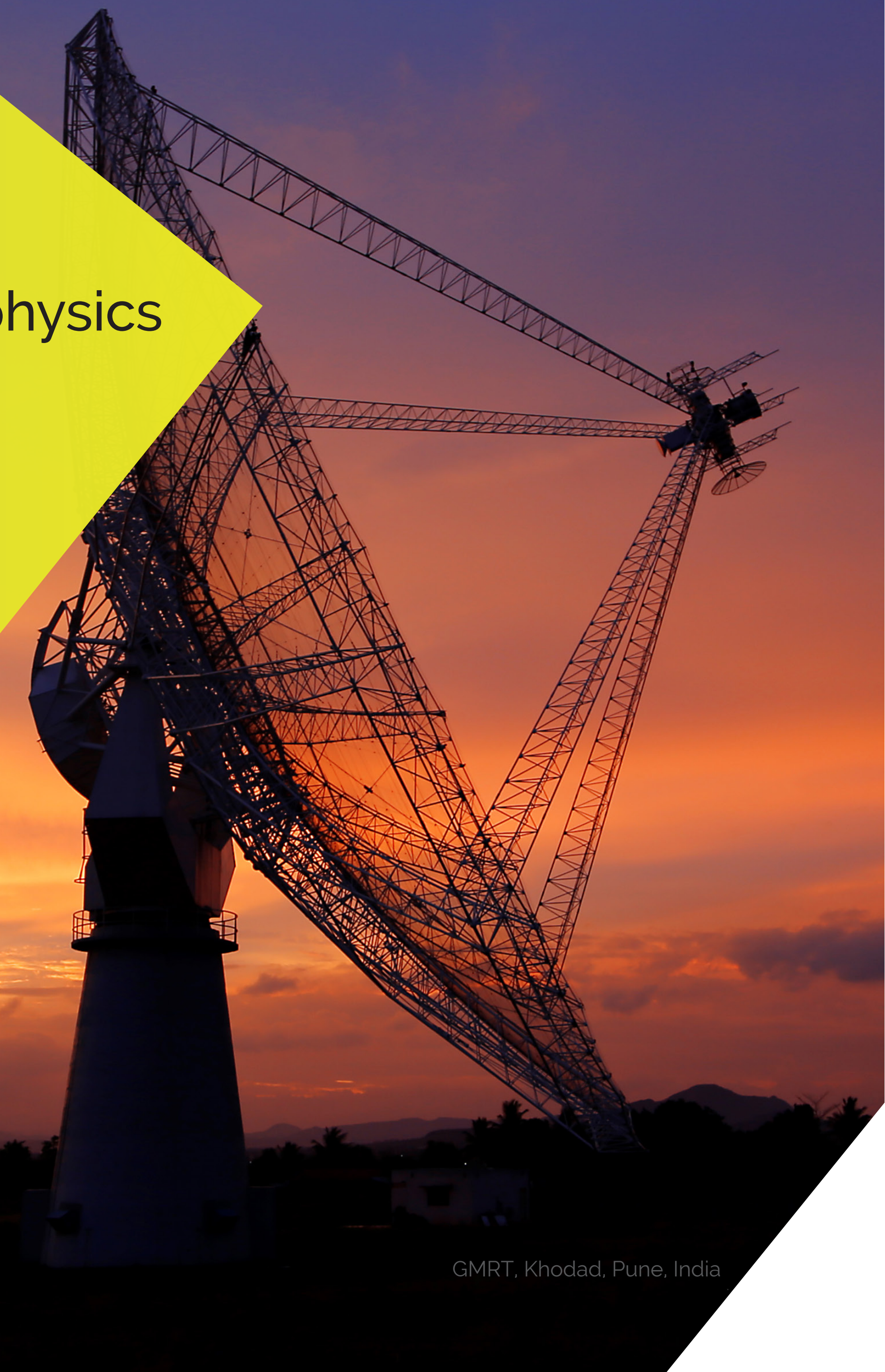
We build and operate amongst the best radio telescopes in the world

National Centre for Radio Astrophysics



GMRT, Khodad, Pune, India

NCRA • TIFR

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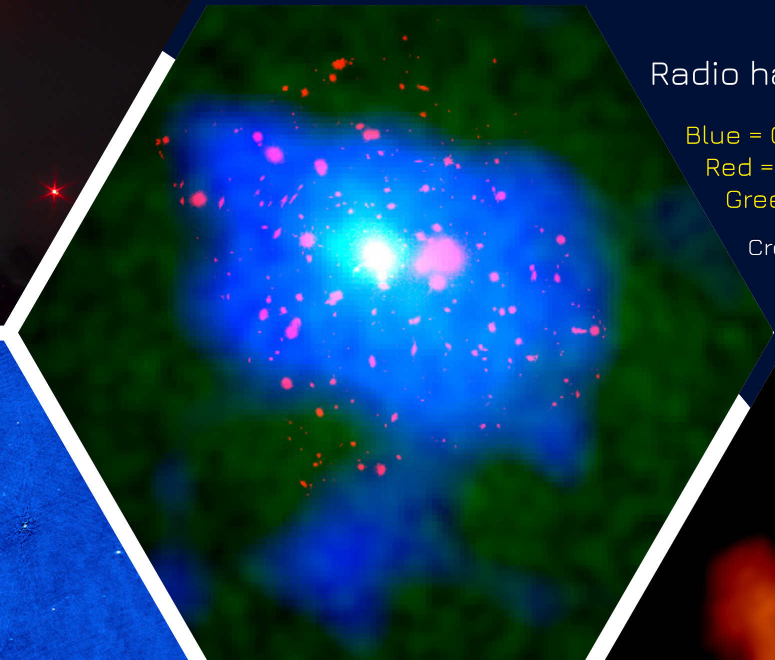
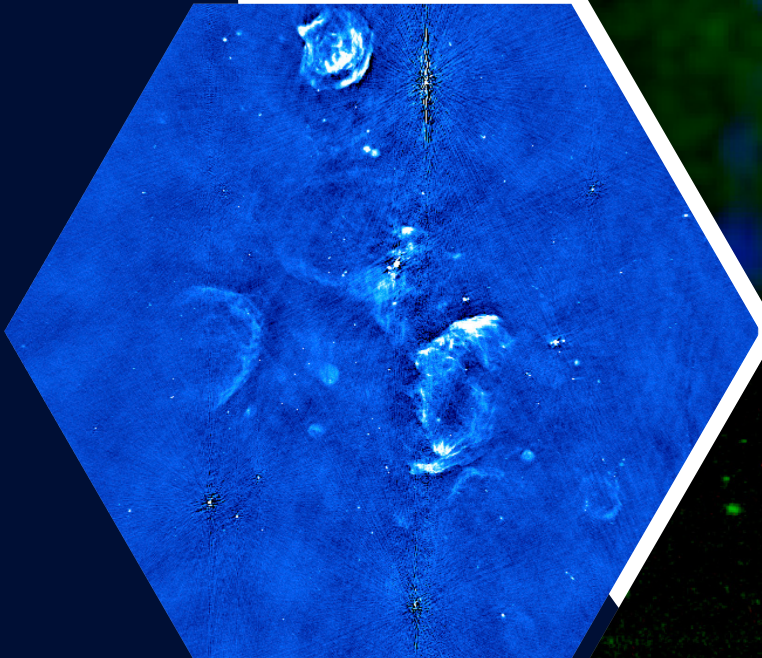


Radio halo in RXCJ0232.2-4420

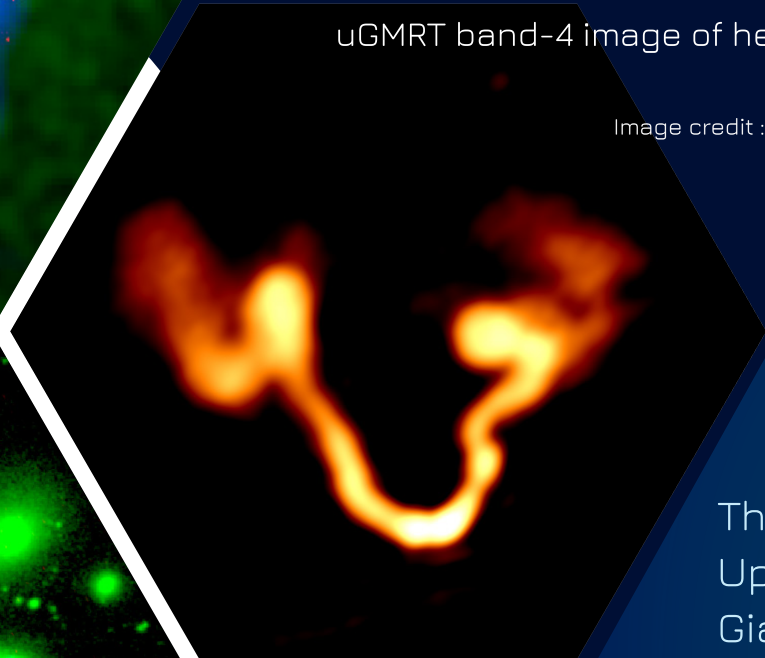
Blue = GMRT 607 MHz
Red = HST optical
Green = Chandra X-ray

Credit: Kale et al 2019



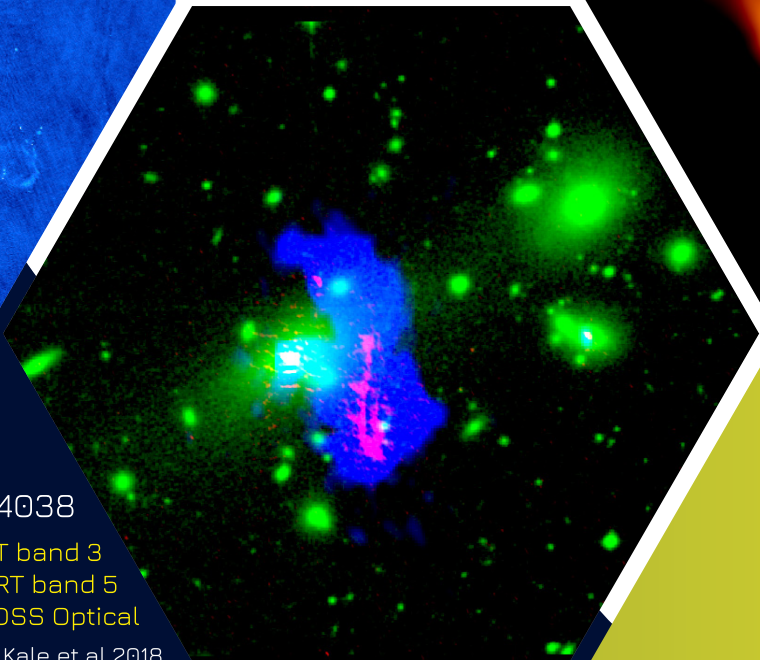
HESS 1850-000 at uGMRT band 3

Credit: P. Chandra.



uGMRT band-4 image of head tail radio galaxy

Image credit : Ishwara Chandra.



A dead radio galaxy in Abell 4038

Blue = uGMRT band 3
Red = uGMRT band 5
Green = DSS Optical

Credit: Kale et al 2018

uGMRT

The Upgraded Giant Metrewave Radio Telescope

Foreword by Govind Swarup

In September 1961, four radio astronomers working abroad M.R. Kundu, T. Krishnan, T.K. Menon and myself wrote a proposal for the formation of a radio astronomy group in India, and sent it to several scientific organisations in the country. The great visionary, Dr. Homi Bhabha, Director of the Tata Institute of Fundamental Research (TIFR), got Council's approval to form a Radio Astronomy Group at TIFR and sent a telegram to us about it in January 1962. I joined TIFR in April 1963, and encouraged by Dr. Bhabha, started to search for an outstanding unsolved astronomical problem.

During the 1960s, there was a major controversy about the basic nature of the Universe : the Big Bang model versus the Steady State theory. While sitting in the library at TIFR and gazing out over the sea, I conceived as to how to measure the angular size of a large number of weak radio galaxies by using the method of lunar occultation, for the purpose of distinguishing between the Big Bang and Steady State models. I proposed the construction of a 500 metres long and 30 metres wide parabolic cylindrical reflector, to be placed in the north-south direction on a suitable hill, so that its axis of rotation becomes parallel to that of the Earth. After a survey of several potential locations in southern India, a suitable site was identified on a hill near the town of Ootacamund (Ooty). In December 1965, Dr. Bhabha approved the construction of the Ooty Radio Telescope (ORT), which became functional on 18th February 1970, with the exciting observation of an uncatalogued radio galaxy getting occulted by the lunar disk that night. At that time, the average age of the TIFR radio astronomy group was only 28 years! By 1975, the ORT provided angular sizes of about 1000 radio sources with arc-second resolution for the first time in the world. We found that the weaker sources have smaller angular size than the brighter sources, providing independent evidence of the Big Bang model. By 1984, a synthesis radio telescope was built at Ooty, with 7 small parabolic reflectors placed up to 4 kms away and correlated with the ORT. During the first 25 years of the TIFR Radio Astronomy Group, 285 papers were published by its members with 20 in Nature, of which one based on observations made with the Kalyan radio Telescope and 11 with the ORT and OSRT.

After the success of the ORT, I proposed in 1976 the construction of a 2 km long x 50 m wide Giant Equatorial Radio Telescope (GERT), with 10 smaller antennas located up to 10 km away, to be located at the Earth's equator in Kenya. It was strongly supported by the Indian authorities and UNESCO, but President Jomo Kenyatta died in 1978 and Kenya went into turmoil. Later, a suitable site was surveyed in West Sumatra, but frequent earthquakes in Indonesia were a concern. In January 1984, I proposed the construction of the Giant Metrewave Radio Telescope (GMRT) at a suitable site in India in order to investigate certain outstanding astrophysical problems that could be studied best only at metre wavelengths. GMRT is an Earth rotation synthesis radio telescope that provides high sensitivity at metrewave lengths. It has been designed and fabricated fully indigenously in India. It has state of the art electronics designed by a group of bright young electronics engineers. GMRT is the world's largest synthesis radio telescope operating at metre wavelengths from ~ 130 MHz to 1430 MHz.

Over the last 18 years, GMRT has been used by hundreds of astronomers from 35 countries in the world, including those from India. It has been used for observations of a wide class of astronomical objects such as Sun, Venus, Jupiter, pulsars, supernova remnants, HII regions, Galactic centre, clusters of galaxies, radio galaxies, quasars, damped Ly-a systems, associated HI absorption, search for HI from galaxies located at high redshifts, determination of the epoch of reionization that occurred after galaxies and quasars were formed in the Universe, etc. Over the last few years, it has been upgraded to operate continuously from 120 MHz to 1460 MHz, by Yashwant Gupta and colleagues, resulting in three times higher sensitivity in most radio bands, and should lead to many more discoveries.
Govind Swarup , March 2019

Main campus of NCRA-TIFR at Pune

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2020 January

1. History of radio Astronomy at TIFR

The radio astronomy group at the Tata Institute of Fundamental Research (TIFR), Bombay was established in 1963 by Govind Swarup. The first major facility that the group set up (in 1965) was the Kalyan Radio Telescope: a grating-type radio interferometer at Kalyan near Bombay, consisting of 32 parabolic dishes of 1.8 m diameter, 24 of which were placed along a 630 m east-west baseline, with the remaining 8 along a 256 m north-south baseline, giving an angular resolution of 2.3’ x 5.2’. This interferometer was used to observe the Sun at a frequency of 610 MHz (Swarup et al. 1966) and amongst its important discoveries was the detection of considerable limb-brightening in the quiet Sun (Sinha & Swarup 1967). The Kalyan telescope was disbanded in 1968 as the group got involved in the more ambitious Ooty Radio Telescope (ORT) project.

In June 1963, Govind Swarup proposed the construction of a large steerable cylindrical telescope to exploit the method of lunar occultation for measuring angular sizes of hundreds of radio sources with arcsecond resolution. This was needed to distinguish between the Big Bang and Steady State models of the Universe, a raging controversy in cosmology at that time. Thus, the ORT was conceived, and the completion of this major facility in 1970 (Swarup et al. 1971) placed India on the world map of radio astronomy. Soon after the commissioning of the ORT, the group built the Ooty Synthesis Radio Telescope (OSRT), which consisted of the ORT and 8 other smaller antennas in an array spread over 4 km, providing an angular resolution of 1’ at the operating frequency of 325 MHz (Swarup 1984). The OSRT continued operating until 1986, and was an important step towards the next big project by the group: the Giant Metrewave Radio Telescope (GMRT). This was motivated by the scope for new explorations at metre wavelengths, such as the study of redshifted 21-cm neutral hydrogen emission, pulsars, and the diffuse radio emission of celestial sources (Swarup et al. 1991). The GMRT, built during the 1990s and available to the international community since 2002, has been one of the most challenging experimental programmes in basic sciences ever undertaken by Indian scientists and engineers.





In 1977, the TIFR centre for radio astronomy was established at Bangalore. In 1987, as the work on the GMRT -- coming up near Pune -- picked up pace, it moved to Pune and became the National Centre for Radio Astrophysics (NCRA). Today, NCRA is a premier research institute covering several fascinating facets of radio astrophysics and related topics, as well as a centre for the development of advanced techniques for radio astronomy, and the home to two major facilities : ORT and the GMRT. Some of these aspects are covered in more detail in the following sections.

1.1 The Ooty Radio Telescope

The Ooty Radio Telescope (ORT) consists of a 530 m long and 30 m wide parabolic cylinder. It operates at a frequency of 326.5 MHz, with a maximum bandwidth of about 16 MHz. Its design makes good use of India’s proximity to the geographical equator -- the long axis of the cylinder is aligned in the north-south direction along a hill which has a natural slope of about 11°, the geographical latitude of Ooty, thus making the long axis of rotation of the telescope parallel to the earth’s rotation axis. This makes it possible to continuously track celestial objects for about 10 hours from rise to set by simply rotating the antenna mechanically about its long axis. The antenna beam can be steered in the north-south direction by electronic phasing of the 1056 dipoles placed along the focal line of the parabolic reflector, covering a declination range of ± 60°. The reflecting surface is made up of 1100 thin stainless steel wires running parallel to each other along the entire length of the cylinder. The surface is supported by 24 parabolic frames on towers located 23 m apart. The ORT has an effective collecting area of about 8500 sq m.

The signals picked up by the dipoles are combined with suitable phase shifters to form 12 independent beams (originally designed to cover the lunar disk), and are useful in sky-survey observations. The telescope can be operated in either total power or correlation mode. The ORT, designed and fabricated with indigenous technological expertise and resources, has been in regular use since 1970, and continues to be a very sensitive radio telescope for specific applications. The receiver system was upgraded in 1993 by placing a radio frequency (RF) amplifier and a phase shifter after every dipole, and by computerising the declination-setting and monitoring system. These changes enhanced the sensitivity of the ORT by a factor of four, and improved the declination range coverage and stability of the settings (Selvanayagam et al. 1993). Since then, there have been several incremental improvements to the technical capabilities at the ORT, including new generation pulsar and spectral line receivers. More recently, the ORT is undergoing a major upgrade that is described in detail in a later section.

The ORT, a 530m long and 30m wide parabolic cylinder with its long axis parallel to that of the earth.

1.2 ORT: Some early results

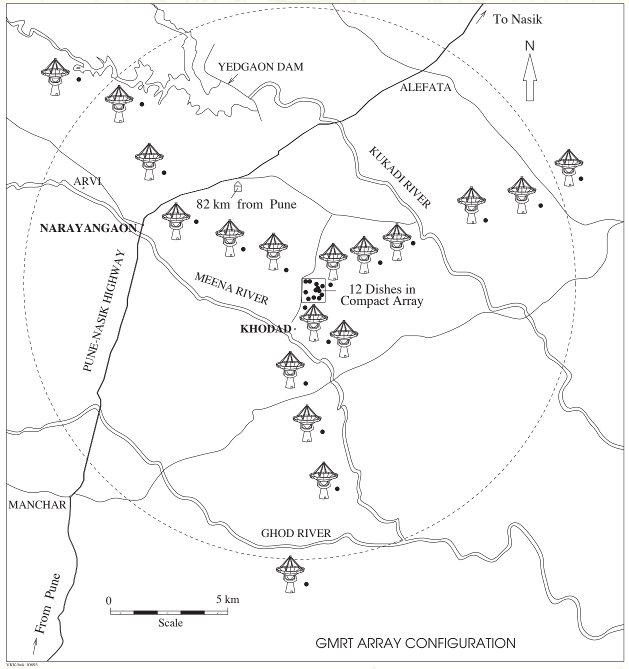
Observations made using the ORT have led to important discoveries and have helped to understand various phenomena occurring in our Solar system and other celestial bodies. During 1970-1978, the ORT tracked the Moon, for a general survey of the sky that provided the one dimensional brightness distributions of about 1000 galactic and extragalactic radio sources of flux density > 0.6 Jy at 325 MHz, with a resolution of ~ 1'' to 10". It was the best resolution achieved at the time, at this frequency. The ORT was used to investigate questions related to the steeper spectral index of high redshift radio galaxies by Kapahi and Kulkarni (1986) and Gopal-Krishna (1988). The ORT observations during the 1980s disfavoured the hot dark matter cosmological models (Subrahmanyan and Swarup 1990). Observations by Sarma and Mohanty (1978) from the ORT group and Anantharamiah and Radhakrishnan (1979) from the Raman Research Institute (RRI) put an upper limit on the Deuterium to Hydrogen ratio. The gravitational lens 1830-21, a bright pair of flat-spectrum radio knots separated by just 1", was serendipitously discovered in the course of a Galactic Plane Survey of scintillating extragalactic radio sources using the ORT (Rao and Ananthakrishnan 1984; Rao and Subrahmanyan 1988). Scintillation studies were also carried out on a well-defined sample of 100 flat-spectrum radio sources. The ORT also contributed significantly to the study of pulsars and the interstellar medium (ISM) of our Galaxy. Using the improved ORT, detailed studies of nulling and sub-pulse drifting behavior of some pulsars revealed interesting new results (Vivekanand and Joshi, 1997; Joshi and Vivekanand 2000). From a comprehensive survey of pulsar scintillation carried out during 1993 - 1998, it was shown that the Sun is immersed in a bubble of low density ISM surrounded by a shell of strongly scattering material (Bhat et al. 1998). It was also shown that the Loop-I bubble (believed to be a nearby supernova remnant) produces enhanced scattering from the plasma associated with its boundary (Bhat and Gupta 2001).

The ORT group has also made important contributions concerning the structure of radio sources, the solar wind and the interplanetary medium based on interplanetary scintillation (IPS) observations of distant radio sources. An extensive IPS survey of the Galactic plane (b < 10°) using the ORT showed an absence of scintillating radio sources of size < 0.5", indicating enhanced scattering towards the Galactic plane. The Ooty IPS studies provided for the first time a complete coverage for imaging of solar coronal mass ejecta structures all the way from the Sun to the Earth (Manoharan et al. 2001).

1.3 The Giant Metrewave Radio Telescope

Located near Khodad (about 80 km from Pune), the GMRT is an array of 30 dishes, each of 45 m diameter, spread out over a40 region of almost 25 km in diameter (Swarup et al.1991). It is currently the largest fully operational low frequency radio telescope in the world. The number and the configuration of the dishes were optimized for the principal astrophysical objectives which require sensitivity at high angular resolution as well as the ability to image radio emission from diffuse extended regions. Of the 30 dishes, 14 are located randomly in a compact central region of size about 1 sq. km, while the remaining 16 are placed along the 3 arms of an approximately 'Y'- shaped configuration over a much larger region, providing longest interferometric baselines of The correlation of radio signals from all the 435 possible pairs of antennas enables radio images of celestial objects to be synthesized with a resolution equivalent to that obtainable with a single gigantic dish of 25 km diameter. The parabolic reflecting surface of the dishes is made up of fine stainless steel mesh panels, instead of solid panels. This, coupled with a novel mechanical design concept initiated by Govind Swarup, and christened SMART (Stretched Mesh Attached to Rope Trusses), ensures low wind load, weight, and cost for the GMRT antennas, relative to more conventional alternatives.

The legacy GMRT system operates in 5 frequency bands around 150 MHz, 235 MHz, 325 MHz, 610 MHz and 1450 MHz. This is achieved by having multiple antenna feeds for the different bands on a rotating turret near the focal point of each dish. The voltage signals received by these dual polarized feeds are amplified and conditioned by low noise amplifiers and associated electronics located at the focus and at the base of the dish, with a maximum bandwidth of 32 MHz. They are then converted to intermediate frequencies and sent to the central receiver



Configuration of GMRT array

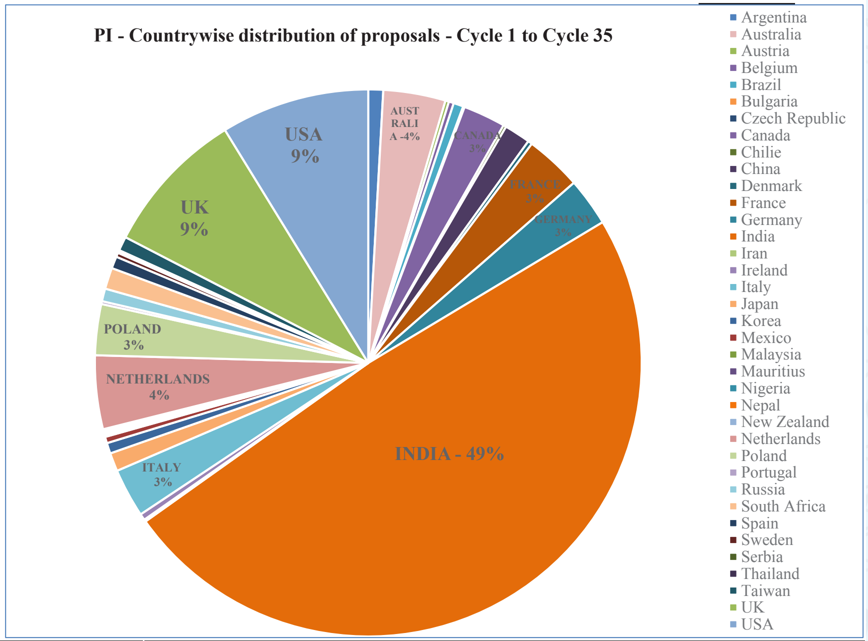
building over optical fibre connections from each dish.

1.4 The GMRT: some early results

The first observations with the GMRT were taken with a test system in 1997, and the telescope came into regular use from late 1998. On October 4, 2001, the facility was declared open to the international community. The GMRT is one of the foremost instruments for spectral line studies of redshifted neutral hydrogen (HI) in the Universe (e.g. Chengalur and Kanekar 2000; Kanekar and Chengalur 2003). Even the partially complete GMRT (8 out of 30 antennas) had the sensitivity and frequency coverage to detect damped Ly- alpha systems in absorption (Chengalur & Kanekar 1999). The GMRT also detected one of the early high redshift (z > 1) HI absorption systems (Ishwara- Chandra et al. 2003), and was the first telescope to carry out surveys for absorption from the OH molecule at cosmological distances (Kanekar and Chengalur 2002).

The first continuum imaging results with the GMRT confirmed three candidate supernova remnants (Bhatnagar 2000). Lal and Rao (2004) presented one of the earliest low frequency (240 MHz) GMRT images of 3C129, and Lal and Rao (2005) successfully demonstrated the popular dual frequency mode of the GMRT with observations of 3C223.1. Early studies of dwarf galaxies revealed ordered kinematics of the hydrogen gas, with dark matter profiles that do not match the expectations of cold dark matter theories (e.g. Begum et al. 2003). Micro-quasars in our Galaxy have been monitored regularly with the GMRT since 2002 (Ishwara-Chandra 2005).

Due to their steep spectrum, pulsars have higher flux densities at lower frequencies, ideally suited for observing with the GMRT and the telescope has been designed with special array modes for these kind of studies (Gupta et al. 2000). The GMRT has discovered some notable pulsars. The first of these was a binary pulsar system with a very highly eccentric orbit (Freire et al. 2004), and the second was a very faint young pulsar in a supernova remnant (Gupta et al. 2005). Early detailed research on pulsars included studies of emission properties and geometry of the emission regions (e.g. Gangadhara and Gupta 2001; Gupta et al. 2004), and follow-up observations of PSR J0737-3039 – the famous double pulsar system (e.g. Joshi et al. 2004).



Country	Nos	Country	Nos	Country	Nos	Country	Nos	Country	Nos	Country	Nos
Argentina	21	Czech Republic	1	Germany	68	Korea	15	New	3	Spain	17
Australia	88	Canada	60	India	1166	Mexico	9	Netherlands	104	Sweden	**6**
Austria	5	Chilie	4	Iran	3	Malaysia	3	Poland	72	Serbia	**1**
Belgium	7	China	37	Ireland	9	Mauritius	3	Portugal	4	Thailand	3
Brazil	14	Denmark	6	Italy	69	Nigeria	1	Russia	18	Taiwan	20
Bulgaria	1	France	80	Japan	26	Nepal	1	South Africa	30	UK	206
Total										USA	210

A view of several GMRT antennas

2. Current research areas at NCRA

Research activities at NCRA-TIFR are centered at low frequency radio astronomy, with members carrying out research in a wide range of areas. The GMRT and the ORT offer challenging opportunities to work at the frontiers of astronomy and astrophysics, as well as in instrumentation development.

2.1 Sun and Heliosphere:

Radio waves provide a view of the Sun that is very different from that at other wavelengths. Low-frequency solar radio emission characterisitics and morphology can change dramatically over short time durations and spectral widths; this variability has long posed a challenge for solar radio studies. NCRA-TIFR researchers have been leading solar studies with the Murchison Widefield Array (MWA), a precursor for the Square Kilometre Array (SKA). The unique high fidelity imaging capability of the MWA over short time spans and narrow spectral widths endow it with an unprecedented ability to simultaneously track changes in solar emissions across time, frequency and morphology over a broad spectral span.
The Sun also emits a wind, essentially a stream of charged particles released from the upper atmosphere. This solar wind affects radio waves from distant sources coming to us, as they travel through the solar system, giving rise to Inter-Planetary Scintillation (IPS). IPS provides an excellent remote sensing probe for the heliosphere, and the ORT has played a pivotal role in the development and application of IPS techniques.

2.2 Milky Way and Interstellar medium:

Understanding the physical conditions in the Milky Way is an important area of research at NCRA-TIFR. Radio imaging and spectroscopy offers insights into conditions in the Milky Way that are not available at other wavelengths. An active area of research is the centre of the Milky Way (the ``Galactic Centre'' region). Astronomers here also use deep radio continuum imaging studies to trace ionized gas structures arising from supernova remnants and ionized hydrogen regions in the Milky Way, and to derive densities, temperatures, and energetics therein. Attempts are also under way to understand acceleration mechanisms in supernova remnants. The astronomers also carry out research on the magnetospheres of massive stars.

Another important area of research at NCRA-TIFR is the interstellar medium (ISM) of the Milky Way and external galaxies, which consists of various gas phases, neutral atomic, ionized, and molecular gas, at different temperatures, pressures, and densities. The neutral atomic ISM is best probed with the hyperfine spectral line of neutral hydrogen at a rest wavelength of ~21 cm.

2.3. Pulsars and transients:

Pulsars is one of the main research areas at NCRA-TIFR. The members are involved in blind and targeted searches that have already resulted in a number of discoveries of new and interesting pulsars. The high sensitivity of the GMRT at low frequencies (< 800 MHz) makes it an outstanding telescope for pulsar surveys. Long term timing of millisecond pulsars is being carried out at NCRA to search for Gravitational Waves. Other research areas, aimed at understanding the origin of pulsar radio emission, include pulsar timing studies, studies of their emission properties such as the evolution of pulse profiles, nulling and mode changing phenomena, as well as scattering and dispersion of pulsar signals by the ISM. Theoretical attempts are also being made to find evolutionary pathways linking different classes of neutron stars.

Transients is a fast emerging research area at NCRA-TIFR. Radio wavelengths are particularly well suited for uncovering the complex transient phenomena since observations at radio wavelengths may suffer less obscuration than in other bands. The new capabilities of the GMRT correlator are being used to search for new types of fast transients. Members of NCRA-TIFR are carrying out multi waveband studies of fast transients to trace the density, temperature and shock conditions that accompany such events.

2.4. Galaxies:

The formation and evolution of galaxies remain an open area in cosmology. Some of the topics of research at NCRA-TIFR include morphological evolution of galaxies, high-resolution studies of the radio-far infrared correlation in galaxies, the magnetic field and diffusion of cosmic rays in nearby galaxies, radio continuum and neutral hydrogen studies of dwarf galaxies and compact galaxy groups, as well as studies of the disk-halo connection in galaxies.

2.5. Active Galaxies and clusters:

Active Galactic Nuclei (AGNs) are galaxies with extremely energetic phenomena, driven by activity around the supermassive black holes at their centres. The identification and detailed study of Compact Steep Spectrum and Gigahertz Peaked Spectrum sources, which constitute a significant fraction of such bright AGNs, are carried out at NCRA-TIFR. Seyfert galaxies are active galaxies exhibiting star-like nuclei superimposed on the centers of spiral galaxies. Several large samples of these galaxies are being observed at GMRT frequencies. Radio spectral studies are providing important constraints on the contributions of stellar versus AGN activity.

Galaxy clusters are the most massive gravitationally bound systems in the Universe and contain thousands of galaxies. The space between these galaxies is filled with diffuse, hot plasma, i.e. the intra-cluster medium (ICM). The galaxies and the gas are held together in the gravitational potential of dark matter which makes about 80-85% of a cluster's total mass. Researchers at NCRA-TIFR are carrying out ICM studies with the GMRT, providing a unique probe for the relativistic electrons and magnetic fields in the ICM. In clusters undergoing violent mergers with other clusters, the shocks and turbulence can lead to the formation of radio halos and radio relics. NCRA-TIFR astronomers use the GMRT and other radio and X-ray telescopes to uncover the processes that govern these phenomena.

2.6 High-redshift Galaxies:

Understanding the nature of high-redshift galaxies is an important research area at NCRA-TIFR. Astronomers here use a wide range of observing frequencies, to probe physical conditions in high- redshift galaxies. The techniques used include neutral hydrogen (HI) 21cm absorption studies, HI 21cm emission studies of individual galaxies, "stacking" of HI 21cm emission, millimetre-wave carbon monoxide (CO) emission and absorption studies, ionized carbon (C+) emission studies, hydroxyl (OH) 18cm absorption studies, radio continuum studies, optical and ultraviolet imaging and spectroscopy, etc.. NCRA-TIFR astronomers use both molecular absorption and emission studies of high-z galaxies to obtain information on physical conditions in these objects.

2.7 Cosmology & Epoch of Reionization:

Scientists in NCRA-TIFR are interested in various aspects of theoretical cosmology, starting from galaxy formation at early cosmic times to understanding the nature of dark matter and dark energy. In particular, a large effort is being spent to understand the physics of galaxy formation using neutral hydrogen across cosmic epochs,. including the GMRT. Work is also being done on theoretical modelling of the EoR, which probes the formation of the first stars in the early Universe. Simulations of the HI 21cm emission signal from neutral hydrogen at different cosmic times are also being carried out.

2.8 Evolution of Fundamental Constants:

Fundamental constants are not expected to change with space or time in the standard model of particle physics or General relativity. Tests of variation of such low-energy fundamental constants are thus tests of the basic assumption of the standard model and relativity, similar to tests of violations of the weak equivalence principle, Lorentz invariance, local position invariance, etc. Astronomical studies allow one to probe such evolution on timescales of billions of years, and to thus test the validity of the standard model on cosmological timescales. Researchers here have come up with new techniques to probe fundamental constant evolution, based on radio spectral lines. They also use radio telescopes to carry out accurate measurements of the redshifts of atomic and molecular radio spectral lines to carry out amongst the most accurate tests of cosmological changes in the fine structure constant and the proton-electron mass ratio.

2.9. Deep Fields and Surveys

Deep multi-wavelength studies of extragalactic fields allows one to study in detail how galaxies and their stars and gas evolve through the age of the Universe. Radio and infrared imaging is especially important in this area, because most actively star-forming galaxies are obscured by dust and are hence not visible in optical images. Researchers here use deep radio images of such extragalactic fields to address the above issues. Systematic surveys that map large areas of the sky with high sensitivity is a major program here.

2.10. Astronomical Instrumentation

Areas of research and development at NCRA-TIFR include wideband antenna feed elements, sensitive frontend analog electronics with high dynamic range, new signal transport systems, and back-end receiver systems combining hardware and software technologies. Of particular interest is the development of flexible software- and hardware-based back-ends. New modes include flexible post-processing of voltage signals, mitigation of terrestrial interference, the detection of transients, new correlation modes for interferometry, etc, which have greatly enhanced the capabilities of both the GMRT and the ORT.

3. Some recent Science results

This section highlights exciting new results with the GMRT and the ORT, as well as other important research by NCRA-TIFR members over the last three years.

3.1 Sun and heliosphere

D. Oberoi and his group have been working on developing the tools and techniques for achieving high dynamic range snapshot spectroscopic Imaging capability with the fine grained and sensitive data from the MWA. Mondal et al. (2019) have developed AIRCARS (Automated Imaging Routine for Compact Arrays for Radio Sun), an unsupervised imaging pipeline which delivers high imaging dynamic range and high fidelity images. These images with dynamic ranges between 1,000 and 100,000 are enabling unprecedented detailed studies of weak emissions and are already leading to new insights. The solar images from this work mark an improvement of two to three orders of magnitude in dynamic range over earlier best efforts, and represent the current state-of-the-art (Fig 3.1.1).

Using AIRCARS, Mohan et al. (2019a) discovered anti correlated second scale quasi-periodic oscillations (QPOs) in the area of the source of type III burst emission and its integrated flux density. They found that these QPOs are too large and too rapid to be explained by local MHD oscillations at mid coronal heights, and must arise at a much lower coronal depths (Fig. 3.1.2). Mohan et al. (2019b) also carried out the very first spectroscopic imaging study of a type I noise storm. It was associated with an active region loop hosting a transient brightening. This work lead to the discovery of 30s QPOs in the radio light curve.

A team including G. Swarup and D. Oberoi (Mohan et al. 2018) carried out polarization and Brightness

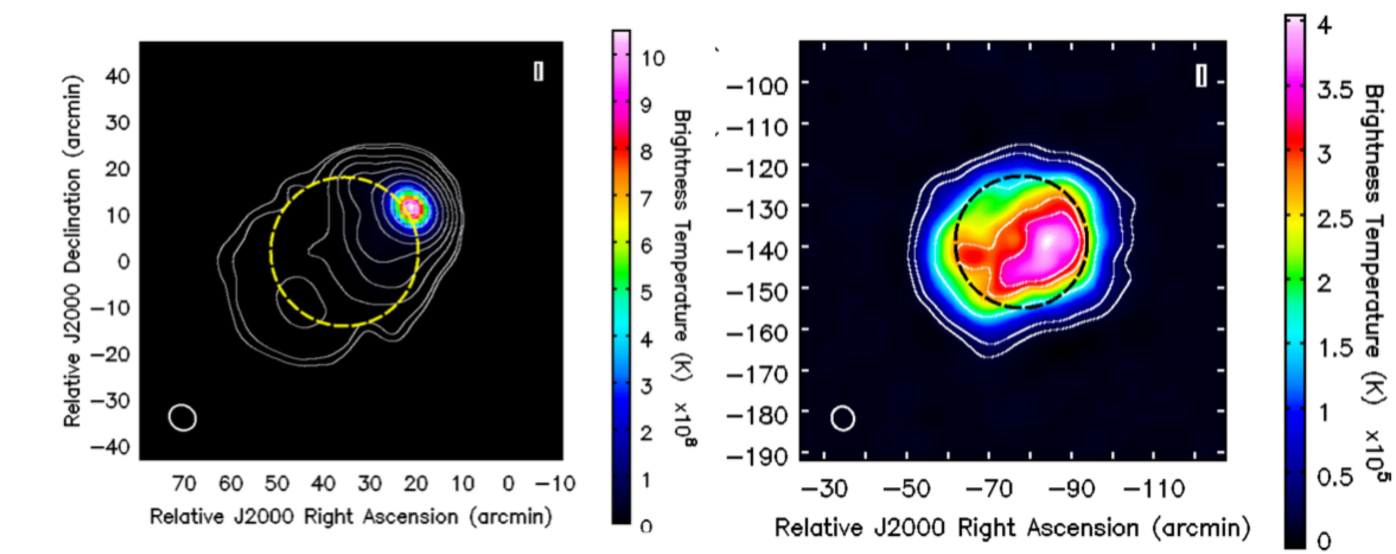


Fig. 3.1.1: AIRCARS images of the Sun with MWA. Left: a CME was in progress and a compact bright source is present. Right: an image from a very quiet Sun.

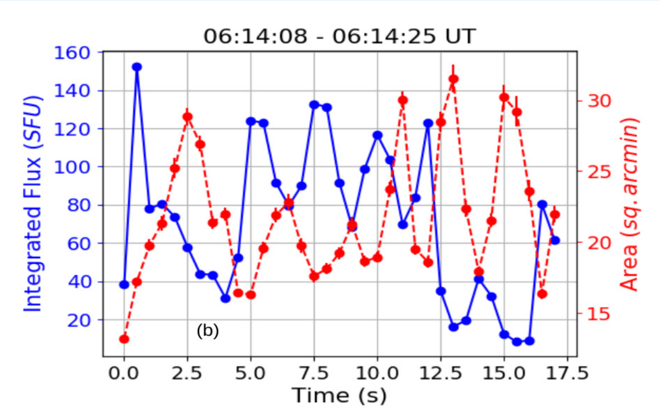


Fig. 3.1.2: The anti-correlation observed between the integrated flux density (blue) and the area of the source of burst emission (red) for one of the groups of type III bursts

Temperature T_b observations of Venus made at 23cm , 49cm, 91cm and 1.28m with the GMRT. Comparing those with high frequency observations, they found that the brightness temperature decreases at 680K at 5 GHz, then decreases continuously to 622K at 23cm, 548K at 49cm, 409K at 91cm and to < 321K at 1.28m indicating that radiation at dcm and m wavelengths is likely to arise from the subsurface of Venus. Using the degree of polarization maps of Venus made with the GMRT and Fresnel equations, the dielectric constant was derived (Fig 3.1.3).

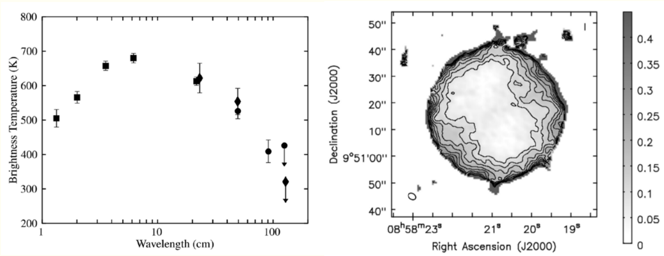


Fig. 3.1.3: Left: A plot of the T_b measurements of Venus. Right: Contour plot of degree of polarization across Venus at 1297.67 MHz

3.2 Milky Way and interstellar medium

P. Chandra and her group are carrying out a survey of magnetic OBA stars to understand their magnetic topology and resulting radio emission. HD133880 is a B-type rapidly-rotating star, characterised by the presence of an asymmetric dipolar magnetic field. In 2015, Chandra et al. reported strong enhancement in the star's radio flux (at 610 MHz and 1420 MHz) at certain rotational phases, but the phase coverage was too limited. Das et al. (2018) carried out detailed study covering full rotational phase aimed to understand the origin of the radio pulses, by using the GMRT 610 and 1420 MHz receivers. The GMRT 610MHz data revealed a dramatic increase (by an order of magnitude) in the star's radio emission at magnetic null(Fig. 3.2.1). The emission was 100% polarized. They attributed Electron Cyclotron Maser Emission (ECME) as the likely cause of the observed enhanced radiation. Previously, only one magnetic star (CU Vir) was known to host this mechanism. They have discovered ECME in two more stars and carrying out ECME studies in a larger sample (Das et al. 2019a,b). The discovery of the maser mechanism emphasizes the importance of low frequency studies of magnetic stars, where ECME is favourable (Fig. 3.2.1).

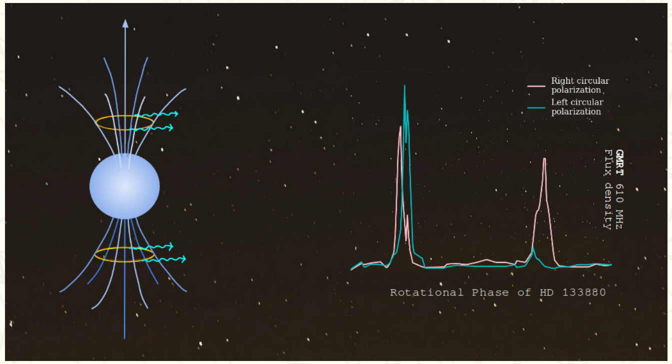


Fig: 3.2.1: Evidence of ECME in HD 133880

Chandra & Kanekar (2017) used the GMRT frequencies to monitor the black hole X-ray binary V404 Cygni during its 2015 June outburst. They find the low-frequency radio emission of V404 Cygni to be extremely bright and fast-decaying in the outburst phase, with an inverted spectrum below 1.5 GHz and an intermediate X-ray state. They identified a spectral turnover in the radio spectrum at ~1.5 GHz on June 26.9 UT, which along with the assumption of equipartition of energy between the particles and the magnetic field was used to infer the jet radius, magnetic field, minimum total energy, and transient jet power. The relatively low value of the jet power, despite V404 Cygni's high black hole spin parameter, suggested that the radio jet power does not correlate with the spin parameter.

Nayana et al (2017) used the GMRT to detect 325 and 610 MHz radio emission from HESS J1731-347, one of only five known very-high-energy (VHE; > 0.1 TeV) shell-type supernova remnants (SNRs). The faintest feature in the GMRT bands corresponds to the peak in the VHE emission. This anti-correlation along with the observed steepening of spectral index can be explained if the observed VHE gamma-ray emission has a leptonic origin (Fig. 3.2.2).

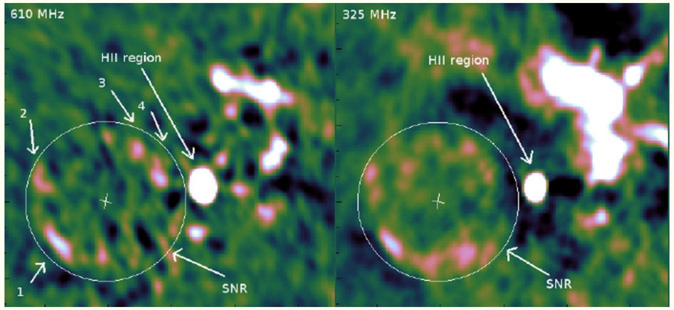


Fig. 3.2.2: 610 (left) and 325 (right) MHz images of SNR HESS J1731-347.

3.3 Pulsars and transients

Pulsars have tremendous untapped potential to probe the behaviour of matter, energy, space and time under extraordinarily diverse conditions. Even though pulsars are frequently getting discovered with ongoing surveys at major telescopes over the world, the presently known pulsar population is only 1% of that predicted by stellar synthesis models. The hitherto unexplored potential of GMRT for low-frequency pulsar surveys has been recently emphasised by the GMRT High Resolution Southern Sky (GHRSS; Bhattacharyya et al. 2016, 2019; survey, a P-band low-frequency survey for pulsars and transients away from the Galactic plane for full southern sky (up to declination of -54 degrees) conducted by a team led by NCRA-TIFR and the Pulsar group at University of Manchester. Having synergy with the time-domain survey with SKA1 Mid Band-1, GHRSS is probing the lower range of the pulsar luminosity distribution and helping in exploring the shape of this distribution which will be vital for understanding how many pulsars the SKA will find. . Over last 6 years from ~ 4000 square degree of survey sky this survey yields discovery of 20 pulsars and two Rotating Radio Transients (RRATs). Out of these, 9 discoveries came from the upgraded GMRT (uGMRT) 300 to 500 MHz observations in Phase-2 of GHRSS. Two significant discoveries over last one year are a compact binary millisecond pulsar (MSP) J1243-47 with ~ 8 hours orbit, the first MSP discovered with the uGMRT and a RRAT J2004-38, the first one discovered via machine learning classifier based on FETCH (Agarwal et al. 2019), which we have successfully implemented in the GHRSS transient search pipeline (FIg 3.3.1).

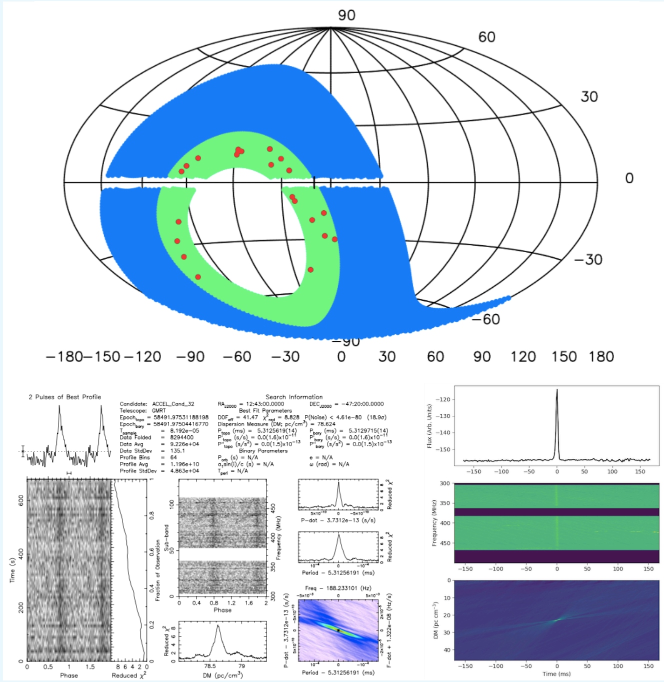


Fig 3.3.1 Top panel: Galactic distribution of pulsars and RRATs discovered from GHRSSn survey. The green shaded region mark the 33% of the target sky covered till now with discoveries marked in red. Current observations are targeting the sky shaded in blue. Bottom panel: 1st MSP discovered with the uGMRT from GHRSS survey (left) and the 1st RRAT discovered via machine learning based classifier implemented for the GHRSS survey (right).

Bhattacharya et al. (2019) have carried out a long term study of three Rotating Radio Transients (RRATs), performed with the Lovell, Parkes and Green Bank telescopes over the past decade. The study also detected, for the first time, a weak persistent mode in PSR J1913+1330, suggesting a possible connection between RRATs and the normal pulsar population. They also studied the post-glitch timing properties of one RRAT, PSR J1819-1458, in detail.

Taking advantage of enhanced sensitivity due to wide-band receivers, commissioned in the recent upgrade of the GMRT, PuGMarks, a pilot uGMRT pulsar survey, was initiated towards the end of 2016 by Y. Gupta and collaborators. This pilot survey covered 300 square degrees of sky near the Galactic center in 512 pointings observed in band 3 of uGMRT (300 - 500 MHz), and band 4 (550-750 MHz). The first new detection was reported by the team in 2017 (Fig 3.3.2), and the second new discovery followed in mid-2018.

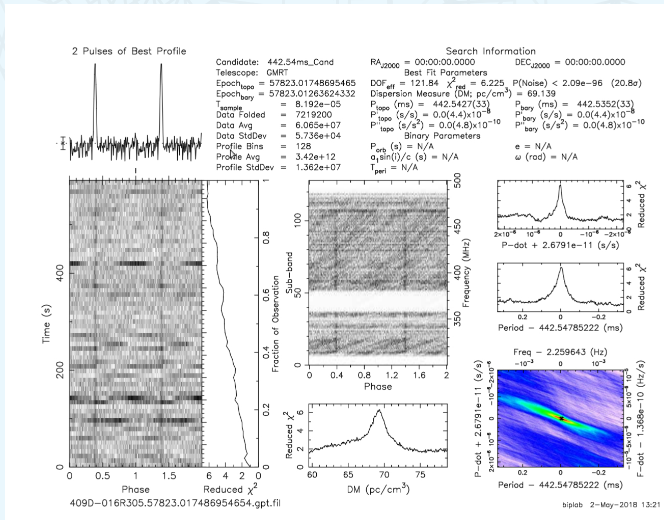


Fig 3.3.2 First new pulsar discovered with the uGMRT

In time-domain survey, Roy, Chengalur and Pen (2018) have developed a post-correlation beam- forming (i.e. beam-forming which involves only phased sums of the correlation of the voltages of different antennas in an array) which significantly improves the capabilities and sensitivity of the uGMRT for discovering new pulsars and fast radio bursts (FRBs). This new technique dramatically reduces the effect of red-noise and radio frequency interference, yielding more than factor of 2 improvements in the GMRT time-domain survey sensitivity.

A. Basu and B. C. Joshi are carrying out a monitoring of young pulsars to detect abrupt increase in their rotation periods, known as a glitch. They detected the largest glitch known so far in the Crab pulsar (PSR J0534+2200) in their high cadence monitoring of this pulsar with the OR and the GMRT. Curiously, the increase in rotation rate in this glitch was not abrupt, but showed a transient with a time-scale of 1.78(1) days (Figure 3.3.3). The fractional changes in the rotational frequency and its derivative in this glitch were 484.39(1) and 5.173(6) respectively, making it twice as large as the previous largest glitch seen almost 13 years back. The post-glitch recovery behaviour in Crab requires a model with a short term transient response and a longer term recovery (Fig. 3.3.3)

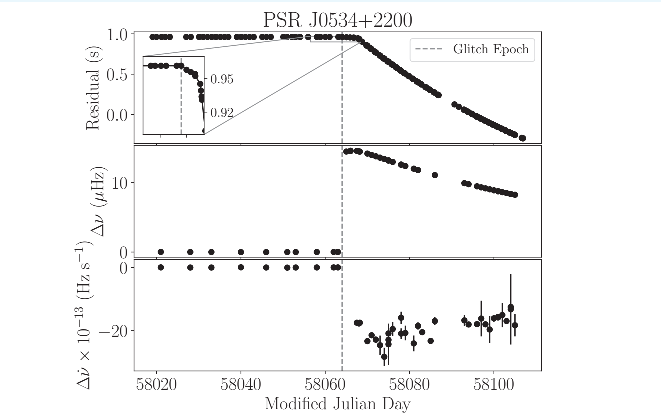


Fig 3.3.3 The giant glitch in Crab pulsar (PSR J0534+2200)

The short term transient response may be described by an over-damped second order transfer function. These measurements constrain the fractional moment of inertia of the crustal super-fluid involved in this event and the physics of its coupling with other parts of the star. This program has discovered 11 pulsar glitch events so far.

Mann et al. found the transient radio emission in the first-ever magneter XTE J1810-197. It has recently transitioned into the second known radio outburst phase. They observed the magnetar at low radio frequencies using the GMRT, soon after the onset of its recent outburst, and reported the first detection of the source at frequencies as low as 300 MHz. The magnetar exhibits radio emission in the form of strong, narrow bursts, with a characteristic intrinsic width of the order of 0.5-0.7 ms. Maan et al. also found that the bursts exhibit spectral structures which cannot be explained by interstellar propagation effects. These structures might indicate a phenomenological link with the repeating FRBs, which also show interesting, more detailed, frequency structures (Fig. 3.3.4)

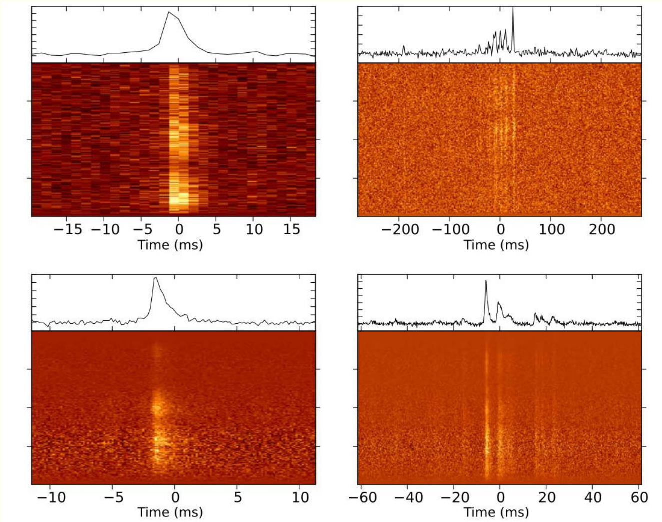


Fig 3.3.4 Radio burst emission from Magnetar XTE J1810-197

Bera and Chengalur observed the Crab pulsar with the NCRA-15m telescope for ~260 hours and detected 1799 super-giant pulses with pulse-energies > 100 Jy ms at an observing frequency of 1.3 GHz. This is the largest sample of giant pulses with pulse-energies > 100 Jy ms at these frequencies, facilitating a statistical study of giant pulses up to pulse energies of ~3000 Jy ms, two orders of magnitude larger than energy ranges probed in similar earlier studies. The sample also contains one of the brightest giant pulses ever observed from the Crab pulsar. They studied the statistical properties of a sub-sample of 1153 super-giant pulses complete down to a pulse energy of 130 Jy ms and compared the distribution to that of the currently known FRBs. They find that the pulse-energy distribution (shown in the top panel of the figure 3.3.5) of giant pulses of the Crab pulsar follows a single power law,

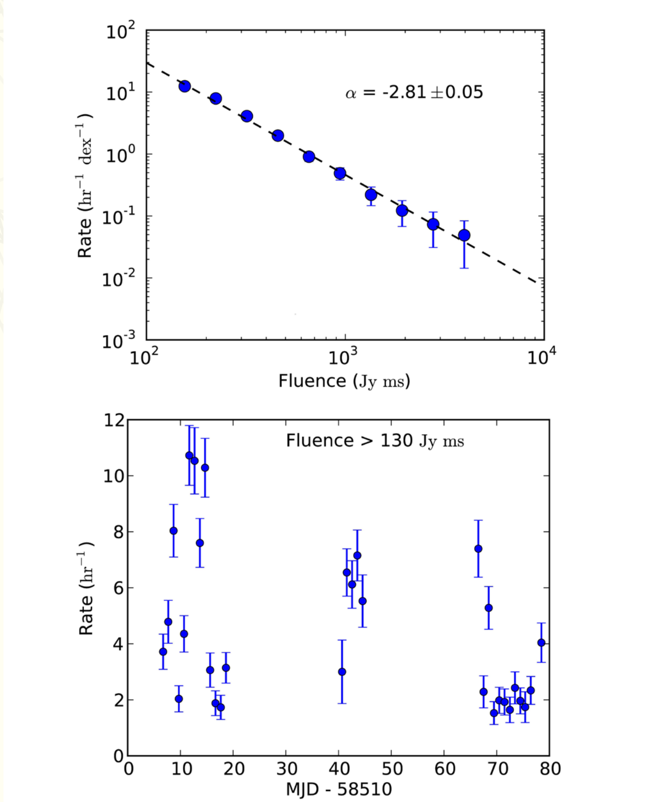


Fig. 3.3.5 Giant pulses from the Crab Pulsar

with power-law index approximately -3, over at least three orders of magnitude in pulse energy, from ~3 Jy ms to ~3000 Jy ms. The power-law index is in excellent agreement with that found for one of the repeating FRBs (FRB 121102). They also find that the rate of occurrence of super-giant pulses varies by a factor of approximately 5 on time scales of a few days (shown in the bottom panel of the figure 3.3.5), although the pulse-energy distribution remains the same within the uncertainties in both the “active” and “passive” phases (with relatively high and low rates of occurrence).

B. C. Joshi and his group has been investigating ionized inter-stellar medium using pulsars as a probe. The multi-path propagation of the pulsed signal broadens the pulse and is an effective probe of turbulence spectrum of electron inhomogenities. Wide-band seamless frequency coverage of the upgraded GMRT and the new upgraded pulsar receiver PONDER at the ORT was used to estimate scatter broadening in pulsars. These were augmented at low-frequencies using data from LOFAR and LWA and at higher frequencies using data from Parkes and Arecibo radio telescopes. The measurements of α by two folds, from 60 such measurements known till 2015 to 137 known as of today. Nearly 65\% of the pulsars show a flatter index (i.e., α < 4.4) than that expected from the Kolmogorov turbulence and (c) α for pulsars with DM > 500 $pc\text{-}cm^{-3}$ is

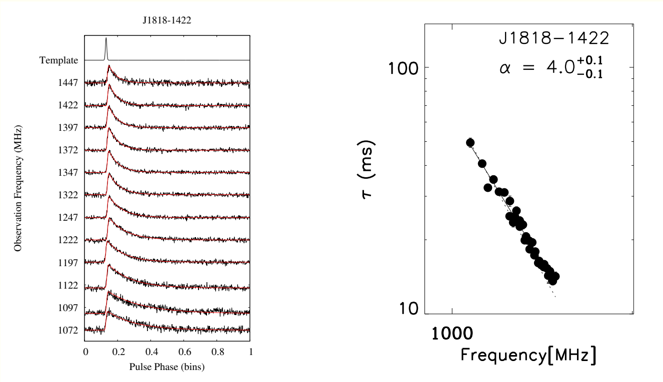


Fig: 3.3.6 Pulse scatter-broadening seen in wideband (400 MHz) uGMRT observations of PSRJ1818–1422

closer to Kolmogorov turbulence and without a trend for flatter α contrary to what was reported earlier (Fig 3.3.6)

B. C. Joshi, Yashwant Gupta and collaborators are carrying out precision timing of a sample of millisecond pulsars with the upgraded GMRT and the ORT. Timing this ensemble of pulsars enables measurement of tiny shifts in their apparent pulse periods caused by passing nano-Hertz Gravitational Waves from a stochastic Gravitational Wave background. This experiment, called Indian Pulsar Timing Array (InPTA), uses the unique frequency coverage of the uGMRT and the ORT to measure epoch-to-epoch Dispersion measures to fifth decimal of precision.

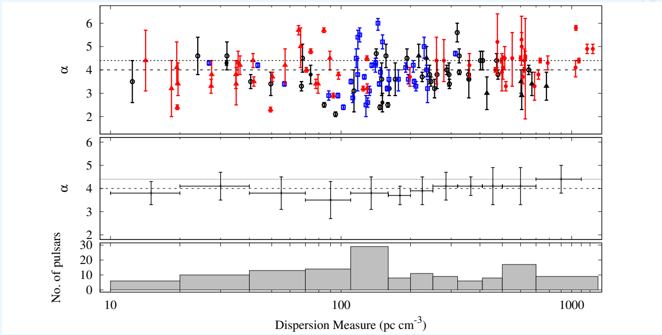


Fig: 3.3.7 Measurements of frequency scaling index, α, from one of the largest such studies using the ORT, the uGMRT, the LOFAR and the Arecibo telescope.

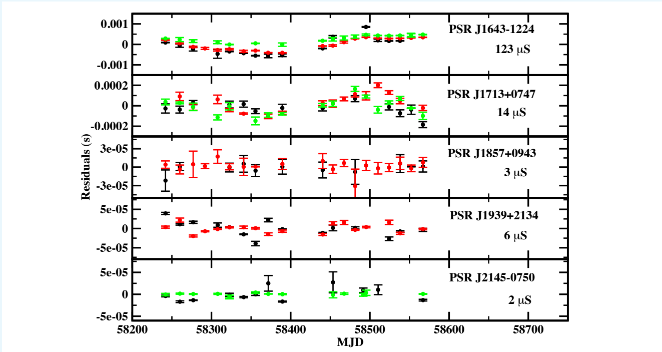


Fig: 3.3.8 The times-of-arrival residuals for the sample of pulsars being monitored as part of Indian Pulsar Timing Array experiment (InPTA

InPTA has so far been able to measure the times-of-arrival of pulsars incorporating these variations up-to a few μs precision and are poised to contribute the data towards a global initiative called International Pulsar Timing Array (IPTA). (fig. 3.3.8)

P. Chandra and her collaboration have worked on the binary neutron star (BNS) merger gravitational wave event GW 170817. They obtained low frequency data from multiple radio telescopes, including uGMRT, VLA, ATCA and MeerKAT. Their studies at early time ruled out the off-axis and on-axis jet models (Hallinan et al. 2017), whereas, the data in first three months were instrumental in establishing that the radio emission is arising from a wider sub-relativistic cocoon, formed via transfer of energy from jet to the polar ejecta (Mooley et al. 2018a). The cocoon interaction with the surrounding medium gives rise to the radio emission. However, in this model, one is not clear whether jet lost all its energy to cocoon, or survived and penetrated out. In their latest radio observations (Mooley et al. 2018b), the steep turn over and sharp decline was consistent with a jet geometry, confirming jet broke through the cocoon. This has, for the first time, provided unambiguous confirmation that short gamma-ray bursts are linked with BNS mergers (Fig. 3.3.10).

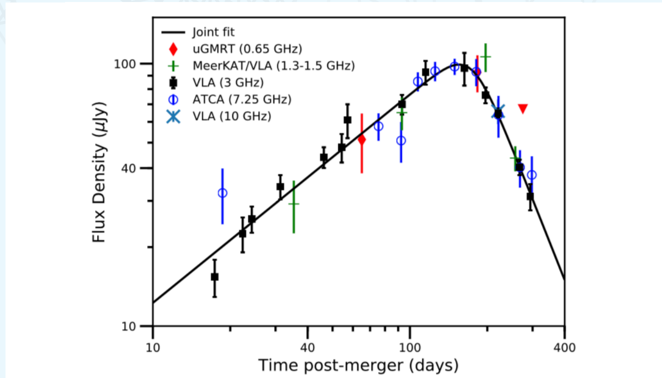


Fig. 3.3.9 The radio light curve of GW170817 at multiple frequencies, and scaled to 3GHz. The -2.17 decay is consistent with a jet model.

A. J. Nayana and P. Chandra are carrying out a GMRT survey to understand low-frequency detectability of core-collapse supernovae. Under this project they have carried out a long term study of a few core collapse supernovae. One of the supernova Master OT J120451.50+265946.6 was followed extensively with the GMRT and they found that the radio-emitting shock is inhomogeneous, with the inhomogeneities confined within the magnetic field distribution. Because of these inhomogeneities, the absorption is due to the superposition of various optical depths caused by varying magnetic fields. The inhomogeneities are primarily visible at low frequencies, and the high-cadence, high-sensitivity GMRT observations were critical in unraveling the nature of the inhomogeneities, which has important implications for the size of radio emitting regions (Fig: 3.3.10).

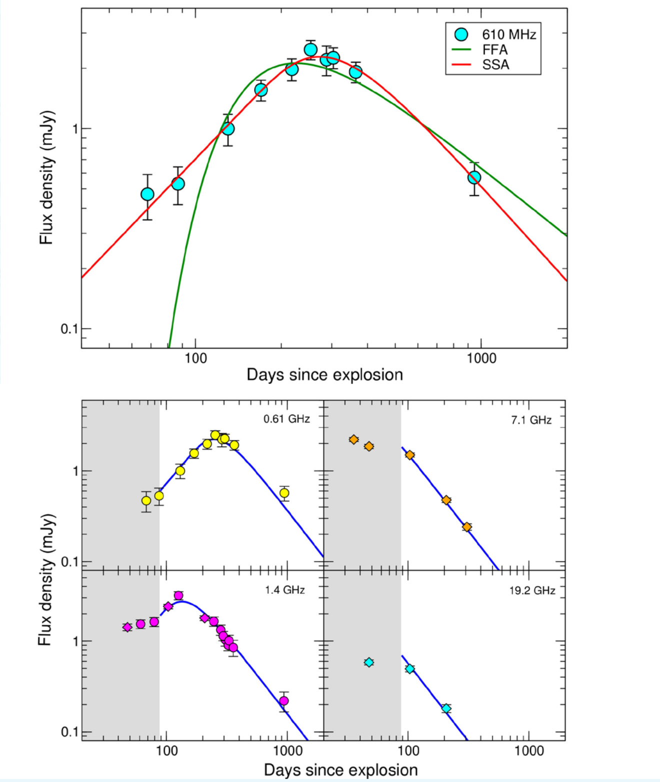


Fig: 3.3.10 - Top: Radio emission models fit to MRT 610 MHz light curve of supernova Master OT J120451.50+265946.6. Bottom: Best fit inhomogeneous model to the data.

The first detection of micropulse emission from millisecond pulsars has been reported with the GMRT. Radio emission from pulsars exhibits various time scales, ranging from seconds, milliseconds, and down to microseconds. The last kind, referred to as "microstructure'' had been seen so far only in normal period pulsars, and it's occurrence in the much more rapidly rotating millisecond pulsars was significantly shorter than those seen in normal period pulsars. They are thus able to extend the relationship between microstructure timescale and rotation period down to millisecond rotation periods and find it to obey the same general proportionality. This remarkable result has important implications for pulsar radio emission theories that attempt to explain the origin of pulsars microstructure (Fig 3.3.11).

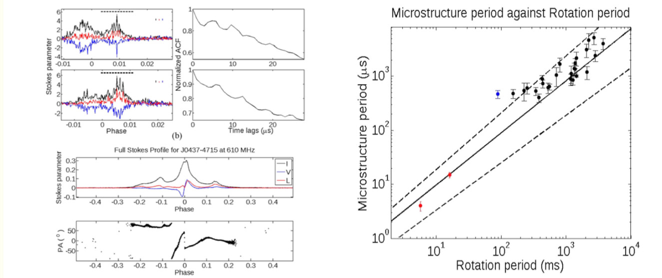


Fig. 3.3.11: First detection of microstructure emission from millisecond pulsars. Left: Two sample single pulses from the millisecond pulsar PSRJ 0437-4715 at 610 MHz, alongwith the average profile below. Right: Microstructure periodicity plotted against pulsar rotation period, with new points in red extending the relationship to millisecond periods.

3.4. Galaxies

Chowdhury and Chengalur used archival GMRT, VLA and WSRT HI 21cm data of five gas-rich wdwarf galaxies and found that the specific angular momentum in these smaller, less massive, dwarf galaxies is significantly higher than that expected from the earlier studies of spiral disks. Kurapati et al. (2018) use high-resolution HI 21cm observations and broad band photometry to measure the baryonic mass and baryonic specific angular momen tum of 11 dwarf galaxies that lie in the Lynx-Cancer void. They found that the specific angular momentum of void dwarf galaxies is similar to that of other dwarf galaxies in average density environments. However, all dwarf galaxies have significantly higher specific angular momentum than expected. They found that the observed amount of observed star formation in their sample galaxies is insufficient to produce the observed increase in the specific angular momentum. It hence appears that some other, as yet unknown mechanism, plays a role in producing the observed enhancement in specific angular momentum (Fig. 3.4.1).

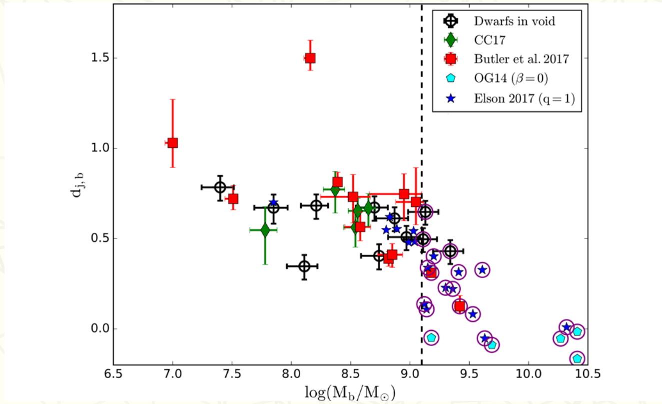


Fig. 3.4.1. The difference between the observed specific angular momentum of dwarf galaxies and the specific angular momentum expected from the bulge-less spiral relation

Bait et al. (2019) discovered an extremely large (diameter approximately 115 kpc) neutral hydrogen (HI) ring, off-centred from a massive quenched galaxy, AGC 203001. The ring does not have a bright extended optical counterpart unlike several other known ring galaxies. Such extended HI structures are rare, with only one other case known so far -- the Leo ring. Conventionally, off-centred rings have been explained by a collision with an "intruder'' galaxy, leading to expanding density waves of gas and stars in the form of a ring. However, in such a scenario the impact also leads to large amounts of star formation in the ring which is not observed in the ring presented in this paper. Alternatively, such a ring could also form due to tidal interactions with a neighbouring galaxy or even major mergers. The exact physical mechanism for the formation of such rings is still under debate (Fig. 3.4.2).

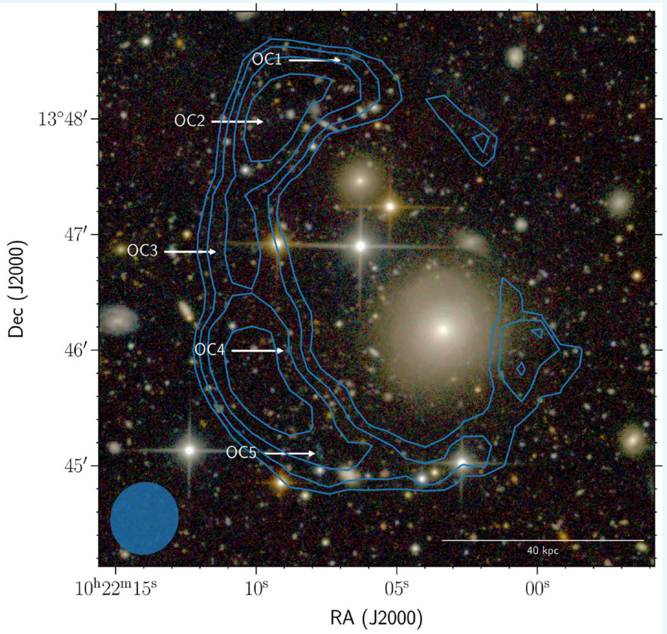


Fig. 3.4.2 Discovery of a large HI ring around the quiescent galaxy AGC 203001

Sebastian and Bait (2019) observed ten of the brightest blueberry galaxies from the sample of Yang et al. (2017), using the uGMRT at 1.25 GHz, and detected 9 blueberries in the uGMRT continuum images. However, the 1.25 GHz continuum flux densities were lower by a factor of approximately 3.4 compared to the values expected from scaling relations obtained from normal star-forming galaxies. Possible explanations for the lower radio flux densities in blueberries include a deficit of cosmic ray electrons (CREs) or low values of magnetic fields due to the young ages of these galaxies and the escape of the CREs via diffusion or outflows. They also calculated the value of magnetic fields and found that, despite their young ages, the blueberries show magnetic fields that are larger than those seen in galaxies with large-scale ordered rotation. They suggest that small-scale dynamo mechanisms play an important role in the magnetic field amplification in blueberry galaxies (Fig. 3.4.3).

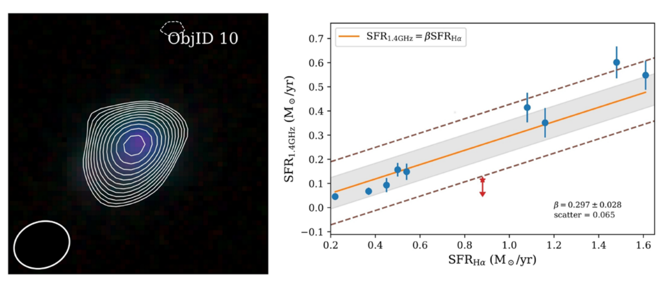
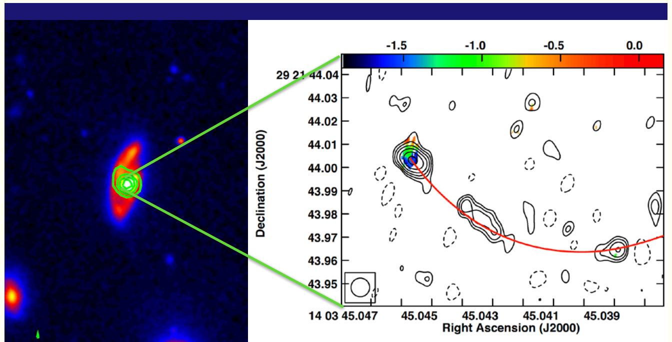


Fig. 3.4.3 Left: The uGMRT 1.25 GHz image overlaid on an optical grz-band colour composite image. Right: the star formation rates (SFRs) derived from the uGMRT radio continum flux densities

3.5. Active Galaxies and clusters

Kharb et al. are studying radio outflows, which are frequently observed in Seyfert galaxies, in spite of their “radio-quiet” AGN status. These can span extents ranging from 10s of parsecs to 10 kpc or more. While nuclear starburst wind contributions to the radio emission cannot be completely ruled out in some Seyfert galaxies, sensitive or phase-referenced very long baseline interferometry (VLBI) observations more often than not reveal parsec-scale radio cores and wiggly radio jets them. In individual sources with multi-scale data on parsec, sub-kpc and kpc-scales, an AGN jet, which



(Left) SDSS optical image of the double-peaked emission-line Seyfert 2 galaxy KISSR 434 with the VLA FIRST radio contours superimposed in green. (Right) 1.5 GHz VLBA radio contour image with the 1.5 - 4.9 GHz spectral index image in colour; the average spectral index is steep (α ~ -1.0). The red curve highlights the curved 150 parsec long jet in this galaxy, which could be precessing. (From Kharb et al. 2019, ApJ)

Fig. 3.5.1: Optical (left) and radio (right) images of Seyfert 2 galaxy KSSR 434.

could be curved in many cases, can connect the emission on different spatial scales, making the case for an AGN origin for the radio outflows. Curved jets could suggest jet-ISM interaction or precession, which in turn could suggest the presence of binary black holes or accretion disk instabilities (Kharb et al 2015, 2017a, 2017b, 2019, Fig. 3.5.1).

A team involving S. Sonkamble (Kadam et al. 2019) has looked at 134ks Chandra data of a peculiar galaxy cluster Abell 2626 and identified two nuclear sources. The systematic study of these nuclear sources exhibited that the NE source that emitted mostly in the soft band in the past disappeared in the recent observations. Instead, an excess emission was seen at 2.2 kpc on its west and required an unrs to be accountealistic line of sight velocity of 675c if is due to its movement. The count rate analysis and spectral analysis exhibited a change in the state of the SW source from a soft state to the hard due to the change in the mass accretion rate. No such spectral change was noticed for the NE source. Detailed picture of two nuclear sources will help understand the peculiar morphology of Abell 2626 (Fig. 3.5.2).

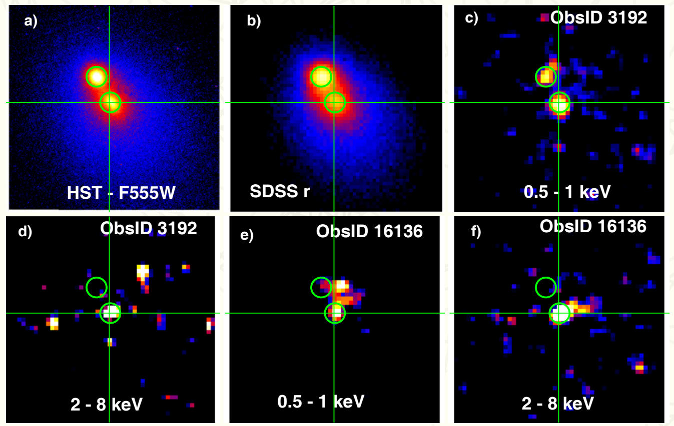


Fig. 3.5.2 SDSS Optical (a,b) and Chandra X-ray (c, d, e, f) images of central 25”x25” of A2626. Each of the Chandra image is divided into two different energy bins: 0.5-1 keV and 2-8 keV

Measurement of the spectra of remnant radio galaxies is important to understand their role as a source of cosmic ray electrons in the intra-cluster medium. With the Upgraded GMRT in the bands 200-500 MHz and 1000-1400 MHz, Kale et al. (2018) measured the spectral curvature across a remnant radio galaxy in the galaxy cluster Abell 4038, for the first time. Remnant radio galaxies like this one are believed to provide the seed relativistic electrons responsible for much larger scale sources called the radio halos. Their spectra are assumed to be simple power-law in simulations. The uGMRT measurements show this assumption is not valid and the measured spectral variation needed for (Fig. 3.5.3).

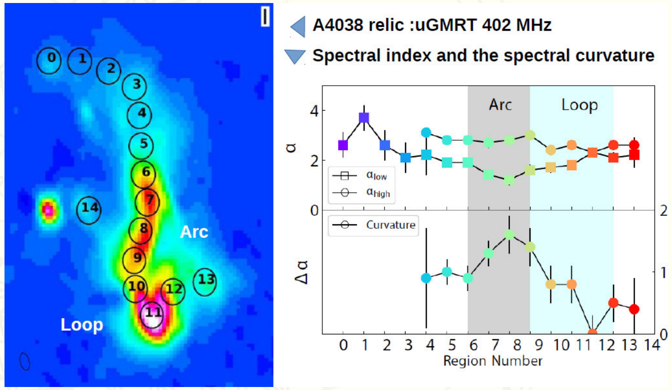


Fig. 3.5.3 : 402 MHz uGMRT image of A4038

Kale et al. report the discovery of a "radio halo", a diffuse radio source, in the galaxy cluster RXCJ0232.2-4420 (SPT-CL J0232-4421, z = 0.2836) using the uGMRT, HST and Chandra. Diffuse radio sources associated with the intra-cluster medium are direct probes of cosmic ray electrons and magnetic fields in the cluster. Although magnetic fields are believed to be ubiquitous in galaxy clusters, such radio sources are rare. The newly-discovered source has an extent of 550 kpc x 800 kpc - a size in the radio halo category. However, it surrounds the Brightest Cluster Galaxy like a typical mini-halo. Kale et al. have compared the radio power of this source with that of known radio halos and mini-halos and found it to be consistent with both populations. In the X-ray bands, this cluster has been classified as a complex system - indicating a state that is neither a merger nor a completely relaxed state. Kale et al. hence propose that this system is among the rare class of transition systems between mini-halos and radio halos (Fig 3.5.4).

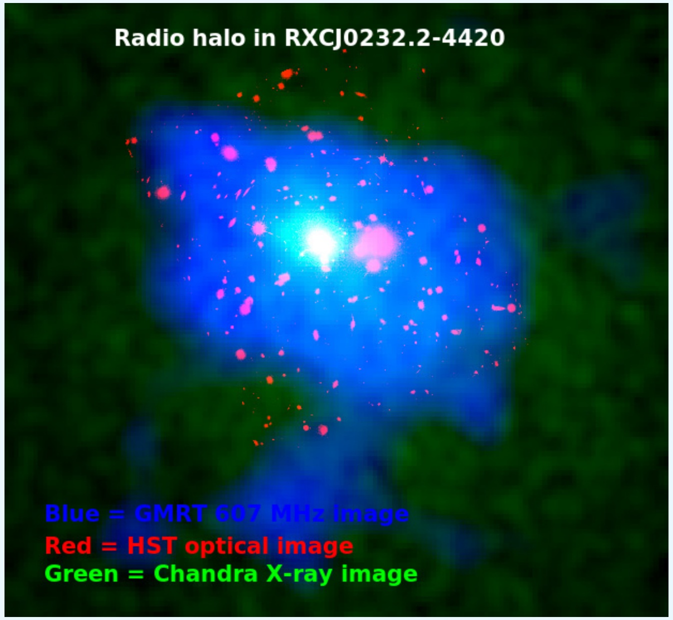
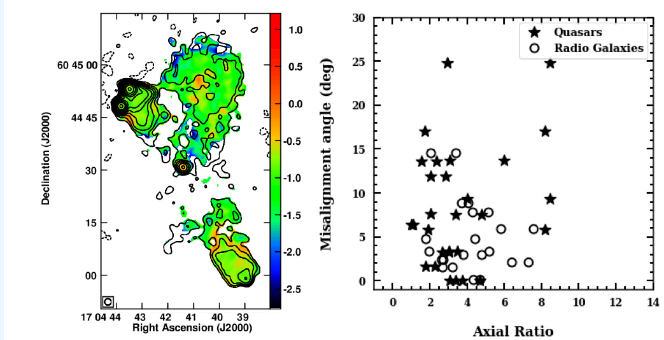


Fig. 3.5.4: GMRT 607 MHz image of galaxy cluster RXCJ0232.2-4420

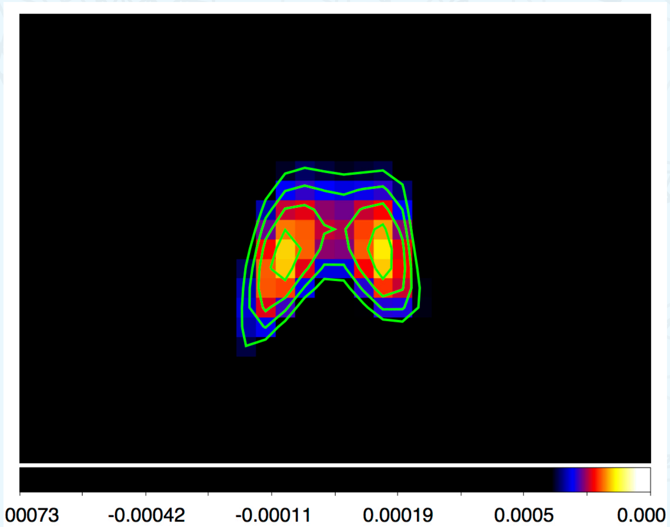
Vaddi et al. (2019) addressed the unification of radio-loud AGNs via statistical and spectral analysis of a sample of 11 steep-spectrum radio quasars and 13 Fanaroff-Riley-II radio galaxies. Matched resolution radio data for the quasars were obtained using the JVLA. Their results were in general agreement with the orientation-based AGN unification. However, the authors found that the environmental effects cannot be ignored. The lack of correlation between the statistical orientation indicators such as misalignment angle and radio core prominence, and the larger lobe distortions in quasars compared to radio galaxies suggest that additional intrinsic or environment effects are at play (Fig. 3.5.5).

Kharb, Lal & Merritt (2017) have used VLBA observations to discover only the second candidate sub-parsec binary black hole. The existence of such binary super-massive black holes (SMBHs) is predicted by models of hierarchical galaxy formation, but only a single such binary SMBH has been imaged until now. Kharb et al. studied the gas-rich interacting spiral galaxy NGC7674 between 2 and 15 GHz, which possesses a kpc-scale Z-shaped radio jet. The leading model for the formation of such Z-shaped sources postulates the presence of an uncoalesced binary SMBH, created during the infall of a satellite galaxy. Their observations resulted in the detection of two radio cores, separated by just 1 light year, at the highest observing frequency, 15 GHz (Fig. 3.5.6).



Left: Quasar 3C 351: 1.4 - 5 GHz spectral index image in color with 1.4 GHz black contours . Right: Misalignment angle vs axial ratio for quasar and radio galaxy sample.
(From Vaddi et al. 2019, MNRAS, 484, 385)

Fig. 3.5.5 Radio quasar 3C351



3.5.6: VLBA image of NGC7674 at 15 GHz

3.6 Intermediate and High redshift galaxies

Bera et al. used the uGMRT to carry out a deep observation of one of the well-known optical deep fields, the Extended Groth Strip, (EGS) covering the frequency range 1000-1370 MHz. This enabled a sensitive search for the 21cm HI in galaxies in the EGS, in the redshift range z~0.05-0.4. They stacked (i.e. averaged) the HI 21cm emission signals from 445 blue star-forming galaxies to infer their average HI gas mass, obtaining an average HI mass of (4.93 +/- 0.70) × 10^9 solar masses at a mean redshift of <z>=0.34. This implies a ratio of average gas mass to average stellar mass of ~1.2 for star-forming galaxies at these redshifts, higher than the corresponding value in the local Universe. They also stacked the rest-frame 1.4 GHz radio continuum emission of the same galaxies, and then used a relation between the 1.4 GHz radio luminosity and the star formation rate (SFR) to obtain a median SFR of (0.54 +/- 0.06) solar masses per year for the galaxies of the sample. If the galaxies continue to form stars at the same rate, their average HI content would be exhausted on a timescale of ~9 Gyr, consistent with values in star-forming galaxies in the local Universe. This suggests that the star-formation efficiency in blue star-forming galaxies has not changed significantly over the last ~4 Gyr (Fig. 3.6.1).

Kanekar et al. (2018) used detections of carbon monoxide (CO) emission with the ALMA to show that five of seven high-metallicity, absorption-selected galaxies in their sample at intermediate redshifts, z ~ 0.5–0.8, have extremely large molecular gas masses and high molecular gas fractions relative to stars. Their modest star formation rates then imply long gas depletion timescales. High-metallicity absorption-selected galaxies at z ~ 0.5–0.8 thus appear distinct from populations of star-forming galaxies at both z ~ 1.3–2.5, during the peak of star formation activity in the Universe, and low redshifts, z < 0.05 (Fig. 3.6.2).

Neeleman, Kanekar et al. have used the ALMA to carry out a search for the ionized carbon ([CII]) 158 mi-

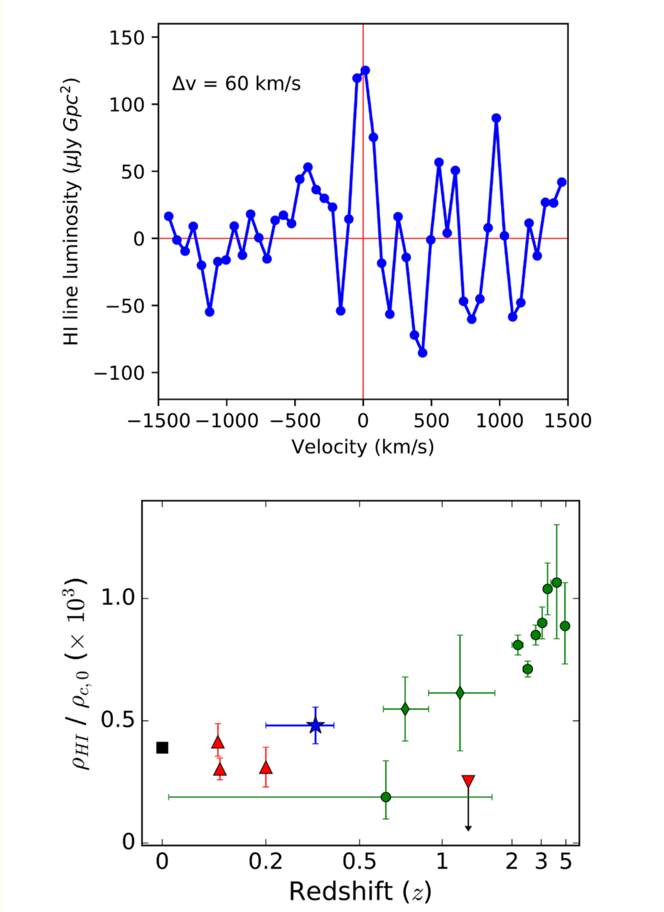


Fig. 3.6.1: The top panel : average HI 21cm emission profile of the 445 blue star-forming galaxies whose spectra were stacked together. The bottom panel : evolution of cosmic HI density from z~5 to today, with the blue star showing the measurement from the present study.

cron emission line from galaxies associated with four high-metallicity damped Ly-alpha absorbers (DLAs) at z~4. They detected [CII] 158 micron emission from galaxies at the DLA redshift in three fields, with one field showing two [CII] emitters. Combined with previous results, Neeleman et al. have now detected [CII] 158 micron emission from five of six galaxies associated with targeted high-metallicity DLAs at z~4. The galaxies have relatively large impact parameters, ~ 16-45 kpc, [CII] 158 micron line luminosities of 0.04-3 billion solar

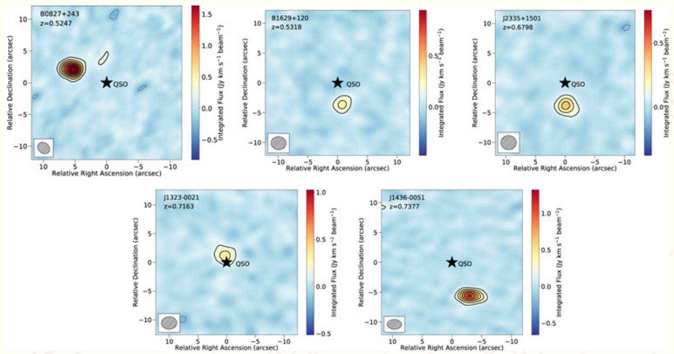


Fig: 3.6.2: Five CO detections with the position of the background quasar indicated by a star.

luminosities, and rest-frame far-infrared properties similar to those of luminous Lyman-break galaxies, with star formation rates of ~7-110 solar masses per year. These observations highlight ALMA's unique ability to uncover a high-redshift galaxy population that has largely eluded detection for decades.

Kanekar et al. (2018b) carried out Hubble Space Telescope Cosmic Origins Spectrograph far-ultraviolet and Arecibo Telescope HI 21cm spectroscopy of six damped and sub-damped Lyman-alpha absorbers (DLAs and sub-DLAs) at z ≤ 0.1 to yield estimates of their HI column density, metallicity and atomic gas mass. This significantly increases the number of DLAs with gas mass estimates, allowing the first comparison between the gas masses of DLAs and local galaxies. They also used Sloan Digital Sky Survey photometry and spectroscopy to identify the likely hosts of four absorbers, consistent with the hosts being dwarf galaxies (Fig. 3.6.3).

Sebastian et al. (2018) used the GMRT to carry out a deep 150 MHz study of a small region of the sky in the Lynx constellation, and discovered a large giant radio galaxy, of size 7 million light years, at a distance of about 5 billion light years, i.e. a redshift of 0.57. The detailed studies suggest it to be a double-double galaxy. Further, the radio core of the galaxy shows an unusually steep spectrum, which may imply that there is yet another

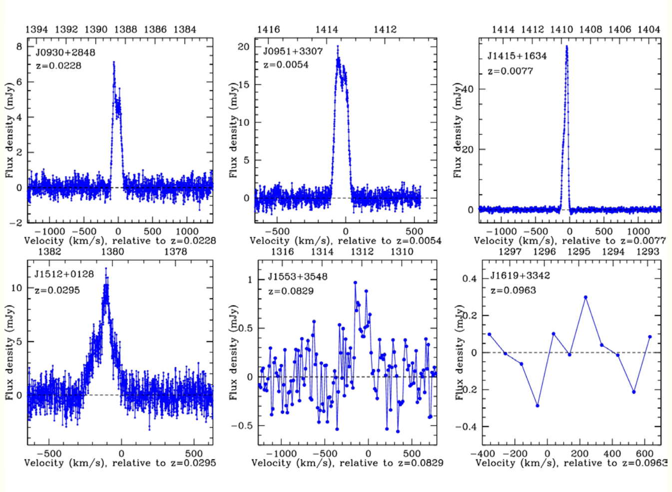


Fig. 3.6.3 The Arecibo HI 21cm spectra for the six DLAs and sub-DLAs.

unresolved pair of lobes within the core, making this GRG a candidate triple-double radio galaxy (Fig. 3.6.4).

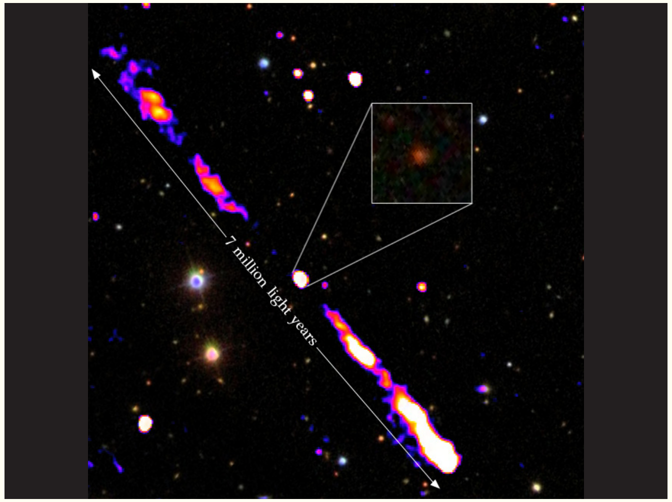


Fig. 3.6.4. Double-lobe galaxy at z=0.57.

3.7 Cosmology and epoch of reionization

T. R. Choudhuri et al. (2019) developed an Image-based Tapered Gridded Estimator (ITGE) to measure the angular power spectrum C_l of the sky signal directly from the measured visibilities. IGTE is used to suppress the sky response when quantifying the fluctuations of the diffuse signal directly from the visibilities measured in radio interferometric observations. In the context of the cosmological HI 21-cm signal, it may also be desirable to mask out the sky signal from specific directions which strong residual foregrounds. They validate the ITGE using realistic 1.4 GHz simulations of VLA observations, and have shown potential to recover the input model angular power spectrum quite accurately (Fig. 3.7.1).

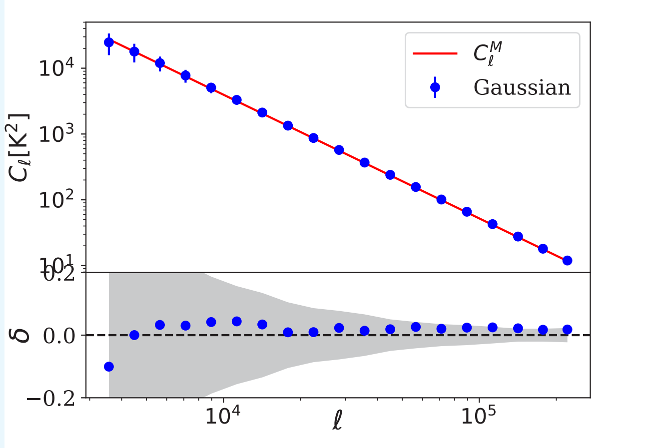


Fig 3.7.1 ITGE simulations for a Gaussian window 7.5’. One can see <10% fractional deviation.

T. R. Choudhury and his group is working on the signatures of the first galaxies that formed in our Universe, an era known as the Cosmic Dawn, imprinted on the surrounding hydrogen gas. The era when the hydrogen is ionized by the radiation from these first galaxies is called the Epoch of Reionization. They are involved in making detailed physical models, both analytical and numerical, of these processes, e.g. Choudhury & Paranjape (2018). These models can be compared and verified with upcoming surveys of the redshifted 21cm signal of neutral hydrogen (Fig 3.7.2 left).

They have shown that at later times, when the hydrogen becomes highly ionized by the stars, the Universe can be probed by Lyman-alpha absorption signatures on spectra of distant quasars. Fig. 3.7.2 shows the distribution of the cosmic gas as predicted by efficient hydrodynamic simulations run by the group in NCRA (Gaikwad et al 2017, 2018), which can be compared with observations of the so-called Lyman-alpha forest. This helps in understanding the properties of the cosmic matter over a wide range of cosmic times.

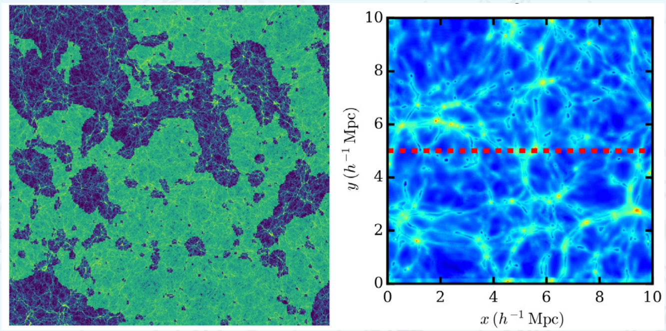


Fig. 3.7.2 Left: A simulation showing the distribution of neutral hydrogen during the Epoch of Reionization. Right: The distribution of cosmic gas, showing the cosmic web structure probed by sightlines towards distant quasars.

3.8 Evolution of Fundamental Constants

Kanekar, Ghosh and Chengalur (2018) used the mighty Arecibo Telescope to carry out 125 hours observations on the hydroxyl (OH) lines from a gas cloud close to the z=0.247 active galactic nucleus PKS1413+135. The satellite OH lines, at rest frequencies of 1720 MHz and 1612 MHz, are “conjugate’’ in this system, mirror images of each other, with the 1720 MHz line in emission and the 1612 MHz line in absorption. Since the 1720 and 1612 MHz line frequencies have different dependences on the fine structure constant, α, and the ratio of the proton mass to the electron mass, μ, this expected perfect cancellation makes the two lines ideal to probe changes in α and μ out to z~0.247, i.e. a lookback time of nearly 3 billion years. If α and/or μ change with time, the lines would shift relative to each other, and would not cancel out. Kanekar et al. found that the OH satellite line remain conjugate within the measurement errors, with no evidence for a shift between the two lines. They used this perfect cancellation to place stringent constraints on changes in α and μ with cosmological time, limiting fractional changes in the two quantities to less than a few parts in a million. This is the most sensitive constraint on fractional changes in α in the literature, and with no known systematic effects (Fig. 3.8).

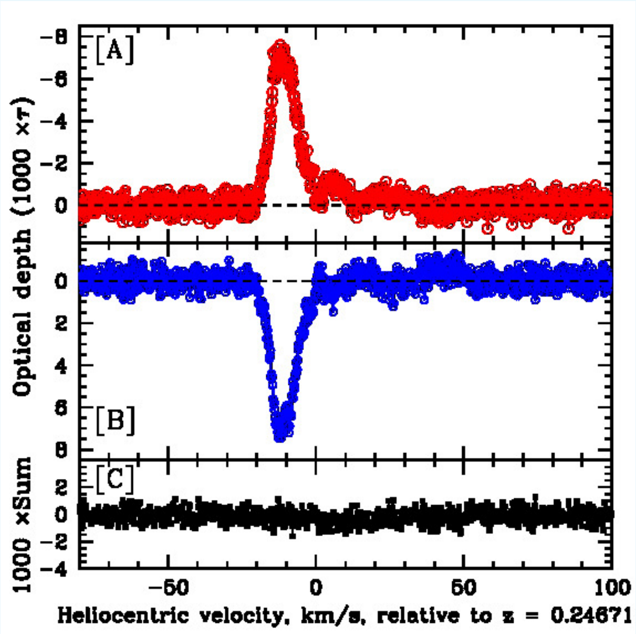


Fig. 3.8. Two OH satellite lines from PKS 1413+135 (top two panels). Bottom Pagel shows the sum of the two optical line depths.

3.9 Deep fields and surveys

Bera et al. (2018) carried out deep GMRT 610 MHz imaging of four fields of the DEEP2 Galaxy Redshift Survey, and stacked the radio emission from a sample of nearly 4000 blue star-forming galaxies at 0.7<z< 1.45 to detect the median rest-frame 1.4 GHz radio continuum emission of the galaxies. They used the local relation between total star formation rate (SFR) and radio 1.4 GHz luminosity to infer a median total SFR of (24.4 +/- 1.4) solar masses per year for blue star-forming galaxies at these redshifts. They detected the main-sequence relation between SFR and stellar mass, and find that the power-law index of the main sequence shows no change over z~0.7-1.45. galaxies at z~1.3. They combined their results with earlier GMRT HI 21cm emission studies of the DEEP2 fields to obtain an upper limit of 0.87 Gyr to the atomic gas depletion time of star-forming galaxies at z~1.3 (Fig. 3.9)

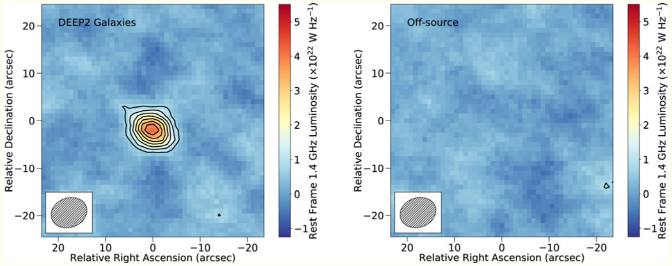


Fig. 3.9. The stacked rest-frame 1.4GHz radio emission of the detected sample galaxies (left). A similar stack at neighbouring locations (“off- source”) which shows no signal, indicating that the detected signal of the left panel is real (right)

4. Technology development and upgrade of facilities

The last few years have seen significant technology development activities at NCRA as both the GMRT and the ORT have gone through and completed major upgrades of their capabilities.

4.1 Upgrade of the GMRT

The GMRT has just completed a major upgrade which includes broad band seamless frequency coverage from

100 to 1500 MHz with improved sensitivity receivers, along with an increase of the maximum instantaneous bandwidth to 400 MHz (from the earlier 32 MHz). This is accompanied by other upgrades such as a next generation monitor & control system, a modern antenna servo system, improvements to the mechanical systems of the antennas, enhancements in data storage and computing resources, along with matching improvements in infrastructure facilities relating to civil and electrical systems. The upgrade required several technology developments and mass production of the new systems, which were carried out without a full shutdown of the observatory. Some of the highlights of these upgrade activities are as follows.

4.1.1. GMRT Front-end and Fibre-optic Systems

The main changes carried out to the front-end systems are the design and implementation of new, broadband feeds; matching RF front-end electronics systems with improved dynamic range; and associated improvements in the support electronics. This has been completed for all 30 antennas for the 4 frequency bands of the upgraded GMRT : 130-260 MHz (Band-2), 250-500 MHz (Band-3), 550-850 MHz (Band-4) and 1000-1450 MHz (Band-5) (Fig. 4.1). Special care has been taken to increase the dynamic range of the receiver chain and to introduce specific filters where needed, to make the system more sensitive and versatile(Fig. 4.2). For the fibre-optic system, there is a new scheme for transfer of broadband signals from each antenna to the central receiver room. It uses RF over fiber with Dense Wavelength Division Multiplexing (DWDM) to bring back the wideband signals (from 50 MHz to 2 GHz) from the upgraded system, while continuing to support the transport of the existing narrow-band IF signals of the legacy system, and includes a 1 Gbe bi-directional ethernet link in addition to support for the existing telemetry signal.

4.1.2. GMRT Back-end Systems

As part of the GMRT upgrade, new back-end systems have been designed and implemented to facilitate direct processing of the broadband RF signals with maximum bandwidth of 400 MHz, while preserving the high dynamic range. A significant feature of the new system is the reduction in electronics at the remote antenna sites and shifting of most of the complex signal processing operations to the Central Electronics Building (CEB) which will reduce the down time of antennas in case of problems. The back-end system is split into the analog back-end and the digital back-end.

The full analog back-end system for all 30 antennas with improved dynamic range, facility for variable gain, selectable signal bandwidth and individual LO signal for each antenna, has been completed and released for use, and is functioning well for more than 2 years now.
The full 30-antenna digital back-end system which implements a GPU-based hybrid correlator and beamformer (with incoherent and coherent modes and a pulsar preprocessor) has been completed and working well for more than a year. It supports full Stokes capability, multi-subarray modes, and upto four incoherent / coherent array beams. This system can currently process 100/200/400 MHz bandwidth signals, with upto 16 K spectral channels. It also has provision for real-time coherent dedispersion of the beamformer data. It has basic provisions for filtering of RFI signals which will be further improved in the future. An option for Walsh demodulation is also being added.

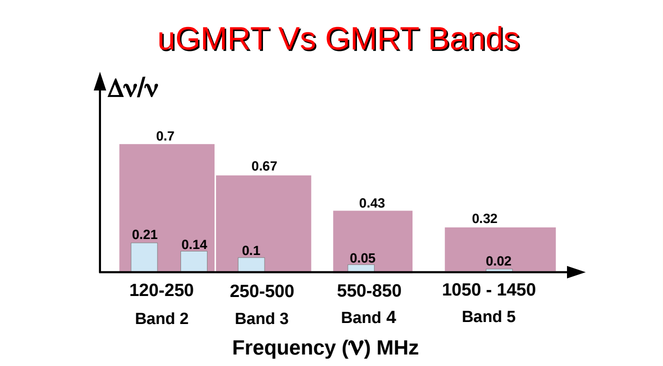


Fig. 4.1 Comparison of instantaneous frequency coverage of uGMRT (purple bars) with legacy GMRT (skyblue bars), showing improved coverage of uGMRT.

4.1.3. Upgraded Servo System

The GMRT servo system has been upgraded with new Brush-less DC (BLDC) motors and drives to replace the aging Permanent Magnet DC motors, on all 30 antennas, as well as development and mass commissioning of PC/104 based digital position loop controller to replace the now obsolete 8086-based controller that was part of the original GMRT servo system. All these works have been completed for all 30 antennas and the systems are working fine with stable and reliable performance.
A prototype version of an improved feed positioning system has also been developed which is now entering into mass production and commissioning phase. The scheme involves new backlash free gearboxes, and a PC/104 platform adapted for this work, alongwith use of absolute encoders to replace the incremental encoders used in the legacy system, and is expected to significantly improve the accuracy and repeatability of the feed positioning operations.

4.1.4. Next Generation Monitor & Control System for the Upgraded GMRT

This system has just been completed and is in final stages of testing before release for regular use. It includes modern hardware and software architectural features, compared to the existing GMRT control system, including futuristic developments that could be of relevance to next generation radio telescopes such as the SKA.

On the hardware front, there are new Monitor and Control Modules (MCM) developed based on Rabbit RCM 4300 micro-controller, completed and installed at all locations, alongwith required firmware developed in-house to implement control of various GMRT sub-systems at antenna base and in the Central building. On the software front, NCRA is actively involved in the development of a next generation M&C system applicable for large systems (including radio telescopes like the GMRT and the SKA), in collaboration with the TRDDC research laboratory of Tata Consultancy Services (TCS) and other partners from software industry, such as Persistent Systems Limited (PSL). As a first step of this effort, a modern M&C system software has been developed for the GMRT, which has completed the last stages of validation and is now ready for release. The software architecture of the new M&C system is based on the TANGO open source software framework, and supports features like data driven configuration, scalability, and facility to evolve.

4.1.5. Mitigation of Radio Frequency Interference at the GMRT

One of the major challenges for the upgraded GMRT is to contain the problems posed by Radio Frequency Interference (RFI) from various sources of electromagnetic signals from man made activities in and around the GMRT array. This includes identifying and mitigating the sources of RFI at their source, to finding techniques for avoiding or reducing the influence of RFI in the receiver chain, and finally to excising RFI at various stages of the receiver system.

One of the biggest threats to the wideband systems of the upgraded GMRT comes from RFI from transmissions by the various man made satellites. To mitigate against this problem, a new, unique scheme has been developed at the GMRT, jointly by the Operations Group and the RFI team. Orbital properties and radio transmission characteristics of all the known satellites visible in the sky at GMRT that transmit within the uGMRT bands have been determined, and an algorithm has been developed that can check for potential interference for any GMRT antenna, from any satellite at any given time at any frequency covered by the uGMRT. This tool has been tested and released and is being used regularly both in real-time mode and in a prediction mode.

In the receiver chain of the upgraded GMRT, special care has been taken to built the electronics systems with high dynamic range to tolerate significant amounts of RFI without getting into saturation, special filters to block very strong RFI signals (such as from mobile telephony, local TV broadcast channels), and special signal processing algorithms in the digital receiver to detect and mask both broadband (impulsive in time) and narrowband RFI signals. These techniques have helped greatly to improve the immunity of the GMRT to harmful RFI signals,

FEEDS

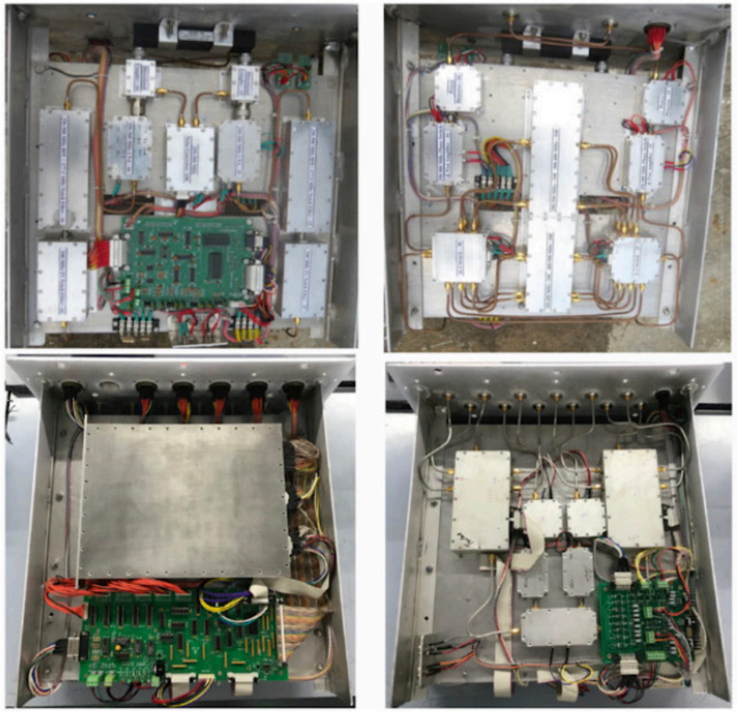
Dual Ring FEED
120 MHz- 240 MHZ

Cone-Dipole FEED
250 MHz-500 MHz

Cone-Dipole FEED
550-900 MHz

Horn FEED
1000-1450 MHz

uGMRT broadband feeds: The objective of the uGMRT is to provide seamless frequency coverage from about 50 to 1500 MHz, with a maximum instantaneous bandwidth of 400 MHz. Presently the redesigned uGMRT feeds provide near seamless coverage from 120 to 1450 MHz.



uGMRT front end receiver system:

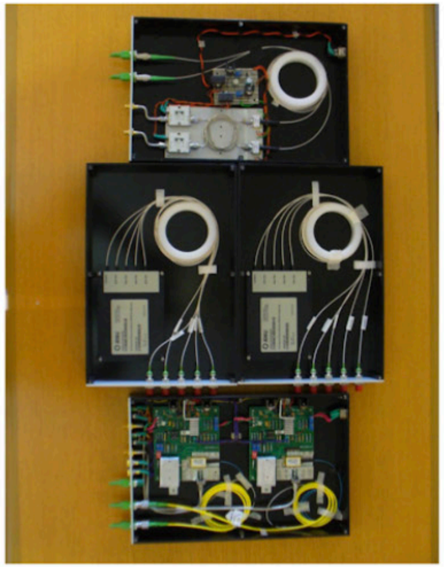
- Provision for Noise as well continuous wave signal calibration.
- Sub-band facility in each of the uGMRT bands using switched filter bank.
- Improved Receiver Sensitivity.
- Increased compression and spurious free dynamic range.
- Walsh switching facility for better isolation.
- RF ON/OFF facility available.
- Seamless frequency coverage from 120 MHz - 1500 MHz.

Fig 1: GAB System at Receiver Room.

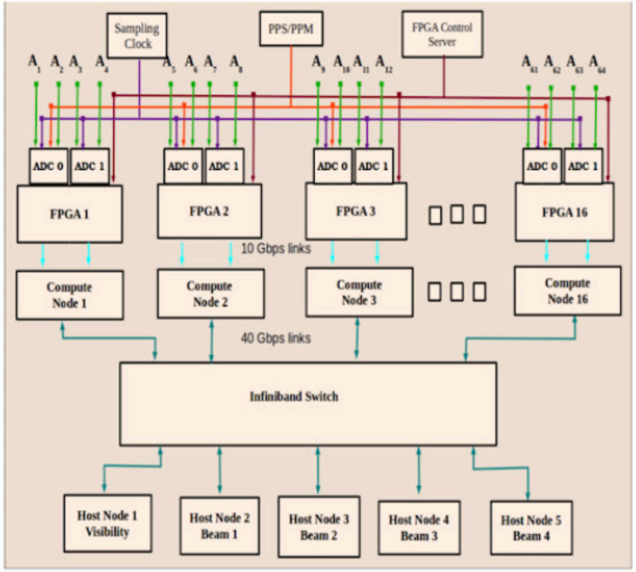
Functions of GAB System:

- Frequency conversion of RF signals received at Central Electronics Building to Baseband frequency.
- Switchable attenuation facility for power equalization at ADC Input.
- Selectable Bandwidth facility to provide 100 / 200 / 400MHz BW.
- **LO frequency :**
  Independent frequency selection for each polarization of each antenna
- **Time & Frequency standard:**
  GPS disciplined Rubidium standard as Time Reference.
  Active Hydrogen Maser disciplined Frequency Reference.

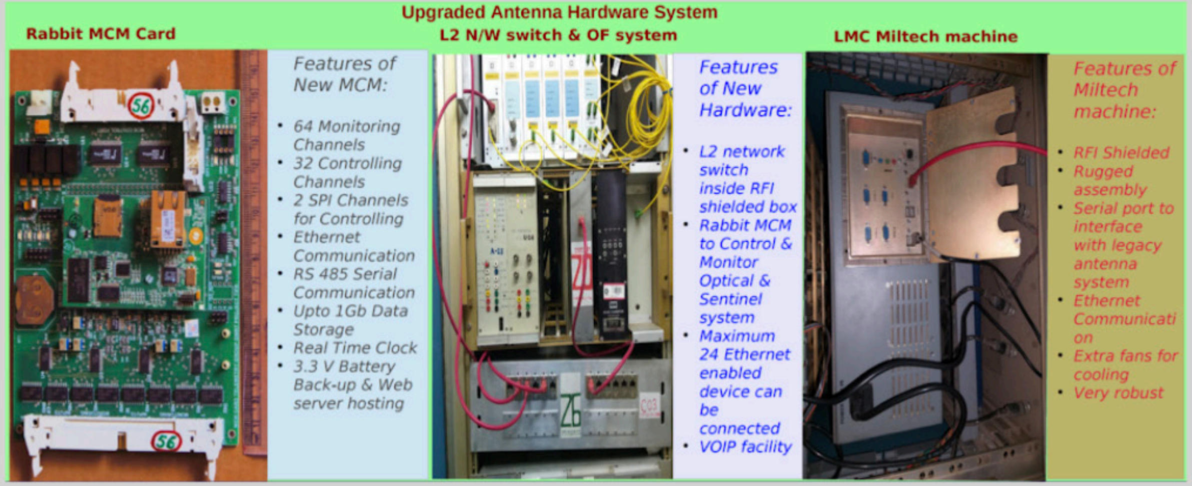
uGMRT analog backend system



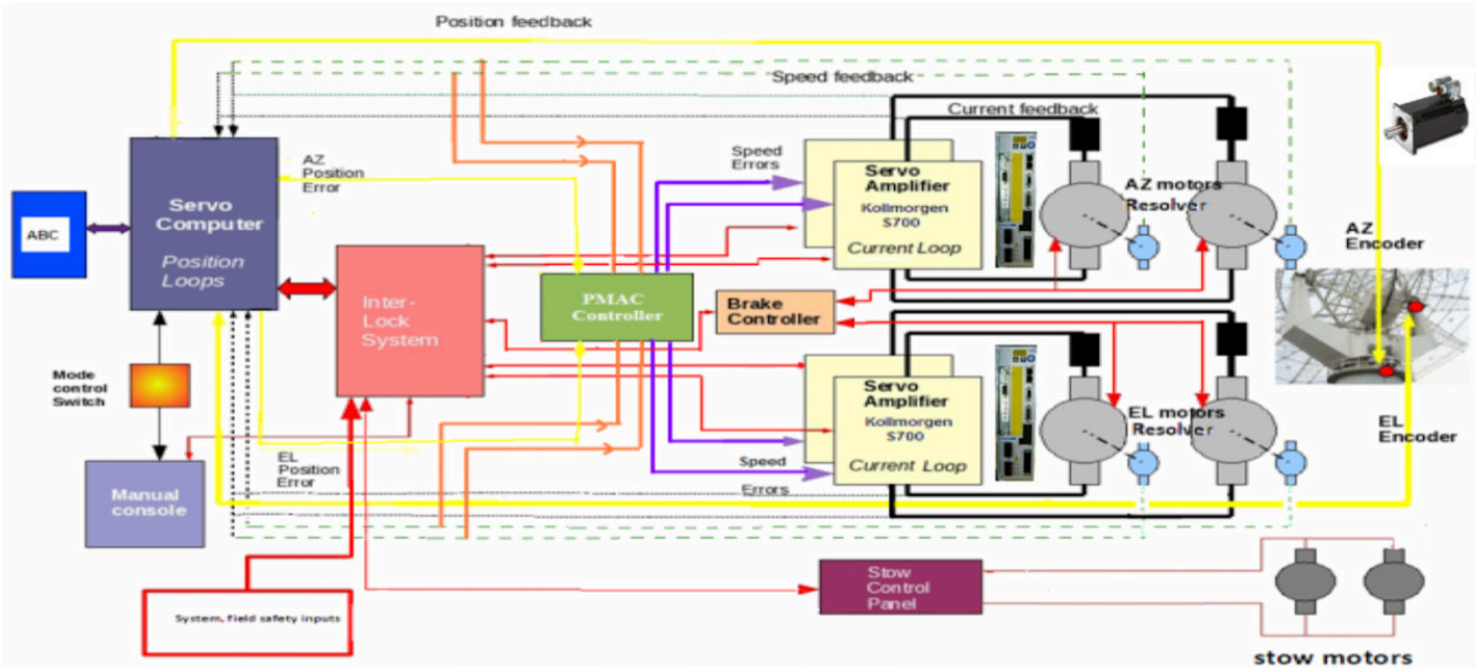
uGMRT optical fibre system



uGMRT digital backend system block diagram



uGMRT monitor and control system hardware



uGMRT servo system

even as there is further scope for improvement in these areas.

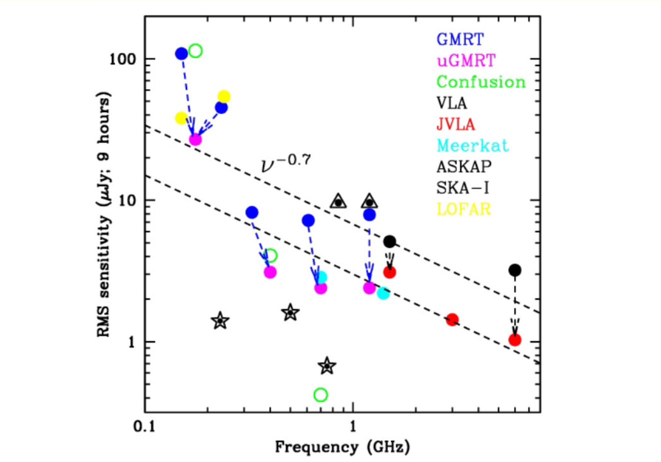


Fig. 4.2 Comparison of sensitivity of uGMRT with legacy GMRT (blue circles) and various other instruments

The third part of the RFI mitigation concerns reducing the effects of self generated unwanted signals. These could come from parts of the receiver system itself (e.g. microprocessors, Network equipment, UPS units etc) or from auxiliary equipment being used at the observatory (e.g. air conditioning equipment, lighting equipment etc). Significant work has been done by the GMRT team to contain such effects by designing special RFI proof enclosures for specific units, and good success has been achieved in these efforts.

4.1.6. Computing, Data Storage and Archival

The GMRT Online Archive (GOA) which has been running stably for the last several years, servicing a large number of requests from users all over the world, has gone through one stage of expansion during the last 2 years. The NCRA Archival and Proposal Submission (NAPS) software that handles the entire process of proposal submission and evaluation for each GMRT observing cycle, also went through a major software upgrade, including options for catering to the upgraded GMRT. Several regular upgrades of the computing facilities have taken place during the last few years, to keep pace with the latest needs and available technologies.

4.1.7. Mechanical, Electrical and Civil Systems

Very good progress has been made on tackling corrosion of the mechanical structure of the GMRT antennas, with all of the worst affected antennas taken care of, and attention shifted to the less critical ones. The refurbishment of the reflecting surface of affected antennas has also been taken up in a major way, with good improvement achieved. Improvements in the main gear box for the GMRT antennas have been carried out, and new gear box for a back-lash free feed positioning system drive chain has been put in place.
Various improvements and upgrades have recently been carried out in electrical and civil systems at the observatory. These include : completion of installations of RFI-free UPS units for all 30 antennas, a major overhaul of the central air conditioning plant for the GMRT receiver room, construction of a new, multi-purpose building at the observatory, and other infrastructure improvements.

4.1.8. Phased release and inauguration of the completed uGMRT

Given the incremental nature of the implementation of the upgrade, it was decided to carry out a phased release of the uGMRT, which has the additional advantage of more time for shake down of the systems. The first release, in the second half of 2013, was an internal release (for NCRA members only) of a prototype 8 antenna system covering 2 of the 4 wavebands (Band-3, and Band-5, along with the wideband signal transport and back-end systems. The fifth release, in October 2018, was an open release (for all GMRT users) for the full 30 antenna GMRT system for all the 4 main RF bands (Band-2, Band-3, Band-4, Band-5), with the capability to process the full 400 MHz bandwidth.
The fully upgraded GMRT with all the main features available for all 30 antenna configuration, was formally inaugurated on 21st March 2019, in a major function at NCRA, Pune, coupled with the hosting of the international conference "The Metre Wavelength Sky II" and the 90th birdhtay of Profess or Govind Swarup.

A snapshot from the uGMRT inauguration ceremony at Pune on 21st March 2019.

The fully upgraded GMRT has been made available to the user community from the GMRT observing cycle starting April 2019.

Along with the above, the fraction of time allotted to users for observations using the uGMRT systems was gradually increased from a maximum of 20% in April 2016 to 50% in October 2016, and with no ceiling from April 2017 onwards. The fraction of proposals (and observing time) asking for uGMRT capabilities, compared to the legacy GMRT, has also increased with every observing cycle, with the cycle 35 (ending in March 2019) having a clear domination of uGMRT over the legacy GMRT, indicating the growing popularity and success of the upgraded GMRT.

4.2. Upgrade of the ORT

The ORT is also completing a major upgrade that will convert it into a synthesis telescope consisting of a uniformly spaced linear array of 264 elements, each of size 1.92m x 30m, and operating over a bandwidth of about 40 MHz centered at 326 MHz, with a significantly increased field of view. This is achieved by digitising the signal from every 4 dipoles in the telescope and cross-correlating all the digitised signals.

This upgrade, being carried out in collaboration with Raman Research Institute, will make the upgraded ORT a modern highly versatile telescope, capable of doing a number of science projects ranging from detection of emission from the large scale distribution of hydrogen in the post-reionisation epoch of the Universe, searches for Fast Radio Bursts and other transients, as well as sensitive studies of the solar wind. All the hardware for this upgraded ORT Wide Field Array (OWFA) has been completed and installed, a real-time software correlator has been developed, and the OWFA is now getting for observations.

5. The SKA-India project

The Square Kilometre Array (SKA) is the logical next step to the sequence of large radio telescopes like the GMRT (India), LOFAR (Holland/Europe), JVLA (USA) etc., which have mostly been national or regional projects. It is an international collaborative project that promises to revolutionise the field of radio astronomy. The full SKA will be at least 30-50 times more sensitive than the best radio telescopes of today, and will address several outstanding fundamental key science topics in astrophysics. The SKA will also drive development of many new technologies, with considerable scope for contributions from industry, e.g antennas, signal transport, signal processing, computing and software. Recently, SKA Phase-I (which is about 10% of the full SKA in capability) has completed the critical review of its design, clearing the way for preparation of the construction proposal. Construction of SKA Phase-I is expected to start in a year or so, with an expected start of early science operations within the next few years.

The SKA is a truly international telescope, with eleven member countries in the SKA Organisation, and actively involved in the design of SKA and other related activities. India has been a member of the international SKA effort from the beginning, and has been a Full Member of the SKA Organisation since October 2015. Indian astronomers are actively involved in many of the SKA Science Working Groups. India is actively involved in the design phase of the SKA, and aims to play an active role in the construction phase. The SKA project has a major low frequency component and the uGMRT, with a total collecting area of 3% of the full SKA and status of a SKA Pathfinder facility, is currently the best platform for exploring some of the front line issues relating to low frequency radio astronomy. Furthermore, the uGMRT provides an excellent platform for synergistic development of technology and science goals of the SKA.

In order to coordinate and oversee the growing SKA related activities within the country, a SKA India Consortium (SKAIC) was launched in February 2015, which presently has membership from 20 different research organisations and universities within the country. The SKAIC has been meeting fairly regularly, and has set-up sub-committees for overseeing science and technical activities within the country. At a higher level of management, a SKA India Steering Committee has been appointed by the DAE, which will provide the overall advice and guidance for all SKA related activities within the country.

On the technical side, one of the main thrust areas that NCRA has taken up for the SKA is the development of a state of the art control and monitoring system for the SKA. Called the Telescope Manager, this system will form the brains and nerve centre of the observatory and will be central to its successful operation (Fig 5.1). After successfully leading the concept design for this work package (during 2010-12), NCRA took up the leadership role, in 2013, with a collaboration of institutions and industries from 7 different SKA member countries for the work on the detailed design of the Telescope Manager.

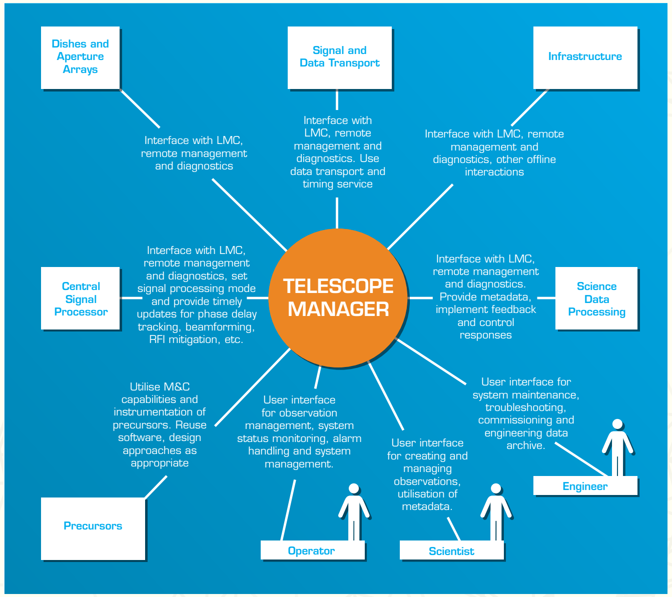


Fig. 5.1 The Telescope Manager system of the SKA, designed by a consortium of members from 7 SKA member countries and led by NCRA (India), will be brain and nerve centre of the entire observatory, interacting with and controlling all other elements of the observatory.

Within India, NCRA is working in collaboration with institutions and Indian companies like TRDDC (Tata Research Design and Development Centre, TCS (Tata Consultancy Services), PSL (Persistent Systems Limited) etc. In synergy with this effort, NCRA also developing a next generation monitor and control system for the GMRT, which will serve the purpose of a small scale prototype technology demonstrator for the main SKA Telescope Manager design.

The India-led Telescope Manager completed the detailed design for this work package, and successfully defended the Critical Design Review (CDR) in June 2018 (Fig. 5.2). This was the first of the 10 design work packages of SKA to complete the CDR, and the work done was widely appreciated by the review panel and the SKA Organisation. Along with the above, science activities related to the SKA have also gained momentum in India.

SKA India Science Working groups, which were formed in March 2014, have been working to develop a science case and enhancing the potential user base within the country. Their activities include carrying out theoretical studies and modeling, as well as using the existing facilities like the GMRT and other SKA pathfinder and precursor facilities to conduct research and investigations that will prepare the scientific community to make the best use of the SKA when it is ready.

Fig 5.2 The leading team members of the Telescope Manager consortium, along with members of SKAO and the CDR panel, at the successful CDR meeting for the Telescope Manager design review, in April 2018.

Coordinators of these groups have been interacting with the international SKA Science Working Groups. Following national level SKA science workshops have been held in conjunction with the Astronomical Society of India meetings since 2014. The science working groups have met regularly amongst themselves and have come up with science case documents. The first version of the SKA India science case was published in a special edition of the Journal of Astronomy and Astrophysics, in early 2017 (Fig. 5.3). India also hosted the international Annual SKA Science meeting in Goa in December 2016.

At present, members of the SKA India Consortium are busy firming up plans for Indian contribution to the construction phase of the SKA, as well as for joining the soon to be formed intergovernmental treaty organisation called the SKA Observatory.

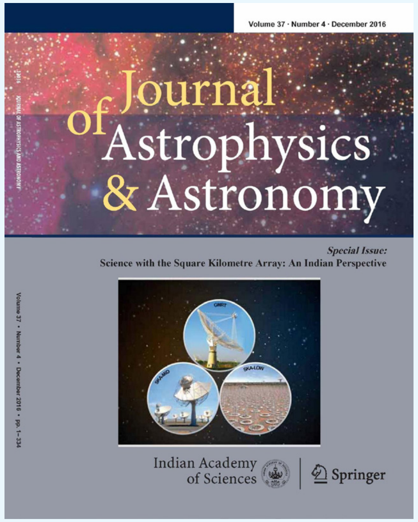


Fig 5.3 The first version of the Indian science case for the SKA was published in early 2017 in the Journal of Astronomy & Astrophysics

6. Outreach Activities

NCRA formally supports some communication and outreach activities via the Press and Media Relations Cell, and some of the staff are also involved in individual capacities in various outreach activities, viz, public talks at colleges and schools, working with amateur astronomers, participating in public campaigns and so on.

6.1 Annual Science Day at the GMRT

The defining event of each year is the celebration of the National Science Day, which falls on 28th February. NCRA celebrates the event on two days : 28th February and the following day, at the GMRT campus every year. This is possibly the largest Science Day celebration in India, with active participation from around 1000 students, and the number of visitors exceeding 20000! Teams from nearby schools and colleges are invited to demonstrate their experiments on any topic in science. These have a vast diversity, ranging from simple experiments on fluid flow to solar panel based demonstrations to complex engineering projects. The topics range from biology and agriculture to chemistry and physics. Around 50 research institutes and university departments, as well as science NGOs, amateur astronomy groups and science toy makers are also invited to put up stalls. In addition, NCRA itself sets up a huge pavilion to showcase the science and engineering aspects of GMRT, along with posters and demonstrations to explain basic astronomy concepts. These two days are eagerly awaited in schools and colleges in towns and villages around GMRT, as well as in Pune. In recent years, several research institutes in and around Pune have also started participating in the Science Day at GMRT, as they find it to be an excellent avenue to reach out to a large population of young students.

6.2 Solar eclipse of 26th December 2019

The line of annularity for the solar eclipse on the 26th of December 2019 passed right over the Ooty Radio Telescope. NCRA Outreach Committee used this opportunity to organise a public viewing of the annular solar eclipse (ASE) at the RAC campus, as well as the Government Arts College in the heart of the Ooty city.

Planned and lead by NCRA, this was a collaboration between a diverse set of institutions and bodies, including citizen science initiatives like Tamil Nadu Science Forum and Khagol Mandal, the Jawaharlal Nehru Planetarium in New Delhi, the Public Education and Outreach Committee of the Astronomical Society of India and multiple departments of TIFR. Arrangements were made at each of the venues for safe observation of the eclipse by looking through optical telescopes equipped with solar filters, and specially made projection boxes and other projection methods. We had a very enthusiastic response, with about a 1000 people visit these venues. In addition, a 1000 eclipse glasses, along with a brochure about the eclipse, were also distributed to the schools in neighbouring tribal areas.

Various outreach activities

7. Research and training opportunities

7.1 Research careers at NCRA

NCRA conducts a regular doctoral programme for students interested in pursuing a Ph.D. in astronomy and astrophysics related topics. The students are selected for this programme via two main avenues: the TIFR entrance test, conducted by TIFR-Mumbai and the Joint Entrance Screening Test (JEST) with the TIFR-Mumbai. They are based on a written test and two interviews. Students with M.Sc. or B.E./B.Tech. degrees are eligible for the main Ph.D. programme, while students with B.Sc. degrees are eligible for the Integrated Ph.D. programme, which includes an extra preparatory phase before joining the main Ph.D. programme. All students admitted to the Ph.D. and Integrated Ph.D. programmes are provided with a stipend and a research grant.

7.2. Student training programmes

In addition to the doctoral programme, NCRA also runs a number of shorter term programmes for external visiting students. These include the Visiting Students' Research Program (VSRP), the Students' Program (SP), the Radio Astronomy Winter School (RAWS), the Radio Astronomy School (RAS), and the Pulsar Observatory for Students (POS). The VSRP is an annual summer programme for students entering the final year of a Master's degree; selected students carry out a 2-month research project with an NCRA faculty member, with the possibility of pre-selection to NCRA's Ph.D. programme. The SP is a more informal programme under which pre-doctoral (usually undergraduate) students may carry out a research project with a NCRA faculty member for up to a year, beginning at any time of the year. The RAS is a two-week bi-annual summer school on advanced radio astronomy, targeting doctoral and post-doctoral researchers.

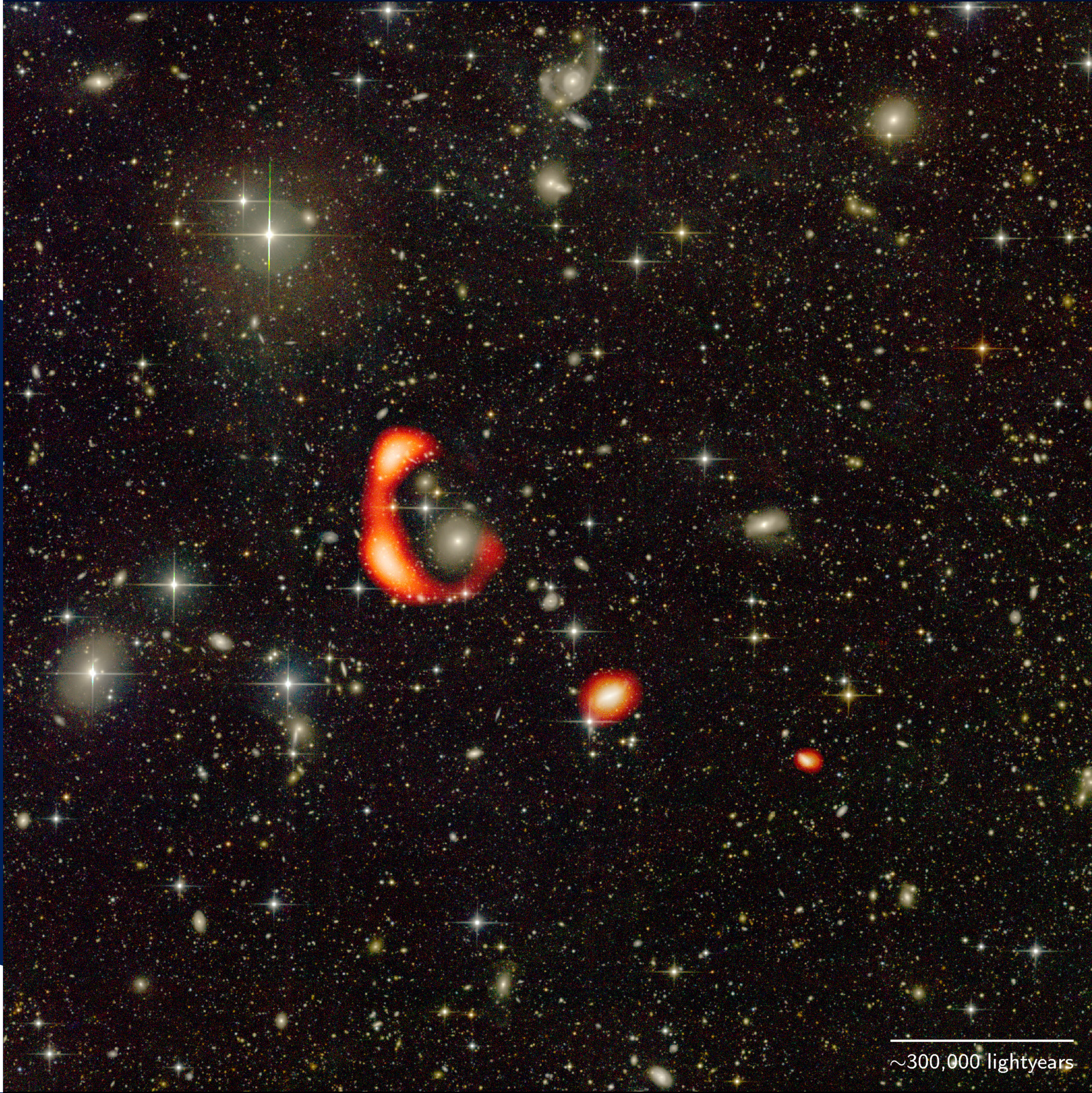
7.3. The Radio Physics Lab

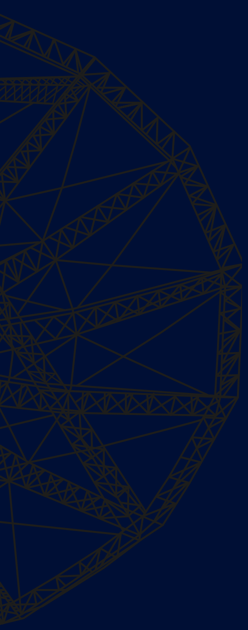
The Radio Physics Laboratory (RPL) was established in 2007 as a joint collaborative initiative between NCRA and IUCAA, to provide a platform for college students to develop an appreciation of radio astronomy techniques through simple hands-on experience. The facilities include a 4-m antenna with receivers and control system, laboratory test and measurement equipment, and radio instrumentation design software. The laboratory provides opportunities for students to build their own radio astronomy instrumentation. The RPL has also developed a few low cost radio astronomy experiments, notable amongst which is the Affordable Small Radio telescope (ASRT), built entirely from off-the-shelf available components used for DTH televisions. The RPL operates 10 day long Radio Astronomy Winter School for College/University Students, which was initiated in 2008 and involves training through hands-on experiments with RPL facilities. Apart from the above, the RPL also provides the laboratory component for NCRA-IUCAA graduate school and Pune University courses.

A giant neutral hydrogen ring around a distant galaxy

This image is of an extremely large ring (seen in the centre in red), composed primarily of neutral hydrogen gas, and rotating around a lenticular galaxy named AGC 203001 was discovered using the Giant Metrewave Radio Telescope (GMRT). The HI ring has no obvious optical counterpart to it as seen from the deep optical image obtained using the wide-field Megacam instrument on the Canada-France-Hawaii Telescope (CFHT) in the background. The ring spans much beyond the optical extent of AGC 203001 and has a gigantic diameter of about 380,000 light-years (about 4 times the diameter of our Milky Way galaxy). AGC 203001 itself is located about 260 million light-years away from the Earth.

Image Credit: O. Bait (NCRA-TIFR/GMRT) & P.-A. Duc (Université de Strasbourg/ CFHT)





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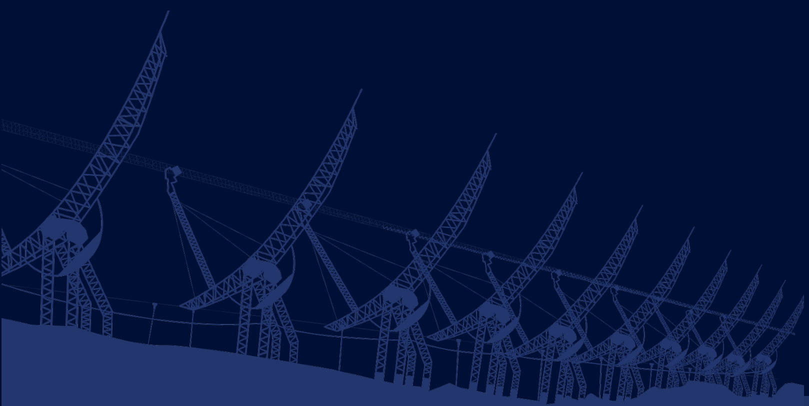

Ooty Radio Telescope, Tamil Nadu, India

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