Introduction to Radio Astronomy

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Outline

NCRA • TIFR

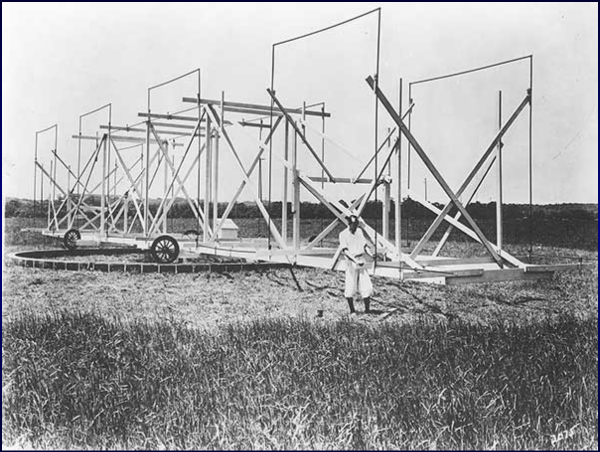
What makes radio astronomy special?

- Reveals invisible universe: many different cosmic objects emit radio waves
- Works day and night, through clouds and from the ground
- Allows us to see through dust that blocks optical light
- Many unique discoveries: pulsars, quasars, CMB, FRBs
- requires synthesis of science and engineering skills

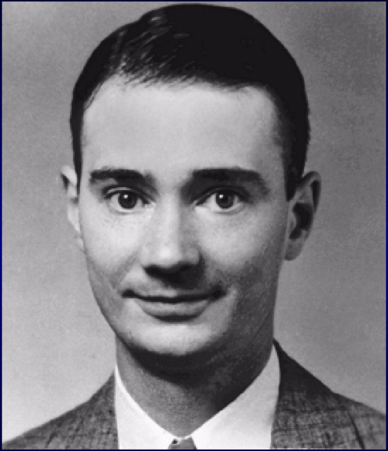
The beginning - Karl Jansky 1933

Discovered radio emission from the centre of the Milky Way

Karl Jansky's radio telescope

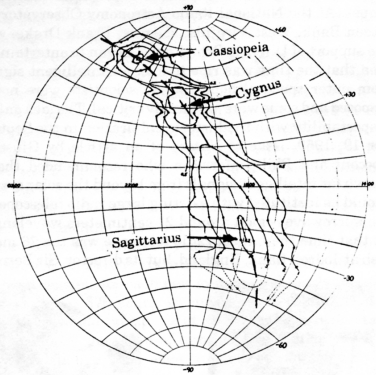


Grote Reber



carried out the first large radio survey 1941-43

First map of the radio sky!



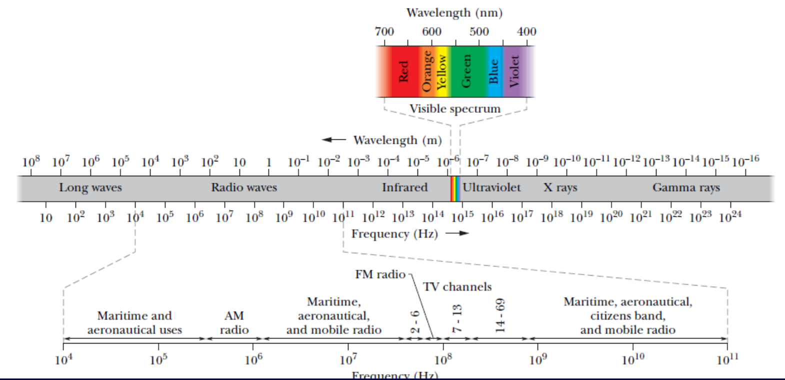
First map of the radio sky as produced by Grote Reber showing strong sources of radiation in Cassiopeia, in Cygnus and in Sagittarius, the center of the galaxy, the region from which Karl Jansky had detected radio emission.

Govind Swarup

Kalyan array

Ooty Radio telescope

The Electromagnetic Spectrum



Radio: longest wavelengths (mm to km), lowest energies

Why do astronomy at different wavelengths?

- Different physical processes emit at different wavelengths
- Temperature: hot objects emit thermal radiation at shorter wavelengths
- Acceleration: charged particles emit radio waves
- Quantum transitions in ions, atoms and molecules: specific wavelengths

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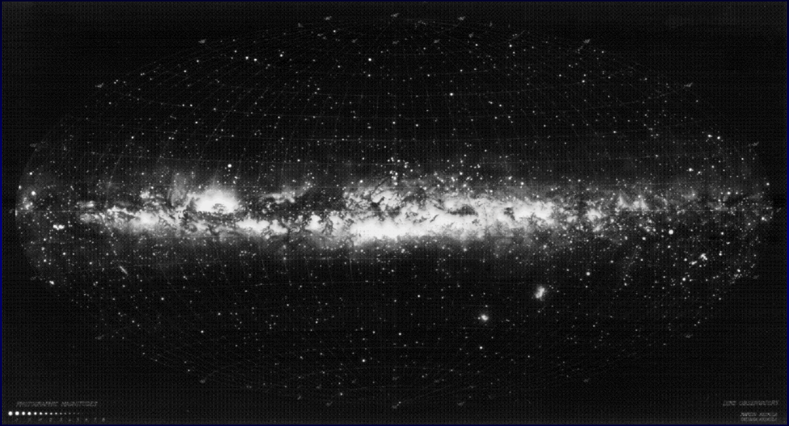
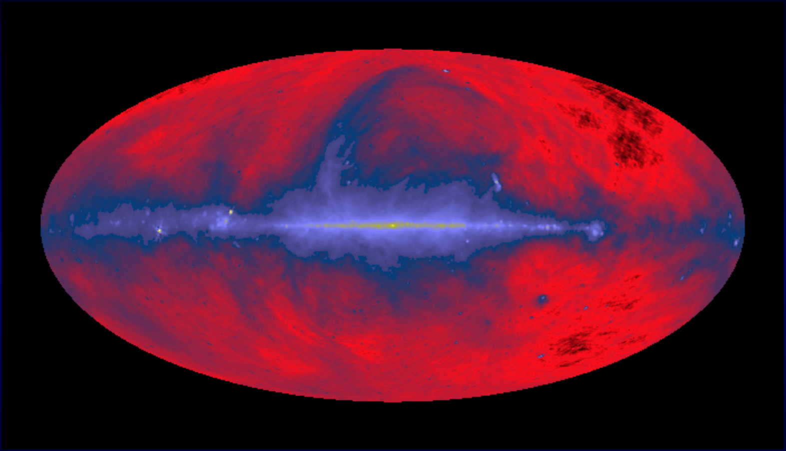
The optical sky



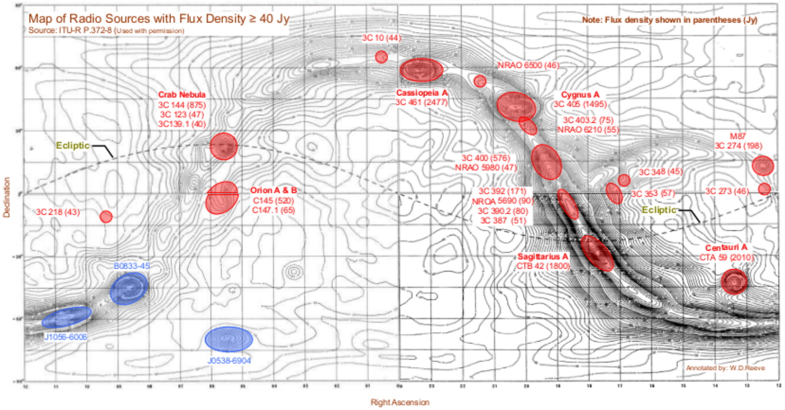
dominated by stars, ionised gas, dust (absorbtion)

The radio sky at 408 MHz



dominated by pulsars, supernova remnants, star-forming regions, and active galaxies - e.g. NGC 5128, Sagittarius A*.

The brightest radio sources

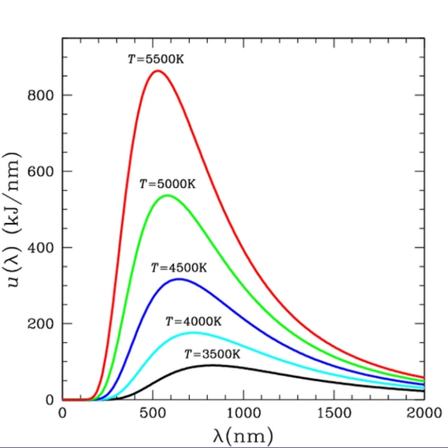


Cas A, Crab Neb, Vela - Supernova remnant; Orion A - star-forming region; Sag A - Milky Way Centre; M87, Cen A, Cyg A - AGN

Question

Bright radio sources are (usually) faint in the optical and vice versa. Why?

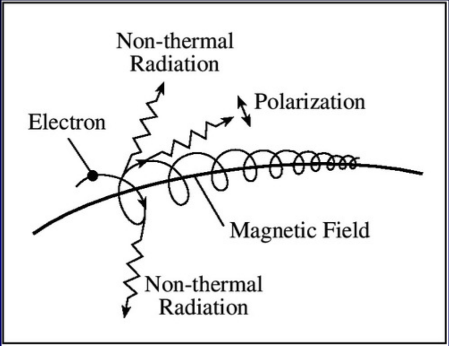
Typical stellar spectrum is blackbody!



Why isn't radio emission thermal?

- Blackbody radiation at radio wavelengths too weak
- Radio brightness requires $T > 10^{12}$ K!
- Most radio emission is non-thermal
- Main mechanism: synchrotron radiation

Synchrotron Radiation



- Relavistic charged particles spiral in magnetic field
- Acceleration causes emission
- Power $\propto$ B^2 γ^2 (γ is the Lorentz factor)
- Spectrum: power law, not blackbody

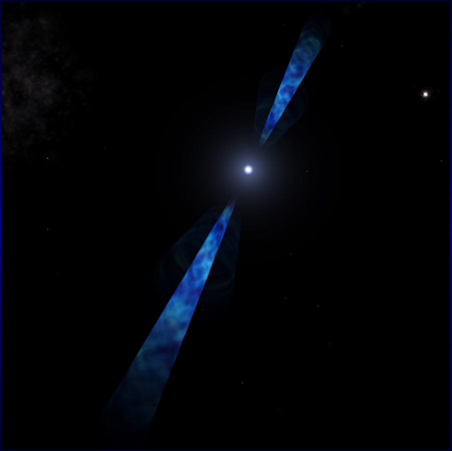
Dominant physical mechanism for *continuum* radio emission

radio emission due to synchrotron emission by **relativistic charged particles** (electrons) in a **magnetic field**.

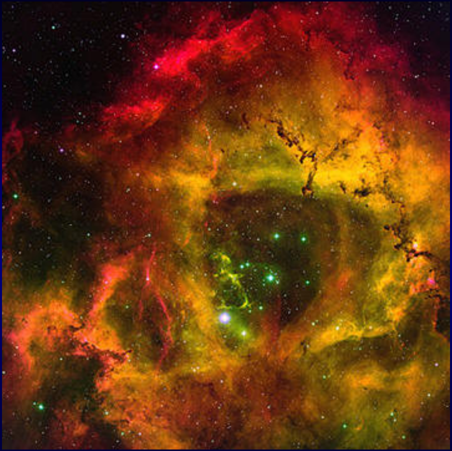
Where would one expect to see continuum radio emission?

What do you think?

strong magnetic fields: pulsars

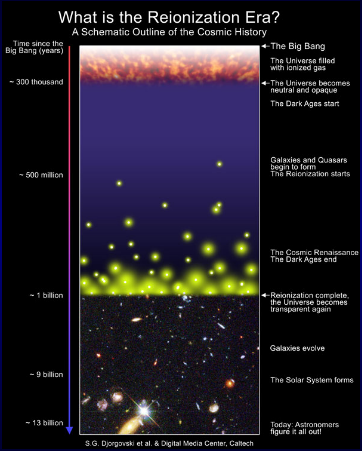


Around luminous stars

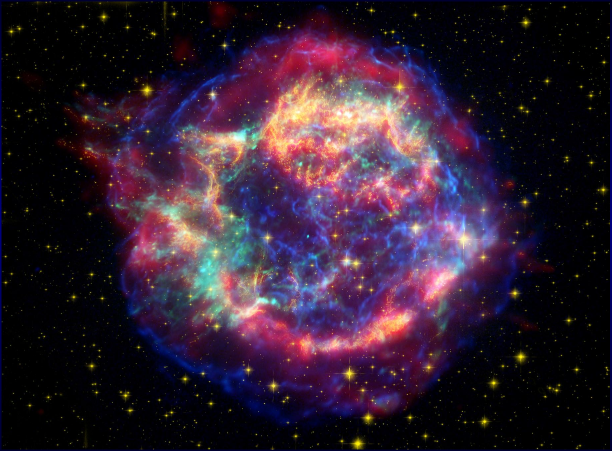


from accelerated winds (charged particles) around luminous stars - star forming regions. Could one detect this from the first stars?

Epoch of reionization



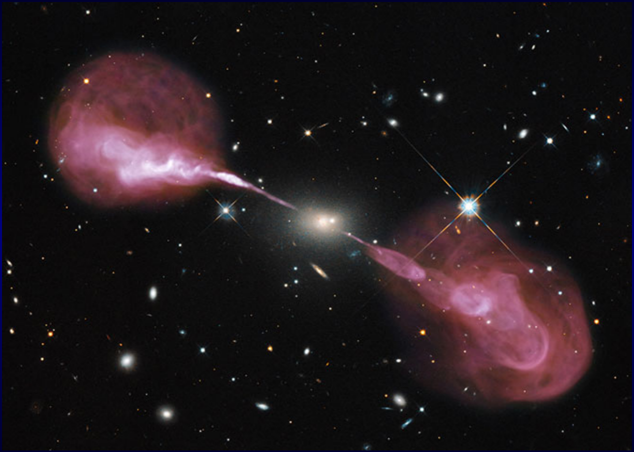
around recent supernovae - Cassiopeia A



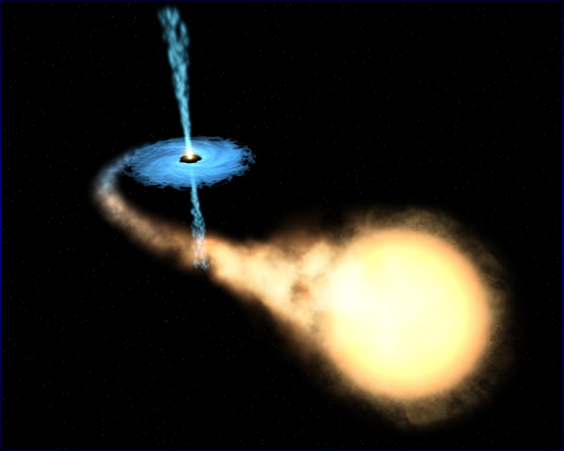
from supermassive black holes - quasars, blazars

Accretion disk and radio jet around supermassive black holes

Hercules A - a radio galaxy



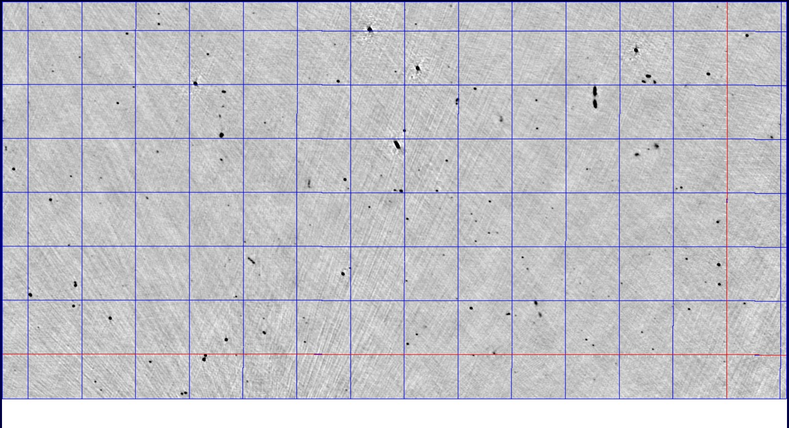
from microquasars



Faint radio sources....

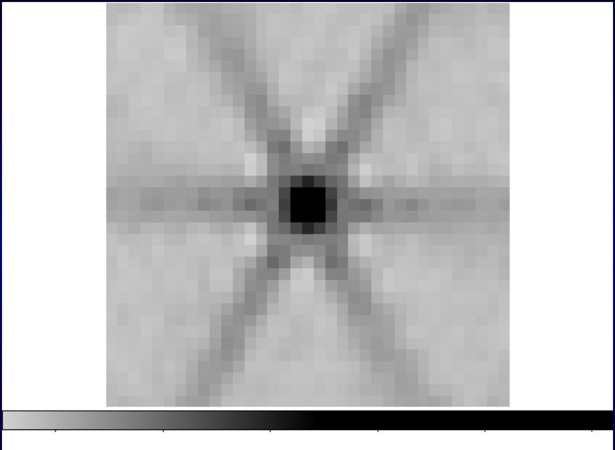
We have only looked at the physical counterparts of the bright radio sources. Faint radio sources are a zoo by themselves - Seyfert galaxies, radio stars, extragalactic HII regions, the diffuse intracluster medium, planets (e.g. Jupiter, even a few extrasolar planets), intelligent life (which we have not found yet).

A deep GMRT Radio image



GMRT proposal 20_006, PI: Wadadekar, rms 150 μJy

Even deep radio images are quite sparse

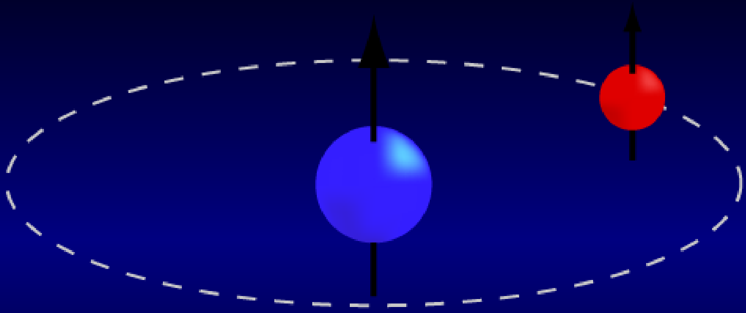


Median stack of FIRST survey at 2e5 quasar positions

Is this all?

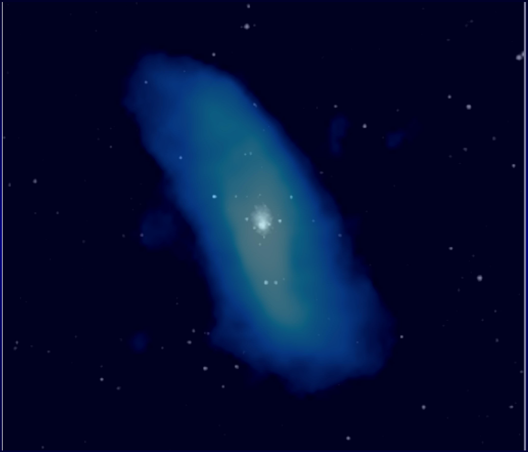
Is there more to be done than continuum imaging?

HI line emission/absorption



An electron orbiting a proton with parallel spins (pictured) has higher energy than if the spins were anti-parallel. The photon emitted when transitioning from a higher energy state to a lower energy one has a frequency of about 1420 MHz (21 cm). Other lines of OH, H_20 and CO also studied.

HI can be used to trace neutral hydrogen



and to measure its kinematics

Types of Radio Emission

- Continuum: Synchrotron, Free-free (thermal), Dust
- Spectral lines: HI (21cm), CO, OH masers, Radio Recombination lines.
- Coherent emission: Pulsars, FRBs, Solar bursts

Why did we build the GMRT?

GMRT is a marriage of the world's two big radio telescopes, the Very Large Array in New Mexico, and Arecibo in Puerto Rico, with the advantages of both.

- Govind Swarup

Arecibo dish in Puerto Rico

Very Large Array, New Mexico

Basic characteristics

- 30 fully steerable dishes of 45m diameter each.
- longest baseline about 25 km; shortest about 100 m.
- dishes are not solid; they have a mesh $\rightarrow$ low construction and operational costs and less wind loading.
- uGMRT has 4 operating bands: 1000 – 1450 MHz (updating L-band), 550 – 900 MHz (replacing 610), 250 – 500 MHz (replacing 325), 120 – 250 MHz (replacing 150).

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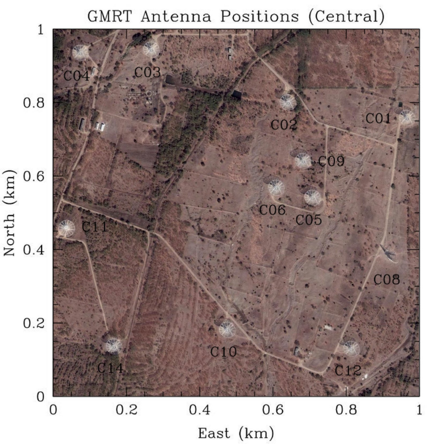
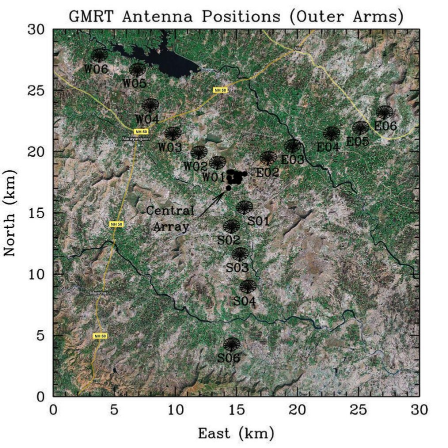
The GMRT mesh

The GMRT feed system

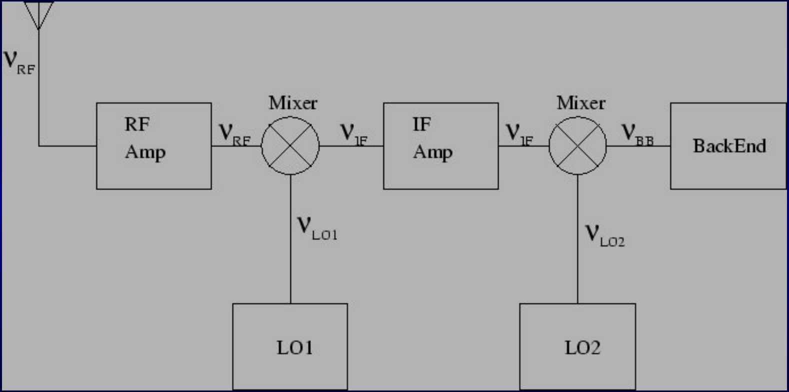
Central Array



The outer arms



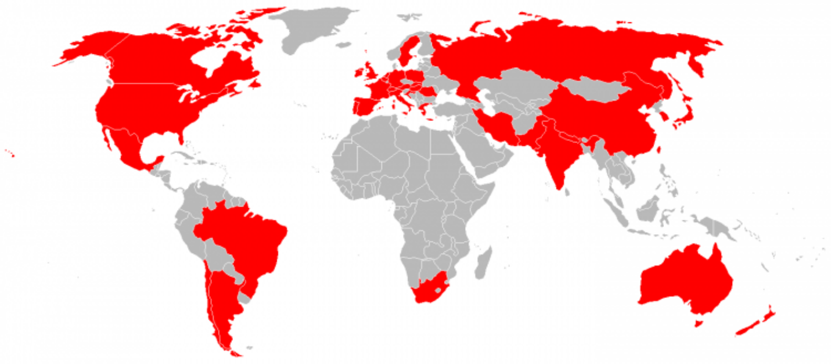
Single dish block diagram



GMRT is an open sky international facility

- proposals invited twice a year (2 cycles of 5 months each)
- proposals reviewed by expert reviewers
- completely open sky policy; time is alloted to the best rated proposals by a time allocation committee
- $\sim$ 75 proposals received in each cycle.
- Cycle 1 in 2002; Cycle 47 started in October 2024.
- astronomers from 35 nations have used GMRT so far

GMRT PIs of successful proposals come from these 35 countries



Titles of some Cycle 40 GMRT proposals

- Magnetic Fields in Star Formation
- Nature of Repeating Fast Radio Bursts
- HI Studies of High-z Radio Galaxies
- Plasma Physics in Cluster Mergers
- Radio Emission from Exoplanets
- Radio-Optical Study of GW Events

Titles of some Cycle 40 GMRT proposals

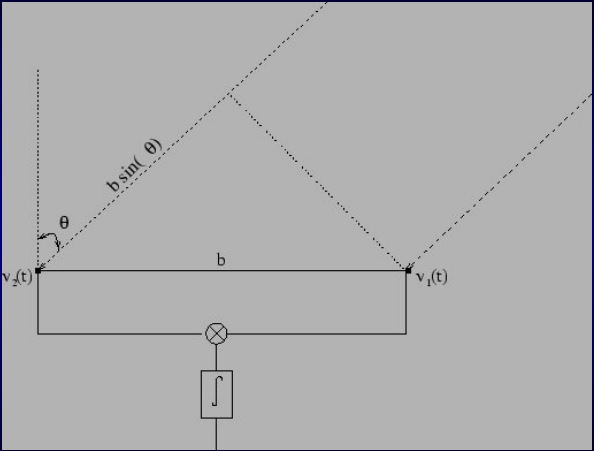
- Radio Monitoring of X-ray Binaries in Our Galaxy
- Deep Search for HI in Ultra-Diffuse Galaxies
- Cosmic Ray Acceleration in Supernova Remnants
- Low-frequency Study of Active Galactic Nuclei Jets
- Mapping the Cosmic Web through Radio Observations
- Radio Properties of Tidal Disruption Events
- Technosignature Search from Nearby Star Systems

The versatility of the telescope is testified by the diverse proposal titles.

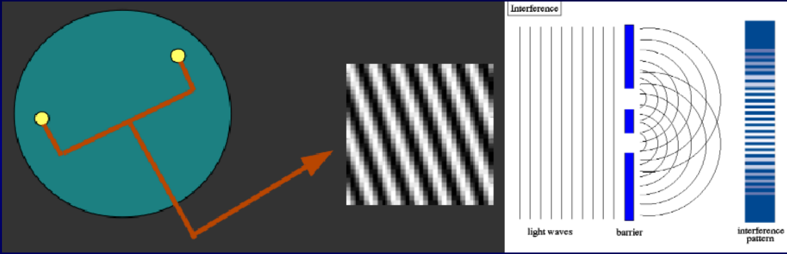
Why are radio telescopes so large?

- Resolution $\propto \lambda/D$
- Optical (500 nm): 1m telescope $\rightarrow$ 0.1 arcsec
- Radio (21 cm): needs 400 km for same resolution!
- Solution: interferometry

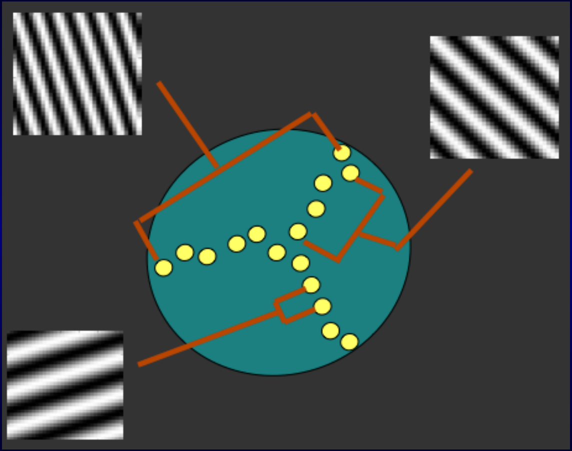
Two element interferometer block diagram



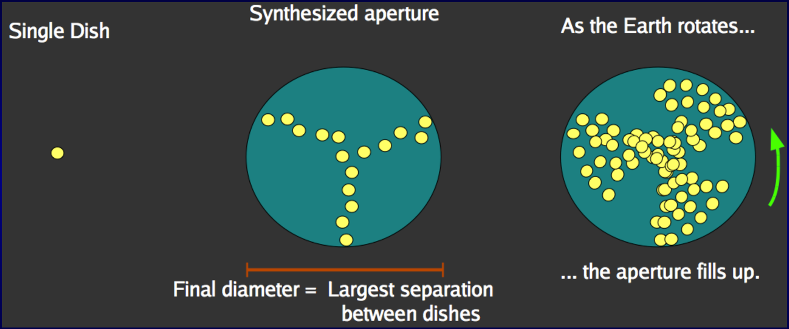
Double slit interference pattern



Every baseline produces fringes



Earth rotation aperture synthesis



Signals from different antennas combined using correlator

How interferometry works - Van Cittert Zernike Theorem

$$V(r_1, r_2) = \langle E(r_1)E^*(r_2)\rangle$$

$$V(r_1, r_2) = \mathcal{F}\{I(s)\}$$

MeerKAT - South African SKA Precursor

64 dishes of 13.5m diameter each in the Karoo region

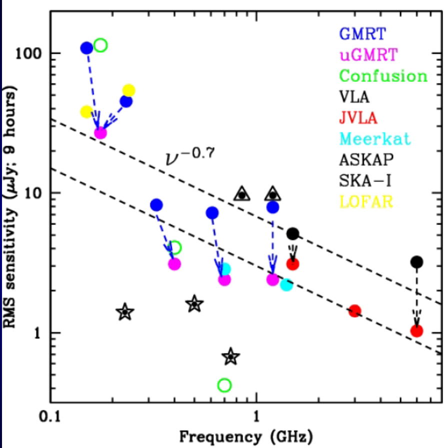
ASKAP - Australian SKA Precursor

36 dishes with revolutionary phased array feeds

Challenges for the GMRT

- **RFI, RFI, RFI**
- competition from other telescopes like LOFAR, MWA, jVLA, MeerKAT, ASKAP, FAST and eventually SKA
- limited human resources

Upgraded GMRT



N. Kanekar

What we want radio telescopes to deliver?

- sensitivity $\rightarrow$ more collecting area
- sensitivity $\rightarrow$ Lower RFI - quiet site, short integrations.
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- Technology constraints: on manufacture, maintenance and upgrade of dishes, feeds, front-end electronics, signal transport, back-end electronics (incl. correlator), offline processing, archiving.

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- Computing: n^2 correllations, CPU, Hard disks, RAM.
- Electricity: GMRT electricity bill is about Rs. 1 crore per year

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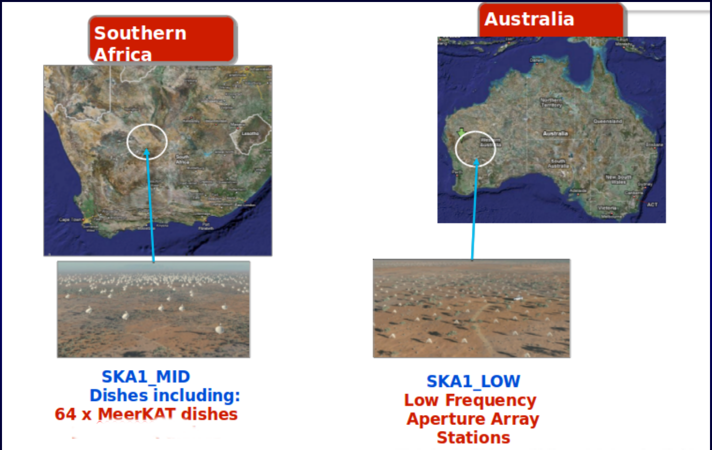
- RFI prevention and removal: remote site logistics

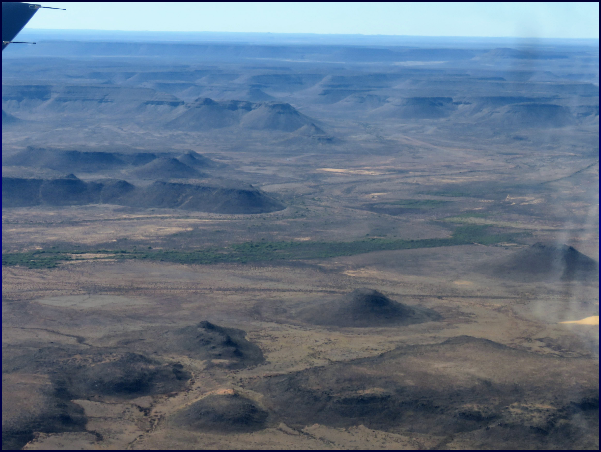
SKA Phase 1 Specifications

- 197 dishes (15m) in South Africa
- 512 low-frequency stations in Australia
- 65,000 m^2 collecting area
- Frequencies: 50 MHz – 15.4 GHz
- Longest Baseline: 150km (mid), 65km (low)
- Data: 0.7 Exabytes/year
- Construction Cost: 1.3 billion euros

SKA Phase 1

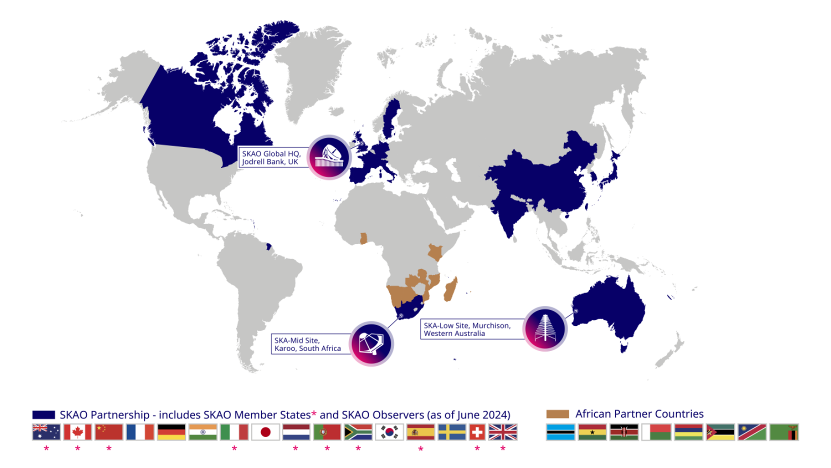

Southern Africa
Australia
SKA1_MID
Dishes including:
64 x MeerKAT dishes
SKA1_LOW
Low Frequency
Aperture Array
Stations

Proposed SKA site in the Karoo, South Africa



Proposed SKA site in Western Australia

An international 12-country collaboration that includes India



SKA Construction Progress

- Construction officially began in July 2021
- Over 100 antenna foundations completed in South Africa by early 2024
- First SKA prototype dish installed at Karoo site in 2023
- Full array of 197 dishes planned for SKA-Mid Phase 1
- Initial science operations expected 2027+

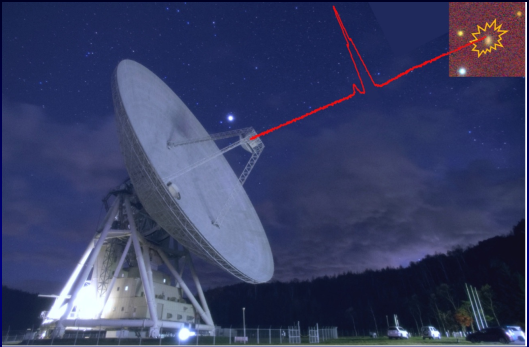
SKA-Low Progress in Australia

- 512 stations planned for Phase 1
- Each station with 256 dipole antennas
- First prototype stations already operational
- Site infrastructure development well advanced

SKA Regional Centres

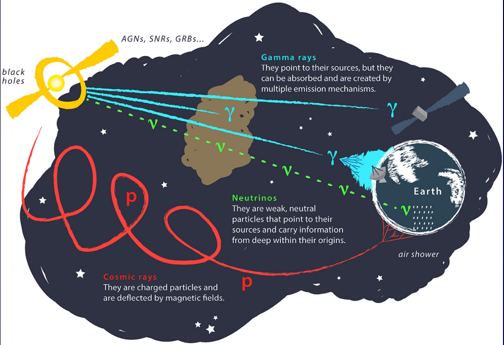
- Network of 13+ interlinked data centers globally
- Expected data rate: 100+ Pb/s of raw data
- Science data products: 600 PB/year
- Advanced ML/AI processing capabilities

Fast Radio Bursts



- Millisecond-duration radio flashes
- Extragalactic origin confirmed
- Some show periodic repetition
- Over 1000 detected, many by CHIME

Multi-messenger Astronomy



- Radio follow-up of gravitational wave events
- Gamma-ray burst afterglows
- Neutrino source counterparts
- Time-domain radio surveys crucial

Modern Processing Techniques

- Real-time calibration and imaging
- Deep learning for source finding
- GPU-accelerated processing
- Cloud computing and distributed analysis
- Automated RFI flagging

Current Scientific Frontiers in Radio Astronomy

- Cosmic Dawn ($z > 6$)
- Magnetism across cosmic scales
- Fast radio transients
- Precision pulsar timing
- Technosignatures (SETI)

Questions and comments?

I will be happy to take your questions and comments.