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Observations of the redshifted 21 cm line with the SKA and its pathfinders: from cosmology to cosmic reionization

Supervisor: Gianni Bernardi

When and how did the first stars and galaxies form? How did they grow and interact with the surrounding intergalactic medium (IGM)? How did they ionize it?

These remain paramount, open questions in modern cosmology. Observations of the cosmic microwave background and absorption spectra from distant quasars suggest that the intergalactic medium was reionized (after its recombination at $z \sim 1100$). Cosmological simulations suggest that the first stars appeared at $z \sim 30$-35, when baryons collapsed into the first dark matter halos. This epoch remains, however, largely unknown and models of galaxy formation and evolution are largely unconstrained, even in the "JWST era".

The 21 cm line emitted from neutral Hydrogen is one of the most promising probes of the high redshift universe, both of the Epoch of Reionization (EoR; when the intergalactic medium was ionized by the first luminous structures) and the Cosmic Dawn (CD; when the first stars and galaxies formed). After reionization, the 21 cm line remains a premiere cosmological probe, allowing to map the growth of structures through the intensity mapping technique and, ultimately, to measure baryonic acoustic oscillations and non-gaussianities in the $0.1 < z < 2$ range.

These goals are among the prime science cases of the Square Kilometre Array Observatory (SKAO; https://www.skao.int/en), the next generation radio interferometer (and the largest to be built), and, in the time frame of this PhD project, the SKAO will deliver its first science observations. SKAO pathfinder telescopes like HERA, uGMRT and MeerKAT have active observing programmes to study reionization and cosmology with the 21 cm line.

The goal of the PhD project is to analyze 21 cm observations taken with SKA pathfinder telescopes and initial SKAO observations in order to improve upper limits in the 21 cm signal (or detect it!), in particular:

- the student will work on HERA (https://reionization.org/) and uGMRT proprietary data with the aim to measure the evolution of the IGM neutral fraction and temperature in the $6 < z < 12$ range. In particular, the student with explore novel techniques to separate the 21 cm line from foregrounds using closure phase quantities and new 21 cm absorptions observations against high redshift sources;

- The student will also become part of the MeerKLASS collaboration (https://meerklass.org/) and use MeerKAT observations to measure the 21 cm signal in the $0.1 < z < 2$.

The student will use the first SKAO science data (expected to come in 2027-2028) to chase the Nobel-award science goal to detect the redshifted 21 cm line.

PhD project in ASTROPHYSICS

Title of the Project: Unveiling the origin of diffuse radio emission in galaxy clusters through MeerKAT and LOFAR observations

Supervisors: Dr. A. Botteon (INAF-IRA), Dr. M. Balboni (Università di Bologna & INAF-IASF Milano), Prof.ssa A. Bonafede (Università di Bologna & INAF-IRA), Dr.ssa R . Cassano (INAF-IRA)

Scientific Case:

Galaxy clusters are the most massive gravitationally bound structures in the Universe and form via a sequence of mergers of other clusters and groups across cosmic time. These processes generate turbulence and shocks in the intra-cluster medium (ICM), which release a large amount of energy that mainly enhances the cluster thermal bremsstrahlung emission in the X-rays, while a small fraction is channeled into the re-acceleration of relativistic particles. In the presence of μG magnetic fields, these particles produce non-thermal, Mpc-scale radio emission known as radio halos and relics (van Weeren+2019). A strong relation between thermal and non-thermal components in the ICM is therefore expected and can be investigated by combining radio and X-ray observations of clusters.

The details of the re-acceleration processes are not understood yet (e.g., Brunetti & Jones 2014). In the next years, the Square Kilometer Array (SKA) will provide a large amount of data that will enable detailed studies. At present, the SKA precursors and pathfinders (LOFAR 2.0 and MeerKAT) already have a great potential to pave the way in constraining particle acceleration mechanisms in the ICM. Surveys of the spatial distribution of radio spectral properties across halos and relics, as well as searches for steep-spectrum radio halos, would provide additional tests for the turbulent and shock re-acceleration models. To date, however, no systematic studies of spectral index distributions in diffuse cluster radio sources have been carried out.

Outline of the Project:

The PhD candidate will investigate the properties of the diffuse radio emission of CHEX-MATE galaxy clusters, employing recently acquired data from the most powerful radio telescopes currently operating on Earth: LOFAR and MeerKAT. The availability of X-ray data from XMM-Newton will enable to relate the properties of the non-thermal emission with that of the thermal gas. In particular, this project leverages the CHEX-MATE sample to investigate two fundamental aspects of cluster physics:

- Interplay between thermal and non-thermal components: the PhD student will study the relation between thermal and non-thermal emission in galaxy clusters by comparing both integrated and spatially resolved quantities derived from X-ray and radio observations (e.g., Balboni+2024, 2025, Botteon+2024, van Weeren+2026). Relations between surface brightness and synchrotron spectral index or ICM temperature can vary depending on the microphysical processes involved, and those variations are reflected in model predictions. Statistically determining whether such relations exist is crucial to constrain parameters of particle acceleration models.
- Systematic spectral analysis and statistical properties of the diffuse radio emission: by leveraging the high quality of LOFAR and MeerKAT radio observations, the PhD student will produce robust measurements of the spectral index of radio halos and relics in a large cluster sample, characterized by many newly discovered sources (e.g. Balboni+2026). Results will be interpreted in the context of current particle acceleration models in the ICM, investigating for example the relationship between the spectral index of the diffuse radio emission and the cluster mass, redshift, and dynamical state (e.g. Cassano+2010, 2023).

The PhD student will be part of the CHEX-MATE and LOFAR collaborations and will be involved in international working groups specialized in radio and X-ray observations of galaxy clusters. In particular, a close collaboration with the INAF-IASF cluster group in Milan is foreseen for the X-ray data reduction and interpretation. Travels to visit collaborators in Europe and a period abroad are also planned.

PhD project in ASTROPHYSICS

Title:
Quenching in Fornax Cluster Galaxies Traced by Atomic Hydrogen

Supervisor: Viviana Casasola (INAF-IRA)
Co-supervisors: Francesco Calura (INAF-OAS), Francesca Pozzi (UniBo), Paolo Serra (INAF-OAC)

Star formation quenching and the processes that regulate it are crucial to understanding galaxy evolution. One key indicator of quenching is the decline in the availability of cold gas (both atomic and molecular), the raw material for star formation. In dense environments such as galaxy clusters, understanding the gas-star formation cycle requires considering a wide range of environmental processes that influence how star formation proceeds in cluster galaxies (e.g., starvation, tidal stripping, thermal evaporation, and gravitational interactions). These mechanisms primarily affect galaxy evolution by perturbing the total gas. Atomic hydrogen gas (HI) is usually the most massive and extended component of the interstellar medium (ISM), extending well beyond the galaxy stellar radius, making it an excellent tracer of the environmental influence on galaxies.

This PhD project aims to investigate quenching in Fornax cluster galaxies using HI observations from the MeerKAT Fornax Survey (MFS; Serra et al. 2023, A&A, 673, A146). With high angular resolution (~1 kpc), fine spectral resolution (1.4 km s^{-1}), and deep HI mass sensitivity (~6×10^5 $M_\odot$, 3σ over 50 km s^{-1}), MFS makes the Fornax cluster at 20 Mpc, the nearest low-mass galaxy cluster, an exceptional laboratory to study how environment shapes galaxy evolution. The project will exploit scaling relations between atomic gas content and other galaxy properties to trace galaxy quenching and quantify how environmental processes regulate star formation. The morphology and kinematics of the HI will be used as diagnostic tools to identify the nature of environmental interactions, providing additional constraints on the physical processes driving gas removal and redistribution. The analysis also benefits from multi-wavelength ancillary data covering galaxy properties such as stellar mass (VST), molecular gas (ALMA), and dust (Herschel), as well as star formation rate tracers (e.g., Hα imaging from VST, optical spectroscopy including MUSE, WISE IR data, UV observations). These datasets will be combined with HI to investigate how environmental processes affect the multi-phase ISM and the star formation efficiency within galaxy disks. The analysis will be performed as a function of galaxy stellar mass and cluster environment, comparing galaxies in the central regions with those in the infalling Fornax A group. This panchromatic study will provide a complete view of the baryonic cycle in a dense environment. Finally, the project will train the candidate for future SKA-era HI surveys at high resolution and sensitivity.

This project is carried out within a team of experts in galaxy evolution and the physics of the cold ISM, spanning observational and theoretical/numerical approaches. The team includes the PI of MFS, ensuring direct access to the data and strong scientific leadership.

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Observations of Fast Radio Bursts with the the SKA and its pathfinders: from neutron stars to cosmology

Supervisors: Gianni Bernardi, Maura Pilia

Fast Radio Bursts (FRBs) are bright (> 1 Jy @ 1.4 GHz), millisecond-long radio flashes whose origin is still largely unknown. They show the typical pulsar-like dispersion signal, where high frequencies arrive earlier than low frequencies, and this delay is proportional to the electron column density between the source and the observer - known as dispersion measure (DM). At the time of writing, ~1000 FRBs are known, a few tens of them are localized to a host galaxy and ~5% of them are repeating sources. As they trace the baryon content up z ~ 2 (the highest redshift FRB observed to date), they are promising cosmological probes.

In 2020, an FRB was observed from the Galactic magnetar SGR 1935+2154, providing evidence that magnetars may be the progenitor source of (a fraction of) FRBs. FRBs are, therefore, probes of extreme environments (extreme magnetic and gravitational fields, dense plasmas, stellar explosions) as well as the large scale structure of the Universe. The goal of the PhD project is indeed to study extreme astrophysical environments and cosmology with FRBs using the Square Kilometre Array Observatory (SKAO; https://www.skao.int/en) and its pathfinder telescopes. In particular the student will work on:

- the localization and redshift characterization of FRBs observed with the CHORD radio telescope (https://www.chord-observatory.ca/home). CHORD is a new radio interferometer under construction in Canada and the will have ~30 dishes by the end of 2026, with a few outrigger dishes that will provide thousand-kilometre baselines, allowing for a sub-arcsecond location of FRBs. Such precise localization will enable the identification of the host galaxies and, consequently, the FRB redshift. The student will work on analysis of CHORD data and constrain cosmological parameters using localized FRBs;
- A new FRB catalogue obtained from a blind FRB survey at 408 MHz with the Northern Cross radio telescope. The Northern Cross will have an 8000 square meter collecting area by the end of 2026 and will be one of the few, wide-area FRB observatories. The student will work on the catalogue definition and will search for the highest redshift FRBs;

The student will use the first SKAO science data (expected to come in 2027-2028) to study FRBs: given its arcsec angular resolution, extreme time resolution and large bandwidth, SKAO observations will instantaneously localize any FRB detected, allowing to both study them as a cosmological probes and as laboratories of extreme environments.

Title: The counterparts of high energy astrophysical neutrinos

IRA-INAF supervisor: Dr. Marcello Giroletti (marcello.giroletti@inaf.it)

Collaborators: Dr. Giulia Migliori, Dr. Monica Orienti (INAF-IRA), Dr. Giulia Illuminati (INFN)

Scientific context

Over the last few years, multi-messenger (MM) studies have blossomed thanks to the coming online of gravitational wave and neutrino detectors, and to the efforts to achieve coordinated synergies with electromagnetic facilities and theoretical works. In the field of high energy neutrinos, this is opening the way to a revolution in understanding acceleration mechanisms in astrophysical sources, especially considering that neutrino emission is a direct proof of the presence of hadronic processes. As they are neutral particles, neutrinos are not affected by local nor large scale magnetic fields, and therefore travel unaffected across cosmic distances. Their weakly interacting nature requires the deployment of large and technologically advanced systems to detect them, and their direction of origin has so far remained characterised with limited precision, giving rise to a significant debate about the nature of their astrophysical counterparts.

In this context, our group has secured observing time with some of the premiere instruments in radio astronomy, with the goals of: (1) searching for the most promising counterparts of individual neutrino detections of astrophysical origin; (2) characterizing the physical properties of candidate counterparts from various populations. Taken together, these are essential steps to achieve a better understanding of the origin of astrophysical neutrinos, shedding light on the above mentioned ongoing debate.

Project outline

In the PhD Thesis project, the candidate will start with familiarising with the astrophysical background on neutrino emission, the existing detectors (IceCube and KM3NeT), the candidate counterparts, and the radio interferometry technique that is used for the follow up observations. In the rest of the first year, data analysis for recently acquired data will be carried out, with the goal of studying the physical properties of candidates of particular interest.

In the second year, when the KM3NeT real-time system will be active, the candidate will work on the direct search for new counterparts, especially thanks to data from MeerKAT (the precursor of the SKAO), obtained in the context of an approved triggered multi-epoch proposal (PI Giroletti).

Lastly, depending on the outcome of the work in the first two years, the third year will be devoted to the in-depth study of the most outstanding events, or on a population based statistical analysis, also considering multi-wavelength information, e.g. from the gamma-ray telescope Fermi or from CTAO.

During the activity, visits to top European institutions in the field of radio astronomy or neutrino detection will be offered to the candidate.

PhD Project: The role of jet redirection in jetted subgalactic-size radio sources

IRA-INAF supervisor: Dr. Carlo Stanghellini

Scientific context

Jetted subgalactic-size (JSS) radio sources are radio-loud AGN whose active radio emission remains confined within the host galaxy. Their physical nature and evolutionary path are still not fully understood. In the standard framework, they are interpreted as young radio sources that will eventually evolve into large-scale radio galaxies. However, their observed number is too high to be explained by a simple youth scenario alone, indicating that a substantial fraction of them may follow a different path.

At present, the short-lived scenario is generally regarded as the most plausible explanation for this overabundance, suggesting that many JSS radio sources undergo an early interruption of their activity and therefore remain compact. At the same time, growing observational evidence suggests that this may not be the only mechanism at work. In particular, some sources may remain compact because the jet changes direction on relatively short timescales, owing to rapid precession or orbital motion in interacting or merging systems. In this jet-redirection scenario, the jet energy is distributed over a wider region, reducing the efficiency of sustained growth along a single direction.

Recent VLBI observations have revealed complex morphologies and kinematics in several compact radio sources, including S-shaped structures, low-surface-brightness lateral emission, and possible non-radial motions of hot spots. The main goal of the proposed PhD project is to establish whether jet redirection is only a marginal effect or instead a statistically significant mechanism contributing to the compactness of a substantial fraction of JSS radio sources.

Project outline

The project will start with the definition of **a representative sample of JSS radio sources selected to allow a meaningful multi-epoch and multi-frequency VLBI analysis**. The first year will be devoted to the construction of the sample, the search for archival radio data, the analysis of proprietary data already available for selected sources, and the preparation of new observing proposals. These will include multi-epoch VLBI observations to monitor source expansion and possible transverse or translational motions of hot spots, as well as low-frequency VLBI observations aimed at detecting diffuse steep-spectrum emission from aged electron populations.

During the second year, archival, proprietary, and newly acquired radio data will be reduced and analysed in order to derive a consistent morphological, spectral, and kinematic description of the sample. In parallel, the host galaxies of the selected sources will be studied to assess whether JSS radio sources are preferentially associated with disturbed systems, merger signatures, or environmental conditions different from those of galaxies hosting extended radio sources.

In the third year, the observational results will be compared with theoretical models and numerical simulations for the evolution of compact radio sources, including jet-medium interaction and jet redirection caused by precession or orbital motion.

The final goal will be to assess the role of jet redirection in the evolution of JSS radio sources and, in particular, whether it contributes significantly to the compactness of a substantial fraction of the population.