Landmark Developments in Radio Astronomy

Great Discoveries in Radio Astronomy: Key Qs. Today

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Outline

- Radio Astronomy: emission mechanisms; great discoveries
- Radio Galaxies, Quasars and Black Holes
- Cosmic Microwave Background Radiation (CMB): Big Bang Model; formation of structures in the Universe.
- Pulsars
- HI 21cm emission: Spiral Structure of our Galaxy; Rotation Curves.
- Radio Telescopes; Radio Interferometers: GMRT.
- Key Questions Today; SKA.
- Conclusion

1. Brief History of Radio Astronomy: a few highlights

- Radio Astronomy began in 1933 when Karl Jansky discovered that radio waves are coming towards the Milky Way. In 1935, Grote Reber built a parabolic Dish of 30 ft diameter and mapped radio emission from our Galaxy. Solar radio emission discovered during world war II

- 1948-60: A few hundred radio galaxies discovered; millions of times more powerful than normal optical galaxies.

- 1963: Discovery of Quasi stellar radio source (Quasar) 3C273 at redshift 0.17.

- 1965; Discovery of Cosmic Microwave Background radiation.

- 1968: Discovery of Pulsars.

- 1965-69: Discovery of Mega-masers (OH; NH_3; H_2O; H_2CO).

Why Radio Waves from the Universe?

- Radio waves like X-rays, UV, light and infra-red are electromagnetic radiation.

- **It is known that any charged particle when accelerated or de-accelerated gives rise to electromagnetic radiation.**

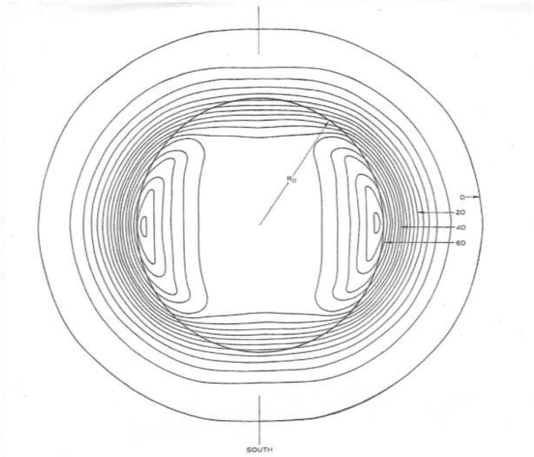
- Synchrotron radiation: Radio waves of extremely high power arise when electrons with relativistic velocities gyrate and radiate in the presence of magnetic fields, giving rise to the synchrotron radiation.

- (a) Brehmstrahlung radiation by hot gas and (b) atomic and molecular transitions are also observed at radio wavelengths from different classes of celestial objects.
- Coherent Radio Emission from Pulsars and other sources (to be discovered!).

Solar Radio Emission

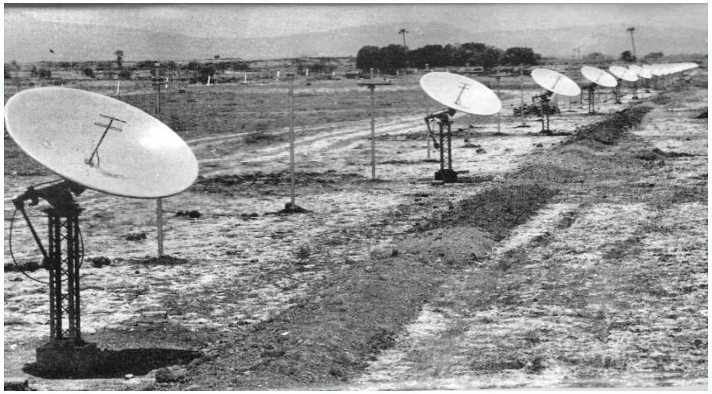
- 1942: Radio waves from the Sun discovered during the World War II (Hey: interference to British radars, not by jamming by Germans but by the Sun!)
- 1946: Brightness temperature of Solar disk has temperature of million degrees! (Pawsey et al. & Martyn)
- 1950-53: Dynamic spectrum of radio bursts from the Sun by Paul Wild
- 1953: First two dimensional map of the Radio Sun using a multi-element interferometer by Christiansen & Warburton
- Today extensive studies of the Solar Activity are being done using radio telescopes and X-ray satellites. Daily measurements of Solar wind velocity by Dr Manoharan using the Ooty Radio Telescope

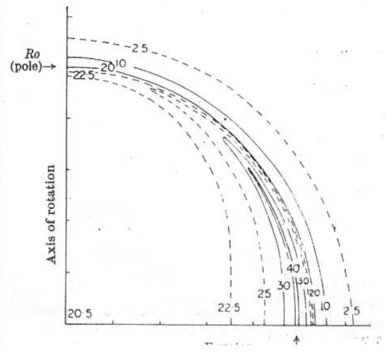
2-dimensional radio maps of the Quiet Sun:



EW Grating Array 1951-53: λ=21cm Christiansen & Warburton CSIRO, Australia

λ=21cm





EW Grating Array at Kalyan: 1963-65: λ=50cm, Swarup et al.

: λ=50cm

2. Great discoveries made in the radio window: what do they tell us?

➢Radio Galaxies and Quasars

⇓

➢

★ Massive Black Holes in Galactic Nuclei

Neutral Hydrogen HI emission

⇓

★ Spiral Structure of our Galaxy
Rotation Curves
re-ionization epoch

➢ Microwave Background 2.7 k Radiation

⇓

➢★ Big Bang origin of the Universe

Molecules in Space

⇓

★Over 100 Molecules
(Ammonia, Alcohol, Water, OH, HCN, CO, etc.)

★ Star Formation

★ Ingredients of Organic Life

Great Discoveries …

- **Pulsars**
  (Pulsating radio sources)

  ⇓

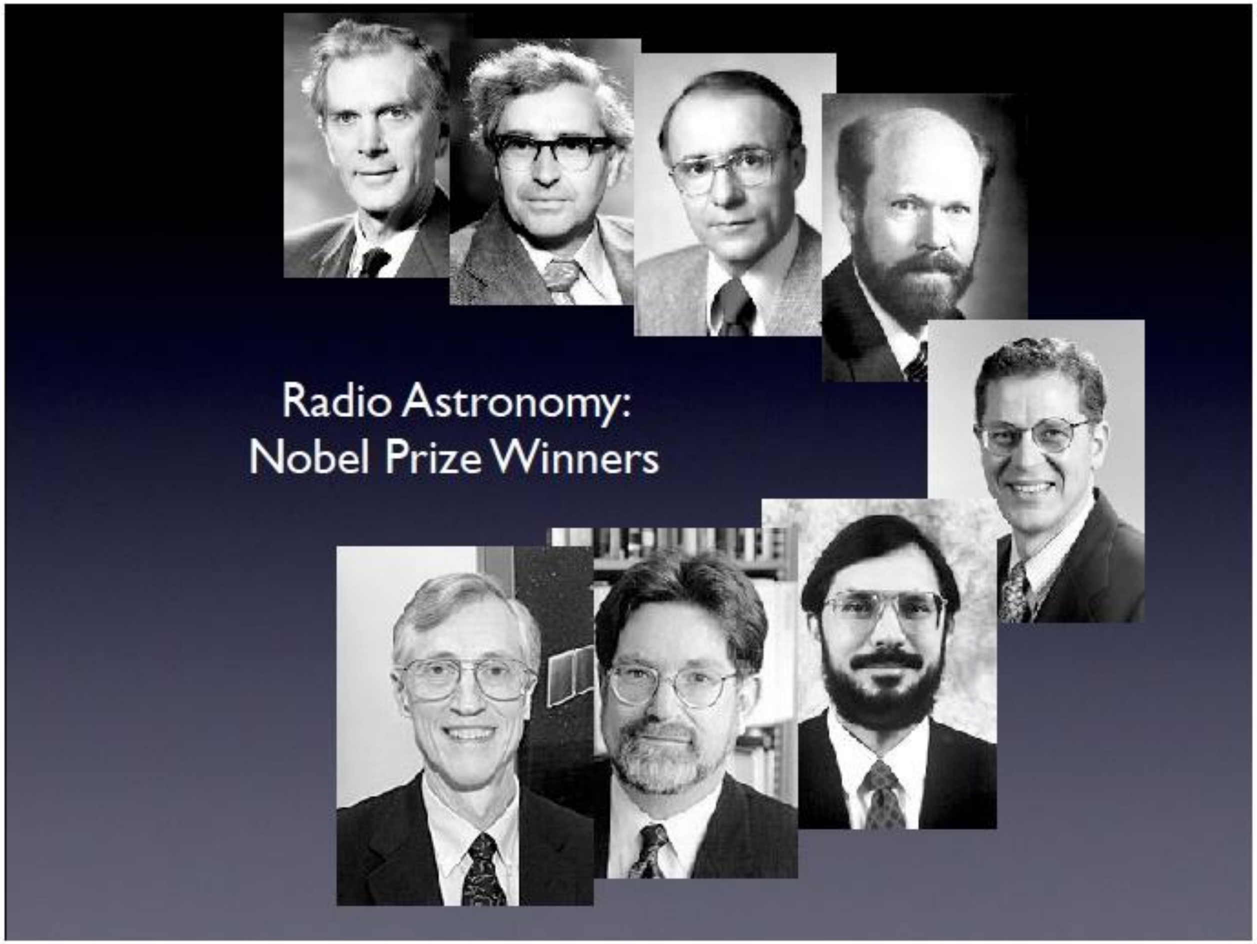
  Collapsed Neutron Stars

  ★ Provides tests of the General Theory of Relativity

- ★ **Gravitational lensing**
  ★ **HI Rotation Curves**

  ⇓

  Dark Matter in the Universe



Top: left to right: 1.Ryle, 2.Hewish, 3. Penzias, 4. Wilson
Bottom: Right to Left: 5.Taylor, Hulse, Smoot, Mather

3. Radio Galaxies, Quasars and Active Galactic Nuclei:

First radio galaxy:
A radio source of very large intensity, called Cygnus A was discovered during 1940s. Its position was measured by Grahm Smith and soon in 1951, it was identified with an optical galaxy at a redshift of 0.07 by Baade and Minkowski, at a distance of more than any known galaxy at that time

what have we learnt,
and what are challenges now?

Radio Galaxies are millions of time more energetic than normal galaxies.

Most radio galaxies are double or triple sources, with two outer radio lobes and a central component associated with a black hole at the centre of the galaxy

Radio source associated with a nearby galaxy Centarus-A is superimposed on the optical image

A radio map of the Quasar 3C175 made by VLA

with a resolution of 0.35 arc-sec showing a central compact radio source near a quasar, a jet of radio emission and two outer lobes.

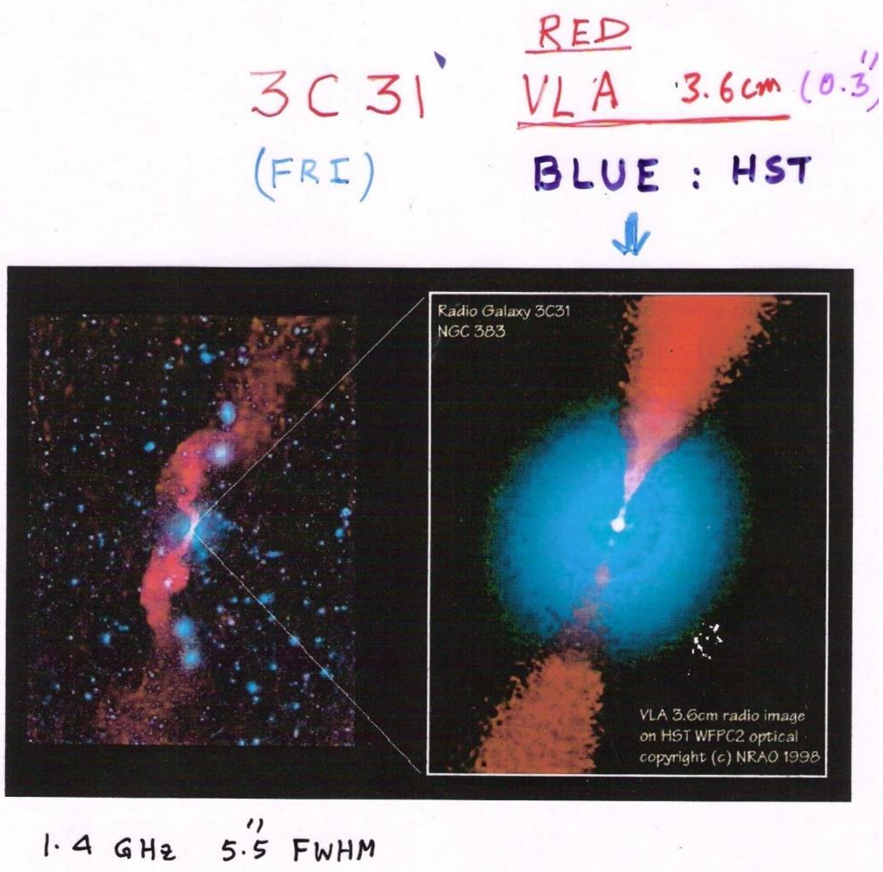
Qs. What gives rise to Radio Galaxies, Quasars and other Active Galactic Nuclei

Numerous observations have indicted the presence of massive Black Holes at the centre of the radio galaxies, surrounded by an accretion disc, that give rise to relativistic electrons resulting in a narrow jet along the minor axis of the galaxy. (Rees and Blandford, 1974)

Some of Challenges in RA:

1. To probe properties of the accretion disc around the central Black Holes by observing HI absorption lines from Compact Radio Sources and by combing with X-ray observations.

2. To search for radio emission from QSOS at highest redshifts



Black Holes in the Universe

Although presence of massive black holes at the centre of active galaxies was firstly established by radio astronomy observations, their existence is now firmly established from Radio, Optical and X-ray observations.

It is now clear that almost all galaxies have massive black holes of millions of solar mass including our Galaxy.

Stellar size black holes have also been discovered in our Galaxy.

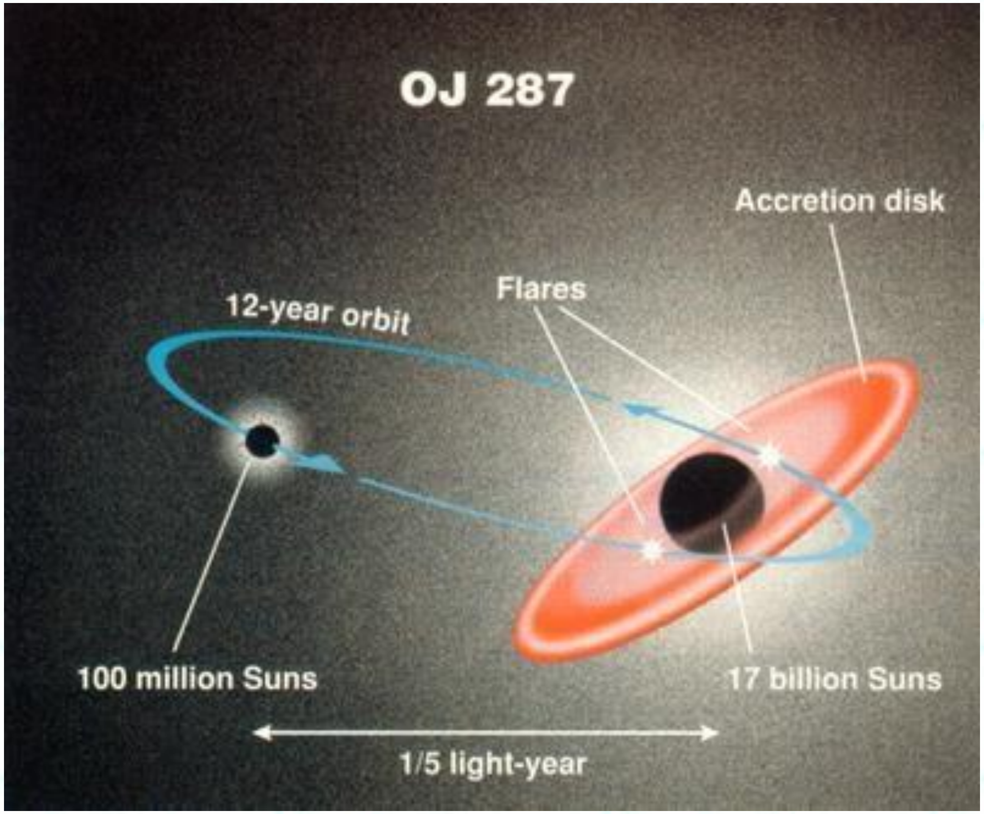
Challenges: Search for evidence of two Black Holes in some of the active galaxies (galaxies grow by merging)

OJ287 is considered to have an object of 100 million Suns in a binary orbit around a Black Hole of 17 Billion Suns.

OJ 287 was first detected in 1970s in the Ohio Sky Survey. From its radio and optical observations, it is classified as a BL Lac object, located 3.5 billion light years away.

It has produced many quasi-periodic optical outbursts going back approximately 120 years, as first apparent on photographic plates from 1891.

Wikipedia

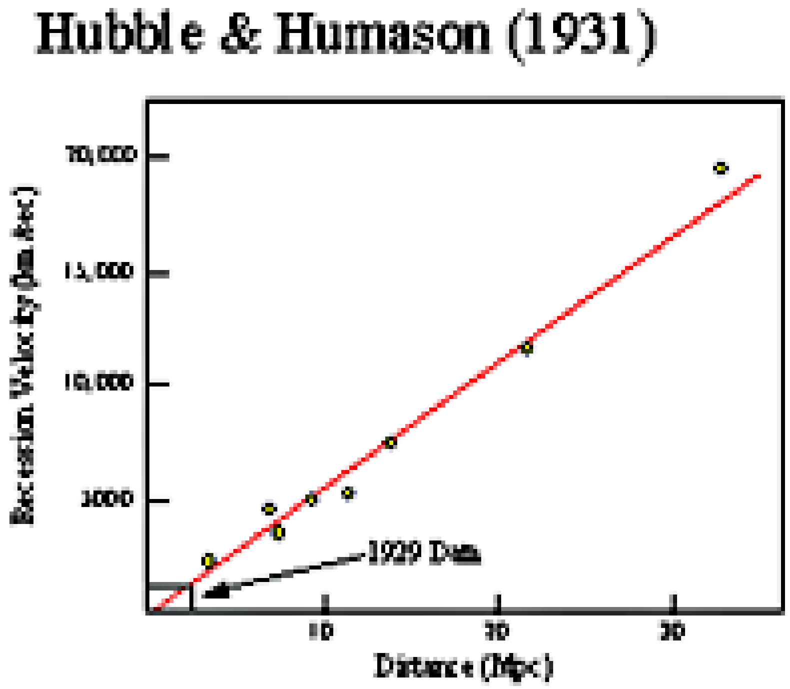


4. COSMOLOGY:

Origin and evolution of the Universe

Hubble's Law

- **In 1929 Hubble made a remarkable discovery** that *farther away is a galaxy located from us, faster it is moving away from us*
- **Conclusion**: **Universe is Expanding**



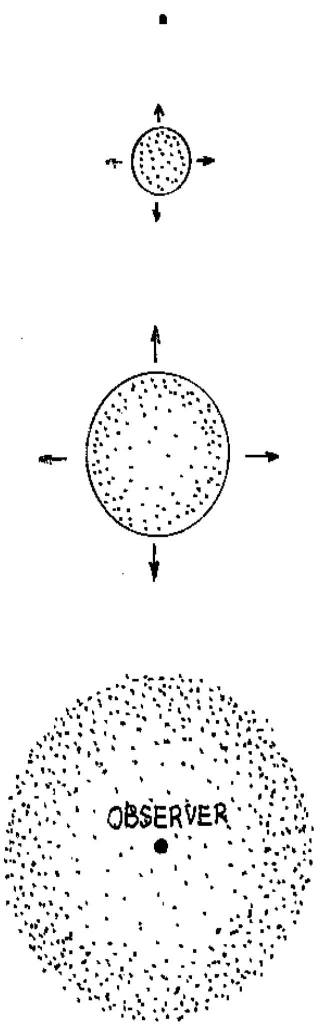
Evolution of the Universe *(Big Bang Model)*

$T=0$

$T=t_1$

$T=t_2$

$T=t_3$
Now



Ooty Radio Telescope: 530m long and 30m wide with its long axis parallel to that of the earth

During 1970's ORT provided angular sizes of about 1000 radio sources with arcsec resolution for the first time PROVIDING independent evidence of the big bang model

Big Bang Model in brief

- According to the Big Bang Model, in the beginning Universe was extremely tiny and highly energetic. Soon after it expanded exponentially.

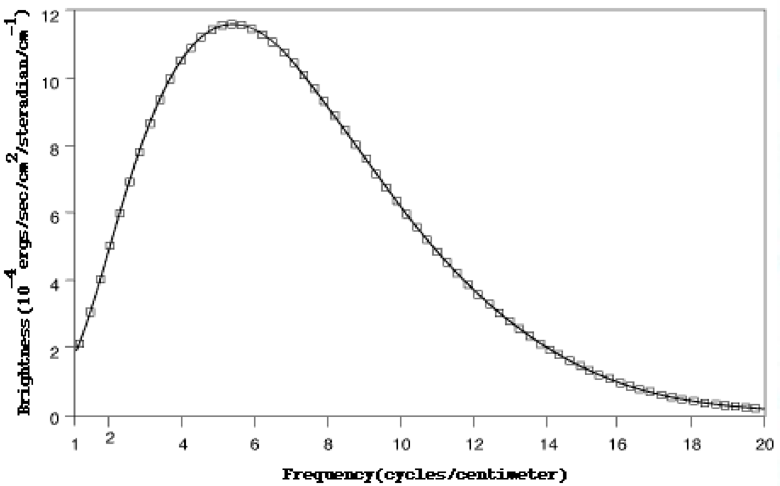
- At the cosmic epoch of fraction of seconds to a few minutes, when the temperature was about billion degrees, there got formed electrons, protons neutrons and neutrinos resulting in ~ 75 % HI, ~24.99 % Helium and only a trace of heavier elements.
- (Broadly: considering $E = kT$ and $E = mc^2$, we get $m \sim kT/c^2$ and hence protons arise when $T \sim 10^{13}$ K; actually more complex model). Also numerous photons are produced.

- At a cosmic epoch of ~ 380000 years, temperature decreases to ~ 4000K when electrons and protons combine; photons freely stream giving rise to the redshifted microwave background radiation.

Cosmic Microwave Background (CMB)

- Penzias & Wilson made a remarkable discovery in 1965 that there exists an all sky microwave background radiation, corresponding to blackbody temperature of about 2.7K. (Nobel Prize in 1978)

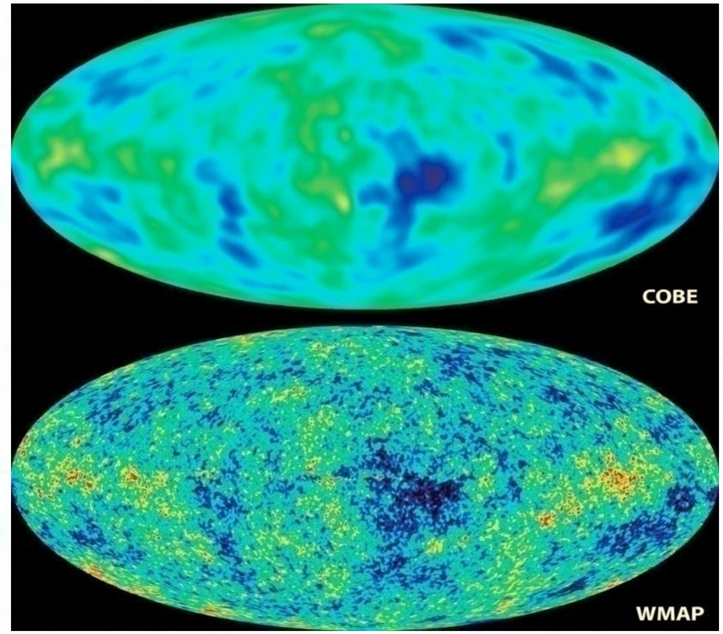
- During 1990s the COBE satellite designed by John Mather and colleagues showed it to be a perfect blackbody radiation, providing strong support to the Big Bang Model (Nobel Prize, 2006)

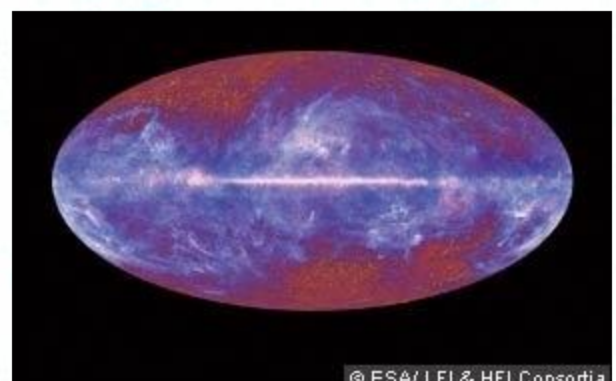


Formation of Galaxies and clusters in the Universe

- Qs.: What are the seeds which later give rise to formation of galaxies by gravitational collapse?

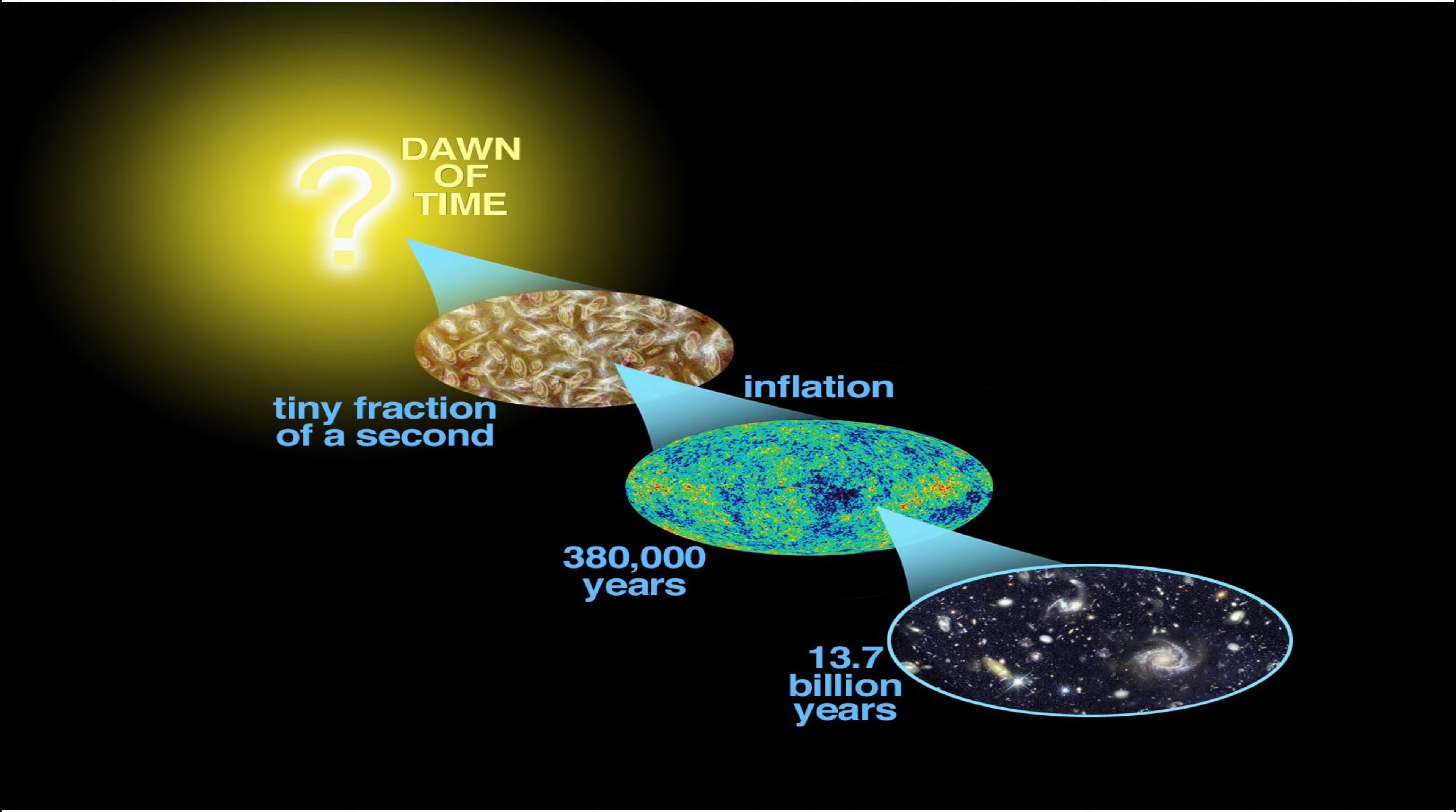
- Ans: Fluctuations have been detected in the Microwave background radiation of about 1 part in 100,000 by COBE (1992) and WMAP satellites (2002).





PLANCK: Afterglow of the Big Bang

History of the Big Bang Model

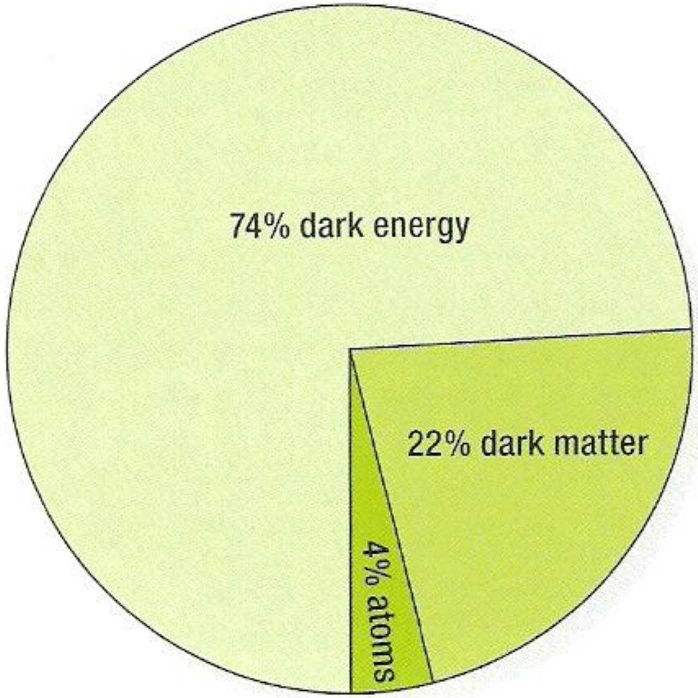


Standard Cosmological Model

Universe is dominated by 74% dark energy, 22% dark matter, and 4% ordinary matter in stars, galaxy and in and around us.

Evidence for dark matter was first postulated by Zwicky in 1930s, later from Flat Rotation Curve by Vera Rubin in 1983 and van Albeda et al. in 1985 and now by Gravitational lensing and WMAP.

Evidence for dark energy by observations of distant supernovae and WMAP.

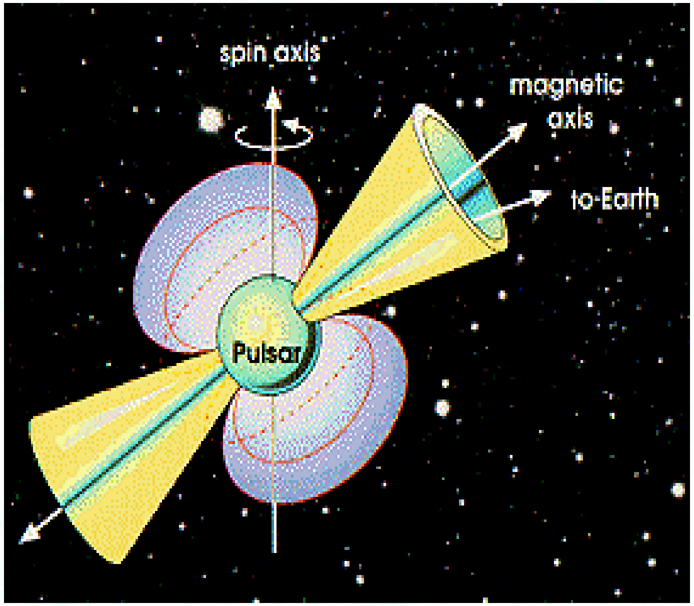


5. PULSARS

(Pulsating Radio Sources)

Pulsars: Pulsating Radio Sources:
An outstanding discovery

1n 1967, Tony Hewish and his student Jocelyn Bell at Cambridge discovered pulsed radio emission towards a celestial radio source, with highly accurate periodicity, These object are called PULSARS



A diagram of a pulsar, showing its rotation axis and its magnetic axis

Pulsars are associated with Neutron Stars that are the end products of the stars when their nuclear fuel runs out (giving rise to a Supernova remnant and a Neutron Star).

The collapsed neutron star starts spinning at a fraction of second. Its magnetic field becomes tens or hundreds of billion Gauss, resulting in beamed radiation in the direction of their magnetic poles.

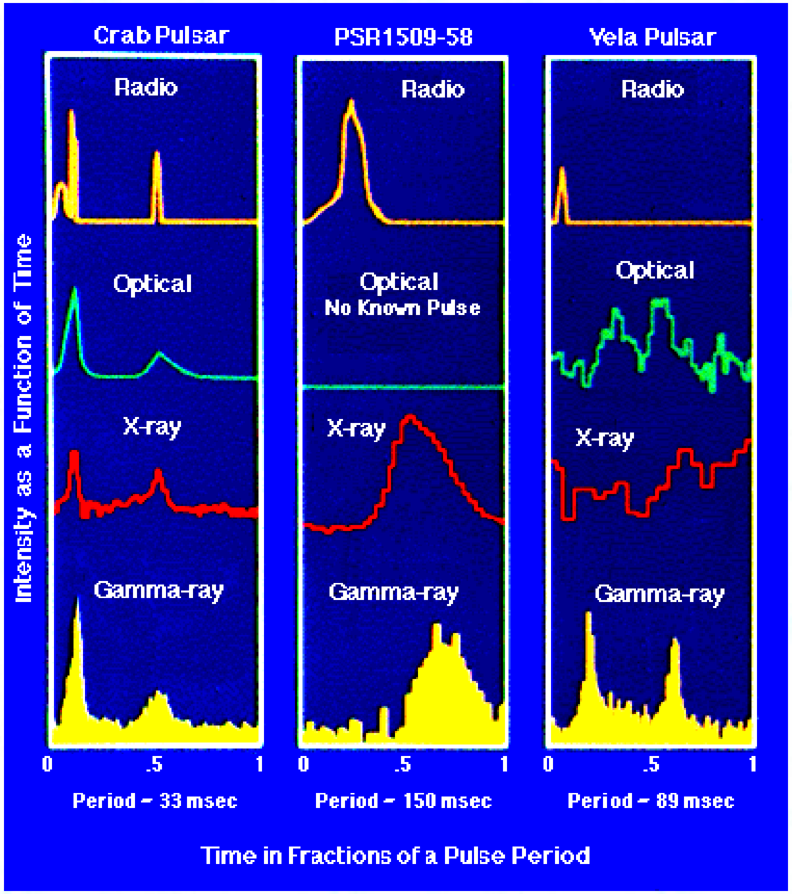
If the rotation axis and magnetic axis are not aligned, we observe PERIODIC PULSED TRAIN.

About 1700 pulsars have been now catalogued so far.

Some Pulsars emit in all electromagnetic windows: Radio, optical, X-rays and Gamma-ray

Pulsar emission mechanism is poorly understood and remains a very active research topic.

Broadly, the magnetic field of billions of Gauss and the rotation of the neutron star gives rise to electric field of billions of volts, accelerating electrons to relativistic velocities that radiate as they travel along curved field lines of the dipole field of the neutron star.



Credit NASA

A new pulsar in a supernova remnant

- Recent discovery of a young pulsar in the supernova remnant G21.5 0.9 by Gupta et al. (2005) using the GMRT.
- Period 61.96 ms; characteristic age ~ 4800 yrs.
- Second highest spin-down luminosity (second only to the Crab Pulsar).
- Chandra's X-ray image is shown in the Top left panel. Pulsar is located near the centre OF THE NEBULA.

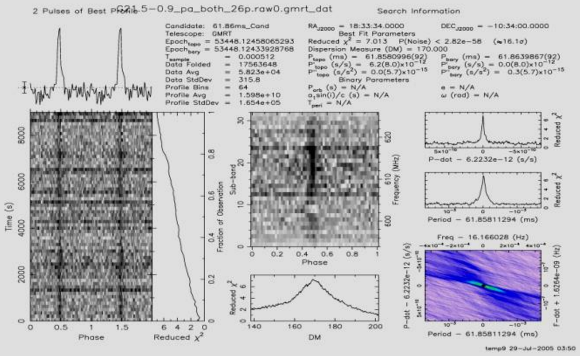
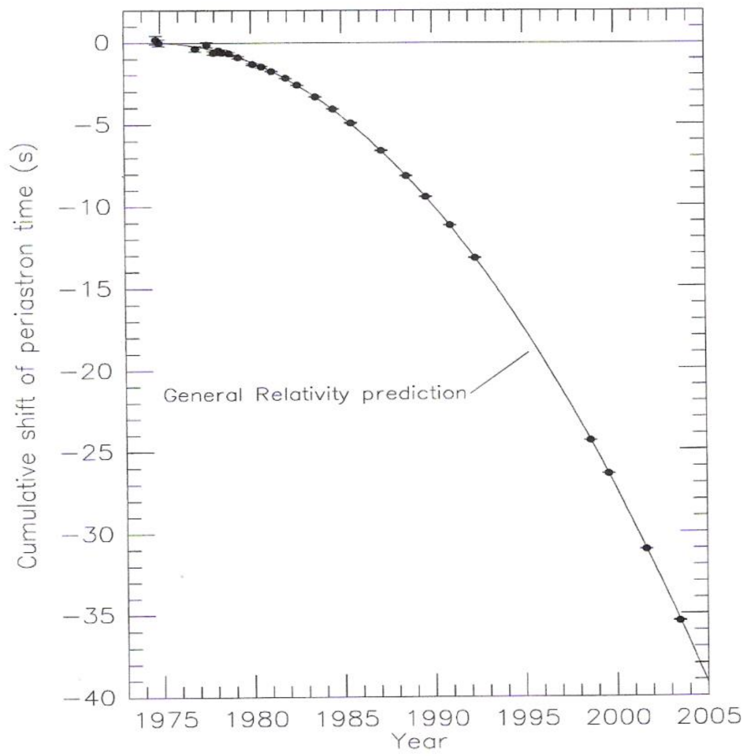


Figure 1: The GMRT has recently discovered a new pulsar (J1833-1024, shown in bottom panel) in the supernova remnant G21.5-0.9, whose image taken with the Chandra X-ray telescope is shown in the top panel – the pulsar is thought to be located very close to the centre of this remnant

First Binary Pulsar (1913+16) discovered by Hulse and Taylor, 1975.

According to General Relativity, a binary star system should emit energy in the form of gravitational waves. The loss of orbital energy results in shrinkage of the orbit.

In 1983, Weisberg and Taylor concluded from accurate timing of the pulse period of the binary pulsar 1913+16 that the Pulsar is giving rise to gravitational radiation as predicted by the Einstein's General Theory of Relativity .
(Nobel Prize to Hulse and Taylor in 1993).



30 years observation of the orbital decay of PSR B1913+16.

6. The 21 cm radiation by the Neutral Hydrogen (HI)

21 cm radiation by the neutral hydrogen (HI)

Predicted by van der Hulst predicted in 1944

Discovered by Ewen & Purcell in 1951

Observations at 21cm wavelength has provided information about the spiral structure of our Galaxy

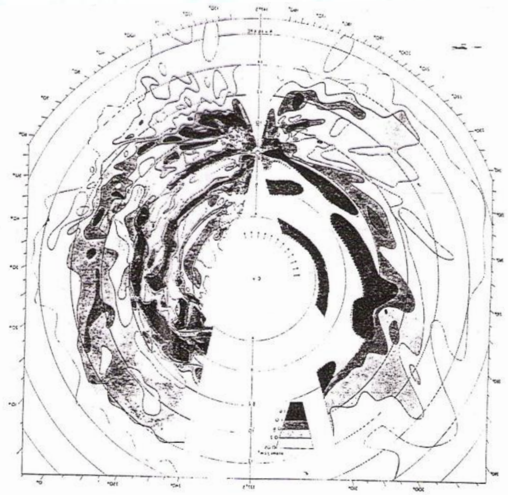
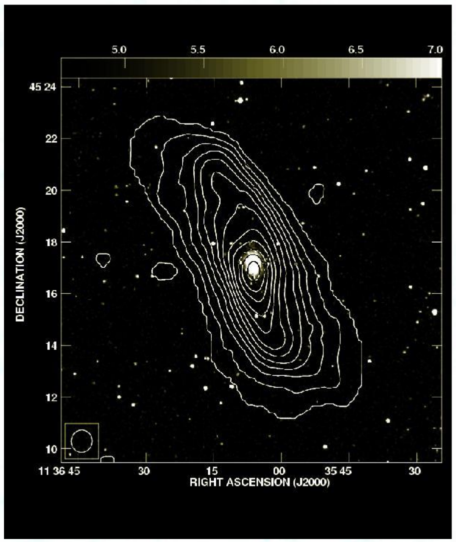


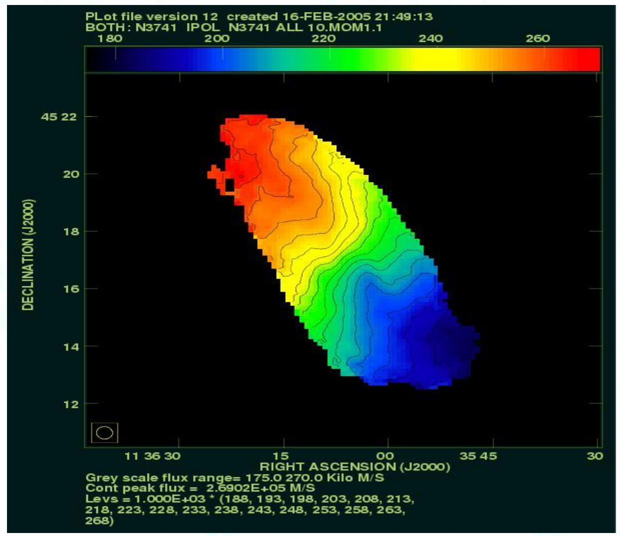
Fig. 10.6. The Oort, Kerr and Westerhout map of the spiral arms of the Galaxy, constructed from a circular model (see Figure 10.3), showing the maximum densities projected on the galactic plane.

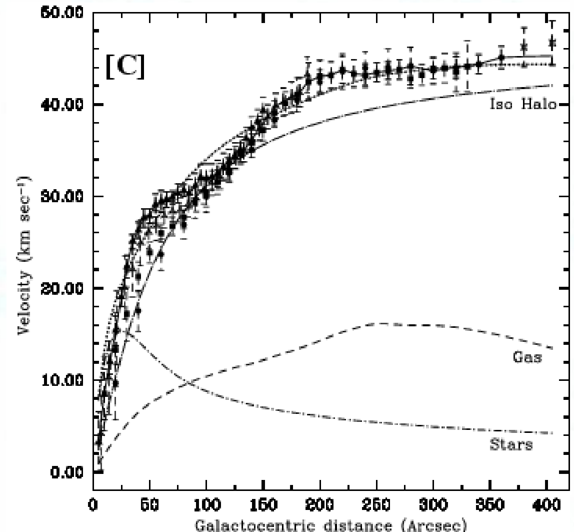
Neutral Hydrogen forms the building block of the Universe. Its observations provide important clues about the origin and evolution of the Universe

GMRT observations of HI in ~ 25 Dwarf galaxies have been made to understand their kinematics.

Begum et al. A&A, 433, L1 (2005)







HI disk extends to ~ 8.3 times Holmberg radius.

. Rotation curve measured to ~ 38 optical disk scale lengths.

M_{dyn}/L_B ~ 107 – one of the “darkest” galaxies known.
Does it also have a small baryon fraction?

Rotation Curve

NGC 3741 M_B ~ -13.1

Search for the Reionization Epoch:

Background: Soon after the recombination epoch at z ~ 1100, the neutral hydrogen condensates started collapsing, resulting in the formation of the first massive star formation at z ~ 30.

Later neutral hydrogen got ionized here and there by Lyman alpha from stars and by first quasars, resulting in a patchwork of absorption and emission.

By ~ z = 6, hydrogen got fully ionized, as has been established by absorption spectra of QSOs.

Search for the epoch of reionization is an extremely important scientific objective that would clarify formation of the epoch of the structure formation in the Universe. GMRT is well suited for this search as it allows sensitive observations ~ 130-200 MHz, covering redshift range ~ 6 to 9.

Observations over few hundred hours have been made with the GMRT by U Li Pen and collaborators in Canada and scientists at NCRA.

Search for the epoch of reionization is also a major objective of the newly constructed LOFAR in Europe.

7. Radio Telescopes

► Angular Resolution ,θ , of an aperture or a telescope is given by wavelength, λ, divided by aperture diameter D . [$\theta = \lambda / D$].

* Resolution of human eye: {λ = (1/2000 mm) / D =1 mm}
= 1/ 2000 radian = 1.5 arc minute.

(One can not decide on a road in the night whether a bright moving light towards you located about 2km away is a car with two headlamps or a motor bike with bright halogen lamp).

* You require 10 cm aperture to get 1 arc second resolution for a telescope observations in visible light.

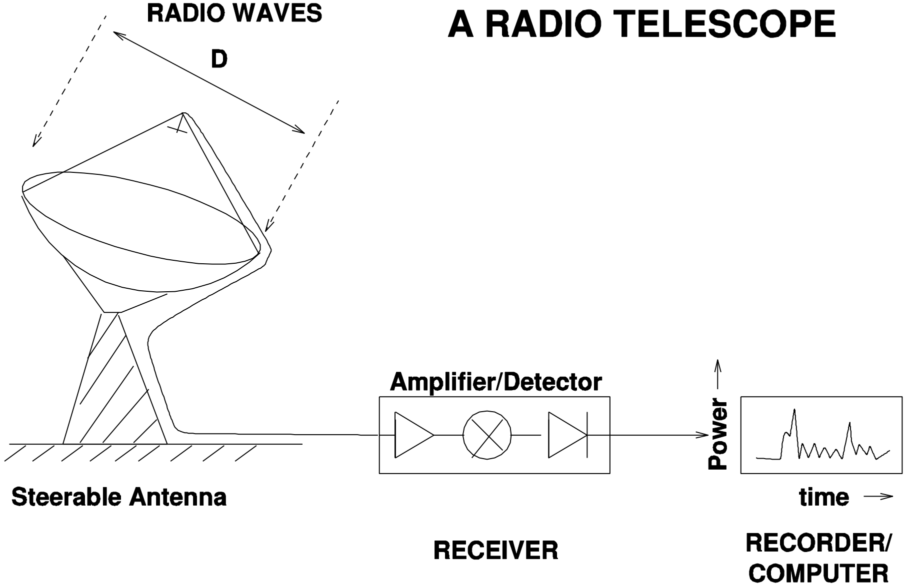
► For a radio telescope receiving radio waves, say at 300 MHz (wavelength of 1 m), we require an aperture of 200km, to get 1 arcsec resolution!

► **How to make such a big telescope: INNOVATION is REQUIRED)**

Radio Telescopes

A SIMPLE RADIO TELESCOPE CONSISTS OF AN ANTENNA, A RECEIVER AND A RECORDER

A RADIO TELESCOPE

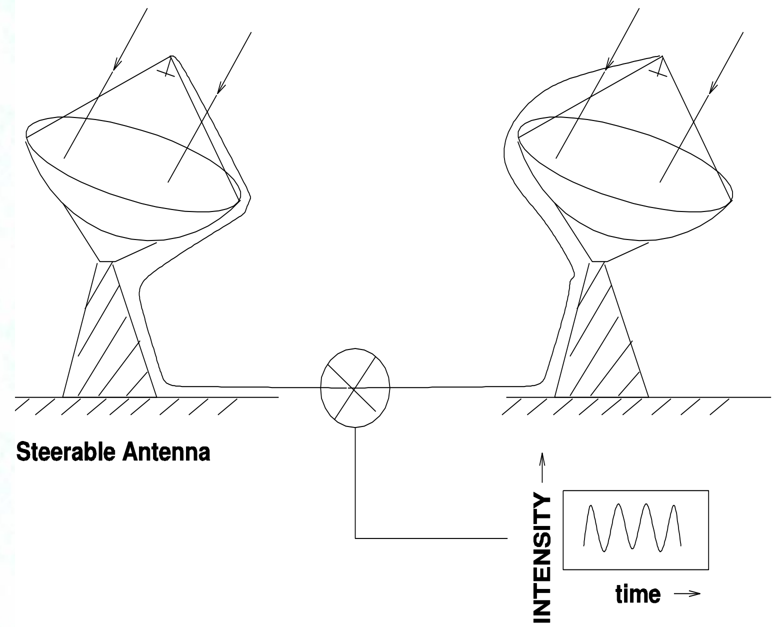


RESOLUTION = Antenna Beam $= \lambda / D$

TO GET ONE ARCSEC RESOLUTION AT A WAVELENGTH OF ONE METRE (300 MHZ) WE NEED D=200KM!

FOR OBTAINING HIGH ANGULAR RESOLUTION SCIENTISTS USE RADIO INTERFEROMETERS

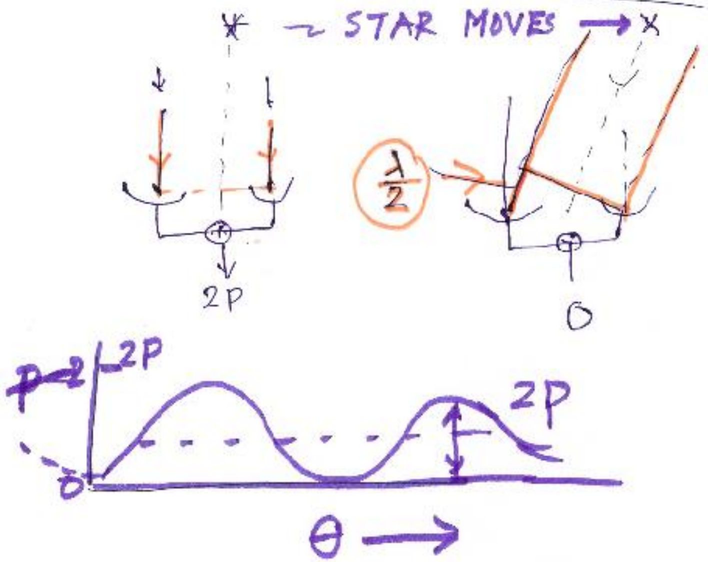
AN INTERFEROMETER



An Interferometer measures one FOURIER COMPONENT OF THE RADIO IMAGE

रेडिओ इन्टरफेरोमीटर

(Radio Interferometer)



- OUTPUT OF AN INTEROMETER GIVES A SINUSOIDAL OUTPUT
- ADD MANY SINE WAVES TO GET A PICTURE

A basic radio interferometer consist of pair of antennas that measure one Fourier component of the radio or optical source.

Earth's Rotation Synthesis Radio Telescope

► Uses principle of a 2 antenna interferometer which measures one Fourier component of the image of the celestial source.

► A picture in a newspaper or a TV is made by black and white dots or colour dots.

►Picture can be also synthesized by its Fourier Sine and Cosine components.

► For N antennas (N(N-1)/2 Fourier components are measured.

► With Earth's rotation, millions of Fourier components are measured and a large aperture is synthesized.

Radio Interferometers: Synthesis Radio Telescopes

For obtaining very high resolution a number of earth's rotation synthesis radio telescope have been built in the world, of which some of the prominent are:

Westerbork Synthesis Radio Telescope.

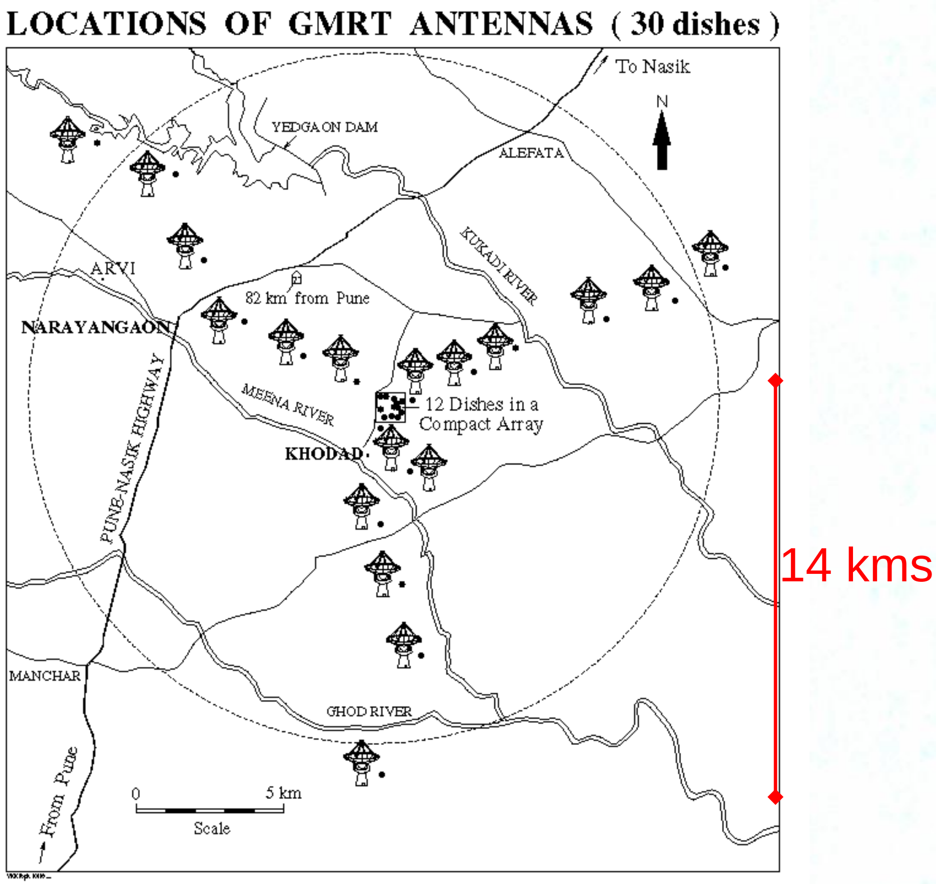
Very Large Array.

Australia Telescope Array.

Giant Metrewave Radio Telescope

Very Large Array (VLA)

GMRT consists of 30 dishes of 45m diameter



GMRT is located in an array of about 25 km in extent.

With the rotation of the earth, the Y array rotates with respect to stars.

***In* 10 hours of observations we get maps as if made with a 25 km dish !**

A close view of one of the 30 nos. of 45 m dishes. Several dishes of the central array are also seen

8. GMRT is a versatile instrument

* Solar system: Jupiter, Sun
* Our Galaxy:
  *** Pulsars**
  *** SNR**
  *** HII**
* Nearby Galaxies: Clusters of Galaxies, Radio Galaxies & QuasarsDamped Ly-a systems; Associated HI absorption
* Search for HI proto-clusters

GMRT is the world’s largest radio telescope operating at decimeter and metre wavelengths.

It is being used by over 300 astronomers from more than 25 countries, including those from Cambridge, Oxford, Stanford, Berkeley, Caltech etc.

There is no other scientific instrument in India that is being used by more than dozen or so scientists from across the world.

A major new scientific development at the GMRT.

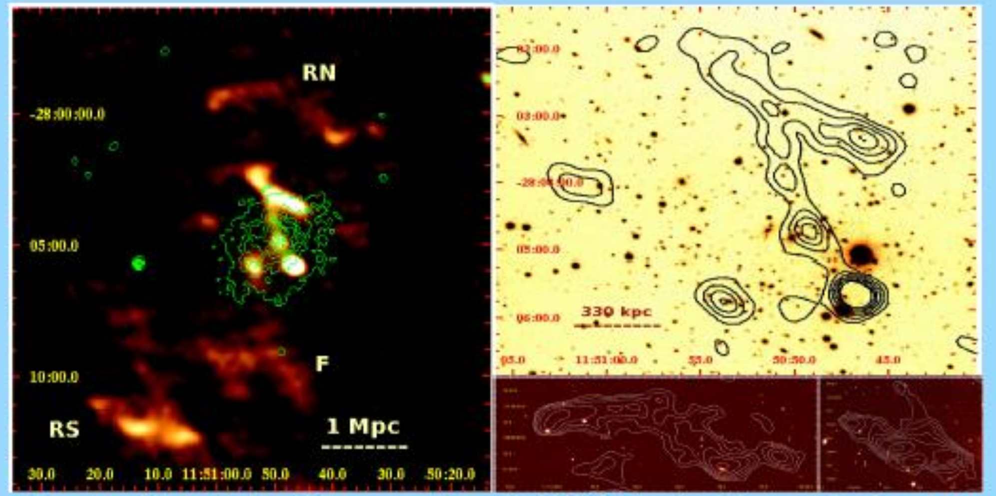
An all sky survey is being made at a frequency of 150MHz, at a 10 time longer wavelength than that done in USA.
Called TIFR-GMRT-all Sky- Survey **(TGSS).**

After years of work special software has been developed and installed on 100 computers that automatically makes image of the radio sky being surveyed.

Data is publicly available and can be used by any student to find new results.

A recent outstanding result regarding formatio of the structure in the Universe by merging of galaxies and clusters. The very first observations of ~ 1000 sq. deg. by TGSS revealed merging of two clusters.(Bagchi et al. Ap.J. Letts. June 2011)

Discovery of giant double radio relic in Planck ESZ cluster



Left: TGSS radio map of the cluster. Superposed are the XMM-Newton X-ray emission contours (green). A pair of giant radio relics at the cluster periphery are marked RN (north relic) and RS (south relic). Right: Zoom of central, RN and RS regions with optical image in background (Ref.: Bagchi et al. ApJL 2011).

- Large-scale diffuse non-thermal radio emission has been discovered in PLCK G287.0+32.9 using the TGSS data.
- TGSS data reveal a pair of giant (>1Mpc) “arc”-shaped peripheral radio relics (signatures of shock waves) of unprecedented scale (∼4.4 Mpc at redshift 0.39).
- These relic sources are unique “signposts” of extremely energetic mergers and shocks (both ongoing and past) that are assembling and heating up this very massive galaxy cluster.
- They are also a probe of the filamentary cosmic-web structure beyond the cluster virial radius.
- PLCK G287.0+32.9 is an exceptionally hot (T ∼13 keV), massive, and luminous galaxy cluster, strongly detected by the Planck satellite in a recent, all-sky blind search for new clusters through Sunyaev−Zel'dovich effect.

9. Qs. Do Fundamental Constants vary with Cosmic Epoch?

9.1. Fundamental Constant Evolution with Conjugate-satellite OH Lines

(Nissim Kanekar, Jayram Chengalur and Tapasi Ghosh, 2010; arxiv:1004.5383.v1)

A consistent velocity offset (2.6 σ) between the OH satellite lines at 1612 and 1720 MHz is found in both the WSRT and Arecibo (AO) spectra, although the two datasets were acquired with telescopes on different continents and at different times; this makes it very unlikely that the offset might be caused by RFI.

The observed offset in satellite line redshifts in PKS 1413+135 implies $\Delta G/G = (-1.18 \pm 0.46) \times 10^{-5}$, where $G = g_p[\mu\alpha^2]^{1.85}$, suggesting that one or more of α, μ, and g_p had smaller values at $z \sim 0.247$ than at the present epoch.

Fundamental constant evolution with conjugate-satellite OH lines

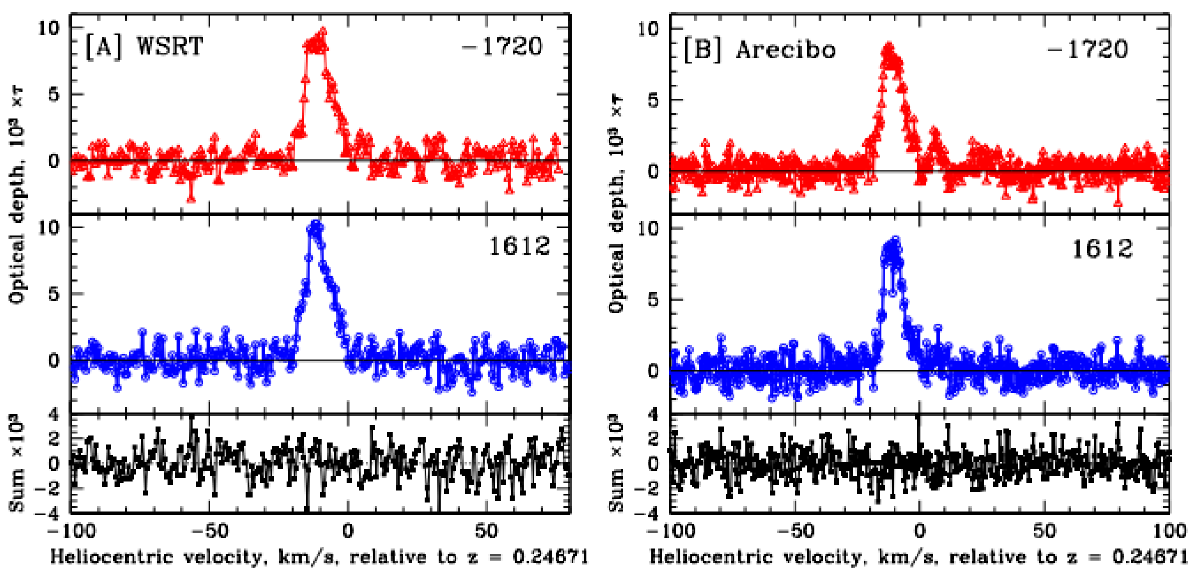


FIG. 1.— Top panels: WSRT and AO satellite OH spectra towards PKS 1413+135, with optical depth ($1000 \times \tau$) plotted against heliocentric velocity, in km/s relative to $z = 0.24671$. The 1612 and 1720 MHz spectra are plotted using open circles and triangles, respectively, with the 1720 MHz spectrum flipped in sign. Bottom panels: The sum of the 1612 and 1720 MHz optical depth spectra from each telescope.

10. Key Questions today for Radio Astronomy investigations

- Q.1. What is ultra-strong field limit of relativistic gravity?: Increased sensitivity of radio telescopes will discover many more pulsars and may , as an example find a pulsar in orbit around a black hole.

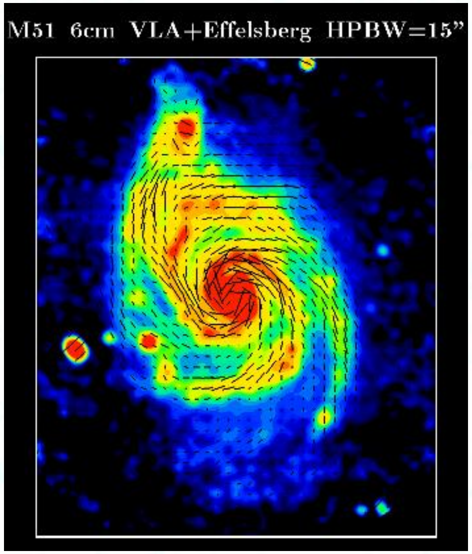
- Accurate timing of a large number of milli-second pulsar may detect primordial gravitational radiation from the inflation epoch of the Universe

Qs.2. Origin and evolution of the Cosmic Magnetism?

M51: visible wavelength

Radio Astronomy is uniquely placed to determine evolution of magnetic field from early times to now,

through studies of Faraday rotation, polarization of synchrotron radiation and Zeeman effect.



M51: 6cm Radio wavelength

Qs. 3. Galaxy evolution and cosmology?

Measurements of the unique 21cm (1420 MHz) radiation of neutral hydrogen (HI) from a large number of galaxies up to large distances will allow understanding of the formation and evolution of galaxies.

- Q.4. When did the first stars form and neutral hydrogen got reionized?

- Theoretical predictions, computer simulations and WMAP measurements indicate that the first stars and galaxies collapsed gravitationally from the primordial neutral hydrogen (HI) at redshifts of about 30. Later, neutral HI got ionized by UV byabout redshift of ~ 6.

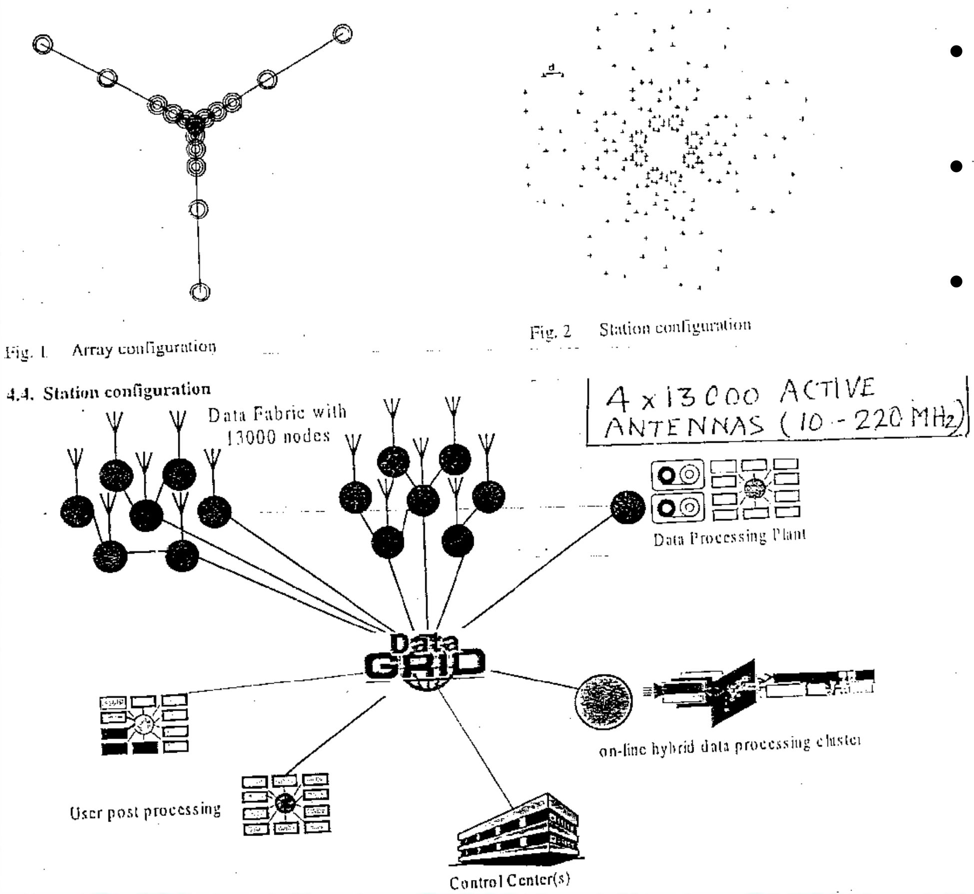
- Details of the Epoch of Reionization is of great importance for studies of the structure formation in the Universe, requiring measurements of emission and absorption of HI in the frequency range of about 50 to 200 MHz.

Qs.5. Search for earth like planets and detecting leakage radiation from extra-terrestrial intelligence transmitters (SETI)?

The proposed Square Kilometer Array (SKA) will allow studying extra-solar terrestrial planet formation and search for possible ETI from millions of stars.

The ambitious ALMA (Atacama Millimeter Array) project of 64 nos. 12m antenna array of US, ESO and Japan in Chile will allow studies of molecules in Galaxies at high redshifts, with potential of great discoveries. The picture shows a recent picture of eight antennas installed (λ = 0.3 mm to 9 mm)

A Software Radio Telescope
LOFAR: Low Frequency Array (Epoch of Reionization)



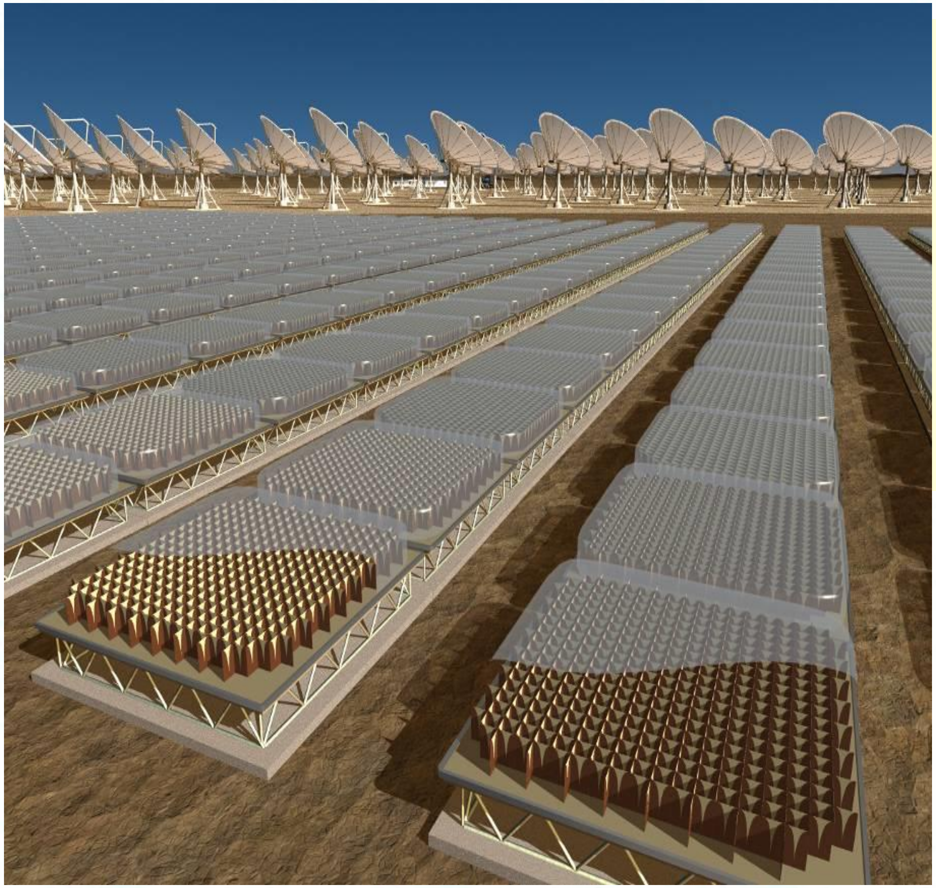
- Frequency coverage ~10 to 240 MHz
- Tens of thousands of active antennas ($l << \lambda$)
- Thousands of frequency channels (10,000)
- Massive use of VLSI, Optical fibre and standard data processing units for 40 terra-flops of data.

1. LOFAR is being developed by NFRA, Netherlands: completion by 2013
2. NRL: US are also planning LWA in USA.
3. Australia, USA and India are constructing MWA in Australia

(Murchison Widefield Array)

MWA in Australia under construction

Next decade: Square Kilometer Array (SKA): a very challenging project in astronomy



100 times more powerful than any existing radio telescope to be built during 2**013 to 2022, by 19 countries:** Australia, China, **India**, South Africa, UK, Netherlands, Italy, Canada, USA, Argentina, Brazil….

Thousands of SKA antennas to be located in a 3000 km array

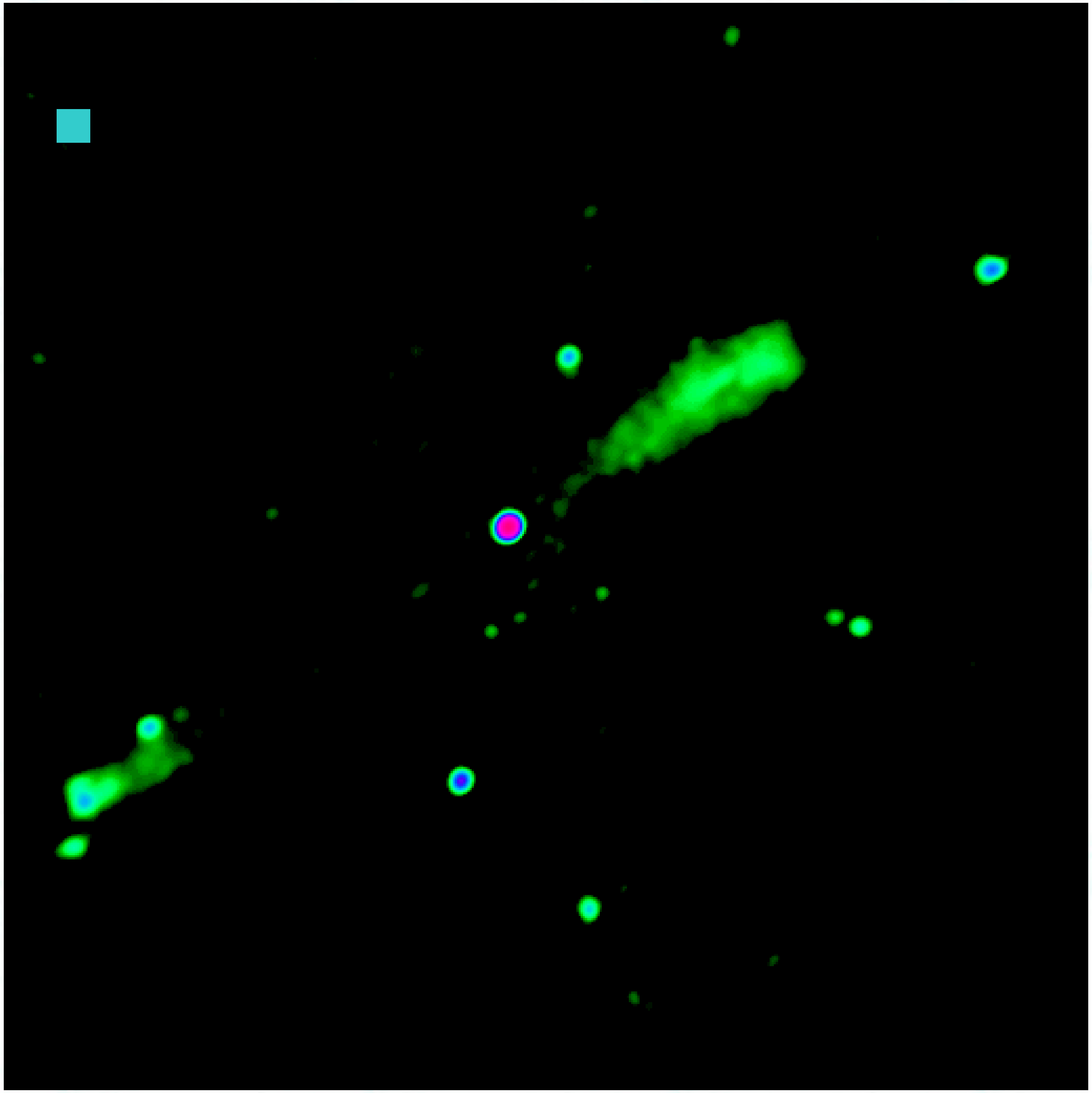
Conclusion

- Astronomical observations have provided strong support to the Big Bang Model.
- Early Universe provides a fascinating and challenging playfield to theoretical physicists, e.g. quantum gravity implications, string theory, etc.
- Five Key Questions form the thrust for new generation of radio telescopes, such as LOFAR, SKA, E-VLA, U-GMRT
- Laboratory searches for Dark matter candidates are crucial and also wide field observations for determining the pressure of the dark energy.
- *Golden age of Astronomical Discoveries is likely to continue for long.*

Time For Questions!.

- Radio Astronomy: emission mechanisms; great discoveries
- Radio Galaxies, Quasars and Black Holes
- Cosmic Microwave Background Radiation (CMB): Big Bang Model; formation of structures in the Universe.
- Pulsars
- HI 21cm emission: Spiral Structure of our Galaxy; Rotation Curves.
- Radio Telescopes; Radio Interferometers: GMRT.
- Key Questions Today; SKA.
- Conclusion

THANK YOU

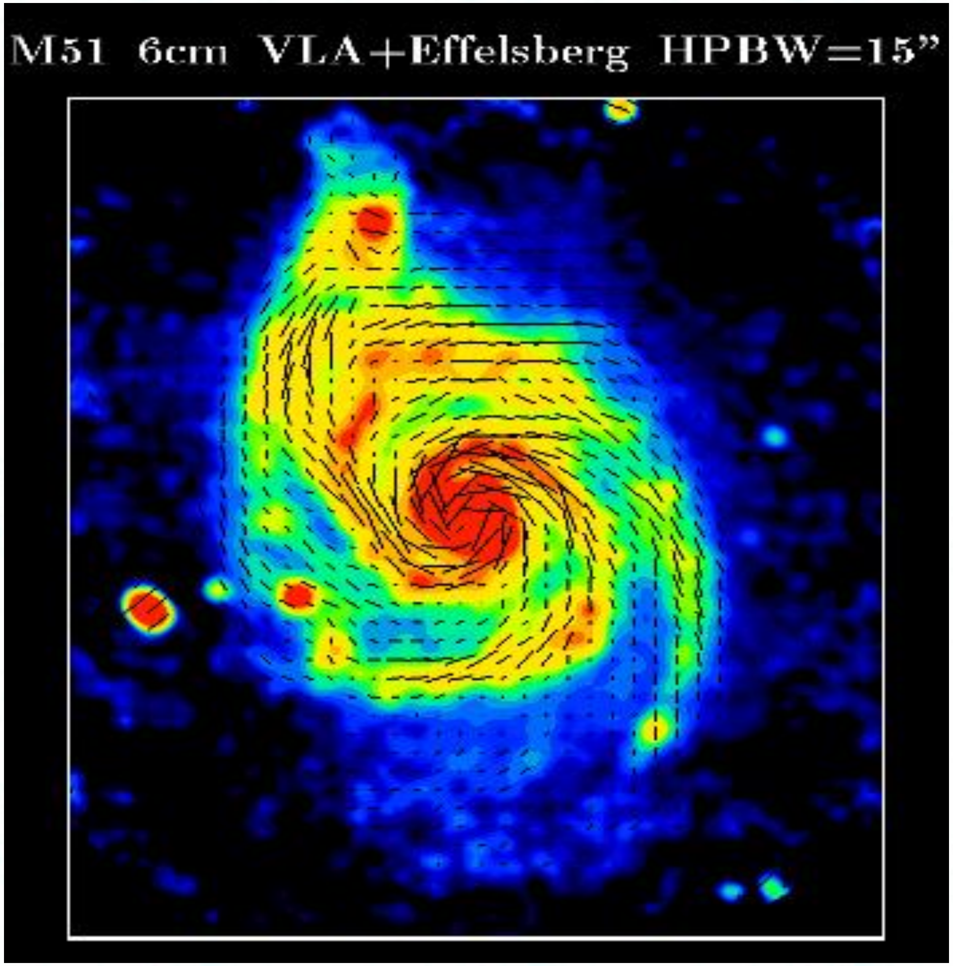


3C236 AT 325 MHZ

GMRT Image of the largest Radio Galaxy 3C236 at 325 MHz (~ 7 Mpc in size)

(S. Roy; GMRT18.8.1999)

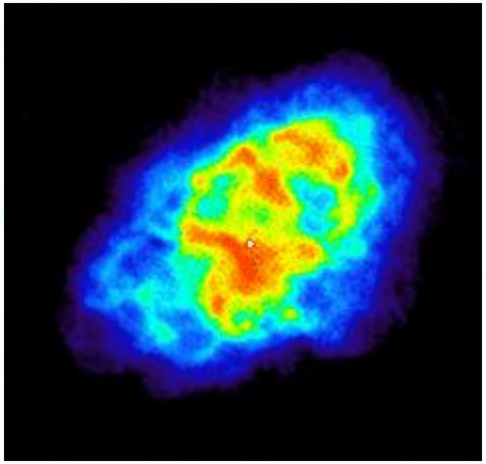
Radio Map of the nearby galaxy M51 at a wavelength of 6 cm showing distribution of large scale magnetic fields

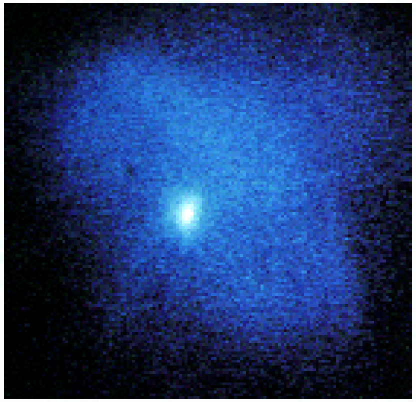


X-ray Observations of Pulsars

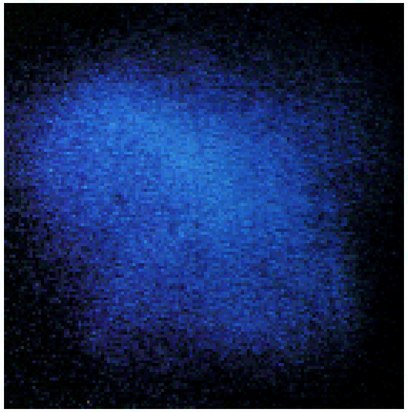
Some pulsars emit X-rays.

Below, we see the famous Crab Nebula, an undisputed example of a neutron star formed during a supernova explosion. The supernova itself was observed in 1054 A.D. These images are from the Einstein X-ray observatory. They show the diffuse emission of the Crab Nebula surrounding the bright pulsar in both the "on" and "off" states, i.e. when the magnetic pole is "in" and "out" of the line-of-sight from Earth.



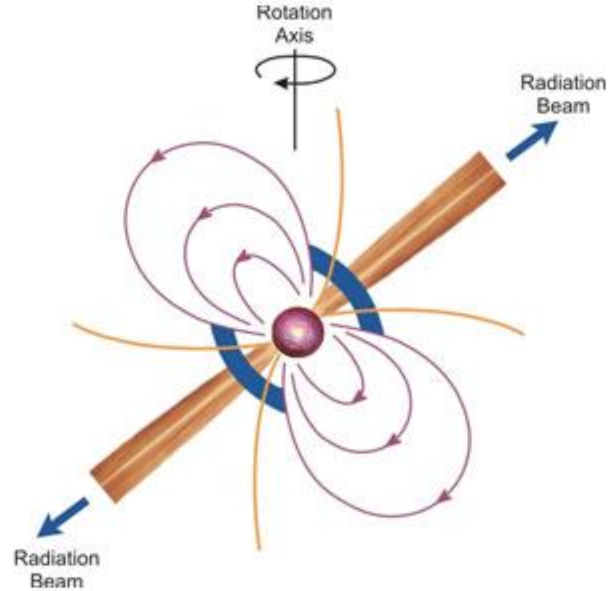


Crab Pulsar ON



Crab Pulsar OFF

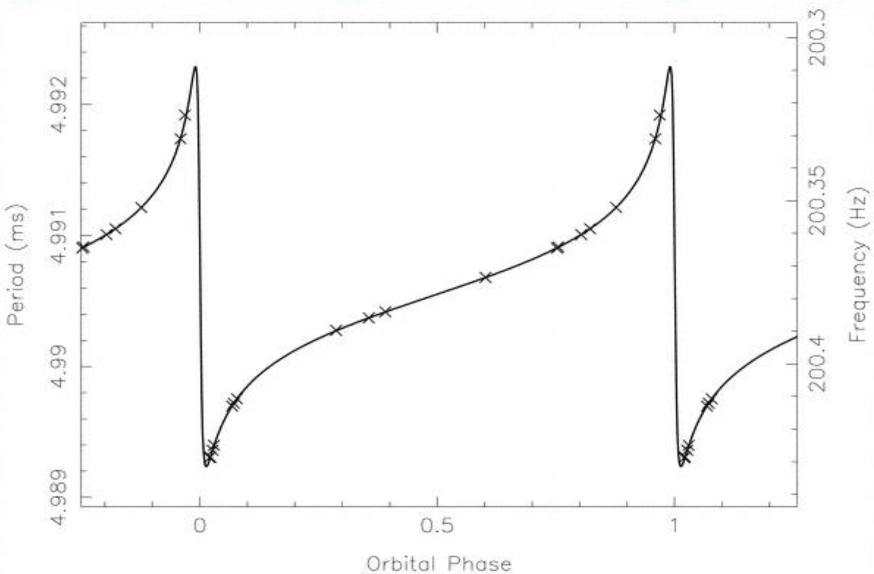
Credit NASA



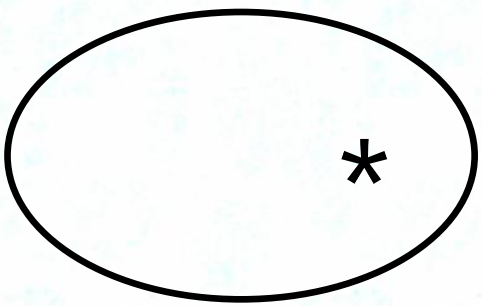
The National Radio Astronomy Observatory, AUI, NSF

Discovery of a millisecond period pulsar in our Galaxy with a highly eccentric binary system

Y.Gupta, S.Ransom, P.Freire, C.H.Ishwara Chandra 2004.

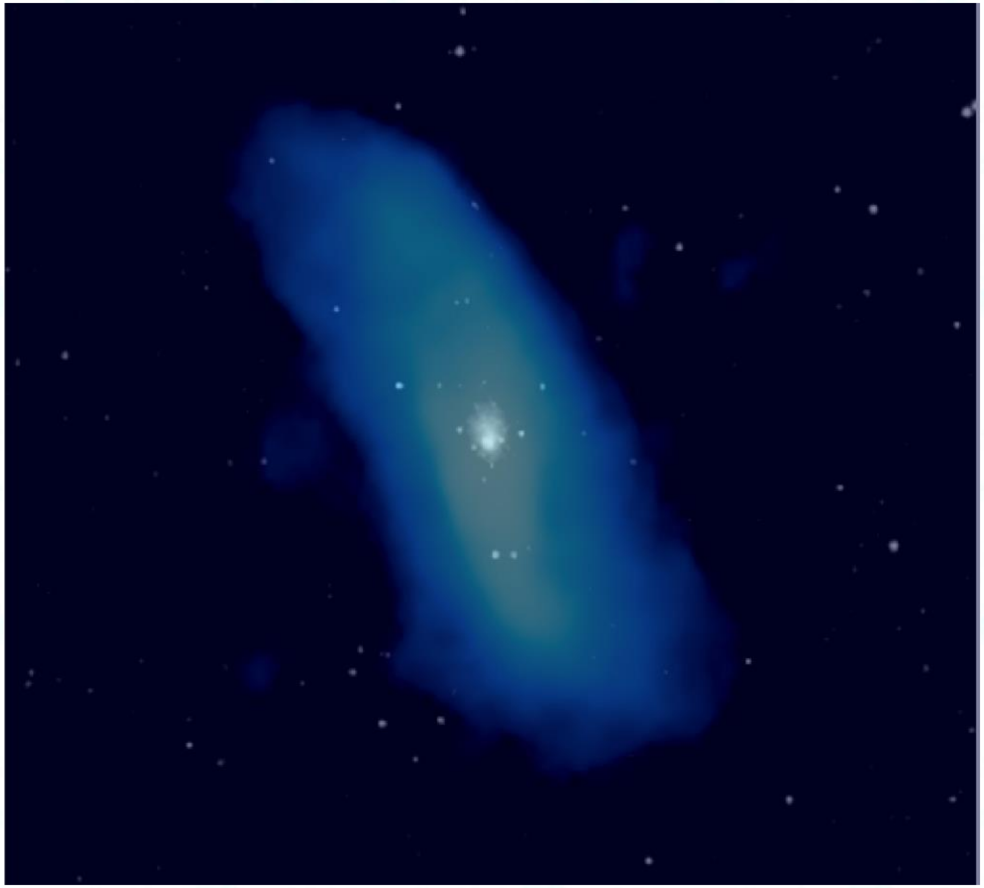


Plot of period versus orbital phase.



Dwarf Galaxy with a Giant Neutral Hydrogen (HI) disk

- The GMRT map of the integrated neutral hydogen (HI) overlaid on the optical image of the dwarf irregular galaxy NGC 3741 (MB ~ -13.1).
- The HI disk extends to a record 8.3 times the Holmberg radius
- The rotation curve is measured up to 38 Optical scale and remains flat.



- (Begum, Chengalur & Karachentsev 2005 A&A, 433, L1)

VERY LARGE ARRAY(VLA) IN USA & GMRT are complimentary Instruments

• VLA	❑**27 antennas of 25 m diameter.** (Area ~ 12270 m^2) Operates at cm and decimetre wavelengths.θ ~ 0.1arc second at 22 GHz
•GMRT	❑**30 antennas of 45-m diameter.** (Area ~ 47700 m^2) Operates at m and d-cm λs. θ ~ 2 arc second at 1.4 GHz

✓***GMRT has 4 to 8 times sensitivity of the VLA at 0.327 GHz***.

✓VLA is optimum at ~1.2 GHz to 22 GHz (cm. wavelengths.

GMRT cost is only ~ 10% !!