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Observation of the Epoch of Reionization with the Square Kilometre Array and its precursors

Supervisors: Gianni Bernardi, Lauro Moscardini (Universita' di Bologna)

The study of when/how the first stars and galaxies formed, how they grew and interacted with the surrounding intergalactic medium and, ultimately, ionized it, is one of the 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 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 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). The Square Kilometre Array (SKA), in particular, is currently under construction and, once completed, it will be the largest radio interferometry ever built. One of its main goals is indeed the characterization of the EoR and CD through the observations of the 21 cm line from the intergalactic medium - a signal that still remains undetected so far. At the time of writing, the first four SKA stations have been deployed and successfully delivered the first sky image. In the next five years, the SKA is expected to deploy about 300 stations that will make it the most sensitive telescope to observe the EoR and CD.

The goal of the PhD project is to analyse SKA observations of the EoR/CD that will be taken in the next few years with the goal of detecting (or placing increasingly improving upper limits) on the 21 cm EoR/CD signal. This activity will be carried out within the SKA EoR/CD international science working group. In particular the goal can be summarized as follows:

- the student will work on the array calibration and foreground characterization. The candidate will test and develop calibration methods and foreground separation techniques that are essential to eventually detect the 21 cm signal, whose intensity is a few orders of magnitude larger than the Galactic and extragalactic foreground. As part of these activities, the student will have the chance to use SKA observations to place the most stringent upper limits on the CD signal, i.e. the 21 cm emission at $z > 15$. In 2018, Bowman et al. claimed the first detection of the 21 cm signal as a sky-averaged signal, with an anomalously high intensity that calls for non-standard physics in the 21 cm simulations. This result still requires independent confirmation and the SKA observations will provide the best sensitivity to confirm or reject such a claim;

- A relevant step to provide a convincing detection of the EoR/CD signal, will be to combine SKA observations with EoR probes at different wavelengths/taken with different instruments. The student will work to compute the cross correlation between SKA and HERA data (HERA is the most sensitive telescope to observe the 21 cm from the EoR/CD in the pre-SKA era, i.e. one of the SKA precursors, and has already delivered the best upper limits to date), between SKA data and MeerKAT observations of high-redshift molecular gas, and between SKA data and observations of VLT high redshift radio galaxies. Any of these cross-correlation probes will be essential to provide confidence on a potential EoR detection from the SKA and to study the formation and evolution of early galaxies.

Title of the Project: ***From Micro to Macro physics of FR0 radio galaxies***

Supervisor INAF-IRA: Dr. Ranieri D. Baldi

Collaborator: Dr. Marisa Brienza (INAF-IRA), Giulia Migliori (INAF-IRA), Alessandro Capetti (INAF-OATO)

Academic advisor: Prof. Marcella Brusa (DIFA)

Scientific Background

A key goal of modern astrophysics is to understand the formation and evolution of galaxies through the Universe. Accreting black holes (BHs) at the hearts of massive galaxies, i.e. Active Galactic Nuclei (AGN), are widely believed to be able to impact galaxy evolution by facilitating a global shut down or regulation of star formation (SF) (e.g. Fabian 2012; Heckman & Best 2014). Galaxy formation models require the injection of energy or momentum into the surrounding gas (via jet-mode or quasar-mode feedback), in order to reproduce key observables of galaxy populations (e.g. BH-bulge scaling relationships, luminosity function; e.g., Silk & Rees 1998; Hopkins+2006). In the local Universe, at z< 2, after the quasar activity peak, adult early-type galaxies are kept mostly quiescent through the continuous ejection of energy by AGN which accrete at low rates. In fact, the vast majority of such AGN channels their accretion power into compact jets expanding in the galaxy-scale interstellar medium (ISM). Such a population of low-luminosity AGN has been recently revealed with characteristics distinct from classical radio-loud jetted AGN (RLAGN). About 80% of local RLAGN (z<0.05), in fact, emanate pc-scale jets, termed FR0s, differing from classical extended FRI/FRII radio galaxies (Baldi 2023). This discovery reshapes our understanding of radio-loud AGN phenomenology, previously focused on large-scale jets (>100 kpc). FR0s outnumber FRIs by a factor of five, indicating they are the most common local RLAGN and provide a snapshot of the ordinary accretion-ejection process in local AGN. FR0s are linked to long-lived AGN activity and are fundamental to galaxy-BH co-evolution. Recent simulations suggest FR0s impact their host galaxies through jet-ISM interactions, altering SF efficiency and regulating gas cooling over long timescales (>10^7 yr). Deciphering their nature and their characteristics allow to better understand how AGN at low regimes are able to affect the the galaxy evolution.

Project Goals

In order to explore the FR0 origin and their role in the galaxy evolution, the PhD project will focus on different aspects of the AGN-galaxy symbiotic relation by analyzing data in radio, X-ray, optical and millimeter bands for a sample of FR0s in comparison with large-scale radio galaxies. The PhD project will involve the statistical analysis of a large sample of compact RLAGN (104 compact sources, z<0.05, Baldi+2018) to investigate the connection among accretion, ejection, large-scale environment and feedback in understanding the role of the FR0 phase into the evolution of RL AGN and ellipticals in the local Universe:

1. **Accretion:** Using eROSITA X-ray data to study accretion properties of FR0s and compare jet kinetic and bolometric luminosity with other classes of RLAGN;
2. **Environment:** Assessing how large-scale environments (cluster richness, dark-matter halo mass) derived from eROSITA data, influence AGN activity. FR0s are expected to be found in lower-density environments than FRIs, which may extend their active phase.
3. **Ejection:** Investigating jet launching mechanisms via LOFAR, VLA, and VLBI radio data. The role of BH spin and jet collimation will be explored.
4. **Feedback:** Probing FR0 jet-ISM interactions using archival ALMA and optical NTT data to study molecular and ionized gas kinematics and assess AGN-driven turbulence in host galaxies.
5. **High-redshift**: selecting and studying FR0s at high redshifts to explore the evolution of the RL AGN population from the quasar activity peak z~2 to the local Universe.

The PhD student will also be involved in international working groups, and travels to visit collaborators and conferences in Italy/Europe are planned.

What does it take to form a massive protocluster?

Supervisors: A. Giannetti (INAF-IRA), E. Vazquez-Semadeni (UNAM Morelia), L. Testi (UNIBO)

Project description:

Numerous examples of massive star-forming clumps, of sizes $L \sim 1$ pc and masses $M \sim 1000$ $M_\odot$, exist in the Milky Way. Yet, these objects lie at the high-mass extreme of the clump mass distribution, and the mechanism leading to their appearance remains unknown. Although evolutionary models of cloud and star formation (e.g., Zamora-Avilés et al. 2012, ApJ, 751, 77) predict that star-forming clouds increase their masses through accretion until they are finally dispersed by stellar feedback, the parameters determining how massive a region can form remain unclear. Numerical simulations of cloud formation and evolution from random compressions of the diffuse ISM starting from the mean ISM density at the Solar galactocentric distance tend to form relatively low-density clouds in which the mass and the SFR are distributed over regions significantly larger than the sizes of massive star-forming regions like the Orion nebula cluster (Jáquez-Domínguez et al, 2023, ApJ, 950, 88).

This project then proposes to perform and analyze a suite of numerical simulations at the scale of a few hundred parsecs varying the initial and boundary conditions, to determine the environmental requirements for the formation of regions that compare favorably to observations of massive star-forming clumps. This will involve the analysis of a few already-existing simulations, as well as the production of new simulations to complete a grid of models, in which a search for massive clumps can be performed, and their formation mechanisms can be identified.

Complementing the numerical simulations, this project will exploit the unprecedented resources of the SEDIGISM and OGHReS surveys (Schuller et al, 2017 AA, 601, 124; Schuller et al, 2021, MNRAS, 500, 3064; Colombo et al, 2021, AA, 655, L2; Urquhart et al, 2024, MNRAS, 528, 4746) in this context. These surveys represent the most complete, highest-resolution and sensitivity surveys of the Galactic plane currently available. Together, they provide the most detailed census of molecular gas in the Milky Way disk, spanning from the Central Molecular Zone to the outer reaches of the molecular disk. The wealth of data from SEDIGISM and OGHReS, particularly the detailed properties of identified molecular clouds and clumps, will serve as crucial observational benchmarks for our simulations. Therefore, beyond identifying the environmental conditions that lead to massive clump formation in simulations, we will be able to verify whether these conditions are actually observed in reality and lead to massive clumps in our own Galaxy, by comparing the simulation outputs with the observational data. This synergy between simulations and observations will provide a powerful approach to understand the formation of massive star-forming regions, which were also the cradle of formation of our solar system.

This project offers a complete research experience that will equip the candidate with extremely valuable skills essential for a successful career in astrophysics. These skills will include proficiency in conducting and analyzing complex numerical simulations, expertise in analyzing large observational datasets, and the critical ability to directly compare and integrate simulation results with observational findings. Furthermore, if the candidate is interested, the supervisory team includes experts in Artificial Intelligence who can introduce and integrate these advanced techniques into the project. This additional skillset would be highly beneficial in both academic and industrial research environments.

Title: Unveiling the physics of jets in X-ray binaries

Supervisor: Marcello Giroletti/Giulia Migliori (INAF IRA Bologna)
Collaborators: Francesco Carotenuto, Piergiorgio Casella (INAF OA Roma)

Black-hole X-ray binaries (BHXBs) are binary systems in which a stellar-mass black hole accretes matter from a low-mass companion star. These systems are the best laboratories for studying extreme gravitational fields. In recent years, it has been established that the dissipation of gravitational energy in the accretion process of BHXBs results in both radiation and collimated jets, carrying a large amount of kinetic energy, just as in active galactic nuclei (AGN). However, in AGN, because of the long dynamic timescales, we are limited in performing population statistics studies to understand the evolution of our observations. This is at variance with BHXBs, where the accretion rate varies on timescales accessible to our studies, ranging from years to fractions of a second. One of the most interesting aspects of these sources is the production of powerful discrete jet ejecta that propagate at apparent superluminal speeds far from the central BH. Covering the full trajectory of these jets allows us to model their dynamics with great accuracy and hence to measure their physical properties, while, at the same time, effectively using them as invaluable probes of the surrounding environment.
While these jets are historically difficult to detect, the MeerKAT radio-interferometer (a precursor of the Square Kilometre Array, SKA) is now revolutionizing the field with its exceptional sensitivity at GHz frequencies, covering the jet propagation up to parsec scales. At the same time, to identify the specific signatures of changes in the inner accretion flow associated with the launching of these jets, we require precise measurements of their initial proper motion, something that is only possible with very long baseline interferometry (VLBI). Targeted state-of-the-art VLBA observations have revealed the existence of a new, different type of discrete ejecta, launched close in time to the one tracked by MeerKAT up to parsec scales, but travelling at drastically slower speeds and showing far lower brightnesses.

The project will focus on the reduction and analysis of MeerKAT BHXB data taken as part of the X-KAT collaboration including new and archival observations with the presence of discrete jet ejecta, complemented by recent VLBA campaigns. The full propagation of both types of jets at large and small scales will be tracked, modelled with blast-wave dynamical models derived from the physics of gamma-ray bursts. These models will be improved by including the time evolution of the jet emission, which can give information on the jet magnetic field strength and the particle acceleration process.

The PhD student will have the opportunity to join the MeerKAT X-KAT collaboration and the SKAO science working groups for Transients and VLBI, to participate in schools for radio astronomy in Europe and Italy, and to carry out a period of activity in top European institutions such as JIVE-ERIC in the Netherlands for data reduction or Oxford University and CEA Saclay near Paris for studies of BHXBs jet physics.

The dark Universe: Expoiting Low Surface Brightness / dwarf galaxies to understand galaxy formation and evoltution

Proponents: I. Prandoni (IRA), R. Scaramella (OAR), Paola Dimauro (OAR) & the EDFS team

The study of dwarf galaxies and low surface brightness (LSB) galaxies is crucial for understanding the structure and evolution of the universe. These galaxies are among the most dark matter-dominated systems, providing key insights into the nature of dark matter and its role in galaxy formation. Additionally, because they are relatively undisturbed by interactions with larger galaxies, they offer a unique window into the processes that shaped the early universe. Studying their stellar populations, gas content, and dynamics helps refine cosmological models and improves our understanding of galaxy formation and evolution.

The study of this extreme population of galaxies, the smallest and the faintest, is undergoing a transformational epoch thanks to a new generation of instruments. In particular Euclid and Meerkat. The first data from Euclid have shown the capability of the instrument: 4 visits in the Perseus cluster gave of the order of 1000 candidates, doubling the known number (Marleau et al 2025a), while the single visit on the Euclid Deep Field North gave an average of ~200 candidates per square degree, some of which have known redshift, up to z ~0.1 (Marleau et al 2025b, submitted). As of today also the Euclid Deep Field South (EDFS), covering 23 sq deg has been similarly observed, therefore one expects to find there over 5,000 of such objects. In Autumn 2025 the number of available Euclid visits will increase to a ten, and in the following years will reach the final 40 visits. With such a depth and area coverage, the EDFS will become the premiere extra-galactic deep field in the Southern sky for such studies, allowing to characterise these objects. In particular the Euclid deep (optical and near-infrared) surface photometry, complemented by the ground-based multi-band imaging provided by the Rubin Telescope, will be instrumental in studying the stellar populations, structure, and morphology of these galaxies, as well as in revealing faint stellar structures, tidal features, and extended halos, which provide insights into past interactions and formation histories.

To complete the picture, however, it is necessary to obtain data on the neutral hydrogen (HI) content of these galaxies. In this way one will have information on the ongoing star formation via the bleuest stars, the past stellar hystory via the reddest star, and the star formation efficiency via the unprocessed baryons, i.e. the HI. Stellar and HI kinematics will also provide information on the dark matter distribution. The student will be in charge of the study of the radio properties of the dwarf and LSB galaxies in the EDFS, as selected from Euclid observations. He/she will analyse the radio continuum images and HI datacubes obtained as part of the MeerKAT pilot project (PI Prandoni). This survey covers the entire EDFS over a frequency range between 950 and 1670 MHz, hence matching well the volume needed for the dwarfs and LSB galaxy sample: it will be able to trace the HI 21cm line up to redshift 0.3, probing, over this redshift range, star formation rates (SFR) of 0.001-1 Msun/yr and HI masses of $\log10[M(HI)/M_{sun}]$ ~8 – 10. These are typical values for LSB galaxies and for compact and Irregular dwarfs.

The student will become part of the Euclid Consortium and will work in close collaboration with the EDFS team, which includes expertise on both Euclid and HI data analysis.

PhD project in ASTROPHYSICS
(one page)

Title of the Project:
"Solar Physics and Space Weather with the Medicina 32-m Radio Telescope: Development, Test and Scientific Exploitation of a Spectro-Polarimetric Imaging System for Solar Radio Astronomy"

INAF supervisors: Simona Righini (INAF-IRA), Alberto Paolo Pellizzoni (INAF-OAC)
UniBO supervisor: Prof. Daniele Dallacasa

Scientific Case:
In the framework of the SunDish Project, a national program devoted to single-dish solar imaging with INAF Radio Telescopes, we propose a challenging Ph.D. program involving technological developments and science exploitation within an innovative and multi-disciplinary approach to Solar Physics applications. The SunDish project is devoted to radio imaging and monitoring of the solar atmosphere at high radio frequencies (at present 18-26 GHz, up to 100 GHz in perspective) through single-dish observations with the Italian radio telescopes.
Mapping the brightness temperature of the solar atmosphere in the radio band allows to reveal plasma processes, mostly originating from free-free emission in the local thermodynamic equilibrium, providing a probe of physical conditions in a wide range of atmospheric layers.
In particular, long-term diachronic radio observations of the solar disk represent an effective tool to characterise the vertical structure and physical conditions of the solar chromosphere, both for quiet and active regions, during their evolution at different phases of the solar cycle. Within this context, the Medicina 32-m and SRT 64-m radio telescopes are increasingly assessing their role in the international solar science panorama.
After a first test campaign aimed at defining and optimising solar imaging requirements for the radio telescopes, the system is ready for systematic monitoring of the Sun to provide:

1. accurate measurement of the brightness temperature of the radio-quiet Sun component, which so far has been poorly explored in the 20-26 GHz range, representing a significant constraint for atmospheric models;
2. characterization of the flux density, spectral properties and long-term evolution of dynamical features (active regions, coronal holes, loop systems, streamers and the coronal plateau);
3. prediction of powerful flares through the detection of peculiar spectral variations in the active regions, as a promising forecasting probe for the Space Weather hazard network.

A fundamental step forward in the project development will be the implementation of spectro-polarimetric capabilities at the Medicina 32-m dish (with the installation of a back-end similar to the one already in use at the SRT), placing our radio telescopes among major international facilities devoted to high-frequency radio monitoring of the Sun, also in connection with the recently approved radio solar observatory in Antarctica (Solaris projects).

Outline of the Project:
The Ph.D. candidate will be part, through her/his involvement, in the following activities:

- test and validation of the solar observing modes adopting the spectro-polarimeters installed at the 32-m Medicina dish;
- execution of observations with the Medicina dish;
- development, test and optimisation of data analysis procedures;
- science exploitation of the acquired data (both using data from Medicina and SRT) in the framework of national and international collaborations/networks including both young enthusiastic researchers and affirmed experts in this field.

Website project SunDish: https://sites.google.com/inaf.it/sundish
Website project Solaris: https://sites.google.com/inaf.it/solaris

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[Cosmic canons: gravitational lensing in the time domain]

INAF-IRA supervisor: Dr. Cristiana Spingola (contact: cristiana.spingola@inaf.it)
UniBO supervisors: Prof. Daniele Dallacasa, Dr. Giulia Despali
Main collaborators: Dr. Marcello Giroletti (INAF-IRA); Dr. Anita Zanella (INAF-OAS); the VLBI/High-energy group at INAF-IRA; Strong lensing at High Angular Resolution Program group (SHARP group)

Scientific context

Dark energy and dark matter together make 95% of the Universe, but they are still poorly understood. Gravitational lensing is one of the most powerful tools for constraining the "dark Universe", as it can directly probe dark energy (via gravitational time delays) and dark matter (via low-mass lenses). Nevertheless, these fundamental cosmological studies using strong lenses are limited by the paucity of lensing systems known to date. **Finding novel and effective ways to identify strong lenses represents a new challenge that has to be addressed now**, when expensive missions with these goals (like Euclid, for instance) have started to release their data. **This PhD project will face this challenge by developing a novel method to potentially find hundreds of lenses in the time domain** (instead of survey images), using available monitoring programmes.

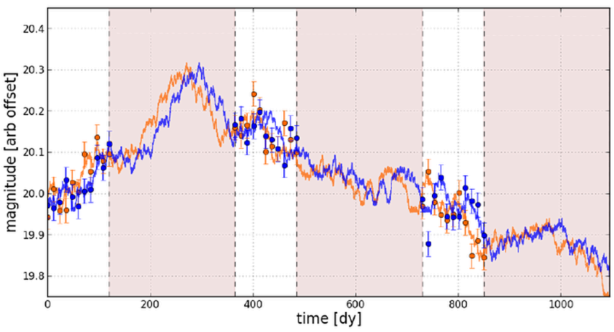
Outline of the project and scientific impact

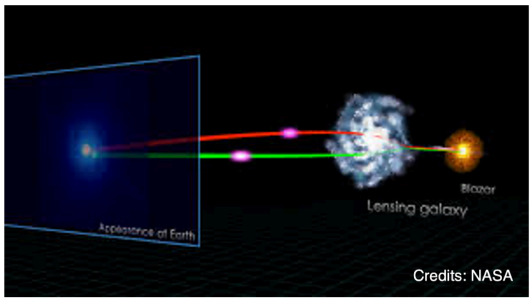
The PhD candidate will exploit the high-time-resolution Fermi-LAT all-sky survey to **discover low-mass lenses** ($M < 10^8 M_\odot$), which are currently missed by standard lens-search techniques. The abundance of low-mass lenses is **a key constraint to the nature of dark matter** (i.e., *cold* versus *warm* dark matter particle models). For these low-mass lensing systems the light curves of each lensed image will be spatially unresolved. Therefore, the candidate will apply the "unresolved light curve method" (Geiger and Schneider, 1996). This method relies on the so-called *autocorrelation function (ACF)*, which consists of finding the correlation of a signal with a delayed copy of itself as a function of delays (like a canon, in music). The best candidates will be followed-up for confirmation using multi-frequency radio observations at milliarcsecond angular resolution, which can directly reveal the lensed images. With this information in hand, it will be possible to constrain the slope of the sub-halo mass function, hence putting constraints on the warmth of the dark matter particle.

This is an ambitious project and it is possible that no new lens will be discovered. However, as a by-product, there will be a new sample of **binary SMBHs candidates** (same ACF method, different time scales). SMBHs binaries are the progenitors of the **loudest sources of gravitational waves in the nHz regime**, which will be detected by the future NASA/ESA mission LISA. Based on the results of the follow-ups, it will be possible to determine the occurrence of SMBH binaries at different redshifts, providing new insights into the **SMBH formation and evolution models** across the cosmic time.

Example of a simple canon

Illustration of the delayed flare (magenta) measured at gamma-rays in B0218+357





Example light curves for a simulated double lensed quasar.
The leading image is in orange, while the delayed image is in blue (Dobler et al. 2015)

Public engagement - During the PhD, if the candidate is interested, it could be possible to work on the *sonification* of gravitational time delays (observed and/or simulated, see Zanella et al. 2022), a project with the aim of developing new (inclusive) methods to perform research and reach a wider audience in terms of outreach (i.e., including people with visual impairment).

Useful readings and links: https://www.youtube.com/watch?v=hAH_0UhRnUo&t=10s ● Geiger & Schneider 1996 ● Shu et al. 2021 ● Bag et al. 2022 ● Cheung et al. 2014 ● Spingola 2023 (Cosmology & VLBI) ● Spingola 2023 (Binary SMBHs at high-z) ● Despali et al. 2025 ● Zanella et al. 2022 (Sonification and sound design for astronomy research, education and public engagement)