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Editorial

New Window on the Radio Emission from Galaxies, Clusters and Cosmic Web—Conference Summary

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Abstract: This manuscript summarizes the contributions presented and discussed during the conference "A new window on radio galaxies, clusters and cosmic web: current status and new challenges". The meeting was held online in March 2021. The works presented during the conference have been published in this associated Special Issue. Here, we outline the scientific context of the published results.

Keywords: editorials notice; radio continuum: general; radio lines: general; large-scale-structure of universe; galaxies: clusters: general; galaxies: general; methods: numerical; methods: observational

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1. Introduction

Radio waves propagating in the Universe from the extra-galactic sky witness the presence of a synchrotron interaction between magnetic fields and relativistic particles on several scales: from stars to planets, from galaxies to clusters of galaxies, up to the largest scale structure, namely the cosmic web.

Considering large-scales object, i.e., galaxies, clusters and the cosmic web, it is well known that relativistic particles and magnetic fields can play a key role in a number of phenomena. For example, they can influence the star formation of galaxies and give rise to diffuse cluster sources such as radio relics and halos. A detailed view on the radio emission from galaxies, clusters and the cosmic web, is therefore of paramount importance to have a complete picture of the physics taking place at such scales.

The current Square Kilometre Array (SKA) pathfinders and precursors are providing unprecedented image quality and fidelity, which are unveiling unexpected details. The present observational facilities together with state-of-the-art numerical simulations are therefore opening a new window on radio galaxies, clusters and cosmic web. The breathtaking advances that we are now experiencing in this SKA era are shedding light on the mechanism at play at such intermediate and large scales. Moreover, they are also opening new challenges both on the technical and scientific sides, challenging our knowledge on the physics of this object.

The aim of this Special Issue and of the associated conference was to review our knowledge in this field of research, present the new challenges we are facing and discuss scientific prospects over the next decade in light of the capabilities of the SKA. Almost 200 researchers at different stages of their career, namely undergraduate students (3%), PhD students (26%), post docs (20%), researchers (28%) and professors (23%), and from different countries (spanning 10 of the Earth time zones) joined the conference. Around 50 of them presented a contributed talk and the majority submitted a contributed paper, which is published on this Special Issue.

The main topics of the conference have been the following:

- Large-scale structure of the Universe;
- Galaxy clusters, groups and diffuse emission;

- Interactions between galaxies and the surrounding medium;
- Radio galaxies;
- Large samples of radio sources.

In the next Section, we highlight some aspects of the works published in the Special Issue for each of the topics. We invite the reader to consult the manuscripts for further details.

2. Topics and Summary of the Works

2.1. Large-Scale Structure of the Universe

Cosmic magnetism is one of the science drivers of the SKA, and several collaborations are already taking advantage of the SKA pathfinder and precursors, such as LOw-Frequency ARray (LOFAR), Murchison Widefield Array (MWA), Jansky Very Large Array (JVLA), Australian SKA Pathfinder (ASKAP), MeerKAT and upgraded Giant Meterwave Radio Telescope (uGMRT), to investigate the origin of large-scale magnetic fields.

Franco Vazza the status of several lines of research attempting to detect the cosmic web at radio frequencies and the recent progress of the MAGCOW project, which investigates the radio signal of the cosmic web with advanced simulations. These efforts have been crucial to discard some magnetogenesis models, although only the deeper sensitivity at low frequencies that will be achieved in the near future with the SKA and LOFAR2.0, both in total intensity and polarization, will help us to better understand the origin of extra-galactic magnetism [1].

Etienne Bonnassieux showed some preliminary results of the Early Science of the New Extension in Nancay Upgrading LOFAR (NenuFAR) operating at $\sim$30 MHz. One of the targets of the Cosmic Filaments and Magnetism Pilot Survey is the Coma Cluster. This galaxy cluster hosts a radio halo, a radio relic and a bridge of emission connecting the two sources. NenuFAR detected the radio halo and radio relic, paving the way for the detection of large-scale emission, which is crucial to explore cosmic magnetism [2].

Viral Parekh drew the attention on the need for state-of-the-art data analysis procedures to provide deep and high dynamic range images, which are crucial to study the diffuse and faint radio emissions in supercluster environments. Concerning this topic, he showed the results obtained applying newer third-generation calibration techniques using CubiCal and killMS software on the MeerKAT observations of the Saraswati supercluster. This analysis advocates for the use of new calibration techniques to maximize the scientific return from new-generation telescopes [3].

2.2. Galaxy Clusters, Groups and Diffuse Emission

An increasing number of merging galaxy clusters show diffuse emission, which is traditionally classified as radio halo and radio relic, depending on several factors, such as their position with respect to the cluster center, their morphology, spectral properties and polarization. Such sources are powered by a relativistic particle population and magnetic fields embedded in the intracluster medium. The origin of this non-thermal component is still debated. During the conference, several aspects of the diffuse radio source were discussed considering what we are learning from recent observations and from numerical simulations.

A talk about galaxy groups, which represents an intermediate stage of the galaxy cluster formation, was presented too.

Denisha Pillay presented a study of the galaxy cluster ACT-CL J0019.6+0336, which hosts a radio halo. To study the cluster properties, XMM-Newton images, Dark Energy Survey (DES) imaging and photometry, Sloan Digital Sky Survey (SDSS) spectroscopic information and 1.16 GHz MeerKAT were combined. They found that this is a merging cluster possibly in a post-merging phase [4].

Valentina Vacca showed the results of a spectral index study of the galaxy cluster Abell 523, known to host a radio halo. The diffuse source is characterized by the presence of two filaments transversely located with respect to the cluster merger axis. Using JVLA observations at 1.410 and 1.782 GHz, they found a steepening of the spectral index of the filaments at frequencies $\geq$1.4 GHz and an indication that bright patches are characterized by flat spectral indices. Their results suggest a scenario of highly efficient turbulence induced by merger phenomena [5].

Sinenhlanhla Precious Sikhosana presented an overview of the uniformly selected and complete sample of 40 galaxy clusters selected via the Sunyaev-Zel'dovich (SZ) effect by the ACT project and its polarimetric extension (ACTPol). Targeted radio observations have been carried out with the uGMRT. They discuss the challenges they faced with the uGMRT data reduction and present a case study of ACT–CL J0034.4+0225. They confirm the detection of a radio halo in the galaxy cluster [6].

Simona Giacintucci presented VLA Low-band Ionosphere and Transient Experiment (VLITE) 338 MHz and GMRT 610 MHz observations of the galaxy cluster CL 0838+1948. The observed morphology and the spectral properties of the central galaxy suggest that this is a restarted radio galaxy. The outer emission is made by old plasma ejected no more than 110 Myr ago. Using archival Chandra X-ray data, they found that the active radio source is contained within the innermost and brightest X-ray region [7].

John ZuHone showed how AGN bubbles can generate radio relics in clusters with sloshing gas motions produced by a previous merger event. In a previous work, they simulated the launch of AGN jets into a cluster atmosphere with sloshing gas motions and determined that sloshing can transport the cosmic ray-enriched material of the AGN bubbles to large radii and stretch it in a tangential direction, producing a filamentary shape resembling a radio relic. By improving the physical description for the cosmic rays, the filamentary features diminish. Therefore, the modeling of cosmic ray physics in the intracluster medium strongly affects the appearance of a radio relic [8].

Denis Wittor presented cosmological simulations of radio relics that, for the first time, include adiabatic compression and expansion. Following the energy spectra of shock-accelerated cosmic-ray electrons using a Lagrangian tracer, they computed the temporal evolution of the energy spectrum. They found that the total radio power and the integrated radio spectrum are not sensitive to the adiabatic processes and explained their results as due to the small changes in the compression ratio over time [9].

Matthias Hoeft explored a toy model for the relic polarization to investigate if it could be the result of a tangential stretch of the magnetic field at the shock surface. They found that the fractional polarization is crucially affected by the magnetic field strength, which influences the decrease downstream, while the shock strength has little effect on the fractional polarization. Shock compression is a plausible scenario that can explain the radio relic polarization [10].

Aritra Basu investigated the lack of polarized emission from radio halos. Using high-resolution (1 kpc) magneto-hydro-dynamic simulations of fluctuation dynamos for varying scales of turbulent driving, they generated synthetic observations of the polarized emission and determined how beam smoothing can affect the inferred diffuse polarized emission. They suggested that observational estimates of, or constrains on, the mean fractional polarization at frequencies equal or larger than 4 GHz could give insight on the turbulent driving scale in the intracluster medium [11].

Błażej Nikiel-Wroczyński discussed the problem of poor knowledge of magnetic fields in galaxy groups. He presented recent low-frequency radio interferometer investigations and also listed the main issues that future observations need to address [12].

2.3. Interactions between Galaxies and the Surrounding Medium

Cluster galaxies have been proven to be able to affect and be affected by the intracluster medium filling the volume between such objects. The following works investigate these aspects.

Quirino D'Amato presented a spectral energy distribution analysis in the optical/infrared band of the host galaxy of a proto-BCG (NVSS J103023+052426) in a proto-cluster at z = 1.7. They showed that this object is a rare example of a proto-BCG caught during the short phase of its major stellar mass assembly. The host galaxy emission at 3.3 mm suggests that it originates from the cold dust in the interstellar medium, even though a minor non-thermal AGN contribution cannot be completely ruled out. Polarization at 1.4 GHz indicates an interaction with the intracluster medium: the proto-BCG heats the surrounding medium and possibly enhances the SFR in nearby galaxies [13].

Ancla Müller summarized the most recent results of the GASP collaboration, addressing the question of how stripped cold gas in cluster and jellyfish galaxies can survive long enough to form new stars outside the stellar disk. In particular, they focused on two textbook examples of jellyfish galaxies: J O206 and JW 100. Multi-wavelength observations from radio to X-ray and numerical simulations suggest that magnetic fields are the key ingredient to form stars in the tails [14].

2.4. Radio Galaxies

The current observational facilities are providing unprecedented details concerning the morphology, polarization and spectral properties of radio galaxies. Several works during the conference outlined recent results, showing the potential of the SKA pathfinders and precursors.

Lawrence Rudnick presented a technique called polarization tomography for the analysis of polarized emission from radio sources. This technique can reveal new features that are not accessible with the standard analysis methods. They showed the results of the polarization tomography on Cygnus A [15].

Lawrence Rudnick addressed the problem of finding a new classification method that can include the overwhelming complexity of radio sources, which is emerging thanks to current radio telescopes. He suggested an innovative way to classify the radio sources, which consists of assigning them #tags reflecting their main properties [16].

Ray Norris discussed Odd Radio Circles (ORCs), unexpected faint circles of diffuse radio emission discovered in recent wide deep radio surveys. In particular, they studied the properties and environments of the known ORCs [17].

Dharam Lal presented a study of a sample of 14 radio galaxies classified as FRI, FRII or FR0 conducted with the uGMRT and MeerKAT. The unprecedented sensitivity and resolution of such radio telescopes showed new morphological features, such as filamentary structures, misalignment and radio emission beyond the hot-spots in three sources [18].

Lawrence Rudnick investigated the presence of "rib" and "tethers" structures of a radio galaxy in Abell 3266 observed as part of the MeerKAT Galaxy Cluster Legacy Survey. "Ribs" are quasi-periodic bright patches observed along the tail that connect to never-seen-before thin transverse extensions, while "tethers" are filamentary connections between the part of the tail far from the host and a triple source found at a distance of $\sim$400 kpc from the host galaxy [19].

Raffaella Morganti summarized recent results on the study of the radio galaxy duty cycles conducted with LOFAR 150 MHz and Apertif 1400 MHz data. They quantified the duration of the 'on' (active) and 'off' (dying) phases in the radio galaxies, comparing the results with evolution models [20].

Nika Jurlin used the Wide-field Infrared Survey Explorer, SDSS photometry and SDSS spectra to study the optical properties in a sample of the remnant, candidate restarted and active radio galaxies selected using the LOFAR 150 MHz data in the Lockman Hole extragalactic field. They found that the radio and emission-line AGN activity appears to be independent and regulated by different mechanisms. The life cycle of the radio may depend on intrinsic reasons [21].

Veeresh Singh presented a systematic search of remnant radio galaxy candidates of small angular sizes ($<$30 arcsec) in the XMM–LSS field. They discovered a new population of small-sized ($<$200 kpc) remnant candidates that are often found to reside in less dense environments and at higher redshifts ($z > 1.0$) [22].

Nadeem Oozeer showed three potential dying radio sources identified in the MeerKAT Galaxy Cluster Legacy Survey (MGCLS): MKT J072851.2-752743, MKT J001940.4-654722 and ACO 548B. They determined the ages, magnetic fields and radio power of the sources. In particular, ACO 548B was previously classified as two peripheral relic radio sources, while this study showed that it is a dying radio galaxy [23].

Heinz Andernach presented the results of a visual inspection of images of the Rapid ASKAP Continuum Survey (RACS) in search of extended radio galaxies. They found 178 newly discovered giant radio sources with LLS > 1 Mpc, 18 of which exceed 2 Mpc, the largest one being 3.4 Mpc. They also investigated the properties of the host galaxies [24].

Eleni Vardoulaki explored the distortion of the radio structure of FR-type radio sources in the VLA-COSMOS Large Project at 3 GHz and relate it to the large-scale environment. They also compared the data to magneto-hydro-dynamical (MHD) adaptive-mesh simulations ENZO-MHD of two FR sources at z = 0.5 and z = 1. They found that the evolution of the ambient medium could be the dominant mechanism affecting the radio structures of FRs [25].

Ranieri Baldi presented the results from high-resolution observations carried out with the eMERLIN array and the European VLBI network (EVN) for a sample of 15 FR0s. Their study supports the scenario in which FR0s are characterized by mildly relativistic jets, possibly as a result of lower-spinning black holes (BHs) compared to the highly spinning BHs of relativistic-jetted radio galaxies, known as FRIs [26].

Kenda Knowles showed the results from a search for high-redshift radio galaxy (HzRG) candidates in the Abell 2751 field using 1.28 GHz data from the MGCLS. Using a 5σ signal-to-noise cut on the radio flux densities, they found a total of 274 HzRG candidates. This demonstrates that MGCLS data are suitable for searching for HzRG candidates in the Southern sky [27].

2.5. Large Samples of Radio Sources

Large-sample studies of radio sources are essential to understanding the physics of these objects. In the following, we summarize the contributions to the Special Issue in this field of research.

Gülay Gürkan presented a VLA snapshot survey that aimed at revealing the inner structures of jets in quasar candidates selected from the LOFAR Two-meter Sky Survey (LoTSS). In total, 15 out of 60 sources (25 per cent) showed clear inner jet structures suggestive of FRI jets, and 13 quasars ($\sim$22 per cent) showed extended structures similar to those of FRI jets. Their study showed that the occurrence of FRI jets in powerful radiatively efficient systems is not common, probably mainly due to two factors: galaxy environment and jet power [28].

Victoria Fawcett summarized recent works where they analyzed the radio properties of SDSS optically selected red quasars and presented new results obtained using four radio surveys: FIRST, VLA Stripe 82, VLA COSMOS 3 GHz and LoTSS DR1. They suggested that the observed radio emission properties of red quasars can be explained by small-scale synchrotron jets, frustrated jets or dusty winds interacting with the interstellar medium [29].

Rodrigo Carvajal presented a new machine learning model that can predict redshift values for WISE-detected AGN in the HETDEX Spring Field. Machine learning could be a very useful tool to determine precise redshift for large samples in an efficient way in terms of time [30].

Avinanda Chakraborty analyzed the properties of radio-loud (RL) and radio-quiet (RQ) quasars with MgII broad emission line (i-band magnitude $\leq$ 19.1 and z $\leq$ 1.9), selected from the parent sample of SDSS DR7 catalog. Focusing on a sample of sources with FWHMs greater than 15,000 km/s that presents a radio loud fraction (RLF) of $\sim$40%, they investigated several aspects such as the bolometric luminosity, optical continuum luminosity, black hole (BH) mass and Eddington ratios of RL and RQ quasars [31].

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Abbreviations

The following abbreviations are used in this manuscript:

ACT	Atacama Cosmology Telescope
AGN	Active Galactic Nucleus
ASKAP	Australian Square Kilometer Array Pathfinder
BCG	Brightest cluster galaxy
FR	Fanaroff-Riley
GASP	GAs Stripping Phenomena in galaxies with MUSE
GMRT	Giant Meterwave Radio Telescope
JVLA	Jansky Very Large Array
LOFAR	LOw-Frequency ARray
LoTSS	LOFAR Two-meter Sky Survey
MGCLS	MeerKAT Galaxy Cluster Legacy Survey
SDSS	Sloan Digital Sky Survey
SFR	star formation rate
uGMRT	upgraded Giant Meterwave Radio Telescope
VLA	Very Large Array

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