

The Radio Sky

Lecture 1

Introduction

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NCRA • TIFR

- ▶ Some information about the course is shared on the webpage:
<http://www.ncra.tifr.res.in/~tirth/Teaching/RadioSky-2025/index.html>
- ▶ Course consists of 24 lectures, 3-4 lectures per week.
- ▶ Lectures start from 13 October, end on 3 December. If we miss too many lectures in between, there will be extra make-up lectures so as to finish by 3 December.
- ▶ Attendance in the lectures is *not* compulsory. However, if you attend the lectures, please try to be punctual.
- ▶ Because of holidays, and my own travels, there are no dedicated tutorial sessions for this course. However, if necessary, we can organise special/extra sessions at a mutually convenient time to clear your doubts and work out steps.
- ▶ In case you need to discuss beyond the lectures, please feel free to contact me in the office.

- ▶ The evaluation would be based on the *Mid-term Examination* and the *Final Examination*.
- ▶ The *Mid-term Examination* will be on 10 November (tentative).
- ▶ The *Final Examination* will be on 8 December (tentative).
- ▶ The evaluation procedure for the course is as follows: your final average score will be computed giving 70% weight to the Final Examination and 30% to the Mid-term Examination.
- ▶ During the Examination(s), you will be free to consult your class notes, any notes you might have made beyond the classes and solved problem sheets. You can also consult print-outs of any notes you have taken using any electronic device, however, those notes must be in your handwriting.
- ▶ To prepare yourself for the Examinations, sample problem sheets would be shared during the course. Although there is no guarantee that the problems in the Examinations would be taken only from those in the sample sheets, they will be a useful resource for your preparation.

Problem sheet 0



- ▶ You will find the zeroth problem sheet on the course webpage.
- ▶ The problems are based on standard topics you would have covered till now.
- ▶ You need *not* submit the answers. However, if you find any of these questions non-trivial/difficult, please revise the corresponding chapters from your textbooks from B.Sc./M.Sc. courses. Else ask me.

Welcome to “The Radio Sky”



Goal: To understand the Universe as seen through the “radio window” of the electromagnetic spectrum.

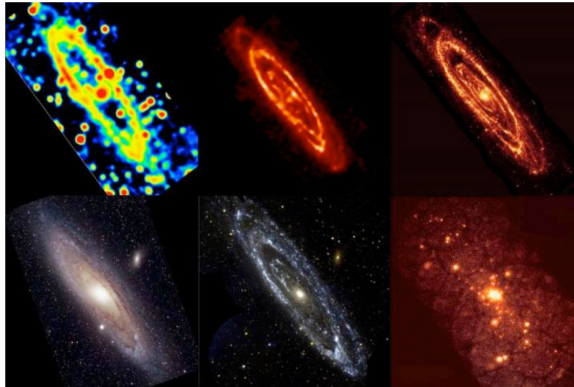
- ▶ We will discuss the properties of radio waves and how to describe them.
- ▶ We will explore the physical processes, both classical and quantum, that generate radio waves.
- ▶ We will survey the “radio zoo”: from planets and stars to pulsars to supermassive black holes to cosmology.

This course is for physicists! We will dive deep into basic physics, from classical E&M to quantum mechanics.

What is radio astronomy?

Radio astronomy is the study of celestial objects at radio frequencies. It reveals a universe that is often invisible in optical light.

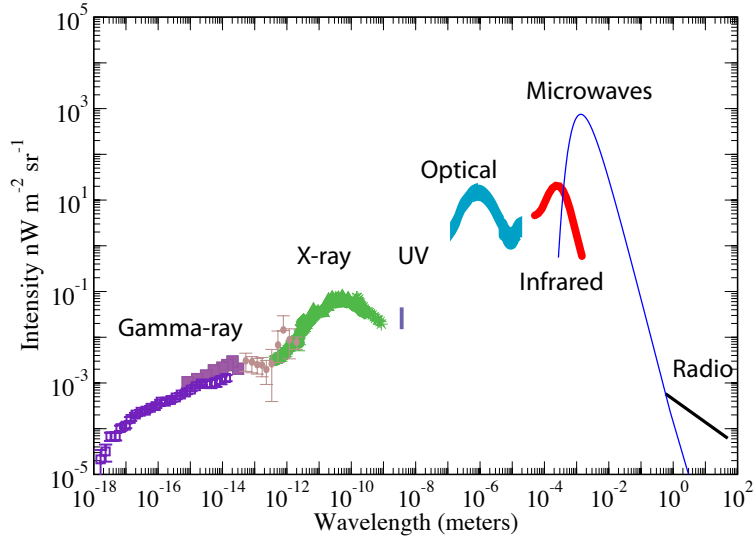
Andromeda galaxy (M31) observed at different wavelengths
[radio, microwave, IR, optical, UV, X-ray]



Credit: ASTRON

Key Idea: Different wavelengths trace different physics and different components of the Universe.

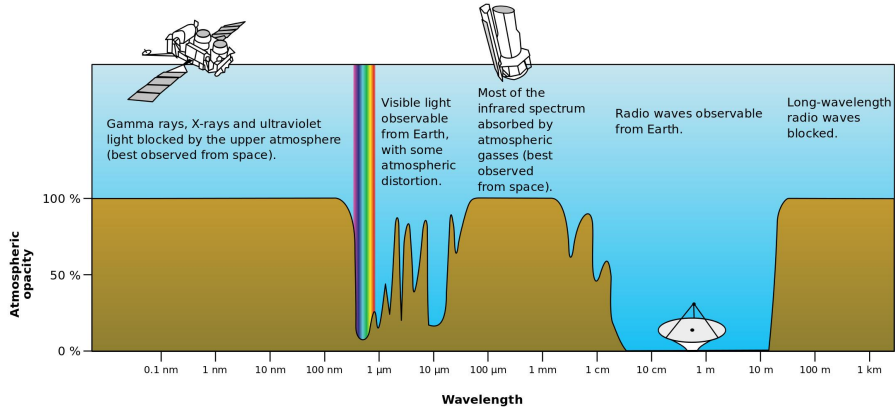
Cosmic background radiation



Cooray (2016)

The radio window

Earth's atmospheric transparency across the EM spectrum



Credit: Wikipedia

- ▶ The atmosphere is opaque to most wavelengths.
- ▶ There are two primary windows for ground-based astronomy: **Optical** and **Radio**.

Limits of the radio window

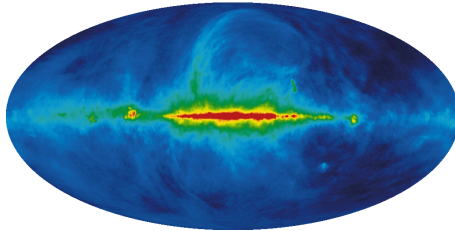


The radio window not infinitely wide. It is constrained by two main effects:

- ▶ **Low Frequencies ($\nu \lesssim 30$ MHz):** The **ionosphere**, a plasma layer in the upper atmosphere, reflects incoming radio waves back into space. The critical frequency depends on the electron density. Radio observations at lower frequencies require space-based facilities.
- ▶ **High Frequencies ($\nu \gtrsim 100$ GHz):** Molecular absorption, primarily by **water vapour (H_2O)** and **oxygen (O_2)** in the troposphere, absorbs incoming signals. This is why high-frequency observatories (like ALMA) are on high, dry sites.

This defines the observable frequency range from the ground: ~ 30 MHz to 1 THz.

Observational considerations: radio vs. optical



Haslam map: full-sky at 408 MHz

(Credit: LAMBDA website of NASA)

Advantages

- ▶ **Transparent universe:**
 - Unaffected by interstellar dust extinction
- ▶ **Continuous operation:**
 - 24-hour observation capability
 - Largely immune to weather (clouds, rain)

Disadvantages

- ▶ **Atmospheric corruption**
 - Ionospheric phase errors (low ν)
 - Tropospheric absorption (high ν , H₂O)
- ▶ **Poor angular resolution (single dish)**
 - Governed by diffraction limit ($\theta \propto \lambda/D$)
- ▶ **Indirect imaging process**
 - Interferometers measure Fourier components
 - Requires complex image reconstruction

Key discoveries in radio astronomy

► 1933: The birth of radio astronomy

- While investigating sources of radio interference for Bell Telephone Labs, **Karl Jansky** identified a persistent, faint signal of extraterrestrial origin, localizing it to the Galactic Centre. This opened a new observational window on the universe.

► 1937: First systematic survey of the radio sky

- **Grote Reber** constructed the first purpose-built parabolic radio telescope. His subsequent sky survey produced the first radio maps, confirming the bright emission from the Galactic plane and centre.

► 1951: Opening the spectral window: the 21 cm line

- The detection of the 21 cm hyperfine transition of neutral hydrogen by **Ewen and Purcell** provided the primary tool for tracing the cold interstellar medium, enabling the mapping of the Milky Way's spiral structure and kinematics.

► 1963: Discovery of Quasi-stellar radio sources (Quasars)

- Following the identification of powerful radio sources like 3C 273, **Maarten Schmidt** measured their enormous redshifts, revealing them to be the most luminous and distant objects then known: the active nuclei of galaxies.

► 1964: Detection of the Cosmic Microwave Background

- **Arno Penzias and Robert Wilson** detected a faint, isotropic, thermal radiation field. This Cosmic Microwave Background (CMB) was quickly identified as the relic radiation from the Big Bang, cementing the theory.

► 1967: The discovery of pulsars

- **Antony Hewish and Jocelyn Bell Burnell** discovered sources of precisely periodic radio pulses. These were identified as **Pulsars**: rapidly rotating, magnetized neutron stars, which serve as natural laboratories for extreme physics.

► 1970s-present: The rise of aperture synthesis

- The development of **interferometry** allows arrays of telescopes (e.g., VLA, ALMA) to synthesize a large virtual aperture, achieving angular resolutions that surpass those of single-dish optical telescopes.

A representative list of major radio observatories (2025)

Single-dish telescopes

- ▶ **FAST** (China): 500m diameter. The world's most sensitive single dish for pulsars and HI science.
- ▶ **Green Bank Telescope (GBT)** (USA): 100m steerable.

Interferometers (meter-wave)

- ▶ **GMRT** (India): 30 antennas. A powerful low-frequency array with a unique hybrid configuration, located near Pune.
- ▶ **LOFAR** (Netherlands/EU): 52 “stations”. A pathfinder for low-frequency transient and EoR science.
- ▶ **MWA** (Australia): Digital tile array. An SKA precursor focused on the Epoch of Reionization (EoR) and solar science.

Interferometers (cm-wave)

- ▶ **Very Large Array (VLA)** (USA): 27 antennas. A highly versatile and reconfigurable telescope.
- ▶ **MeerKAT** (South Africa): 64 antennas. An SKA precursor with high sensitivity and survey capabilities.

Interferometers (millimeter/sub-mm)

- ▶ **ALMA** (Chile): 66 antennas. The revolutionary mm/sub-mm interferometer for studying planet formation and early galaxies.

Very long baseline interferometry (VLBI)

- ▶ **VLBA / EVN / EHT**: Global networks creating an Earth-sized telescope to achieve the highest angular resolution in astronomy.

The Next Generation: Under Construction

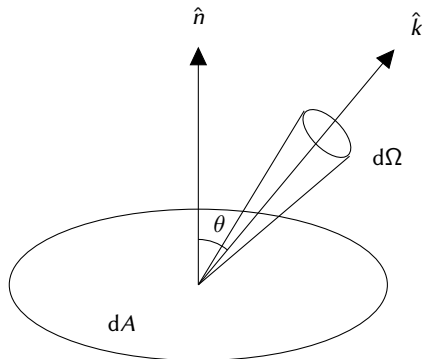
The Square Kilometre Array (SKA): An intercontinental radio telescope being built in South Africa and Australia, set to revolutionize the field with unparalleled sensitivity and survey speed.

How we measure radio light: Intensity

In physics, the fundamental quantity for radiation is **Specific Intensity** or **Brightness**, I_ν :
Defined as the energy per unit time, per unit projected area, per unit frequency, per unit solid angle.

$$d\mathcal{E} = I_\nu(t, \vec{x}, \hat{k}) dA \cos \theta dt d\nu d\Omega$$

Units: $[\text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1} \text{sr}^{-1}]$ or $[\text{W m}^{-2} \text{Hz}^{-1} \text{sr}^{-1}]$



Crucial Property: In a vacuum, I_ν is constant along a ray path. It does not fall off with distance! (The solid angle subtended by a source does).

How we measure radio light: Flux

In telescopes, we measure the **Flux Density**, F_ν : defined as the specific intensity integrated over the solid angle of the source, Ω_s .

$$F_\nu = \int_{\Omega_s} I_\nu(\theta, \phi) \cos \theta d\Omega = \frac{d\mathcal{E}}{dA dt d\nu}$$

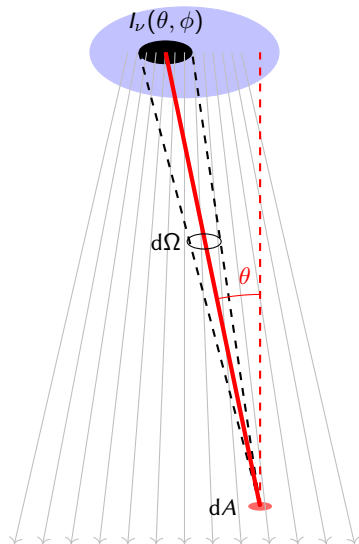
Units: [$\text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1}$] or [$\text{W m}^{-2} \text{Hz}^{-1}$]

In radio astronomy, we use a special unit: the **Jansky (Jy)**.

$$1 \text{ Jy} = 10^{-26} \text{ W m}^{-2} \text{Hz}^{-1}$$

$$1 \text{ Jy} = 10^{-23} \text{ erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1}$$

This reflects how incredibly faint cosmic radio sources are.



Brightness temperature

- ▶ At radio frequencies, the energy of a photon ($h\nu$) is much smaller than the thermal energy ($k_B T$) of the emitting gas.

$$h\nu \ll k_B T$$

- ▶ This allows us to use the **Rayleigh-Jeans approximation** of the Planck Law for a blackbody:

$$B_\nu(T) \approx \frac{2\nu^2}{c^2} k_B T = \frac{2k_B T \nu^2}{c^2}$$

This shows a *direct proportionality between intensity and temperature*.

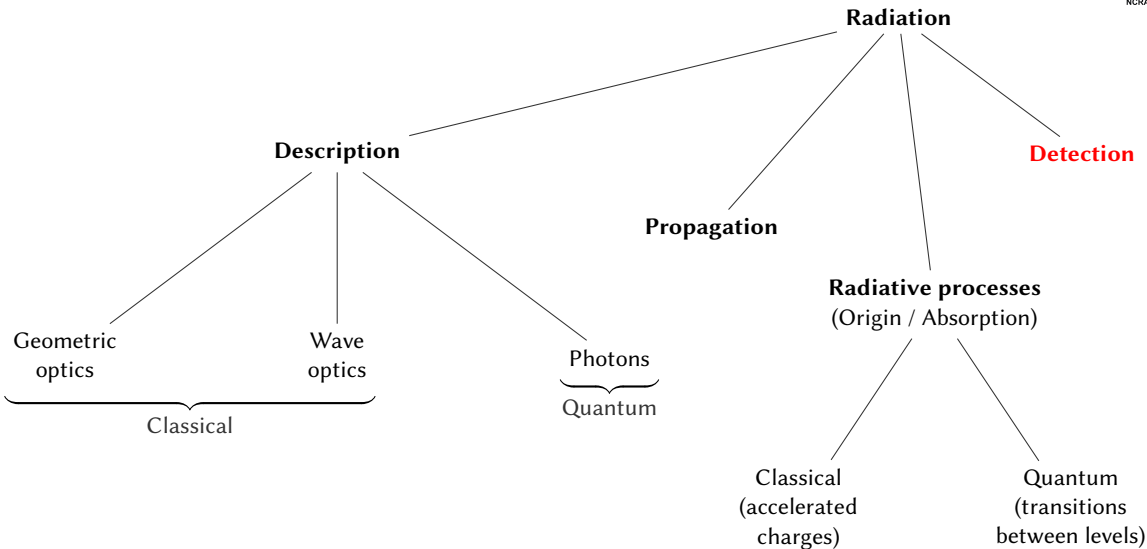
- ▶ We define the **brightness temperature** T_b as the temperature a blackbody would need to have to produce the observed intensity I_ν at that frequency.

$$I_\nu \equiv \frac{2k_B T_b \nu^2}{c^2} \implies T_b = \frac{c^2}{2k_B \nu^2} I_\nu$$

So, T_b is a measure of intensity in temperature units.

- ▶ Even for non-thermal sources, we use T_b to describe the “effective” temperature of the emission.

The radiation “tree”



Course structure

Part I: Classical treatment (Lectures 2-8)

- ▶ Electromagnetic waves and geometric optics
- ▶ Radiative transfer
- ▶ Wave optics: diffraction and interference
- ▶ Polarization
- ▶ Plasma effects
- ▶ Bremsstrahlung
- ▶ Synchrotron

Part II: Quantum treatment (Lectures 9-16)

- ▶ Quantization of electromagnetic field
- ▶ Matter-radiation interaction
- ▶ Dipole approximation and selection rules
- ▶ Cross section
- ▶ Line radiative transfer
- ▶ Relativistic quantum mechanics
- ▶ Fine-structure and hyperfine lines
- ▶ Molecular transitions

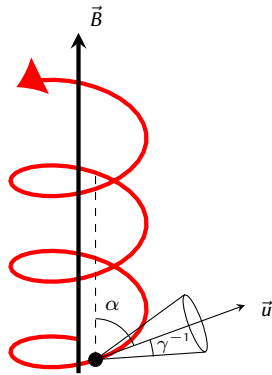
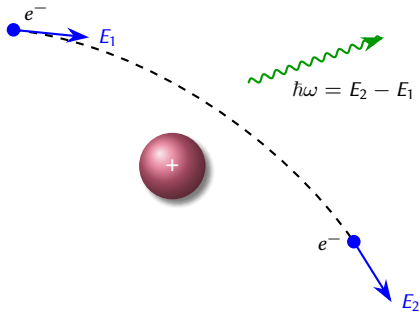
Part III: Astrophysical systems (Lectures 17-24)

The origin of radio continuum: accelerating charges

Radio waves are efficiently generated by the acceleration of free electrons in cosmic-scale electric and magnetic fields.

Bremsstrahlung (“braking radiation”): An electron is accelerated (deflected) during a Coulomb encounter with an ion in a plasma.

Synchrotron Radiation: A relativistic electron gyrates around a magnetic field line, experiencing constant acceleration.



Note: Inverse Compton scattering, where a relativistic electron upscatters a low-energy photon, is a closely related process.

The origin of radio lines: low-energy transitions

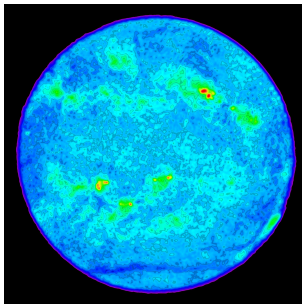


Radio photons ($E = h\nu$) have very low energies, allowing them to uniquely probe transitions between finely-spaced quantum energy levels.

- ▶ **Radio recombination lines (RRLs):** Transitions between high- n Rydberg states of an atom (e.g., H109 α). At high principal quantum number n , the energy levels become extremely crowded. Probing the physical conditions (temperature, density) inside HII regions.
- ▶ **Hyperfine Transitions:** Interaction between the magnetic moments of the electron and the nucleus (spin-spin interaction), e.g., **HI 21 cm line** from the spin-flip in the ground state of neutral hydrogen.
- ▶ **Molecular Rotational Transitions:** Transitions between quantized rotational energy levels of molecules in the gas phase, e.g., the “rotational ladder” of **Carbon Monoxide (CO)**, the primary tracer of cold, dense molecular gas where stars are born.

The solar system: thermal and non-thermal emission

- **The Sun:** A highly variable radio source.



Courtesy: NRAO

- **Quiet Sun:** Thermal Bremsstrahlung from the chromosphere and corona ($T_B \sim 10^4 - 10^6$ K).
- **Active Sun:** Intense, non-thermal bursts (gyro-synchrotron) from flares and Coronal Mass Ejections (CMEs).

► Planets & Moons:

- **Thermal Emission:** Probes temperatures below cloud tops (gas giants) or in the shallow subsurface (rocky planets).
- **Non-Thermal (Jupiter):** Powerful synchrotron radiation from relativistic electrons trapped in its magnetosphere.

- **Exoplanets:** Searches for coherent Electron-Cyclotron Maser Emission (ECME) from star-planet magnetic interactions.

The interstellar medium: gas, stellar nurseries & remnants



Courtesy: CSIRO

The Diffuse Gas

- ▶ **Atomic (HI):** The 21 cm line traces the bulk of neutral gas, revealing galactic structure and kinematics.
- ▶ **Molecular (CO):** Rotational lines trace the cold, dense clouds that are the sites of star formation.
- ▶ **Ionized (WIM):** Probed by pulsar dispersion and thermal emission.

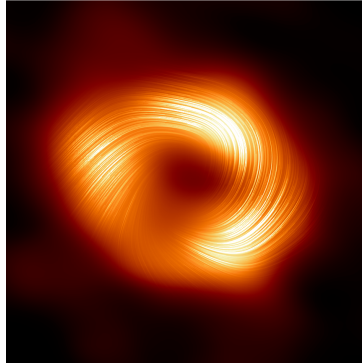
Sites of Action

- ▶ **HII Regions:** Ionized by young O/B stars. They are archetypal thermal (Bremsstrahlung) sources with flat spectra.
- ▶ **Supernova Remnants:** Expanding shells from stellar explosions. They are archetypal non-thermal (synchrotron) sources with steep, power-law spectra.

The Galactic centre

The innermost parsecs of the Milky Way, best studied in radio.

- **Sagittarius A* (Sgr A*)**: The bright, compact radio source of our $4 \times 10^6 M_{\odot}$ supermassive black hole, powered by a radiatively inefficient accretion flow.

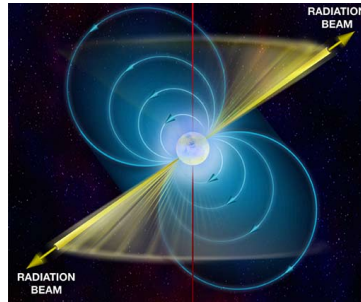


Courtesy: EHT Collaboration

- **Non-thermal radio filaments (NRFs)**: Unique, highly-ordered structures tracing strong ($\sim$ mG) magnetic fields.
- **The central molecular zone (CMZ)**: A vast reservoir of dense molecular gas with complex kinematics and suppressed star formation.

Pulsars: probes of extreme physics and the ISM

Rapidly rotating, magnetized neutron stars acting as cosmic laboratories.



Courtesy: NRAO

- ▶ **Emission:** Coherent, beamed radiation from the magnetosphere (the "lighthouse model").
- ▶ **Propagation effects:**
 - **Dispersion measure (DM):** Measures the integrated column density of free electrons (n_e).
 - **Faraday rotation (RM):** Measures the integrated parallel magnetic field ($B_{\parallel} n_e$).
- ▶ **Applications:** Testing General Relativity, mapping the ISM's structure and magnetic field, gravitational wave detection (PTAs).

Normal star-forming galaxies

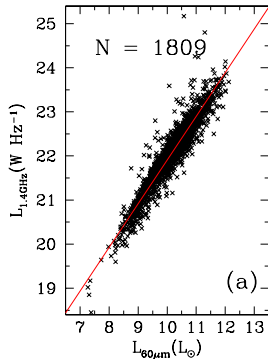
Radio emission from a typical galaxy is a composite tracer of its massive star lifecycle.

► Two-component emission:

- **Thermal (Bremsstrahlung):** From HII regions, tracing current high-mass star formation.
- **Non-thermal (Synchrotron):** From cosmic rays accelerated in SNRs, tracing time-averaged star formation.

► The FIR-radio correlation:

- A tight, linear correlation between a galaxy's far-infrared (dust) and radio luminosity, making radio a powerful, dust-unbiased star-formation rate indicator.

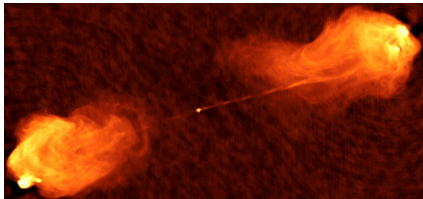


Yun et al 2001

The most massive structures: AGNs and galaxy clusters

Active galactic nuclei (AGN) / radio galaxies

- ▶ **Engine:** Powered by accretion onto a Supermassive Black Hole (SMBH) in a galaxy's center.
- ▶ **Structure:** Launches relativistic jets that inflate vast lobes of synchrotron-emitting plasma (FR I / FR II types).
- ▶ **Interaction:** These jets inject enormous amounts of energy into their surroundings, particularly within galaxy clusters.



Courtesy: NRAO

Galaxy clusters

- ▶ **The ICM:** Filled with a hot (10^8 K), diffuse plasma that is bright in X-rays.
- ▶ **Diffuse radio sources:** Major cluster mergers:
 - **Radio haloes:** Cluster-scale synchrotron emission from turbulence-reaccelerated electrons.
 - **Radio relics:** Arc-like emission tracing merger shock fronts.
- ▶ **Sunyaev-Zel'dovich (SZ) Effect:** A unique spectral distortion of the CMB caused by its photons inverse-Compton scattering off the ICM's hot electrons.



Courtesy: NRAO

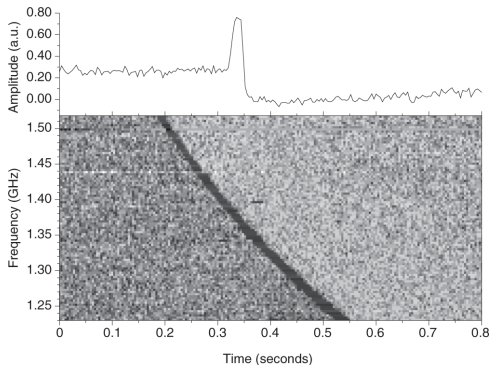
Fast radio bursts

► Fast radio bursts (FRBs):

- Bright ($\sim$ Jy), millisecond-duration bursts of extragalactic origin.
- Leading progenitor model involves highly magnetized neutron stars (magnetars).

► Probing the “cosmic web”:

- The pulse’s Dispersion Measure (DM) is dominated by its path through the diffuse plasma between galaxies: the **Intergalactic Medium (IGM)**.



Lorimer (2018)

- FRBs act as background sources to map the density, turbulence, and magnetization of this otherwise invisible baryonic component of the universe.

21cm cosmology: mapping the Universe's structure

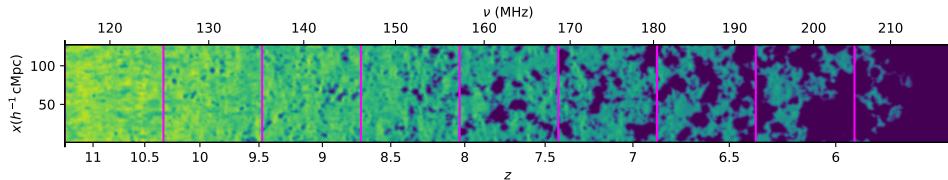
Using the aggregate HI signal to perform a tomography of the universe over cosmic time.

► Intensity mapping

- Does not detect individual galaxies. Instead, measures the statistical fluctuations of the integrated 21 cm brightness temperature from large volumes of space.

► Key science goals:

- **Cosmic dawn (CD) & epoch of reionization (EoR):** Probing the formation of the very first stars and galaxies by observing the state of the neutral IGM before and during its ionization.



Using semi-numerical simulation SCRIPT

TRC & Paranjape (2018)

- **Post-reionization:** Mapping the large-scale structure to constrain cosmological parameters, such as dark energy, via Baryon Acoustic Oscillations (BAO).

► Status: A frontier field with experiments like HERA, CHIME, LOFAR, MWA, and the SKA.

Recommended books



There are many excellent textbooks on the subject. The students are welcome to choose books which they find convenient. Some of the books which I have found useful are given below:

1. George B. Rybicki & Alan P. Lightman, Radiative Processes in Astrophysics.
2. T. Padmanabhan, Theoretical Astrophysics (Volume I: Astrophysical Processes).
3. Frank H. Shu, The Physics of Astrophysics (Volume I: Radiation).
4. James J. Condon & Scott M. Ransom, Essential Radio Astronomy.