 1.5$) radio halo in MACS J1149 with multifrequency radio and X-ray data. We compared its radio emission with theoretical predictions to investigate its origin and found a correlation between the radio and X-ray surface brightness profiles. The paper describing this work was published in June 2021.
2. At the end of my 1st year, I was involved in a project aimed to exploit the 2nd Release of the LOFAR Two Meter Sky Survey (LOTSS-DR2), which covers 5600 deg^2 and includes ~ 300 galaxy clusters from the second Planck Sunyaev-Zeldovich catalogue (PSZ2); this is the largest sample of galaxy clusters observed in the radio band to date. As a preliminary work, I tested the imaging pipelines developed by the collaboration. In $\sim 40\%$ of the PSZ2-DR2 sample, no cluster-scale diffuse emission is detected. Obtaining upper limits is needed to understand if non-detections are intrinsic (i.e. the clusters are radio quiet) or extrinsic (due to instrumental and/or sensitivity limits). Previous works (e.g. Bonafede et al. 2017, George et al. 2021a) computed upper limits for Giant Metre-wave Radio Telescope (GMRT) observations; thanks to the sensitivity reached by LOFAR, still deeper limits can be obtained for ~ 100 non-detections in the PSZ2-DR2 sample. To this aim, I developed a python-based code which models mock radio halos by means of the "injection" technique, and re-images the simulated+real data. By injecting mock halos of different flux densities and angular sizes, we explored with unprecedented accuracy the imaging algorithms, and we investigated the flux density losses associated with the uv-coverage due to missing short baselines (which are those that sample the extended emission). With the images and the azimuthally-averaged profiles of our mock halos, we determined the fraction of recovered flux density, and found that losses due to the uv-coverage are negligible for LOFAR (at least for targets with angular scales $< 20'$). By combining ~ 40 injections on 10 clusters, we found that limits are functions of the injected diameter, beam, and rms of the maps; therefore, we fitted a correlation that allows us to calculate upper limits for all the objects in our sample, without performing additional and computer time-consuming simulations. I will describe this work in a paper, and our upper limits will be used by collaborators in their papers which exploit the LOTSS-DR2 clusters and their statistical analysis (we plan to submit them by the end of 2021 / beginning of 2022).
3. At present, I am spending 3 months (15 July – 15 October) at Leiden Observatory through the "Marco Polo" grant, under the supervision of R. van Weeren, H. Rottgering, and T. Shimwell. Here I learnt the reduction of uncalibrated LOFAR data, by using deep observations of the galaxy cluster A2142. A2142 is known to host a radio halo with two different morphological and spectroscopical components. We combined our deep LOFAR data with multifrequency radio, X-ray, and optical data. Our analysis is an advanced stage; in particular we detected a third, likely very steep ($\alpha > 1.5$) component on larger scales, that is visible only in the LOFAR images. The paper describing

our results is in preparation. In addition, we submitted a LOFAR proposal to investigate the diffuse emission in A2142 with deep ultra-low frequency (50 MHz) data.
4. In my last month in Leiden, we are making experiments with the stacking of radio data (both in the uv- and image- planes). We aim to determine the best strategy to perform the stacking and obtain still deeper upper limits than those discussed above; this work will be finalized in Bologna.

WORKSHOPS, CONFERENCES & MEETINGS

- 23-25 November 2020, online workshop “Exploiting Archives for radio astronomy in the SKA-era”
- 8-11 March 2021, online conference “A new window on the radio emission from galaxies, clusters and cosmic web”
- Weekly PhD seminars (recurring; contribution with a talk on 27 January 2021)
- DIFA/INAF/OAS/IRA Astrophysics talks
- LOFAR (galaxy cluster working group) meetings (recurring; active contribution in discussion)
- LOFAR (Leiden Observatory working group) meetings (recurring; contribution with a talk on 28 September 2021)

PhD SCHOOLS

INTERNAL COURSES

- 30 November - 2 December 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”

ISA LECTURES

- 27 October 2020 “Scholarship and Arts: visual and intellectual encounters across the Mediterranean” (by A. Contadini)
- 26 January 2021 “RNA: Biological Functions and Therapeutic Potential” (by M. Marcia)

RESEARCH PERIOD ABROAD

- 15 July – 15 October 2021, research period at Leiden Observatory as part of the Marco Polo program (supervisors: Prof. H. Rottgering and Dr. R. J. van Weeren) to work on diffuse radio emission

COMPETITIVE TELESCOPE/COMPUTER TIME ALLOCATIONS

- Obtained 2 nodes of the LOFAR-IT infrastructure for the CPU-intensive data analysis of large samples of LOFAR data.
- Obtained 11 hours observations with uGMRT (India) as part of the proposal “Multifrequency uGMRT observations of the X-shaped radio galaxy in Abell 3670” (PI: L. Bruno, proposal code: 40_050)
- Requested 23 hours observations with uGMRT (India) as part of the proposal “Probing the spectral properties of the X-shaped radio galaxy in Abell 3670” (PI: L. Bruno, proposal code: 41_020, under evaluation)

- Requested 12 hours observations with uGMRT (India) as part of the proposal “LEDA 71322: the interaction between radio tails and gas motions in the ICM” (PI: X. Zhang, Co-I: L. Bruno, proposal code: 41_035, under evaluation)
- Requested 48 hours observations with LOFAR LBA as part of the proposal “The legacy survey of Abell 2142 and Corona Borealis superclusters” (PI: L. Bruno, proposal code: LC17_012, under evaluation)

OTHER RELEVANT ACTIVITIES

- 21 September - 2 October 2020 - Tutor for the VLA module (Prof. M. Gitti) of the Astrophysics Laboratory course (Prof. C. Vignali) of the Two Year Master in Astrophysics and Cosmology at UniBo

PUBLICATIONS

- 19 November 2019, Bruno et al., A&A: “Multifrequency JVLA observations of the X-shaped radio galaxy in Abell 3670” (*https://doi.org/10.1051/0004-6361/201936240*)
- 4 June 2021, Bruno et al., A&A: “The LOFAR and JVLA view of the distant steep spectrum radio halo in MACS J1149.5+2223” (*https://doi.org/10.1051/0004-6361/202039877)*
- Bruno et al. in preparation: “The curious case of Abell 2142: deep LOFAR observations of its multi-component radio halo”
- Bruno et al. in preparation: “LOTSS-DR2: Upper limits on diffuse radio emission in PSZ2 galaxy clusters”