SPARCS X

Capturing Science from the Pathfinder Survey Data

(15-19th November 2021)

List of Presentation Abstracts

This document lists the abstracts of invited and contributed talks at the SPARCS X workshop. Abstracts are grouped by the theme of the session in which they are presented (see table of contents below) and then listed alphabetically by surname of the presenter.

Contents

Surveys

The Apertif Imaging Surveys

Betsey Adams

I will provide an update on the Apertif imaging surveys, including data releases.

V-LoTSS: The deepest and widest low-frequency circularly polarised survey

Joseph Callingham

One key question that astronomy is attempting to answer is whether there are habitable planets around stars other than our Sun. While we have entered an era where identifying nearby exoplanets has become standard, discerning whether the environmental conditions dictated by the host stars are suitable for life has proved far more elusive. The detection of low-frequency radio emission from an M dwarf or an exoplanet provides a direct probe of extrasolar space weather and the planet's magnetic field - information crucial for assessing the potential habitability of the planet. In this talk, I will outline our LOFAR survey of stellar systems, with a focus on our recent detection of strong, highly circularly polarised low-frequency radio emission associated with nearby stars - the expected signpost of star-exoplanet interactions. I will discuss how our survey represents the most comprehensive observations of stellar systems at low frequencies, and the implications of this new population in understanding the magnetosphere of M dwarfs and exoplanetary magnetic fields.

uGMRT and uGMRT continuum surveys
Ishwar Gupta

In this talk, we give an overview of upgraded GMRT (uGMRT). The GMRT was upgraded recently with instantaneous bandwidth upto 400 MHz. The upgrade has resulted in several fold increase in the sensitivity. With the improved sensitivity, the uGMRT is nicely placed between LOFAR and JVLA/MeerKAT. We present some early results from the wide area survey of legacy fields with the uGMRT.

Science updates from the GAMA 23 ASKAP survey
Gulay Gurkan

Deep wide-field radio surveys in conjunction with available multi-wavelength data open a range of new exploration windows to the Universe. A 60 sq degree southern region was observed with the Australian SKA Pathfinder (ASKAP) at 887.5 MHz as part of the early science programme of Evolutionary Map of the Universe (EMU), reaching 35 microJy/beam sensitivity and 10 arcsec resolution. The observed region has excellent legacy data sets: (i) optical spectroscopy up to $z \sim 0.4$ provided by the Galaxy And Mass Assembly (GAMA) project; (ii) photometric data from optical to mid- and far-infrared; (iii) photometric redshifts reaching distances beyond the spectroscopic limit. Cataloguing and source identification processes along with visual inspection provided $\sim$ 42000 radio sources detected at 5σ, of which 70% have optical counterparts. Initial investigation of the radio sources in the field has revealed new giant radio galaxies (GRGs). There are 37 GRGs with $z < 1.7$ (one of which is a giant double-double radio galaxy) with sizes going up to 2.7 Mpc. A number of these GRGs show linearly polarised emission. The sample of GRGs allows us to not only constrain AGN evolution but also enables us to study polarization properties and the magnetic fields associated with these rare objects. As part of ongoing studies of normal and active galactic nuclei (AGN), we exploited the GAMA spectroscopic data to investigate the link between jet and radiative feedback in radio-quiet AGN. The results confirm previous findings about a strong correlation between the radio luminosity and AGN outflows. I will present the radio survey along with the initial science results, which are the first steps towards the exciting science with ASKAP in the pre-SKA era.

The Rapid ASKAP Continuum Survey
Catherine Hale

Combining sensitivity, large field of view and angular resolution, the Australian SKA Pathfinder (ASKAP) is a revolutionary telescope for radio astronomy survey science in the lead up to the Square Kilometre Array (SKA). The Rapid ASKAP Continuum Survey (RACS) is one such large area survey from ASKAP which has recently released images and catalogues over the majority of the Southern Hemisphere to a northern most declination of +40 degrees. These observations involved using 903 individual pointings each observed for 15 minutes centred on 888 MHz. This is the first survey to be completed with ASKAP which covers such a large fraction of the sky and is typically deeper than surveys such as NVSS and SUMSS. In this talk I will present, on behalf of the RACS team, an overview of the RACS survey and the first Stokes I catalogue that we have produced from these observations. These observations will be of great use to the radio astronomy community and will only continue to be improved with future higher frequency observations, as well as the release of polarisation products. I will therefore continue to discuss both the initial science produced with observations from the RACS survey as well as the current status and future plans with RACS.

The VLA Frontier Fields Survey
Ian Heywood

The Frontier Fields campaign involves a 560 orbit Hubble Space Telescope observations of six massive galaxy clusters. The goal is to use deep imaging combined with the natural magnification of the clusters to study the faintest and most distant galaxies in the Universe. The HST observations are complemented by observations with numerous other instruments, and we present here 3 and 6 GHz Very Large Array observations of three of the clusters. The deepest observation reaches 0.7 uJy/beam RMS noise at an angular resolution of 0.7". We describe the survey, the unified optical/radio catalogue, and some initial results. We obtain some new, high resolution views of some diffuse relic and halo emission, and the detection of a source with a demagnified peak brightness of 0.9 uJy/beam, making it a candidate for the intrinsically faintest radio source ever detected. The VLA Frontier Fields project is a public legacy survey, and the images and catalogues are freely available.

The EMU Survey
Andrew Hopkins

The goals and current status of EMU will be presented. EMU aims to deliver the deepest and largest area radio continuum survey, covering the southern sky up to +30 deg declination, to an rms sensitivity of 15 microJy, at resolutions around 15 arcsec. EMU will measure around 40 million radio sources and produce the best radio continuum images of the Milky Way Galaxy and nearby galaxies including the Magellanic Clouds yet possible. EMU's scientific goals are broad, and encompass cosmology and fundamental physics, galaxy and large scale structure evolution, the astrophysics and evolution of AGN and star formation, to the properties of Galactic sources including pulsars. To date EMU has observed hundreds of square degrees of sky through ASKAP's Pilot surveys, delivering catalogues of hundreds of thousands of radio sources, supported the development of a sophisticated value-added data pipeline "EMUCAT", and led to more than 40 publications. The main survey is expected to start in early 2022.

The GaLactic and Extragalactic MWA All-Sky eXtended (GLEAM-X) Survey
Natasha Hurley-Walker

The Murchison Widefield Array (MWA) is a Square-Kilometer Array (SKA) path-finder instrument that is made up of 4096 individual dipole antennas arranged to form 256 tiles. Coupling its 'radio-quiet' location in rural Western Australia and its exceptionally large field-of-view (FoV), it is positioned well as an extremely efficient survey instrument operating at frequencies between 70 to 300MHz. As the successor to the GaLactic and Extragalactic All-sky MWA (GLEAM) survey, GLEAM-eXtended uses the Phase II extended configuration of the MWA to survey the low-frequency sky at twice the resolution and up to an order of magnitude higher sensitivity. In 2020 we completed our observing campaign, which is stretched across three years and $\sim 30,000$ individual observations, and covers the entire celestial sphere south of ~ 30 degrees. In this talk I will discuss first data release, covering 2,000 square degrees, down to an RMS noise level of < 1.5 mJy/beam in all Stokes parameters. We cover 72 — 231 MHz with 20 spectral channels, illuminating the low-frequency behaviour of over 150,000 radio sources and their complex spectral behaviour. By exploiting the exquisite lambda-squared coverage of these data, precise rotation-measures of polarised sources may be determined. Through creating the first data release we have learned valuable lessons on calibration, ionospheric behaviour, and source-finding. We plan a public release of this data toward the end of 2021, and the

full sky in years to come.

The MeerKAT Absorption Line Survey (MALS) : An Overview
Preshanth Jagannathan

The MeerKAT Absorption Line Survey (MALS) is a large project to blindly search for HI 21-cm and OH 18-cm absorption lines with the primary goal to better characterize the cold atomic and molecular gas in and around galaxies at $0 \leq z \leq 1.8$. The survey is well underway using the 32K channel mode of the correlator spanning both L (900-1670MHz)and UHF (580-1015MHz) bands. Due to the excellent sensitivity of the MeerKAT telescope and the large field of view of the telescope, the $\sim$ 500 pointings of the survey will also deliver an extremely competitive HI 21-cm emission line and deep radio continuum ($\sim$million sources) survey. I will highlight some exciting science results such as (1) the first detection of OH 18cm satellite lines at z = 0.89 of the well studied source PKS1830-211, and (2) the first detection of HI 21-cm emission from a low-z DLA, and synergies with various other multi-wavelength surveys. The excellent channel resolution and sensitivity across the wideband allows for fantastic modeling of in-band spectral indices and high resolution faraday synthesis but also poses unprecedented challenges related to the large data volume (1.5 PB raw visibilities), stringent requirements on polarization and direction-dependent calibration and imaging. I will elaborate on these challenges, the data processing plan and the first results from the survey.

The MIGHTEE Survey
Matt Jarvis

An overview of the MeerKAT International GHz Tiered Extragalactic Extrapolation survey

The VLA 10GHz Survey of GOODS-N: current status and plans for the data release
Eric Faustino Jiménez-Andrade

The "VLA 10GHz Survey of GOODS-N" is the first high-resolution (0.2 arcsec), high-frequency observational campaign to fully map an extragalactic deep field (rms=0.8μJy/beam). The overarching goal of this VLA Large Program is to better trace the star formation history of the Universe. Surveying the extragalactic sky at 10GHz has the advantage of yielding higher angular resolution imaging while probing thermal (free-free) radiation of high-redshift galaxies, which is more directly proportional to the rate of massive star formation. In this talk, I will present the ongoing efforts to calibrate and combine the full survey data. After describing the first results of the survey, I will describe plans for the public release of the final data products. Finally, I will discuss how the "VLA 10GHz Survey of GOODS-N" will serve as a pathfinder for future ngVLA observations to trace the sub-kpc scale distribution of star formation in high-redshift galaxies.

Continuum source catalog for the first Apertif data release
Alexander Kutkin

A new wide field radio continuum source catalog is important for many kinds of astrophysical studies. In this work we present one for the first data release of the Apertif imaging surveys. In order to recover a correct flux scale of the calibrated images we propose a method to determine the shapes of Apertif compound beams based on Gaussian process regression and NVSS catalog data. The method does not imply any a priori assumptions or parametrization, and can be used to probe the compound beam shapes for any given observation date. It allows us to perform the corresponding flux correction and

compile continuum source catalog which contains $\sim 250,000$ sources. We introduce the catalog and highlight some interesting scientific applications.

The VLA Sky Survey and science-ready data products
Mark Lacy

One of the challenges of radio interferometry is producing data products that astronomers in other wavebands can use easily, without them necessarily being experts in radio astronomy. At NRAO, we are currently working on implementing a Science Ready Data Products (SRDP) program with this aim in mind. One aspect of this program is the VLA Sky Survey (VLASS), a 2-4 GHz survey at 3-arcsec resolution (comparable to ground-based optical/IR data) over the whole sky above Dec. -40. Three epochs of sky coverage are planned, and we are now halfway through the second epoch of observations. Quick Look images are release 2-4 weeks after the observations to facilitate the rapid identification of transients. Higher quality images for each epoch (including linear Stokes information) and for all three epochs combined, are in the process of being designed and produced. In addition, for PI-driven VLA observations, SRDP is producing pipeline calibrations for standard continuum observations at high frequencies, and will shortly begin pipeline imaging. In this talk I will present some lessons learned from both VLASS and the broader SRDP effort, along with some early science results from VLASS.

A 325 MHz Survey of the Lockman Hole Field using the GMRT
Aishrila Mazumder

This work presents the findings from a 325 MHz survey of the Lockman Hole region using the GMRT, an SKA pathfinder telescope. The frequency used is of interest for studying astrophysics of radio selected sources, and also for foreground studies for sensitive radio observations. Additionally, the band covers an overlapping frequency range for both SKA1-Low and SKA1-Mid, thereby making it interesting to observe using pathfinders to provide insights for future sensitive observations using the SKA. It covers a field of view of $6^\circ \times 6^\circ$, with a sensitivity limit of 50 μJy beam^{-1}. Two point correlation function as well as source counts have been obtained for compact sources. The results agree with previous observations and also show some interesting deviations from the detailed semi-empirical SKADS simulation in the terms of the bias parameter and clustering length. This points towards the requirement for more low frequency observations to provide better constraints on underlying cosmology controlling the evolution of matter in the Universe, as well as for development of better models of the radio sky. Angular power spectrum has also been determined for the diffuse emission present in the region. The value of the power obtained lies between 1-100 mK2, which is very high compared to the expected strength of the cosmological 21-cm signal. This shows that even at locations far away from the galactic plane, diffuse synchrotron emission from the Galaxy pose a major hurdle for sensitive radio observations from the early Universe.

Latest results from the e-MERLIN/VLA e-MERGE deep radio survey of GOODS-N and e-MERLIN+EVN observations of AGN systems in the Northern SPARCS Reference Field
Tom Muxlow

The initial results of the e-MERGE deep radio survey of GOODS-N (Data Release-1 DR-1) have been made available to the consortium, and the survey description paper has been published. This release involves deep VLA imaging + 25% of the e-MERLIN L-Band data. The latest results from joint e-MERLIN+VLA 1.5GHz imaging are presented along with a short discussion of combination imaging with datasets with differing sensitivities,

and the suite of combination images chosen for optimum science extraction. Issues covered in the discussion will include the point-spread function (PSF) of such datasets in combination imaging – and the problems encountered in flux measurements when such PSFs are significantly non-Gaussian. (A fuller discussion non-Gaussian PSF issues encountered when imaging with core-dominated arrays will be given by Dr Jack Radcliffe). The e-MERGE results will demonstrate the ability of high-resolution low-frequency imaging to spatially resolve regions of radio emission associated with star-formation and differentiate such regions from those associated with active AGN-jet systems.

In addition, an update of the relaunched L-Band imaging mosaic programme from e-MERLIN on the Northern SPARCS reference field will be given, after the shutdown of e-MERLIN due to COVID-19. This coincides with the completion of an engineering project to install new notch filters on all e-MERLIN antennas to prevent receiver saturation issues associated with the introduction of 4G+ mobile bands which lie within the e-MERLIN L-Band frequency range. The original central element of the mosaic has also been observed with the EVN and imaging of a number of AGN systems within the field has been performed at varying angular resolutions to investigate the radio structures associated with such systems.

The LOFAR Two-metre Sky Survey

Timothy Shimwell

In the LOFAR Two-metre Sky Survey (LoTSS) second data release (DR2) we have imaged 27% of the northern sky at a resolution of 6" and median sensitivity of 0.083mJy/beam. From the 120-168MHz Stokes I continuum images we have catalogued 4,396,228 radio sources and we have detected over 2,000 and 100 sources in linear and circular polarisation respectively. The data release will more than double the number of known radio sources in the entire sky and thus represents a big step forward in the field. Presently LoTSS-DR2 is under review but once published over 200TB of data will be made publicly available including: Stokes I high (6") and low (20") continuum images; Stokes Q and U image cubes (20" and 4' resolution); Stokes V continuum images (20" resolution); and uv-data with corresponding ionospheric calibration solutions. In this talk I shall overview LoTSS-DR2 focusing on aspects such as the data processing procedures, the image quality and the scientific highlights/opportunities in various areas. I shall also discuss the future of LoTSS as we have now accumulated data covering $\sim 70\%$ of the northern sky and there are plenty of opportunities to exploit the many unique aspects of these datasets (e.g time, frequency, spatial resolution, sensitivity).

SPICE-RACS: Spectra and Polarization In Cutouts of Extragalactic sources from RACS

Alec Thomson

Despite the fundamental nature of cosmic magnetic fields, many questions remain regarding their origin, evolution, and structure. We are able to illuminate these otherwise invisible fields in a broad range of environments throughout the Universe via observations of background polarized radio sources. By measuring the Faraday rotation this polarized emission experiences along the line of sight, we are able to reconstruct the magneto-ionic structure of foreground features, such as the Milky Way Galaxy. This technique would also be applicable to foreground objects with smaller angular extent, such as galaxies and clusters, but we are typically limited by the on-sky density of background sources detected by a given radio survey. The Rapid ASKAP Continuum Survey (RACS) is the first all-sky survey undertaken by the Australian SKA Pathfinder (ASKAP). RACS is now the state-of-the-art survey of the Southern sky at these frequencies, with a typical

noise-level of 300µJy/beam, angular resolution of ∼15", and 2.1 million sources detected in total intensity at 888 MHz. Through a collaboration between the ASKAP Observatory and the Polarization Sky Survey of the Universe's Magnetism (POSSUM) survey team, SPICE-RACS will catalogue linearly polarized sources from RACS. SPICE-RACS will deliver a polarized source density 3-5x higher than the current state of the art, with Faraday rotation measures that are reliable and sufficiently precise to uncover weak magnetic fields and low-density ionized gas in diverse objects. I will present linearly polarized observations from the first data release of SPICE-RACS, covering $\sim$ 1000 square degrees towards the nearby Spica HII region. I will share both our preliminary polarisation catalogue and highlight a number of early science outcomes that will be yielded from these new observations.

A Pilot Fast Continuum Imaging Survey with ASKAP
Yuanming Wang

We developed a new technique (so called fast imaging pipeline) dedicated to deep fields observed by Australian Square Kilometre Array Pathfinder (ASKAP), e.g. GW S190814bv field or the Evolutionary Map of the Universe (EMU) survey, to search for radio transients and variables on image domain at shorter timescales (minutes to hours). We conducted a pilot survey on 40 deep fields from ASKAP archival data at a central frequency of 888 MHz, 943.5 MHz and 1367.5 MHz, with a typical rms sensitivity of $\sim 30\,\mu$Jy/beam. The total area of the pilot survey footprint is $\sim$ 1600 square degrees, revealed 34 highly variable and/or transient sources: 7 of them are known pulsars, including 3 millisecond pulsars; 7 of them are stars; and 19 of them are active galactic nuclei or associated with galaxies, including 6 extreme inra-hour variables. The remaining one has no multiwavelength counterparts and is yet to be identified. It has substantial polarisation properties, and more follow-up investigations are underway.

This is the first radio transients survey that covered a large sky area at minutes-to-hours timescales down to sub-mJy sensitivity level. The results presented here demonstrate pipeline's capability to detect transients once future ASKAP surveys such as full EMU (covering the entire sky $< +30$ deg in declination) begins operations — it will result in more findings on the poorly-explored parameter space.

The POlarised GLEAM-X Survey (POGS-X): First results
Xiang Zhang

Our understanding of the polarised Southern sky is still quite limited. In the past a few years, the POlarised GLEAM Survey (POGS) was carried out using MWA Phase I, leading to the detection of 517 sources with 200 MHz linearly-polarised flux densities above 10 mJy. In this talk, we introduce the upgraded POlarised GLEAM-X Survey (POGS-X), discussing the challenges in data reduction and presenting the first results. POGS-X is a blind survey using MWA Phase II continuum survey (GLEAM-X) data between 200-230 MHz. It covers the entire sky south of Dec +30, achieving an RMS of $\sim$ 1 mJy/beam and a resolution of 45 arcsec. In a pilot study covering 1200 square degrees, we detect 57 linearly polarised sources. We reveal some additional polarised structure of radio galaxy PKS J0636-2036, including a new polarised source close to its host. The Rotation Measure variance across the galaxy indicates Faraday complex components surrounding its host and southern lobe. We will also introduce the Stokes V detections, including known pulsars and potential circularly polarised emission from AGNs.

Tools, Methods and Pipelines

Cross-Identification for Radio Surveys using Ridgelines

Bonny Barkus

Cross-identification of radio sources with optical and infrared catalogues is essential for determining host properties and distances, leading to intrinsic properties such as luminosity and size; but it is also far from straight forward. For simple, compact or isolated sources this can be done in an automated fashion. However, for extended sources or those which contain multiple components this becomes more complicated and has more often been achieved through human classification. As surveys become larger and sources more numerous this method becomes less efficient. The LOFAR Two metre Sky Survey (LoTSS) is the largest radio survey to date in terms of numbers of sources and data volume and is sensitive to both compact and extended emission, making it ideal for the study of radio sources. Using the LoTSS data release 1, we have applied the innovative idea of ridgelines, tracing the path of a jet, to link radio sources to their host galaxies. It is important to be able to correctly catalogue source populations and retrieve their properties, in SKA pathfinder surveys, to enable accurate modelling.

In this talk I will introduce ridgelines in the context of extended radio sources, and how they have been successfully integrated into established methods for cross-identification. I will discuss the results from LoTSS DR1 demonstrating the effectiveness of the method with a sample of sources with known hosts. I will then discuss how this new statistical method can be applied to current and upcoming surveys in the form of LoTSS DR2, and the adaption to MeerKAT. This talk aims to demonstrate improvements in the cross-identification process which can be applied across surveys to reduce the time and resources spent on alternative methods, such as citizen science approaches; providing a thorough data set upon which to build precise models of the radio sky.

The MeerKAT toolbelt: a waist of data

Jordan Collier

A number of tools and systems have been developed or adopted to deal with the PB scale of MeerKAT data at the Inter-University Institute for Data Intensive Astronomy (IDIA), Cape Town. I will present a number of these tools and underlying systems, including those for storage, processing, visualisation, and data transfer. I will present a worked example of processing MeerKAT data via the IDIA pipeline, a fully automated end-to-end pipeline that is efficient, flexible, scalable, and user-friendly, and designed to operate across the ilifu cluster using SLURM and MPI. Our unique setup uses an IDIA cloud-based platform running on hardware provided by the ilifu national facility, taking advantage of cluster-level parallelism, resource management and software containers. Altogether this represents a pathfinder science regional data centre, and a good framework for solving many of the broader challenges of the SKA.

Stacking the presence of confusion

Eliab Malefahlo

The is a wealth of information from sources that are too faint to be individually detected. Various stacking techniques have been developed over the years to explore the information available below this detection threshold. We apply these techniques to the MIGHTEE field. However, given the depth of such fields, we had to adapt current algorithms to take into account the extra confusion of detected and undetected sources. Combined with a P(D) analysis, we obtain source counts, luminosity functions, from

which an estimate of the star-formation rate density of the universe can be determined.

EMUcat: The EMU Value-added Catalog
Joshua Marvil

This talk will review the design and developmental progress of the EMU Value-added Catalog (EMUcat). The primary aim of the EMUcat project is to digest the pipeline-processed data products from each ASKAP-EMU observation and prepare them for use by the EMU science teams and the broader community. The first stage of EMUcat processing is to consolidate the individual observations into a full-sensitivity, all-sky radio component catalog. The next stages group components together into physical sources of radio emission, and for extragalactic sources identify the host galaxy producing this emission. Further stages assemble a suite of multiwavelength photometry and other value-added information for each source, compute derived properties, and assign textual labels to aid in source selection and classification.

A novel vocabulary for the development of cross-identification techniques
Jelle Mes

There are multiple scientific drivers behind the large radio surveys of the current age. Most of these rely on the availability of optical/IR counterparts of the radio sources, which are obtained through the process of cross-identification (cross-ID). Large, extended radio sources which are relevant for our understanding of cluster formation and AGN feedback, are difficult to cross-ID reliably. New cross-ID methods therefore need to be developed. I will present an overview of recent advancements in cross-identification techniques as well as a foundation of concepts and performance metrics. By sharing this vocabulary, the field will be able to evaluate and compare different cross-ID techniques.

Source analysis services for the SKA and precursors
Simone Riggi

New developments in data processing and visualization are being made in preparation for upcoming radio astronomical surveys planned with the Square Kilometre Array (SKA) and its precursors. A major goal is enabling extraction of science information from the data in a mostly automated way, possibly exploiting the capabilities offered by modern computing infrastructures. In this context, the integration of source analysis algorithms into data visualization tools is expected to significantly improve and speed up the cataloguing process of large area surveys. To this aim, the CIRASA project was recently started to develop and integrate a set of existing and newly ML-based services for source extraction, classification and analysis into the ViaLactea visual analytic platform and knowledge base archive. In this contribution, we will present the project objectives and tools that have been developed, interfaced and deployed so far on the prototype European Open Science Cloud (EOSC) infrastructure provided by the H2020 NEANIAS project.

Technical and Calibration

Characterising the Apertif primary beam response

Helga Denes

Phased array feed (PAF) receivers are a new technology in radio astronomy that make it possible to conduct large-scale sky surveys in an efficient way. The Apertif instrument on the Westerbork Synthesis Radio Telescope (WSRT) can form 40 overlapping beams simultaneously on the sky, which increases the field of view of the telescope by a factor of ~ 40 and the survey speed by a factor of ~ 20. The new receiver also means that the primary beam response of the telescope has changed. Compound beams are formed digitally for each Apertif dish by applying beam weights to the signal coming from the 121 individual antenna elements in the receivers. New beam weights are measured at the start of each observing period, approximately every two weeks. Depending on the health of the system and on intermittent radio frequency interference (RFI), the shapes of the compound beams can slightly change. In radio astronomy it is important to understand the shape of the primary beam, or in this case the compound beams, of a telescope to be able to properly reconstruct the images and the fluxes of radio sources. For this reason, we measure the primary beam response of the individual Apertif compound beams with two independent methods: (i) comparing the measured radio continuum fluxes of point sources with other catalogues and reconstructing the beam shapes with a Gaussian regression method; and (ii) measuring the beam response with drift scans on a bright radio continuum source. Images of the Apertif compound beam shapes are one of the data products of the Apertif surveys and can be used in combination with Apertif continuum images and data cubes. In this talk I will discuss the results from the drift scan method. I will present how the beam shapes are derived, how the beam sizes change as a function of frequency, and how the beams change as a function of time.

Modelling Antenna Aperture Illuminations & Image Plane Leakage Corrections

Preshanth Jagannathan

We present the the A-to-Z solver methodology to model the full Jones antenna aperture illumination pattern (AIP) with Zernike polynomials. In order to achieve thermal noise limited imaging with modern radio interferometers, it is necessary to correct for the instrumental effects of the antenna primary beam (PB) as a function of time, frequency, and polarization. The wideband AW projection algorithm enables those corrections provided an accurate model of the AIP is available. We present the A-to-Z solver as a more versatile algorithm for the modeling of the AIP. It employs the orthonormal circular Zernike polynomial basis to model the measured full Jones AIP. These full Jones models are then used to reconstruct the full Mueller AIP repsonse of an antenna. I will show that with the full Mueller AIP response of an antenna we can correct for the off-axis Mueller elements in the image plane.

Third-generation calibration for MeerKAT observations

Viral Parekh

Next-generation radio telescopes have already started to provide path-breaking and novel scientific results. Recent developments in technology and software have played a significant role to provide deep and sensitive radio images. In this talk, we will show our deep radio images of galaxy clusters and superclusters observed with the MeerKAT radio telescope. In order to generate these high sensitive radio maps, we used simultaneous peeling and facet based, direction-dependent 3GC calibration software such as CubiCal

and killMS. Both these techniques have given high dynamic range images, which allow us to study faint and diffuse radio sources with great details. In particular, we will show the results of five mini halo clusters and one double radio relic cluster in the supercluster environment. We will also discuss how statistically these observations have been improved from 2GC to 3GC.

The challenges associated with the beams of interferometers - a warning to the SKA-era

Jack Radcliffe

There are two different beams present in any interferometric observation. These are the primary beam response and the point-spread-function (PSF) / dirty beam. We will be discussing each of these during this talk.

In the first part of the talk, we will discuss the PSF which describes the response of an instrument to a normalised point source. The PSF fitting algorithms assumes that the interferometric dirty beam is approximately Gaussian. This is well justified for arrays like the VLA and ALMA, but this assumption breaks down for interferometric arrays with uneven or sparse uv coverage (such as e-MERLIN, LOFAR-VLBI, MeerKAT and the forthcoming SKA) resulting in highly non-Gaussian, 'shouldered' PSFs. We show how the combined effects of non-Gaussian PSFs and a finite deconvolution depth conspire to significantly affect the recovered fluxes in a interferometric maps. Understanding and accounting for this effect will be of utmost importance for core-dominated arrays such as MeerKAT, LOFAR and the SKA otherwise systematic flux offsets will be present in all these data. We will present a re-weighting scheme which can alleviate this effect in the case of e-MERLIN with minimal sacrifice to the imaging sensitivity and resolution, as well as an outline of the means to arrive at such a weighting scheme for different arrays and antenna configurations.

In the second part, we will discuss the primary beams response of heterogeneous arrays and their influence on the image quality. Using simulated VLBI arrays, which are highly heterogeneous, we demonstrate that inadequate modelling and correction of these beams can have dire effects on the image quality and the achievable dynamic range. This is of utmost importance to SKA-mid who will combine two completely different antennae namely the 13.5m MeerKAT dishes and the 15m SKAO dishes. We present some correction schemes that can be applied to SKA and SKA-VLBI data which can alleviate these issues.

Polarization Calibration for MIGHTEE

Srikrishna Sekhar

MIGHTEE is a MeerKAT Large Survey Project (LSP) designed to study the microJy population of sources over a wide field of view. We discuss the details of MIGHTEE polarization calibration as implemented in the IDIA calibration pipeline, as well as our strategy to deal with off-axis polarization leakage via the AW projection algorithm. We achieve a high level of linear polarization accuracy and are also sensitive to circular polarization at the 0.1% level. We will present a few early science results from MIGHTEE-pol to demonstrate the efficacy of this approach.

Machine Learning

Using ensemble Machine Learning to predict high-redshift Radio Galaxy detections

Rodrigo Carvajal

The study of the centre of galaxies, and Active Galactic Nuclei in particular, is fundamental to comprehend the processes involved in the birth and overall evolution of Super-Massive Black Holes (SMBH) and their surroundings.

Recent observations have revealed the presence of SMBHs at very early epochs –redshift values greater than 6–. Simulations and models have projected that these objects might be detected in radio frequencies, despite the fact that their properties and processes they host are still quite unspecified.

It has been estimated that a large number of high-redshift AGN might be observed, but up to this moment, only around 300 AGN at redshift higher than 6 have been detected. And only a small fraction of them have radio detections. The lack of radio measurements might be due, in part, to the lack of sufficiently deep radio observations over a large fraction of the sky. Additionally, current AGN selection criteria require optical or NIR detections, which are difficult to obtain at the highest redshift values.

In view of the development and operation of future large-scale radio observatories (e.g., SKA) and their ongoing precursors (EMU, MIGHTEE, LoTSS), which will deliver very large data volumes, identifying high-redshift radio-powerful AGN poses a challenging task. The application of regular AGN detection and redshift determination techniques will become an inefficient task in terms of running time and computational resources. Critical attention has been drawn then to the development of Machine Learning (ML) methods and procedures to predict the detection of an AGN using previously available information.

In an attempt to tackle this issue, we have developed a series of ML models that, using multiwavelenght photometric data, can produce a list of high-redshift Radio Galaxy candidates, along with their predicted photometric redshift values.

We will present the results of training these models with data of the HETDEX Spring Field (~ 400 deg^2), which is covered by the LoTSS Survey, and applying them to photometric data on the Stripe 82 Field (~ 100 deg^2).

Detection of variable sources in the Northern SPARCS reference field with Machine Learning

Soumen Deb

As a pilot survey for the SPARCS Northern reference field (15:30, +29:00), the DRAO Synthesis Telescope has produced 47 pointings of 21-cm radio continuum maps covering altogether 8 square degrees. Thanks to the large field of view of the DRAO-ST, the observations, covering 4.5 years, include a large number of low-brightness (> 5 mJy) sources, which could be investigated for variability with timescales of the order of days up to years. The variability of such sources would otherwise be impossible to detect. In this work, we implement Statistical and Machine Learning algorithms for identifying those variable sources.

Discovery of new circular and peculiar radio sources with ASKAP using Machine Learning

Nikhel Gupta

The next generation of large and deep continuum radio surveys will produce a dramatically large number of radio source catalogs. In addition to the advancement in our

understanding of galaxy evolution, these will have a huge potential for new discoveries. To capture the full potential of these surveys comes the need to transform the data analysis and interpretation techniques. In recent years, machine learning (ML) has emerged as a powerful tool to model highly non-linear data. ML models for computer vision have shown a remarkable capability to accurately learn the differences between a set of images. In this talk, I will present a machine learning technique that is used to find the rarest radio sources in ASKAP surveys. I will present the newly discovered circular and peculiar systems in the Evolutionary Map of Universe pilot survey (EMU-PS), the Deep Investigation of Neutral Gas Origins survey (DINGO) and the Survey With ASKAP of GAMA-09 + X-ray (SWAG-X). A part of the talk will focus on the multiwavelength observations of these systems and the rest will be dedicated to other advancements in ML algorithms.

Anomaly Detection in Astronomical Data using Machine Learning
Michelle Lochner

The next generation of telescopes such as the SKA and the Rubin Observatory will produce enormous data sets, far too large for traditional analysis techniques. Machine learning has proven invaluable in handling large data volumes and automating many tasks traditionally done by human scientists. In this talk, I will discuss how machine learning for anomaly detection can help automate the process of locating unusual astronomical objects in large datasets thus enabling new cosmic discoveries. The developed framework, called Astronomaly, is publicly available and I will demonstrate it with some preliminary results on MeerKAT data.

Radio Galaxy Redshift Estimation using Machine Learning
Kieran Luken

Next generation radio telescopes are beginning to produce their first survey catalogues, increasing our knowledge of the radio sky. However, the vast majority of the newly discovered radio galaxies won't have a measured spectroscopic redshift, reducing the science possible from these new surveys. The samples from these surveys differ from conventional optically-selected samples in having a much higher median redshift, and containing a large fraction of active galactic nuclei. We will present our efforts to apply Machine Learning to the problem of estimating the redshift of this radio selected sample, providing a first look at the estimated redshifts for the EMU Pilot Survey.

DECORAS: detection and characterization of radio-astronomical sources using deep learning
Samira Rezaei

We present DECORAS, a deep learning based approach to detect both point and extended sources from Very Long Baseline Interferometry (VLBI) observations. Our approach is based on an encoder-decoder neural network architecture that uses a low number of convolutional layers to provide a scalable solution for source detection. In addition, DECORAS performs source characterization in terms of the position, effective radius and peak brightness of the detected sources. We have trained and tested the network with images that are based on realistic Very Long Baseline Array (VLBA) observations at 20 cm. Also, these images have not gone through any prior de-convolution step and are directly related to the visibility data via a Fourier transform. We find that the source catalog generated by DECORAS has a better overall completeness and purity, when compared to a traditional source detection algorithm. DECORAS is complete at the 7.5 sigma level, and has an almost factor of two improvement in reliability at 5.5 sigma. We find that DECORAS can recover the position of the detected sources to within 0.61 mas, and the

effective radius and peak surface brightness are recovered to within 20 per cent for 98 and 94 per cent of the sources, respectively. Overall, we find that DECORAS provides a reliable source detection and characterization solution for future wide-field VLBI surveys.

Active Galactic Nuclei

Discovery of 178 Giant Radio Galaxies in 1059 deg^2 of the Rapid ASKAP Continuum Survey at 888 MHz

Heinz Andernach

We report the results of a visual inspection of images of the Rapid ASKAP Continuum Survey (RACS) DR1 in search of extended radio sources (RS) over a contiguous high Galactic latitude area of 1059 deg^2 (-50d<Dec<-40d), which is covered by deep optical images of the Dark Energy Survey, and in which previously only three RS > 1 Mpc were known. Our search in optical and infrared images resulted in hosts for 1440 RG, for which spectroscopic and photometric redshifts from various references were used to estimate their projected linear size (LLS). This resulted in 178 newly discovered giant RS (GRS) with LLS>1 Mpc, of which 18 exceed 2 Mpc and the largest one is 3.4 Mpc. Their redshifts range from 0.02 to ∼2.0, but only 10 of the 178 new GRS have spectroscopic redshifts. For the 146 host galaxies the median r-band magnitude and redshift are 20.9 and 0.64, while for the 32 QSOs or candidates these are 19.7 and 0.75. Merging the six most recent large compilations of GRS results in 458 GRS larger than 1 Mpc, thus our work increased this number by 39 per cent to now 636. We show some examples of GRS in clusters and their orientation with respect to galaxy filaments. We estimate equipartition parameters and discuss trends with redshift.

Resolved Spectral Properties of 3C295 with LOFAR-VLBI

Etienne Bonnassieux

3C295 is a bright, compact steep spectrum source with an integrated radio spectral energy distribution(SED) which is well-known from 132 MHz to 15 GHz. Spatially resolved spectral studies, however, have been limited due to a lack of high resolution images at low radio frequencies, which are crucial for measuring absorption processes and anchoring the overall spectral modelling of the radio SED. We have used the International LOw-Frequency ARray(LOFAR) Telescope (ILT) observations of 3C295 to study its spatially resolved spectral properties with sub-arcsecond resolution at 132 MHz, combining our new 132 MHz observation with archival data at 1.6 GHz, 4.8 GHz, and 15 GHz. We find that the spectral properties of the hotspots provides evidence for low frequency flattening, while the spectral shape across the lobes is consistent with a Jaffe-Perola spectral ageing model. We also fit low-frequency absorption models to the integrated hotspot flux values,finding that both free-free absorption and synchrotron self-absorption models provide a better fit to the data than a standard power law. Although we can say there is low-frequency absorption present in the hotspots of 3C295, future observations with the Low Band Antenna of the ILT at 55 MHz will be necessary to lift degeneracies in the available model fits.

Filamentary AGN remnant radio emission in the SKA era

Marisa Brienza

In recent years the unprecedented sensitivities provided by SKA precursors/pathfinders have started revolutionising our view even of previously well-known objects such as jetted AGN. Observations at MHz-frequencies are especially suited to unveil the oldest plasma injected by AGN jets in their surrounding environment, providing new insights into its

interaction with the external medium over long timescales. Spectacular filaments of radio emission surrounding the lobes of radio galaxies are becoming more and more commonly observed, whose origin is still debated. Overall, studying these filaments could reveal important information on the magneto-ionic properties of the intracluster medium and deserves further investigation.

Here, I will briefly discuss some spectacular systems, where we have detected old large-scale AGN plasma with complex filamentary morphology and in particular I will focus on our recent study of the galaxy group NGC507. Thanks to new LOFAR and uGMRT observations, we have discovered and investigated, previously undetected, filamentary radio emission associated with past AGN activity of the central galaxy NGC507. The striking spatial coincidence observed between the radio filaments and the discontinuities in the X-ray surface brightness distribution as probed by XMM, clearly suggests that the thermal and non-thermal components are interacting. Based on the complex spiral morphology of the X-ray emission, we consider NGC 507 the clearest example of old AGN remnant plasma transported by sloshing in a galaxy group. Our results are consistent with simulations, which suggest that filamentary emission can be created by the cluster/group weather disrupting AGN lobes and spreading their relativistic content into the surrounding medium.

Are all very massive ellipticals radio AGNs?

Michael Brown

We have measured the 888 MHz emission from all $m_{\rm K} < 9.5$ elliptical galaxies using the ASKAP RACS survey of the sky south of +40 degrees. ASKAP RACS is roughly 3 times deeper than NVSS due to its median RMS of 250 uJy per beam and lower frequency. The vast majority of the elliptical galaxies in our sample are detected, with all elliptical galaxies with absolute magnitudes of $m_{\rm K} < -26$ being radio sources. It's thus plausible that all very massive ellipticals are radio AGNs. At a fixed absolute magnitude, we find radio powers span over four orders of magnitude and distribution of log radio powers is skewed, with some elliptical galaxies having radio powers three orders of magnitude more powerful than the median.

Search & Analysis of GRGs with Associated Nuclei (SAGAN), updates and its scope with the SKA

Pratik Dabhade

The Giant Radio Galaxies (GRGs) represent an extreme class of active galaxies with linear sizes in the range of 0.7 Mpc to $\sim$ 5 Mpc which places them among the largest single astrophysical objects known to us. It is still debated whether the large sizes of GRGs are due to the high efficiency of the radio jets ejected from the powerful central AGN or their sparser environments or a combination of both. Until 2016, only about 300 such GRGs were known in the literature since their discovery in 1974. Small sample studies over the years have enriched our knowledge about their radio properties and morphology; however, the nature of their AGN properties remained unexplored. To understand the formation, growth and evolution of GRGs, a project called the 'Search & Analysis of GRGs with Associated Nuclei' (SAGAN) was initiated. In order to study properties of GRGs ranging from megaparsec to parsec (AGN) scales, multi-wavelength data of a statistically significant sample is needed. Hence, under the project SAGAN, we have (a) carried out an extensive search for GRGs from radio surveys like NVSS and LoTSS-DR1 using our developed methodology, (b) made a complete compendium of all known GRGs using uniform cosmological parameters, and (c) studied the AGN and environmental properties of the largest sample of GRGs to date. As a result of our search,

we found large samples of GRGs from NVSS (162) and LoTSS (225), which almost doubled the known GRG population and a GRG-catalogue of $\sim$ 820 sources was compiled by us. The GRG-catalogue allowed us to probe the nature of accretion, feedback and their excitation types of the AGN of GRGs. Using our GRG catalogue we were able to establish that the black hole mass and radio spectral index of GRGs and normal-sized radio galaxies (RGs) are similar. We classified the AGN excitation type of a large number of GRGs and found that GRGs do not have preferentially high or low excitation type AGN. We also find that GRGs with high excitation type AGN statistically have larger sizes, total radio power, jet kinetic power and Eddington ratio. Our environmental study of GRGs shows that only about 10% of GRGs reside at the centres of the clusters of galaxies, which tend to be of relatively low mass. We have also carried out a study of GRGs with GMRT at low frequencies to study its large scale radio properties and with the IRAM-30m millimetre wave telescope to study the molecular gas properties of the host galaxy. These studies have yielded interesting results which will be presented. An all-sky radio continuum survey with SKA1 (low) will provide us with a wealth of data unveiling thousands of GRGs having low surface brightness features. Most essentially, due to high sensitivity and resolution of the SKA, it will be possible to search for very distant GRGs and possibly use them as probes of the high-redshift Universe. The discovery of a large sample of GRGs in the distant universe with SKA will be boosted by synergy with other optical surveys with telescopes like LSST, JWST, and EUCLID. Currently, the most deep radio images with LOFAR and MeerKAT have already started unveiling unique features associated to radio galaxies and emissions associated with clusters. We will discuss our above-mentioned results along with their implications and the scope of SKA for such studies.

The genesis of the first sample of radio loud AGN in the EoR: a candidate at $z \sim 8$

Guillaume Drouart

With the very recent discovery of radio luminous AGN at $z > 6$, a new window of opportunity is finally opening in the study of the galaxy evolution at the end of the Epoch of Reionization. The nature of radio selection presents the advantage of being insensitive to orientation-dependent obscuration and it allows us (i) to study simultaneously the co-evolution of the supermassive black hole and its host galaxy, (ii) to enable the study of the IGM through the HI absorption line and, (iii) to complete our view on AGN evolution with the existing $z > 6$ quasar samples. Our pilot programme in the 60 deg^2 GAMA-09 field uses a new selection technique taking advantage of the large frequency coverage of GLEAM, an all-sky 70-230MHz survey performed by the MWA. By selecting compact, steep and curved sources, we were able to confirm one new powerful radio galaxy, 0856+0224 at $z = 5.55$. A second source, 0917-0012, present signs of an even higher redshift, but eluded us for the last few years. Thanks to the extensive multi-wavelength coverage from follow-up observations with ALMA, JVLA, and more recently HST grism spectroscopy, we finally start to confidently place this source at a likely $z \sim 8$. I will also briefly mention the status of the larger sample from a 20 times larger area (encompassing the whole VIKING survey).

The GLEAM 200 MHz Local Radio Luminosity Function for AGN and Star-forming Galaxies

Tom Franzen

The GaLactic and Extragalactic All-sky Murchison Widefield Array (GLEAM) is a radio continuum survey at 76-227 MHz of the entire southern sky (Dec ¡ +30 deg) with

an angular resolution of $\sim$ 2 arcmin. We have combined GLEAM data with optical spectroscopy from the 6dF Galaxy Survey to construct a sample of 1,590 local (median z 0.064) radio sources with $S_{200\,\mathrm{MHz}} > 55\,\mathrm{mJy}$ across an area of $\sim 16,700\,\mathrm{deg}^2$. In this talk, we present the local radio luminosity function for AGN and star-forming galaxies at 200 MHz and discuss the typical radio spectra of these two populations between 76 MHz and $\sim$ 1 GHz. Among the AGN population, we find that flat-spectrum sources are more common at lower radio luminosity, suggesting the existence of a significant population of weak radio AGN that remain core-dominated even at low frequencies. However, around 4 per cent of local radio AGN have ultra-steep radio spectra ($\alpha < -1.2$) at low frequencies. These ultra-steep-spectrum sources span a wide range in radio luminosity, and further work is needed to clarify their nature.

Origin of Kpc-scale radio structure in Seyfert galaxies using GMRT observations

Rubinur Khatun

Radio outflows in Seyfert galaxies have primarily been studied at higher frequencies (> 1 GHz) in the literature with long-baseline interferometers that fail to pick up low surface brightness emission distributed over larger angular scales. Such high-frequency surveys miss the detection of faint kpc-scale radio structures (KSRs) that are fairly common in Seyfert galaxies. Very few studies have been carried out to investigate the origin of KSRs and to search the fraction of these KSRs among Seyfert populations. In this project, we are studying a sample of 28 well-selected Seyfert galaxies from the larger samples showing signatures of kiloparsec scale radio structures (KSRs). We have observed these with the GMRT at 325 MHz and 610 MHz. They also have archival GMRT and VLA data at other frequencies. We are trying to separate radio emission from AGN activity and starburst winds using radio morphology, spectral index map, Radio-FIR correlation etc. We have also detected signatures of misaligned, S-shaped jets as well as signatures of the jet-ISM interactions. I will be presenting further implications of these detections to enlighten our understanding of the KSR in low-luminosity AGN.

Cosmic evolution of jet-mode AGN in the LOFAR Deep Fields

Rohit Kondapally

Over the past two decades, it has become evident that active galactic nuclei (AGN) can have a significant effect on their host galaxies by regulating their growth or suppressing star formation (AGN feedback). A crucial missing piece in galaxy evolution models is to understand the role of AGN feedback in shaping the observed galaxy population from early epochs to the present day. Of particular importance in the life-cycle of massive galaxies and clusters are the radio jet-mode AGN; recurrent feedback from these AGN is believed to keep galaxies 'red and dead' once quenched. However, the cosmic evolution of feedback from the jet-mode AGN remains largely unconstrained beyond $z \sim 1$. The LOFAR Deep Fields represent one of the deepest radio continuum surveys to date but with an order of magnitude larger sky area coverage than previous surveys; this forms a novel sample to statistically study the growth of AGN activity and feedback across cosmic time. Using this sample of $> 10,000$ AGN, I will present the first robust measurement of the evolution of the jet-mode AGN population out to $z > 2$; we discover the existence of a new dominant population of jet-mode AGN hosted by star-forming galaxies at high redshifts. I will present an analysis of the radio-AGN mass fractions and the evolution of the host-galaxy properties to understand the nature of this new population, and draw conclusions about the evolving role of jet-mode AGN feedback across cosmic time.

Mrk 273 : A LOFAR and APERTIF view
Pranav Kukreti

Mergers of galaxies are spectacular events, and are considered to be an important mechanism for triggering nuclear activity in galaxies (AGN), including powerful radio galaxies. Optical and FIR-selected major mergers are typically characterised by mergers of gas-rich disc galaxies with large tidal tails of stars and HI gas. However, extended radio continuum emission has been rarely observed in such major mergers and not much is known about it. We observe spectacular large scale radio continuum emission in one such merger — Mrk 273. With the International LOFAR telescope (ILT), we observe at 144 MHz, smoothly curved arcs of $\sim$ 100 kpc size and a bright ridge of radio emission $\sim$ 45 kpc. Using the international stations of the ILT, we also study the continuum emission from the nucleus at 0.3" resolution at 144 MHz and pinpoint the location of the proposed radio AGN in Mrk 273. Combining it with higher frequency data up to 8.4 GHz, we investigate the spectral properties and origin of these different continuum features. We propose that the giant arc feature is a signpost of radio AGN in the nucleus of Mrk 273, and find spectral gradients across the arc that are likely caused by merger induced shocks. The low spectral age of the arc emission also points towards other mechanisms like in situ particle re-acceleration being active in this region. This is the first time such a spatially resolved spectral study has been performed for extended radio emission from a merger. We also discuss the synergy between LOFAR and APERTIF surveys that can now allow us to explore the origin of radio emission from many such merger systems.

High resolution imaging of 3C radio galaxies at low frequencies
Vijay Mahatma

In the past, sub-arcsecond imaging of radio galaxies at GHz frequencies have revealed the detailed structures in their jets, lobes and hotspots, giving information on jet-environment interactions, particle acceleration and lobe energetics. These studies have been useful in providing the understanding that we have today on the microphysics of radio galaxies. However, such detailed imaging has, to date, not been performed at low ($\sim$ 150 MHz) frequencies due to a lack of sensitivity and long baselines in past instruments, leaving a gap in our understanding in the low frequency regime where the radio emission generally peaks. Here, I present some of the very first images of a small sample of famous 3C radio galaxies at sub-arcsecond resolution at 150 MHz, using data from the LOFAR Two Metre Sky Survey (LoTSS). I discuss their (previously unseen) morphological characteristics and their polarization behaviour in relation to GHz-frequency information from the literature, and the implications for future wide area surveys at sub-arcsecond resolution.

AGN accretion mode versus radio morphology: news from the LOFAR Deep Fields
Beatriz Mingo

The recent LOFAR Two Metre Sky Survey (LoTSS) first data release unveiled a wealth of new information about AGN, their activity cycles, the galaxies they inhabit, and the large-scale environments around them, showing a very different picture of radio AGN from that painted by old, higher-frequency surveys. Among other results, we discovered a new population of low-luminosity FRII (edge-bright) radio AGN, unseen by previous surveys, which challenges the established paradigm between large-scale radio morphology and jet power.

Our latest investigations using the recently-released LOFAR Deep Fields survey data, with outstanding multiwavelength coverage, delve into the relationship between radio

morphology and black hole accretion. Our results show that the overwhelming majority of these low-power FRIIs are slow, radiatively inefficient accretors (LERGs) . The key parameter determining whether a low-power jet ends up as an FRI or an FRII seems to be the host stellar mass.

Most surprisingly, we found that 2/3 of the radio-powerful FRIIs observed by LOFAR are also slow accretors. This is in striking contrast to the traditional view associating powerful FRIIs with fast-accreting, radiatively efficient AGN (HERGs - Seyferts and quasars) and results from older radio surveys, and it hints to a much larger fraction of radio AGN than currently estimated, with important implications for future surveys.

The key determining factor in the black hole's accretion mode at all luminosities seems to be the host galaxy's gas content - the same supply that fuels star formation. We also find that it's not possible to distinguish fast- from slow-accreting and faint from luminous FRIIs based on their radio properties alone.

AGN science with sub-arcsecond imaging at MHz frequencies
Leah Morabito

The LOw Frequency ARray (LOFAR) has baselines up to 2,000 km, making it capable of achieving sub-arcsecond resolution at frequencies below 200 MHz. Although it is technically and logistically challenging to process LOFAR data at this resolution, recent results have more than doubled the number of published science results which exploit this capability. In this talk, I will give an overview of the calibration strategy for high-resolution work with LOFAR and a review of the recent science results which have been accepted to a forthcoming special issue of Astronomy & Astrophysics. This will include a demonstration of the calibration strategy using a typical LOFAR Two-metre Sky Survey field, a summary of the Long Baseline Calibrator Survey, and highlights from the 8 new results on radio-loud AGN led by early career researchers. I will briefly outline current and future work to post-process the LOFAR Two-metre Sky Survey (LoTSS) data at high resolution, providing the first ever sub-arcecond Northern sky radio survey.

The evolution of the Low-frequency radio AGN population
Emmanuel Ocran

To properly understand the evolution of galaxies since the first galaxies in the early universe, we need to observe galaxies in different wavelengths, including visible light (optical), infrared, x-ray and radio. In radio, often the brightest things we see are active galactic nuclei, when supermassive black holes in the centre of galaxies create powerful jets of matter that shine bright in radio. Understanding the different sources of light is a complex disentanglement exercise where physically-motivated models of the phenomena are compared to observations. In work, we study in faint radio sources, galaxies that emit faintly in radio with the GMRT at 610 MHz covering 1.8 sq deg of the ELAIS N1, and find a relationship with star formation activity taking place in these galaxies. In so-called radio loud sources , the relationship was however contaminated, and we suspect that this comes from radio jets. We derive the 610 MHz radio luminosity function for the AGN population, constraining its evolution via continuous models of pure density and pure luminosity evolution.

A larger picture of radio emission in quasars with outflows
James Peltey

Broad absorption line quasars (BALQSOs) show strong signals of fast-moving outflowing gas in their spectra. These outflows make BALQSOs natural feedback candidates. Quasars that show these signals have a puzzling enhancement in their radio detection

fraction, showing around 2-3 times the detection fraction of the general population. Despite knowledge of this high detection rate for over a decade, the physical origin of this radio enhancement is unknown. Radio surveys to date have not been deep enough to rule out different emission mechanisms in these largely radio-quiet sources.

Using the latest LOFAR Two-Metre Sky Survey DR2 results we are building a better picture of the radio emission from these sources. With an order of magnitude improvement in sensitivity over FIRST, we are able to study the radio properties of BALQSOs in new detail. Using this larger sample of BALQSOs, we focus on the outflow strength, optical colour and species of broad absorption lines observed, all of which are known to connect to radio emission in quasars.

In this talk I will present these new results along with ongoing work involving the newly released LOFAR VLBI pipeline, with which we provide a clear method to distinguish the origin of the radio emission in these sources.

Modelling remnant radio galaxies in SKA precusor era
Ben Quici

Energetics of radio-loud AGN offer valuable constraints on their underlying jet duty-cycle and can be extracted by modelling the dynamics of their radio lobes. Modelling remnant radio galaxies, e.g. those in which the AGN is currently switched off, is particularly challenging due to the unknown time over which the jets have been inactive. This issue can be resolved by modelling their radio spectrum, however this places a large demand on radio data to adequately sample the observed spectral curvature, and to resolve the spectra arising from individual regions across the lobes. Using an updated Lagrangian particle-based radio AGN model, which can produce intensity maps of simulated radio lobes at a range of input frequencies, we conduct an initial test on a sample of mock remnants to find that the remnant fraction can reasonably be recovered when limited spectral coverage is coupled with well-resolved radio maps at 0.15, 1.4, 2.1 and 5.5GHz (e.g. a typical LOFAR-MeerKAT-VLA observation). Using a remnant radio source selected in the GAMA23 field coupled with new radio data collected using the MWA, uGMRT, MeerKAT and ATCA, we conduct a comprehensive modelling of its spectrum and dynamics to accurately derive its intrinsic parameters. We find that even by deselecting the observational constraints on the break frequency set by the integrated spectrum, comparing the observed spatially-resolved maps of the lobes to those produced by the model allows us to recover the same intrinsic parameters. The viability of this technique using modern radio facilities is explored.

A Scintillating Survey: Spectral Variability with the MWA and ATCA
Kat Ross

Determining the origins of low-frequency ($\sim$MHz) variability of extragalactic sources has, until recently, largely been limited to small populations and/or single frequencies. Variability offers a unique opportunity to study both intrinsic properties of sources as well as the intervening media between source and observer. However, large population studies with significant spectral and temporal coverage have only recently become available with the development of radio telescopes like the Murchison Widefield Array (MWA). The SKA era offers a unique opportunity to conduct variability surveys covering a large population with vast temporal and spectral coverage. Using two epochs of the Galactic and Extragalactic All-sky MWA (GLEAM) survey, we have conducted a variability analysis of over 23,000 sources across 100—231MHz over a year-long timescale, the only spectral variability study of its kind. We identify a population of over 300 variable AGN and monitor 15 of these sources simultaneously with the MWA and the ATCA several times

over the course of one year. We present the results of this unique follow up campaign and detailed analysis and discuss potential explanations for the observed variability. In the SKA era, as large-scale, spectral variability surveys become achievable, rigorous statistics and understanding of the origins of low-frequency variability is needed. This study provides the first standardised methodology for future statistical analyses and classifications of low-frequency spectral variability.

Understanding radio outflows in radio-quiet and radio-intermediate AGN
Silpa Sasikumar

The origin of radio emission in radio-quiet (RQ) and radio-intermediate (RI) AGN is poorly understood. Our pilot low-frequency study of 22 Palomar Green (PG) quasars using upgraded GMRT (uGMRT) reveals copious amounts of low frequency diffuse emission in these sources and marginally detects jet/lobe-like features in some sources which are later confirmed from their follow-up EVLA observations. The spectral index images suggest jet origin for their steep radio spectrum, instead of AGN/starburst winds as suggested in the literature. We find that the radio emission in the radio-loud quasars and nearly one-third of the RQ quasars is AGN dominated whereas the remaining sources have contributions from both stellar-related processes and the AGN. Our radio polarization study using uGMRT and EVLA reveals a composite radio outflow comprising of a collimated jet and a wind-like component in the RI PG quasar, III Zw 2. Our multi-frequency, multi-scale radio polarization study using EVLA has also revealed a composite jet and 'wind' radio outflow in the Seyfert 1 galaxy and BALQSO, Mrk 231. Our EVLA polarization study in conjunction with [O III] emission-line study of five type 2 RQ quasars reveals an anti-correlation between radio polarized emission and [O III] emission, suggesting depolarization of radio emission by the emission line gas.

Hydrodynamic simulations of the radio galaxy lifecycle
Stas Shabala

Sensitive, high-resolution radio continuum observations are uncovering details of the complex interaction between kpc-scale AGN jets and their environments. I will present theoretical work on modelling the dynamics and synchrotron emission of these interactions, using a combination of numerical and analytical techniques. In this approach, the jet dynamics is described by 3D relativistic hydrodynamic simulations, while synchrotron emissivity is calculated in post-processing using an analytical model which fully accounts for the relevant loss processes.

Covering a broad range in jet and environment parameter space, our simulations successfully reproduce both FRI and FRII radio galaxy morphologies, and make predictions for spatially resolved evolution (including full radio SEDs) for active and remnant lobes. I will discuss the prospects for insights into radio galaxy physics from a combination of these models and observations, and present a possible scenario for the formation of Odd Radio Circles.

Remnant radio galaxies in deep fields
Veeresh Singh

Remnant radio galaxies (RRGs), characterized by the cessation of AGN activity, represent a short-lived last phase of radio galaxy's life-cycle. Contrary to the predictions of evolutionary models, the population of detected RRGs is low. The statistical study of RRGs derived from uniformly deep radio surveys can give us vital insights into the AGN duty-cycle and cooling mechanisms in lobes. Deep low-frequency radio continuum surveys are considered advantageous to discover new population RRGs that often show steep

radio spectra arising from the diffuse low-surface-brightness emission from the remnant lobes. In this talk I shall discuss our recent attempts to search and characterise RRGs in deep extra-galactic fields by using combination of 325 MHz GMRT survey, 150 MHz LOFAR survey and 1.4 GHz JVLA survey.

Probing the circumgalactic gas of AGN host galaxies with SKA pathfinder surveys
Jeroen Stil

The circumgalactic medium is the gas that surrounds galaxies roughly out to the virial radius of the galaxy. Many observations suggest that the circumgalactic medium is a dynamic multi-phase medium influenced by accretion and outflows in the form of a galactic wind or a jet powered by an active galactic nucleus. Its location, from a few tens to a few hundred kpc from the nucleus of the host galaxy, is the front line for galaxy formation. The angular scale occupied by the CGM of a large elliptical galaxy at redshift 1 ranges from a few arcseconds to a few tens of arcseconds, so its effects may become noticeable in the statistics of polarization and Faraday rotation of AGN radio sources that are marginally resolved by ASKAP. In this presentation, I will present evidence for a change in polarization of AGN powered radio sources at the corresponding scale, with new insights and perspectives for the future from SKA pathfinder surveys.

Classification games at the high-resolution and sensitivity radio universe
Eleni Vardoulaki

State of the art radio observations of the universe enable us to image in high resolution and sensitivity the AGN radio population, and, by using multi-wavelength data available, to extract information about the radio properties and their interaction with the environment. I will discuss visual and machine learning techniques to identify and classify radio AGN in the COSMOS field using VLA and MeerKAT data, in order to provide a widely applicable tool for automatic classification of radio sources suitable for use in the SKA era.

Critical examination of Agn Jets of NGC 2663
Velibor Velovic

AGN jets in NGC 2663 ($\sim$ 28.5 Mpc) span a total of 355 kpc on both sides of the nearby, making them the fifth largest in the nearby Universe. We combine multiwavelength data, from radio observations by the Murchison Widefield Array (MWA), the Australian Square Kilometre Array Pathfinder (ASKAP) and the Australia Telescope Compact Array (ATCA), to X-ray data from Chandra, Swift and eROSITA. After analysis of intensity, rotation measure, polarisation, spectral index and X-ray environment maps. The southern jet shows simultaneous narrowing and brightening of the jet, which is indicative of the recollimation of the jet by external, environmental pressure, though it could indicate an intermittent AGN or complex internal jet structure.

Radio galaxies in the MIGHTEE survey
Imogen Whittam

MIGHTEE is a galaxy evolution survey currently underway with the MeerKAT radio telescope. Once complete, the survey will cover 20 square degrees in four fields to a depth of $\sim$ 1 uJy rms/beam at 1.28 GHz, providing a unique combination of depth and breath. Crucially, the MIGHTEE fields have excellent multi-wavelength coverage, enabling a full census of galaxy properties. The MIGHTEE-continuum Early Science data has recently been released - I will discuss what we can learn from these data about the composition of the faint radio sky, and the properties of radio galaxies. In particular, I will discuss

whether or not there is evidence for a dichotomy in the accretion rates of high-excitation and low-excitation radio galaxies, and the implications this has for the role radio galaxies play in galaxy evolution.

The Fanaroff/RIley classification with the G23 field
Miranda Yew

Using the G23 field, we explore the correlation between peak radio luminosity and Fanaroff/Riley classifications. With our sample of 711 extended radio-loud sources, we compare and confirm previous findings that radio luminosity does not unambiguously define whether a source is FRI/FRII. We also find populations that do not fit the original definition, including hybrids and a new class we termed FRx due to resolution effects. A similar study will be also be conducted on the EMU pilot survey field.

Starforming Galaxies

MeerKAT+LOFAR+GMRT+VLA+JVLA: Radio spectral properties at 150 − 5000 MHz of star-forming galaxies
Fangxia An

A well-determined radio spectrum for star-forming galaxy (SFG) is critically important for studies that are based on rest-frame radio power, especially those at high-redshift where k-corrections are generally extrapolated the most. In this talk, I will introduce two of our recently completed projects based on the MeerKAT+VLA+GMRT data in the COSMOS field and the LOFAR+GMRT+JVLA data in the ELAIS-N1 fields. I will present our measured radio spectral index between the observer-frame frequencies of 150-5000MHz and show the correlations between radio spectrum and physical properties of radio-selected SFGs. With these results, I will discuss the possible physical mechanisms that determine the radio spectrum of SFGs. I will also show how the adoption of these different radio spectral indices (from low- and high-frequency) in k-correction affects the study of far-infrared-radio correlation of SFGs.

Star-forming galaxies in three LOFAR deep fields
Rachel Cochrane

Radio wavelengths offer a unique view of star formation and AGN activity, in which dust obscuration does not play a significant role. In this talk, I will present new analyses of the radio-identified star-forming galaxy population, using the LOFAR Two-metre Sky Survey deep fields. These data provide an enviable combination of depth ($\sim$ 20uJy rms at 150MHz) and area ($\sim$ 26 deg^2 across three well-studied fields, ELAIS-N1, Bootes and Lockman Hole). Complementary high quality multi-wavelength ancillary data from UV to FIR has enabled the reliable separation of star-forming galaxies from AGN, and characterisation of the physical properties of the star-forming population. Our efforts have enabled us to map star formation in a self-consistent and dust-unbiased manner, to well beyond the peak of cosmic star formation. I will present new work on the evolution of the 150MHz radio luminosity functions of star-forming galaxies, and comparisons of different methods to estimate the cosmic star formation rate history.

Source Counts Spanning Eight Decades of Flux Density
Jim Condon

The sky density of extragalactic sources with 0.25 microJy $< S <$ 25 Jy was determined from (1) counts of NVSS sources between 2.5 mJy and 25 Jy at 1.4 GHz, (2) counts of sources with 10 microJy $< S <$ 2.5mJy at 1.266 GHz in the confusion-limited

MeerKAT DEEP2 image, and (3) the source density between 0.25 and 10 microJy best fitting the DEEP2 confusion amplitude distribution. Historically troublesome biases caused by corrections for missing sources and partial resolution were minimized by the use of low-resolution images with sufficient brightness sensitivity to detect normal spiral galaxies and diffuse radio lobes. Errors associated with highly skewed count distributions were reduced by comparisons with realistic sky simulations. Small statistical uncertainties were ensured by large sample sizes. Combined with the 1.4 GHz local luminosity function, the accurate new counts tightly constrain the evolution of radio emission from star-forming galaxies and AGNs. About 99% of the source background is resolved into discrete sources stronger than 0.25 microJy, and a significant contribution by fainter discrete sources that cluster as strongly as galaxies can be ruled out.

Capturing the radio SED of high-z starburst galaxies by combining deep pathfinder surveys

Sarah Leslie

Starburst galaxies are rare in the local universe but are more common at high redshifts, where they make an important $(20-50\%)$ contribution to the cosmic SFR density. Individual starburst galaxies are now well-studied in the radio at low redshifts ($z < 0.2$; e.g. Galvin et al. 2018) and it is clear that a single power-law rarely characterises the radio continuum emission. At low frequencies, free-free absorption can flatten the spectrum below a turn-over frequency that has been observed even above 700 MHz in nearby starburst galaxies (regardless of the viewing angle) and in high-redshift SMGs (e.g., Ramasawmy et al. 2020). We have compiled the latest deep multi-frequency radio continuum data from LOFAR (Sabater et al. 2021), GMRT (Ishwara-Chandra et al. 2020, Ocran et al. 2021), and the VLA from 150MHz to >1.4GHz to study the radio SED for ~ 100 bright star-forming sources at $0.3 < z < 1$ across 8 square degrees in the ELIAS-N1 field. In this talk, I will report the fraction and properties of sources that show spectral steepening at high frequencies, spectral flattening at low frequencies, and those which show a turn-over. By understanding the radio SED, we can accurately calculate radio-derived SFRs in the SKA era, and use multi-frequency observations to probe the ISM properties of high-redshift galaxies.

A MeerKAT 1.28 GHz Continuum Study of Luminous Infrared Galaxies in the Southern Hemisphere: MeerLIRGs

Lucia Marchetti

We have just completed a MeerKAT survey (MeerLIRGs) of 298 southern galaxies selected among the brightest IRAS galaxies ($S(60\mu\mathrm{m}) > 5.24$ Jy). This campaign provides complete high-resolution L-band continuum coverage of the all-sky IRAS Revised Bright Galaxy Sample (RBGS) in the Southern hemisphere which also includes 201 luminous starburst galaxies (plus a few AGNs) parts of the Great Observatories All-sky Luminous Infrared Galaxies Survey (GOALS) and some merger systems. These new MeerKAT data together with the available multi-wavelength data are providing crucial information to distinguishing between AGN and Star formation activities in these galaxies and improve the local radio luminosity and FIR-Radio correlation function of starburst/AGN galaxies. Moreover, given the nature of this sample, it will also be possible to trace the evolution of dust-obscured merger-driven starbursts as a function of the merger stage. In my talk, I will present the survey and some preliminary results obtained so far.

The Cosmic star-formation history measured at 1.4 GHz

Allison Matthews

Most of the stars in the universe were formed during an era at $z \sim 2$ called "cosmic noon," which marked not only the peak of star-formation activity but also the peak of dust attenuation. Radio emission is entirely unaffected by dust and is generated by supernova remnants of the same short-lived massive stars emitting primarily in the UV and optical. Unfortunately, star-forming galaxies are extremely weak radio sources and it is necessary to measure their source count below 1 microJy at 1.4 GHz to constrain their evolution. Radio source counts from the DEEP2 image were measured down to 0.25 microJy, equivalent to the flux density of the evolved Milky Way at a redshift of 4. The product of luminosity and density evolution of radio sources is directly related to the total star-formation rate density (SFRD) evolution through the FIR/radio correlation. By analyzing a volume-limited sample of $\sim 4,300$ star-forming galaxies in the local universe, we have found that the FIR/radio correlation is distinctly non-linear. The cosmic SFRD derived from our evolutionary models and updated FIR/radio correlation implies that star-forming galaxies evolved more strongly than predicted by Madau and Dickinson (2014) from FUV and IR data.

New constraints on the faint radio source population from LOFAR
Isabella Prandoni

The Lockman Hole, the Bootes and the Elais-N1 regions are among the most well known northern extra-galactic fields, and the deepest of the LOFAR Two-Metre Sky Survey (LoTSS) Deep Fields so far. We exploit these deep observations to derive the deepest radio source counts at 150 MHz to date. Our counts are in broad agreement with those from the literature, and show the well known upturn at ∼few mJy, mainly associated with the emergence of the star-forming galaxy population. More interestingly, our counts show for the first time a very pronounced drop around $S \sim 2$ mJy, which results in a prominent 'bump' at sub-mJy flux densities. Such a feature was not observed in previous counts' determinations (neither at 150 MHz nor at higher frequency). While sample variance can play a role in explaining the observed discrepancies, we believe this is mostly the result of a careful analysis aimed at deblending confused sources and removing spurious sources and artifacts from the radio catalogues. This 'drop and bump' feature cannot be reproduced by any of the existing state-of-the-art evolutionary models, and appears to be associated with a deficiency of AGN at intermediate redshift ($1 \lesssim z \lesssim 2$) and an excess of low-redshift ($z \lesssim 1$) galaxies and/or AGN. We exploit the value-added catalogues produced as part of the LoTSS Deep Field Data Release to further investigate the sources responsible for the observed discrepancies, by deriving source counts, luminosity and star formation rate functions for each sub-population (radio-quiet and radio loud AGN, star forming galaxies), and by characterizing their multi-band, multi-frequency properties. The results of this work have been published in two papers (Mandal et al. 2021; Bonato et al. 2021). A third paper is in preparation (Prandoni et al.).

Studying star-formation in Radio Deep Field using uGMRT
Akriti Sinha

Faint radio emissions from distant extragalactic sources have opened up a new window for studying the cosmic evolution in a large variety of sources. The synchrotron emission from these sources arises from star-formation in galaxies and from powerful jets in active galactic nuclei (AGN), thereby allowing us to probe both these distinct populations. We study a sample of 2528 radio sources detected at 300–500 MHz in deep uGMRT observations of the ELAIS-N1 field that covers 1.8 sq. deg of the sky reaching a sensitivity of 15μJy beam^{-1}. The ELAIS-N1 is a well-studied extra-galactic field with extensive multi-band ancillary data covering a wide range of frequencies, essential for characterising the

physical and evolutionary properties of the various source populations. We thus classify the sources in SFGs and AGN to study the radio-IR relations up to $z \sim 2$ by using the rest-frame fluxes obtained by k-correction in both the wavebands. We study the variation of monochromatic q parameters with redshift at 24 and 70 μm and of the bolometric qTIR obtained by integrating between 8 and 1000 μm. We find q24 to increase with z which can also be attributed to an increase of dust temperature for the sources in the ELAIS-N1 field. We observe a tight correlation between the radio luminosity at 1.4 GHz with total infrared luminosity having a super-linear slope, b = 1.08 ± 0.02 for SFGs up to $z \sim 2$. In fact, the radio–FIR relations also have super-linear slopes with radio-MIR relations showing sub-linear slopes. The quantity qTIR for SFGs shows a slight variation with redshift: qTIR = $(2.60 \pm 0.03)\ (1+z)^{(0.11 \pm 0.02)}$ out to $z \sim 2$ and the probable reason can be accounted to the non–linear slope of the radio–IR correlation.

Clusters and the Cosmic Web

The deepest images at the lowest frequencies of a galaxy cluster
Andrea Botteon

Abell 2255 is a nearby (z=0.08) galaxy cluster that has been observed for 72h with LOFAR HBA (150 MHz) and 72h with LOFAR LBA (50 MHz). Recently, it has been awarded for additional 216h LOFAR HBA observations that will be carried out in the next two years and that ensure that this this field will remain competitive and unique even once the SKA will be fully operational. These large LOFAR datasets represent the deepest observations at low frequencies ever performed on a galaxy cluster and give us the opportunity to push the study of non-thermal phenomena associated to cluster galaxies and the intra-cluster medium into a completely new and uncharted territory.

In this talk, I will focus on the results of the first set of observations, reporting the discovery of a low surface brightness emission that embeds the cluster and that is extended up to its virial radius. This detection probes the presence of cosmic rays and sub-microGauss magnetic fields diffused on extremely large scales. I will discuss the possible origin of this giant "envelope" of emission and highlight how this discovery opens a new frontier for studying magnetic fields and acceleration mechanisms in large-scale structures.

Studying a merging cluster with uGMRT
Swarna Chatterjee

Galaxy clusters are the largest virialized structures in the universe and also a perfect laboratory for studying astrophysical plasma processes. With the recent advancement in radio observational techniques in low-frequencies and the increased sensitivity of SKA pathfinder telescopes like uGMRT, many peculiar and interesting nonthermal radio features in the ICM in the forms of radio halos and relics have been discovered. The spectral index maps from multi-frequency radio observation and their comparison with X-ray can provide us with significant insight into cluster dynamics and also increase our understanding of the large-scale particle acceleration process. Here we will present some interesting results about a massive merging cluster, A1351. With our radio and X-ray analysis, we will also shed some light on the particle acceleration process going on there.

The MeerKAT Galaxy Cluster Legacy Survey
Kenda Knowles

The MeerKAT Galaxy Cluster Legacy Survey (MGCLS) is a programme of long-track MeerKAT L-band (900-1670 MHz) observations of 115 galaxy clusters. I will present an overview of the cluster survey and the set of legacy products being made available to the

community, as well as some of the preliminary science exploitation carried out to date. With excellent surface brightness sensitivity at ~ 8 arcsec resolution, a wide bandwidth for in-band spectral indices, and Faraday rotation and HI mapping capabilities, the MG-CLS has immense science potential over a wide range of research areas.

A low-frequency survey of member galaxies associated with the Coma cluster
Dharam Lal

We have made new high-resolution, high sensitivity deep image of ~ 7.5 sq. deg field of the Coma cluster at the angular resolutions of 6.1 arcsec and 3.7 arcsec, respectively at 250-500 MHz and 550-850 MHz bands of the upgraded Giant Metrewave Radio Telescope. Additional observational data for the cluster is culled from a variety of sources. Among several, our two key goals are to present statistics of radio sources associated with the Coma cluster, and to investigate the dynamics of the Coma cluster from the orientations of the radio morphologies of extended radio sources. We will present our first results from this study.

Unprecedented view of the filamentary radio relic in Abell 2256 at low frequencies
Kamlesh Rajpurohit

Radio relics are extended, highly polarized, diffuse radio sources located at the outskirts of galaxy clusters. They trace shock fronts induced into the intracluster medium by cluster mergers, leading eventually to the acceleration of particles. Thanks to their high spatial resolution and sensitivity, low frequency radio telescopes, such as LOFAR and uGMRT in combination with data at GHz-frequency, can provide important constraints on models for the formation of radio relics. Here, we present the first high-resolution low frequency images of the galaxy cluster Abell 2256, hosting one of the brightest and most complex relics known to date, featuring a remarkably spectacular network of enigmatic filamentary structures. Because of its flat spectral index and a break in the integrated spectrum at high frequency, past works had raised questions about whether the standard merger shock model can work for this intriguing relic. Using new LOFAR, uGMRT and archival JVLA observations, we find instead that the integrated spectrum of this relic is consistent with a simple power law spectrum with a spectral index stepper than -1 between 144 MHz and 4 GHz. Combined with insights from recent numerical simulations, our results highlight that the long filaments covering the entire relic, very likely traces the complex shock front, with a broad distribution of Mach numbers, propagating through a turbulent medium. Unlike previous claims, our findings indicate that the Abell 2256 relic can be consistently explained by the standard scenario for relic formation. The cluster also has one of the richest varieties of complex ultra-steep spectrum radio galaxies, which I will also discuss.

Fossils, relics, and remnants in Abell 3266: cluster archaeology with ASKAP-EMU and the ATCA
Chris Riseley

Clusters of galaxies provide ideal physical laboratories for studying a wide range of physical processes associated with hot gas (thermal components) and magnetic fields (non-thermal components). However, studying cluster magnetic fields in detail is difficult, due to the wide variety of physical processes undergone by clusters during their lifetime. Diffuse radio sources (such as the canonical relics and haloes) and tailed radio galaxies (which are frequently found in clusters) can provide key signposts to these physical processes, and thus help us understand the magnetic field topography. Abell

3266 is a rich, Southern cluster undergoing a particularly complex merger event, and as such provides a golden opportunity to study the thermal and non-thermal properties of the intracluster medium (ICM) on a broad variety of scales. In this talk, I will present the results of new, deep radio observations performed with the Australia Telescope Compact Array (ATCA) and Australian Square Kilometre Array Pathfinder (ASKAP). These observations reveal a plethora of previously-unseen diffuse, steep-spectrum radio sources associated with the ICM; additionally, we detect a multitude of active and remnant radio galaxies that are now resolved in unprecedented detail. Using our exquisite new radio data in conjunction with X-ray observations from XMM-Newton, I will discuss the properties of these newly-discovered sources, and what we can learn from them – both about their nature and the dynamical history of Abell 3266 – as well as what this means for upcoming cluster surveys with ASKAP.

Stacking Filaments of the Cosmic Web
Tessa Vernstrom

On the largest scales there is the cosmic web; voids, clusters and filaments in a weblike pattern.This synchrotron emission from filaments of the cosmic web is expected to be faint and diffuse, making direct imaging challenging. Here I will present the first detection of the stacked radio signal from large (1-15 Mpc) filaments connecting pairs clusters using large-area low-frequency maps. This signal appears roughly compatible with the non-thermal synchrotron emission from the shocked cosmic web, and provides a direct evidence for one of the pillars of the physical picture of structure formation in the Universe. I will also go into some detail about some strange things that can happen and unexpected things when working below the noise

Cosmology and Dark Matter

Constraining Axion decay with MeerKAT UHF band data
Yin-Zhe Ma

Dark matter is the dominant matter in the Universe. A compelling dark matter candidate of increasing scientific interests in recent years is Axion, which was originally postulated to solve the strong CP problem in particle physics. Axions can be converted into monochromatic radiation in the neutron star's magnetosphere, constituting a unique window to probe its existence with a radio telescope. In 2020's MeerKAT open-call for proposal, we were granted 10 hours of observation time. We recently completed the observations towards the isolated neutron star RX J0806.4-4123 in the UHF band. In this talk, I will present the results of the constraints on Axion DM decay rate from the newly observed MeerKAT data. I will show that the (new) upper limit of the axion decay constant is in the mass range of 2.5—5 mu-eV (micro-Electronvolt), which corresponds to MeerKAT 544-1,088 MHz. The constraints from MeerKAT complements the laboratory-based axion dark matter searches and fills the gap between 810—1,090 MHz gap between ADMX and RBF experiments. I will also discuss the future prospects of MeerKAT potential for Axion search.

Cosmological inference from LOFAR LoTSS DR2 and CMB cross-correlation
Szymon Nakoneczny

In my talk, I will describe an ongoing cosmological project in the LOFAR survey, based on cross-correlations between LoTSS DR2 and Planck lensing and temperature maps. I will show preliminary results on constraining redshift distribution and bias function of the radio galaxies, as well as cosmological parameters. I will discuss the current significance

of the integrated Sachs-Wolfe effect measurements from LOFAR sources, and prospects for using them to constrain dark energy properties.

Cosmology from the large-scale continuum surveys of EMU-PS and RACS
David Parkinson

In this talk we will summarise measurements of the large-scale clustering statistics from EMU (Evolutionary Map of the Universe) and RACS (Rapid Area Continuum Survey), and the cosmological inferences that can be extracted from this data. In particular we focus on the galaxy bias, matter density, and the imprint of the accelerating universe. We also demonstrate the importance of generating accurate mock data and random catalogues, through the use of the noise map.

Searching for WIMPs in the Large Magellanic Cloud
Marco Regis

We present a radio search for WIMP dark matter in the Large Magellanic Cloud (LMC). We make use of a recent deep image of the LMC obtained from observations of the Australian Square Kilometre Array Pathfinder (ASKAP), and processed as part of the Evolutionary Map of the Universe (EMU) survey. LMC is an extremely promising target for WIMP searches at radio frequencies because of the large J-factor and the presence of a substantial magnetic field. We detect no evidence for emission arising from WIMP annihilations and derive one of the most stringent bounds on WIMPs from indirect searches.

Galactic Science and the Magellanic Clouds

The Impact of SKA on Galactic Science: a glimpse at the Galactic plane with SKA precursors
Francesco Cavallaro

About $50-70\%$ of the first five years of SKA operations will be devoted to KSPs, and probably also to Generic Surveys that maximize commensality to a wide range of scientific objectives. There are already several proposed KSPs focused on Galactic Science and we foresee many other KSP concepts being submitted under the breadth of Our Galaxy SWG. SKA, providing better sensitivity and angular resolution than any of ongoing/planned surveys of the Galactic plane, will give the opportunity to create a sensitive wide-field atlas of Galactic radio emission and to address several topics in the field of Galactic radio astronomy. The Galactic plane has always been a formidable challenge for radio interferometers. A concentration of extended sources and the Galactic diffuse emission make it difficult to obtain a radio map devoid of imaging artefacts. This hampers the imaging performance of the instrument, reducing the quality of the final images (in terms of signal-to-noise ratio) and makes data reduction and analysis a particularly demanding task.

In this paper we summarize our ongoing work, carried out with SKA precursors, aimed at achieving skills and expertise in the run-up to the development of the full SKA to be ready and competitive for leading and participating to a SKA KSP dedicated to Galactic studies and for a full exploitation of the survey data.

Multi-frequency surveys of Magellanic Clouds
Miroslav Filipovic

This is an exciting time for the study of nearby galaxies other than our Milky Way. They offer an ideal laboratory as they are near enough to be resolved yet located at relatively known distances. Various new generation surveys of Magellanic Clouds through

the entire waveband reflect a major opportunity to study different objects and processes in the elemental enrichment of the interstellar medium (ISM).

I will review the most recent science outcomes from various new high resolution (∼arcsec) and sensitivity surveys of the Magellanic Clouds such as ASKAP, MWA, ATCA and MeerKAT (radio). This is in addition to large multi-frequency surveys from XMM-Newton & eROSITA (X-rays), Herschel and Spitzer (IR), MCELS (optical) and HESS (gamma rays).

Characterising supernova remnants with the SKA precursors
Adriano Ingallinera

Supernova remnants (SNRs) are the relics of the most violent stellar explosions. More than 300 Galactic SNRs have been identified, at least 1000 are expected. SNRs are thought to be one of the most relevant sources of Galactic cosmic rays. In fact, particle acceleration is known to take place in these objects, however the extent of cosmic ray production is still debated. High-resolution, high-sensitivity radio images are invaluable in solving this puzzle. The possibility to investigate the different spectral regimes of a single SNR sheds light on the different plasma conditions within the source. The integrated spectral index and its deviation from a theoretical value of -0.5 have been largely used in past studies to derive the underlying physical mechanisms responsible for the SNR emission. In this talk we present our preliminary findings in SNR characterisation thanks to new data collected with ASKAP and MeerKAT, along with literature data from MWA. We show how the synergic use of the three precursors is proving fundamental to achieve our goals. New precise measurements of the integrated spectral index refine the literature values, sometimes with significant deviations. This is especially true in the southern hemipshere, where many SNRs are still poorly studied. Spectral index maps reveal that the integrated spectral index can be a misleading indicator of the plasma condition in some SNRs, where multiple, unrelated regimes emerge.

THOR's perspective on magnetism in the inner Galaxy
Russell Shanahan

We present the results of polarization observations at 1-2 GHz from The HI/OH/Recombination line (THOR) survey of the inner Galaxy. In the Galactic longitude range $32^\circ < l < 67^\circ$ we find Faraday rotation measures (RMs) in the range of -567 rad/m2 $\leq$ RM $\leq$ 4219 rad/m2. With respect to previous surveys at these longitudes, we find a strong excess in RMs with the highest values concentrated within a degree of $l = 48$ at the Sagittarius arm tangent. The RM drops rapidly for $l > 49^\circ$, while at $l < 47^\circ$ a higher mean RM is observed as well as a larger standard deviation than for RMs at $l > 49^\circ$. We attribute this RM structure to the Sagittarius arm acting as a significant Faraday screen within the Galaxy. We will also present the observations of polarized emission and Faraday rotation of the SNRs G46.8-0.3 and G39.2-0.3. We observe two component Faraday rotation that we attribute to internal effects within the SNRs. From the Faraday depth distribution of these SNRs, we propose that our observations reveal polarized emission from the near and far sides of the SNR shell. Fractional polarization maps of these SNRs reveal evidence of a disordered magnetic field within regions where synchrotron emission is the brightest.

The MPIfR Galactic Plane Survey (MGPS) with MeerKAT
Sarrvesh Sridhar

The MPIfR Galactic Plane Survey is a 3000-hour commensal beamformed and imaging survey in the L- and the S-bands using the MeerKAT radio telescope, covering 900 and

300 sq. degrees respectively. It is the only SKA pathfinder survey where both continuum/imaging and time-domain surveys are observed commensally. This survey will be the most sensitive polarization survey of the southern Galactic plane with the broadest frequency coverage.

The beamformed survey's key science driver is the search for isolated and relativistic binary pulsars in the Galactic plane and the Galactic Centre. The polarized imaging survey will probe the Milky Way magnetic fields using a rotation measure grid from galactic and extragalactic sources, and characterize the broadband polarization properties of extragalactic radio sources.

The L-band survey started early in 2021 while we expect the S-band survey to commence in the coming months once the S-band system has been commissioned. In this talk, I will present an overview of the survey, the processing pipeline, and some early imaging results. Preliminary images show that we can produce total intensity images at 8" resolution with sensitivity $\sim 20\,\mu$Jy/beam close to the theoretical sensitivity.

Structure and energetic of the interstellar medium in nearby galaxies
Fatemeh Tabatabaei

Studying factors regulating the formation of young massive stars is vital to understand the evolution of galaxies. Radio continuum emission is a dust-unbiased tracer of both the thermal and the non-thermal processes in the interstellar medium (ISM) linked to the formation of massive stars in normal star forming galaxies. There are increasing number of studies showing that the ISM structures are controlled mainly by the non-thermal pressures inserted by cosmic rays, magnetic fields, and turbulence. Using the multi-wavelength observations with the SKA pathfinders such as the JVLA, LOFAR, and the MWA, we investigate the role of these factors in the evolution of star formation in nearby galaxies after generating maps of the cosmic ray electron energy index, magnetic field strength, and thermal electron density. I will present our findings for the Magellanic Clouds, M33, and IC342.

Polarisation

Polarised sources in the Apertif SVC fields
Björn Adebahr

The Apertif Science Verification (SVC) Campaign was carried out in April 2019 and served as a testbed for the capabilities of the Apertif system and the now ongoing Apertif surveys. Here we will present the first polarisation survey results from Apertif. We surveyed an area of 56 square degrees down to noise levels of 15 μJy and detected 1170 polarised sources using automatic routines for source detection, catalogue generation and cross-matching with infrared and optical counterparts. We confirmed the reliability of the Apertif measurements by comparing them to NVSS catalogue information. We found that the faint polarised sky at the μJy-level is dominated by radio-load AGN of the FRII-class, which are mostly hosted by actively star-forming galaxies. An outlook will be given with respect to the polarisation capabilities of the full Apertif surveys.

Statistical analysis of faint polarised sources using Apertif
Anna Berger

Using data of the Apertif Wide Extragalactic Survey, we aim to study the nature of faint polarised sources. Their source composition and redshift dependence contain information about the strength, morphology and evolution of magnetic fields over cosmic time scales. With 6 adjacent mosaics of the GOODS-N field observed with Apertif at 1.4 GHz,

we cover a total area of about 60 deg^2, with central RMS values down to 8 μJy. Using a semi-automatic pipeline we create a catalogue of polarised sources, finding about 150 polarised sources per pointing. Using infrared data from the WISE survey we classify all our sources as being dominated by AGN emission. We present euclidean normalised polarised differential source counts as well as cumulative source counts, finding good agreement of Apertif observations with previous deep fields. Using the possibility to have wide and deep observations at the same time, we also study the fractional polarisation over the total flux density, as observations from previous small deep field observations showed different trends. We also study the behaviour of fractional polarisation over redshift.

Polarisation of Micro-Jansky Radio Galaxies
Lennart Heino

This study explores the polarised radiation of very faint radio sources in order to better understand the nature, origin and evolution of cosmic magnetic fields. The high sensitivity and broad spectrum observational data are obtained from the instruments MeerKAT. Its powerful surveys are a precursor to Square Kilometre Array (SKA) magnetism science. The data allow polarised radio emission to be detected for very distant galaxies in the early universe, thereby providing an opportunity to chart the evolution of polarised emission from galaxies over cosmic time.

This study broadly characterises the polarisation properties of microJy source population. MeerKAT surveys allows detection of polarised emission for a large number of radio sources down to total intensity flux densities of order 100 microJy. At this flux density the source population is increasingly dominated by Star Forming Galaxies (SFG) and Radio Quiet Active Galactic Nuclei (RQ AGN). Multi-wavelength data sets are used to classify objects as SFG and RQ AGN. Polarisation and Faraday dispersion data are used to search for polarised emission from high redshift SFG and for a comparative analysis of the polarisation properties of SFG and RQ AGN as a class, and to compare to models of Faraday dispersion spectra of AGN and disk galaxies. The multi-wavelength catalogues extend the study to the lowest possible flux density using stacking techniques. I will show preliminary results of the MeerKAT polarisation studies of radio galaxies down to a sensitivity at the micro-Jansky level.

Rotation Measure maps of Radio Galaxies with ASKAP
Paddy Leahy

We are studying the Rotation Measure and depolarization distributions across a sample of 43 radio galaxies using ASKAP observations taken for POSSUM Early Science and the POSSUM and EMU Phase 1 Pilot observations. The targets were selected to have solid angles larger than 2 square arcmin at the survey sensitivity. The majority of such objects are FRIs at $0.02 < z < 0.1$, although the sample includes eight FR II sources presumably at larger distance: none have known redshifts. Although selected without reference to polarization properties, the large majority have extended polarized emission which yield RM maps. These reveal a variety of patterns including several side-to-side asymmetries related to the Laing-Garrington effect. Faraday complexity is seen frequently, but frequently and perhaps always is due to unresolved RM structure rather than line-of-sight effects within the lobes. We characterise the RM distributions using structure functions.

Effects of Depolarizing Intervening Galaxies on Background Radio Emission
Rikuto Omae

Extragalactic polarized emission can suffer from depolarization caused by hidden intervening galaxies (absorber systems). The depolarization can mislead our studies of

magnetic fields of radio lobes and clusters as well as statistical studies using RM grids. It is likely that extragalactic emission passes through depolarizing intervening galaxies (DINGs); about half of SDSS quasars are known to accompany Mg II absorber systems in front of the quasars (Zhu & M'enard 2013). We are studying theoretical models and depolarization effects of the DINGs. In this talk, we report on our progress with simple models without turbulent magnetic fields to focus on the effect of global magnetic fields of a DING. We confirm that the depolarization depends on a variety of parameters not only the observing frequency and the beam size but also the redshift, the viewing angle, and the magnetic field configuration of DING. Large surveys of extragalactic RMs may determine the RM as the peak Faraday depth at which the Faraday dispersion function has the maximum value. We demonstrate that such the peak Faraday depth is very different from that of beam-averaged, resulting in an overestimation or underestimation of DING's magnetic field. Interestingly, we see depolarization at low frequencies even when the effect of DING is not clearly seen in the Faraday spectrum. Such a case happens when a weak magnetic field such as a halo magnetic field is present. These results suggest that we need to carefully examine the existence of DINGs when we explore intrinsic polarization properties of the background source as well as investigate RM along the line of sight.

Other Talks

Unravelling the mystery of Main sequence Radio Pulse emitters
Barnali Das

Main sequence Radio Pulse emitters (MRPs) are magnetic early-type stars that emit periodic radio pulses similar to the pulsars. The emission mechanism behind has been identified to be the electron cyclotron maser emission (ECME). For more than a decade, only one such star was known leading to the idea that such objects are extremely rare. This is puzzling since a hot magnetic star possesses every ingredient to produce ECME. A burning question has been under what condition ECME is triggered in a hot magnetic star. In an effort to answer this question, we initiated a survey with the Giant Metrewave Radio Telescope (GMRT) at 610 MHz. Our survey has been highly successful and currently out of the total 15 MRPs, 11 have been discovered by the GMRT. By considering the magnetic early-type stars with similar physical properties, we inferred that at least 32% of these stars are MRPs, which suggests that ECME is a ubiquitous phenomenon in magnetic early-time stars. The relatively large number of MRPs also enabled us to conduct a statistical analysis comparing the physical properties, for the first time. This resulted in finding the 'X-factor' that controls the efficiency of the phenomenon in hot magnetic stars, and might be the answer to the more relevant question of what suppresses ECME in a magnetic early-type star.

An Unusual Pair of Odd Radio Circles
Peter MacGregor

Odd Radio Circles, or "ORCs", were first discovered in the ASKAP Phase 1 Pilot Survey of the Evolutionary Map of the Universe. ORCs present as circular objects in the radio regime, approximately 1 arcminute in diameter, with a typical low surface brightness of 100–200 μJy/beam. Of the five ORCs published (Norris 2021, Koribalski 2021), ORC 2 and ORC 3 (J2058-5736b and J2058-5736a) stand out as having a different morphology; presenting as a pair in close proximity, whereas the other three appear as single objects with no apparent neighbours. I will present details on ORCs 2 and 3 from observations with ASKAP and MeerKAT.

Exploring equatorial ionosphere using the Giant Metrewave Radio Telescope (GMRT)

Sarvesh Mangla

Radio astronomical measurements can be used to model Earth's ionosphere and infer the properties of ionospheric structures in them. The same ionospheric data is also required to correct for ionospheric effect upon radio visibility data. As upcoming radio telescopes are becoming larger, ionospheric effects must be corrected to get a better image of the sky. Square Kilometer Array (SKA) pathfinder GMRT (∼19N) is located in geophysically sensitive regions between the magnetic equator, and the northern crest of the equatorial ionization anomaly is an excellent candidate to study ionosphere in various array configurations (centre square as well as arms antennas).

Our recent analysis of a bright radio source (3C68.2) with GMRT has demonstrated this telescope capability to detect variation in total electron content (TEC) with amplitudes $\leq 1e^{-3}$ TECU and can measure TEC gradients with a precision of about $7e^{-4}$ TECU/km. For this study, we are introducing methods to do spectral studies on the computed TEC gradient using the two-dimensional polynomial-based method. This method effectively tracks individual waves associated with large scales and medium scales travelling ionospheric disturbances (TIDs) and estimates the speed and directions of travelling ionospheric waves.

The puzzle of ORCs

Ray Norris

The single Odd Radio Circles (ORCs) are rings of radio emission, about 1 MPc diameter, that surround galaxies at a moderate redshift (∼0.2-0.6). Only 3 examples are so far known, and their mechanism is still a puzzle. Here I describe Meerkat and ASKAP observations of the first single ORC to be identified, which show the ORC has internal structure which is hard to explain. Here I discuss possible mechanisms, and the modelling we have done to try to identify the correct mechanism, although none so far quite fits the observations.

Measuring the baryonic Tully-Fisher relation below the detection threshold

Hengxing Pan

In light of a range of ongoing SKA radio pathfinder surveys, we are entering the SKA era, supplemented with multi-wavelength ancillary data. In this talk I will present a novel 2D flux density model for observed HI emission lines combined with a Bayesian stacking technique to measure the baryonic Tully-Fisher relation below the nominal detection threshold, using multi-wavelength surveys. To demonstrate this idea I generate a galaxy catalogue, which includes HI lines described either with Gaussian or busy function profiles, and HI data cubes with a range of noise and survey areas similar to the MIGHTEE survey. With prior knowledge of redshifts, stellar masses and inclinations of spiral galaxies, I will show this model can reconstruct the input baryonic Tully-Fisher parameters (slope and zero point) most accurately in a relatively broad redshift range from the local Universe to $z = 0.3$ for all the considered levels of noise and survey areas, and up to $z = 0.55$ for a nominal noise of 90 μJy/channel over 5 deg^2. This model can also determine the MHI – Mstar relation for spiral galaxies beyond the local Universe, and account for the detailed shape of the HI emission line, which is crucial for understanding the dynamics of spiral galaxies. In summary I will introduce a Bayesian stacking technique for measuring the baryonic Tully-Fisher relation for galaxies at low stellar and/or HI masses and/or those at high redshift, where the direct detection of HI requires prohibitive exposure times.

Detecting complex observations in ASKAP pilot survey data
Gary Segal

The EMU Pilot Survey has brought to light a number of unexpected and unusual sources such as Odd Radio Circles. The detection of 'unknown unknowns' by an algorithm is a difficult problem to solve, as these observations may not share features with previous interesting observations. In this work we use the concept of apparent complexity, previously applied to detect multi-component radio sources, and use it to scan the EMU Pilot Survey data for complex and interesting objects. This method is computationally efficient, and generalises well when applied to new data after being calibrated on a very small sample. This generalisability positions apparent complexity as a suitable measure for identifying complex observations with unanticipated features.

Calibrated on a small ATLAS sample , this approach allows us to scan the EMU Pilot Survey data in a fully blind manner. In this talk I will explain the complexity measure and how we applied it to the Pilot Survey data. I will also discuss next steps to assess the recall (completeness) and purity of the interesting objects detected.