

The Radio Sky

Lecture 1

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PHY-236.3



Introductions

Opening diagnostic

An unknown source

- Flux density $S_\nu \propto \nu^{-0.7}$ between 0.3 and 3 GHz
 - 20% linearly polarized
 - Resolved: tens of arcseconds across
1. Which class of emission mechanism is plausible?
 2. What evidence is still missing before the source can be correctly classified?

Opening diagnostic

An unknown source

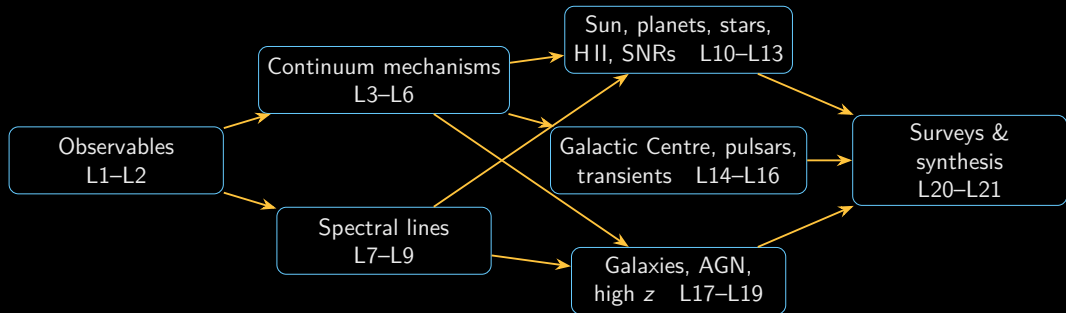
- Flux density $S_\nu \propto \nu^{-0.7}$ between 0.3 and 3 GHz
- 20% linearly polarized
- Resolved: tens of arcseconds across

1. Which class of emission mechanism is plausible?
2. What evidence is still missing before the source can be correctly classified?

Plausible: incoherent synchrotron radiation from relativistic electrons in an ordered magnetic field.

Missing: distance, morphology at other resolutions, lines, counterparts, variability. Spectral index alone does not classify a source.

Course map



How this course connects to other courses

Builds on (already completed)

- **Intro to Astronomy & Astrophysics:** units, observables, stars, ISM, galaxies, compact objects, elementary cosmology
- **Radiative Processes:** radiative transfer, LTE and non-LTE, bremsstrahlung, synchrotron, polarization, absorption
- **Astronomical Techniques:** flux calibration vocabulary, antennas and arrays, basic interferometry
- **Computational Astrophysics I:** fitting, uncertainties, Fourier methods
- **GR I:** compact objects, relativistic effects

Hands off to (later courses)

- **Radio Telescopes, Radio Interferometry** (PHY-335.3, PHY-336.3): receivers, calibration, correlators, aperture synthesis, imaging
- **Fluids & Plasmas, Galaxies & ISM, AGN, Cosmology:** deeper treatment of the physics we use only at the minimum level needed

What is new here

- Radiative processes → **real radio sources**
- Science-ready data → **physical interpretation**
- Which measurement would discriminate between explanations

How you will be assessed

Component	Marks	Format
Mid-semester exam	20	Closed book, after Lecture 9
End-semester exam	40	Closed book, cumulative
Seminar on a seminal paper	25	25 min talk + 5 min questions
Class participation	15	Questions asked; concept-test answers

- Exams will be mostly drawn from a released question bank: problems of 3–8 logical or calculation steps.
- Seminar paper list: [course website seminarpapers.html](#)
- Choose a seminar paper in about 2 weeks.

Syllabus: 21 lectures

Foundations

L1 What is the radio sky?

L2 Radio observables, brightness temperature

Continuum emission

L3 Source classification, radiative transfer

L4 Free-free and synchrotron emission

L5 Ageing, self-absorption, energetics

L6 Gyrosynchrotron and electron-cyclotron maser

Spectral lines

L7 Line foundations and diagnostic logic

L8 The HI 21-cm line

L9 Molecular and maser lines

Our neighbourhood

L10 The radio Sun

L11 Planets, stars and exoplanets

The Milky Way

L12 H II regions, star-formation tracers

L13 Supernova remnants, pulsar-wind nebulae

L14 The Galactic Centre

Compact objects and transients

L15 Pulsars: clocks, beams, plasma propagation

L16 Fast radio bursts and slow transients

Extragalactic radio sky

L17 Normal galaxies: star formation, cosmic rays

L18 Radio galaxies and AGN

L19 High-redshift continuum and line diagnostics

L20 Radio surveys and source counts

Synthesis

L21 Diagnostic synthesis and capstone

Textbooks

Code	Book	Publisher, edition
ERA	J. J. Condon & S. M. Ransom, <i>Essential Radio Astronomy</i>	Princeton University Press, 2016
TRA	T. L. Wilson, K. Rohlfs & S. Hüttemeister, <i>Tools of Radio Astronomy</i>	Springer, 6th ed. 2013
IRA	B. F. Burke, F. Graham-Smith & P. N. Wilkinson, <i>An Introduction to Radio Astronomy</i>	Cambridge University Press, 4th ed. 2019
Kraus	J. D. Kraus, <i>Radio Astronomy</i>	Cygnus-Quasar, 2nd ed. 1986
FRA	R. L. Snell, S. E. Kurtz & J. M. Marr, <i>Fundamentals of Radio Astronomy: Astrophysics</i>	CRC Press (Taylor & Francis), 2019

Reference text:

R&L	G. B. Rybicki & A. P. Lightman, <i>Radiative Processes in Astrophysics</i>	Wiley, 1979 (reprint 2004)
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Only selected chapters are used; each lecture lists them by title, since page numbers differ between editions. ERA is free online from NRAO.

Course website

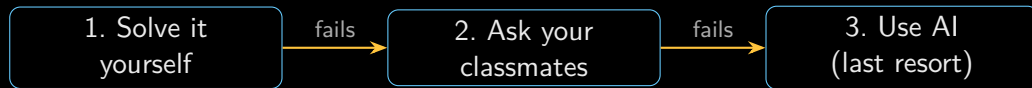
ncra.tifr.res.in/~yogesh/radiosky26

The website will contain:

- Lecture PDFs, posted as the course proceeds
- Links to the seminar papers: the list of seminal radio-sky papers, with DOI links
- The question bank(s) from which exam problems are drawn

Policy on AI

- No graded assignments in this course (my preferred mode of evaluation in the past). Exams are closed book, closed notes.
- I use AI to turn my notes into $\text{\LaTeX}$ Beamer slides for each lecture.
- You may use AI in a limited way, to solve problems that none of you can solve (unlikely situation for this course!).
- You learn best by solving the problem yourself, and better still by explaining the solution to someone else.



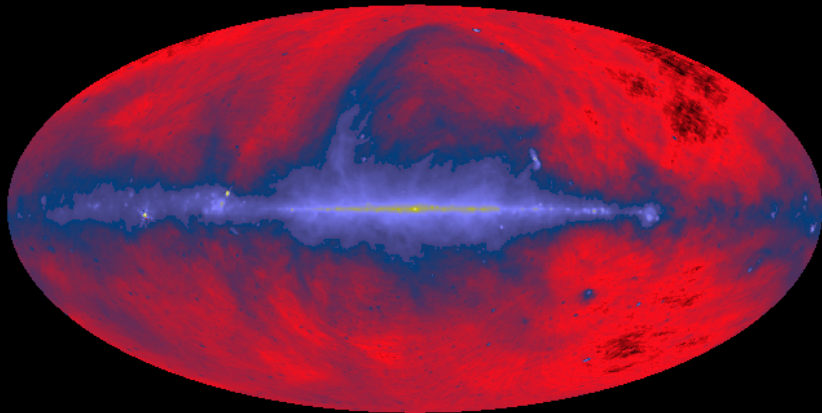
Remember: AI is not available to you in the exam.

TIFR policy on generative AI

- The student is **solely responsible** for any content they produce, whether or not it is partially or fully generated by generative AI tools.
- All work must abide by the prevailing **academic honesty** guidelines: AI inputs are treated on par with external sources, or with ideas from a discussion with a colleague.
- Any use of generative AI tools should be **acknowledged** as appropriate. Each subject board (SB) may specify permissible uses that need no acknowledgement.
- Inform yourself about responsible use of these tools, and be aware of their **pitfalls**.
- Book grant / contingency funds may be used to purchase professional software that uses generative AI.
- These are broad guidelines for all subject boards. Each SB may add policies for specific contexts (synopsis, thesis, assignments, etc.).

Source: [TIFR academic procedures \(tifr.res.in\)](https://tifr.res.in)

The sky at 408 MHz



Credit: All-sky radio continuum map, Galactic coordinates.

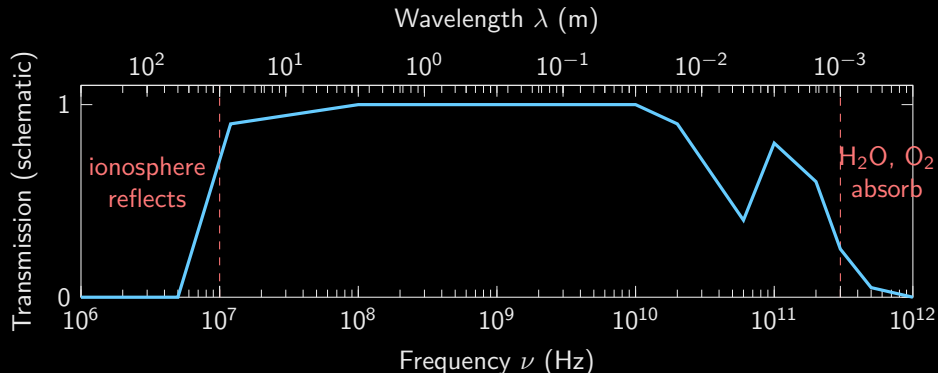
What we see in that map

- The Galactic plane dominates: **diffuse synchrotron** from cosmic-ray electrons in the Galactic magnetic field.
- Large loops and spurs: nearby old supernova remnants and bubbles.
- Bright discrete sources: Cas A, Cyg A, Sgr A, the Crab.
- Point sources at high latitude: mostly distant **radio galaxies and quasars**.

Contrast with the optical sky

- Stars contribute almost nothing.
- Dust is transparent.
- Most of the emission is *non-thermal*.

Radio is the long-wavelength window through the atmosphere



- Low-frequency edge: plasma frequency $\nu_p \approx 8.98 \text{ kHz } (n_e/\text{cm}^{-3})^{1/2}$. Ionospheric $n_e \sim 10^5\text{--}10^6 \text{ cm}^{-3}$ gives $\nu_p \sim 3\text{--}9 \text{ MHz}$.
- High-frequency edge: molecular absorption; sites must be high and dry.

Curve is schematic, not measured transmission.

Why radio sees things other bands cannot

Penetration

Interstellar grains have sizes $a \lesssim 1 \mu\text{m} \ll \lambda$. Their extinction cross-section falls steeply for $\lambda \gg a$. Radio passes through the Galactic disc and dusty galaxies.

Low photon energies

Radio transitions are excited in gas at 10–100 K.

What radio traces

- Cold atomic gas (H I 21 cm)
- Molecular gas (CO, NH₃, ...)
- Ionized gas (free-free, recombination lines)
- Relativistic electrons and magnetic fields (synchrotron)
- Coherent plasma processes (pulsars, FRBs, bursts)

Karl Jansky and cosmic radio noise (1932–33)



Karl Jansky at Holmdel.

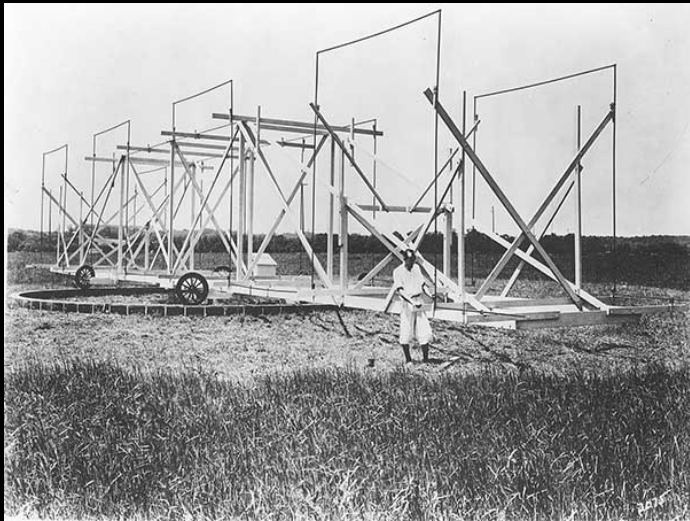
- Bell Labs, Holmdel, New Jersey: Jansky studied short-wave static that limited transatlantic radio telephony.
- Rotating antenna, $\lambda = 14.6$ m ($\nu \approx 20.5$ MHz): static from nearby and distant thunderstorms, plus a **steady hiss** of unknown origin.
- The hiss peaked daily, but the peak **advanced by about 4 minutes per day** against clock time.

Why this points outside the Solar System

A fixed source on the sky returns every sidereal day: one extra rotation per year gives $P_{\text{sid}} = 24 \text{ h} \times 365.2422 / 366.2422 = 23 \text{ h } 56 \text{ m } 4 \text{ s}$. The Sun repeats every 24 h. Jansky's period was sidereal, so the source lay among the stars, toward the Galactic Centre region.

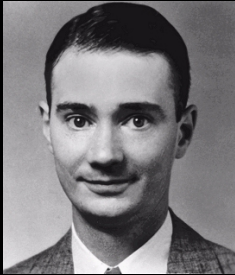
Jansky 1933, *Proc. IRE* **21**, 1387; doi:10.1109/JRPROC.1933.227458

Jansky's rotating antenna at Holmdel



Credit: Jansky's rotating short-wave antenna, Holmdel, NJ (c. 1932).

Grote Reber: the first radio telescope and sky survey (1937–44)



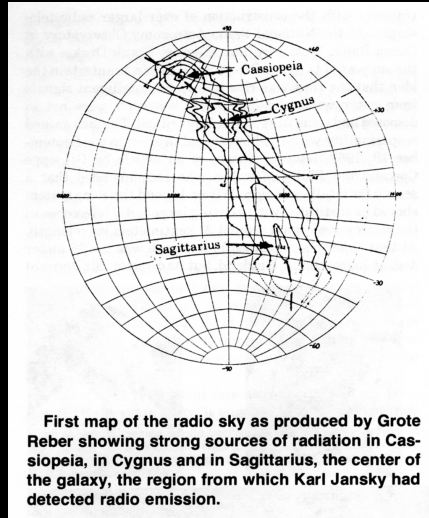
Grote Reber.

- Reber, an engineer and radio amateur, read Jansky's paper and built a **9.4 m parabolic dish** in his back yard in Wheaton, Illinois (1937).
- Searches at 3300 and 900 MHz found nothing; at **160 MHz** he detected emission from the Milky Way (Reber 1940, *ApJ* **91**, 621; doi:10.1086/144197).
- Surveyed the sky at 160 MHz and found the Galactic plane and discrete sources in Cassiopeia, Cygnus and Sagittarius (Reber 1944, *ApJ* **100**, 279; doi:10.1086/144668).

A puzzle that drove the field

The emission grew *brighter toward lower frequencies*, the opposite of a thermal source of $T_b \sim 10^4$ K in the Rayleigh–Jeans regime. A non-thermal mechanism (synchrotron radiation, Lecture 4) was needed.

Reber's first map of the radio sky



Govind Swarup: from Allahabad to Stanford



Govind Swarup (1929–2020).

- Born 1929; M.Sc. Allahabad 1950; National Physical Laboratory, New Delhi, 1950–53.
- **1953**: CSIRO Radiophysics Laboratory, Sydney (Pawsey, Christiansen, Bolton, Mills): hands-on interferometry at Potts Hill.
- **1956–57**: Harvard radio astronomy station, Fort Davis, Texas: solar radio bursts.
- **1957–63**: Stanford with Ron Bracewell: Ph.D. 1961; phase-equalization technique for antenna arrays; a steep-spectrum bridge between the lobes of Cygnus A.
- **April 1963**: returned to India to build a radio astronomy group at the Tata Institute of Fundamental Research (TIFR), at the request of Homi Bhabha.

Sources: Swarup biography (Wikipedia) and Kembhavi & Chengalur 2023, *Biogr. Mem. Fellows R. Soc.* **75**, 455; [doi:10.1098/rsbm.2022.0049](https://doi.org/10.1098/rsbm.2022.0049)

1962–65: the Bhabha telegram and the Kalyan array

CLASS OF SERVICE	WESTERN UNION	SYMBOLS
This is a fast message unless its delayed character is indicated by the proper symbol.	TELEGRAM	DL = Day Letter NL = Night Letter LT = International Letter Telegram
The filing time shown in the date line on domestic telegrams is LOCAL TIME at point of origin. Time of receipt is LOCAL TIME at point of destination.		

1255P PST JAN 20 62 0A165
O CDU609 WUD326 UWS3986 SKA253/SJEEQ EO PD INTL FR CD BOMBAY
VIA RCA 20 2245
ETAT IMPORTANT DOCTOR G SWARUP RADIOSCIENCE LABORATORY STANDORD
UNIVERSITY STANFORD CALIF
NUMBER 450 STOP REFERENCE PROPOSAL FROM MENON KUNDU KRISHNAN
AND YOURSELF FORWARDED BY MENON IN SEPTEMBER WE HAVE DECIDED
TO ESTABLISH RADIOASTRONOMY GROUP STOP LETTER FOLLOWS WITH
OFFER
BHABHA.

Handwritten: 2620, 2739, 20 45, 888

Stamp: 1-2739, 7-239, To 888

Telegram from Homi Bhabha to G. Swarup, 20 January 1962: TIFR decides to establish a radio astronomy group.



The Kalyan array near Mumbai (1965): the first radio telescope array in India.

The Ooty Radio Telescope (ORT)



Credit: Ooty Radio Telescope, 530 m $\times$ 30 m parabolic cylinder.

ORT: a cylinder on a hillside that is already equatorially mounted

- Designed 1963, built 1965–70; first observation (a lunar occultation) in February 1970.
- **530 m × 30 m** parabolic cylinder at $\nu = 326.5$ MHz: collecting area $\approx 530 \times 30 \approx 1.6 \times 10^4 \text{ m}^2$.
- The long axis lies along a hill whose slope ($\sim 11^\circ$) equals the latitude of Ooty. The axis therefore points at the celestial pole, and rotating the cylinder about it tracks a source for ~ 9.5 h.
- Diffraction limits ($\lambda = 0.92$ m, order of magnitude): $\approx 6'$ along the cylinder, $\approx 1.8^\circ$ across it.

Science

- **Lunar occultations:** arcsecond angular sizes for $> 10^3$ weak radio sources; evidence against the steady-state cosmology.
- Interplanetary scintillation: solar-wind and space-weather monitoring.
- Upgraded to the Ooty Wide Field Array for 21-cm intensity mapping and transients.

Swarup et al. 1971, *Nature Phys. Sci.* **230**, 185; [doi:10.1038/physci230185a0](https://doi.org/10.1038/physci230185a0)