


Radio Astronomy

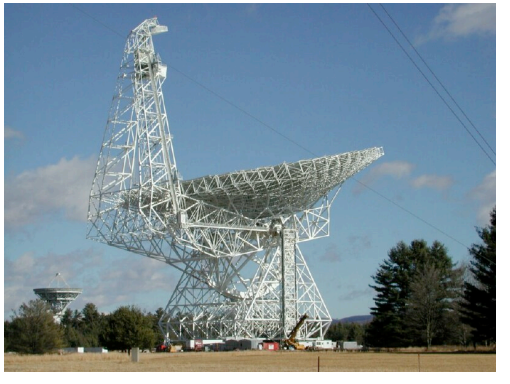
Lecture 1

The History of Radio Astronomy: Past to Present

Lecturer: Jason Hessels (hessels@astron.nl)

B0.209 - April 2nd, 2013



Course outline

Course Goals

Give a broad overview of the science, techniques and context of radio astronomy.

Enable the student to feel comfortable with using radio astronomical observations as part of their multi-wavelength science approach.

Get you excited about radio astronomy!

Resources

Course Wiki

http://www.astron.nl/astrowiki/doku.php?id=uva_msc_radioastronomy_2013

Includes valuable links:

- Lecture slides
- Materials from other similar courses
- Recommended books

Lecturers

Jason Hessels (hessels@astron.nl)
Joeri van Leeuwen (leeuwen@astron.nl)
Michael Wise (wise@astron.nl)

Teaching Assistant

Dario Carbone (D.Carbone@uva.nl)

Marking Scheme

25% - Observing proposal and presentation
25% - Data analysis and report
50% - Final exam

Lectures

Lecture 1: April 2, 2013 - The History of Radio Astronomy: Past to Present - Jason

Lecture 2: April 4, 2013 - The Science of Radio Astronomy: Extragalactic - Michael

Lecture 3: April 8, 2013 - The Science of Radio Astronomy: Galactic and Solar System - Joeri

Lecture 4: April 11, 2013 - Emission Mechanisms in Radio Astronomy - Jason

Lecture 5: April 15, 2013 - The Radio Telescope - Joeri

Lecture 6: April 18, 2013 - The Techniques of Radio Interferometry I: The Basics - Jason

Lecture 7: April 22, 2013 - The Techniques of Radio Interferometry II: Calibration - Michael

Lecture 8: April 25, 2013 - The Techniques of Radio Interferometry III: Imaging - Michael

Lecture 9: May 2, 2013 - Field Trip to LOFAR and Westerbork - Michael + Joeri + Jason + Dario

Lecture 10: May 6, 2013 - The Techniques of Time-Domain Radio Astronomy I: Single-dish techniques - Joeri

Lecture 11: May 13, 2013 - The Techniques of Time-Domain Radio Astronomy II: High time resolution with interferometers - Jason

Lecture 12: May 16, 2013 - Project Presentations - Michael + Jason + Dario

Lecture 13: May 21, 2013 - The Future of Radio Astronomy - Michael

Lecture 14: May 23, 2013 - Final Exam - Dario + one other

Practica

Lecture 1: April 2, 2013 - None

Lecture 2: April 4, 2013 - Basic account setup etc.

Lecture 3: April 8, 2013 - Writing of mock observing proposal I

Lecture 4: April 11, 2013 - Writing of mock observing proposal II

Lecture 5: April 15, 2013 - Writing of mock observing proposal III

Lecture 6: April 18, 2013 - Radio interferometry data analysis project I

Lecture 7: April 22, 2013 - Radio interferometry data analysis project II

Lecture 8: April 25, 2013 - Radio interferometry data analysis project III

Lecture 9: May 2, 2013 - Field trip

Lecture 10: May 6, 2013 - Time domain data analysis project I

Lecture 11: May 13, 2013 - Time domain data analysis project II

Lecture 12: May 16, 2013 - Project presentations

Lecture 13: May 21, 2013 - None

Lecture 14: May 23, 2013 - Final Exam

Questions?

The History of Radio Astronomy: Past to Present

Lecture outline

- Key figures in the pre-history of radio astronomy
- Key figures in early radio astronomy
- Seminal discoveries and nobel prizes
- Key instruments
- The current landscape

Key figures in the pre-history of radio astronomy

James Clerk Maxwell

(1831-1879)

- Maxwell's equations encapsulated all that was known about electricity and magnetism.
- Unify electricity and magnetism as a single electromagnetic force.
- Maxwell's equations predict electromagnetic waves.
- Light is a form of electromagnetic radiation.

So do natural (astronomical) sources produce em-waves?

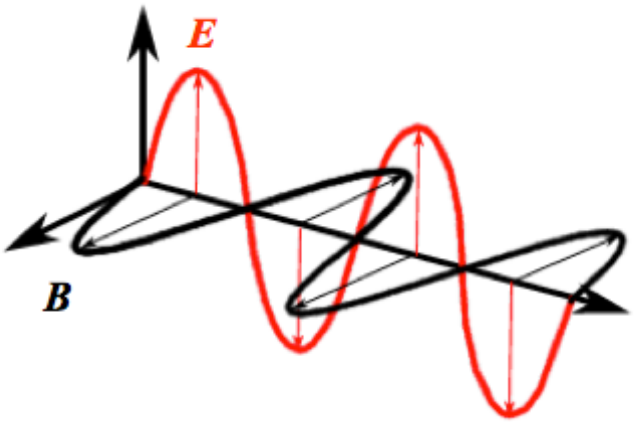
Maxwell's Equations

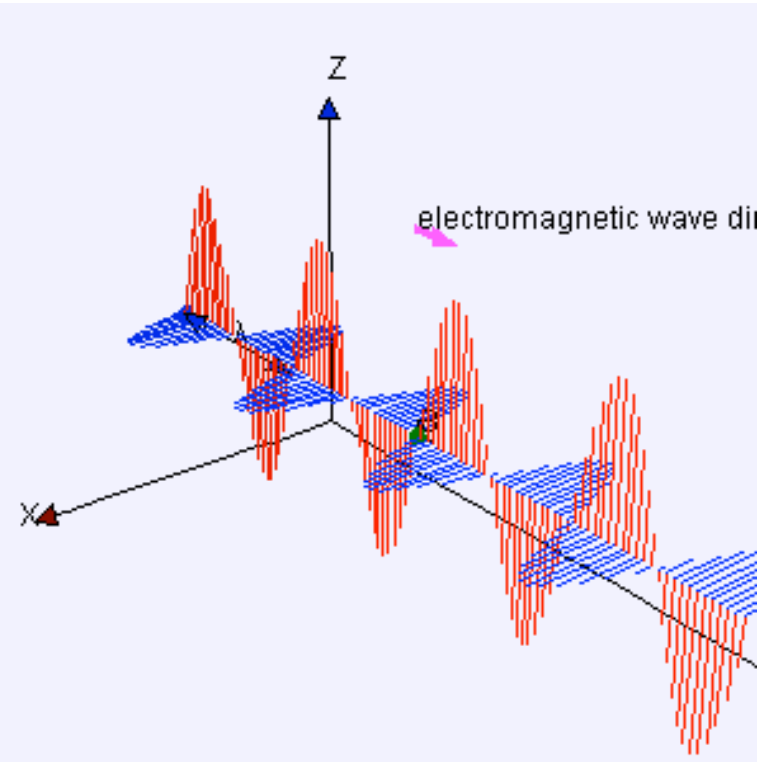
Gauss's Law	$1.\ \nabla \cdot \boldsymbol{E} = 4\pi\rho$
Faraday's Law of Induction	$2.\ \nabla \times \boldsymbol{E} = -\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t}$
Gauss's Law for Magnetism	$3.\ \nabla \cdot \boldsymbol{B} = 0$
Ampere's Circuital Law	$4.\ \nabla \times \boldsymbol{B} = \frac{4\pi \boldsymbol{J}}{c} + \frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t}$

Maxwell's Equations

$$\boldsymbol{E}(\boldsymbol{r},t) = \boldsymbol{E}_0 \sin(\omega t - \boldsymbol{k}\cdot\boldsymbol{r} + \varphi_0)$$

$$\boldsymbol{B}(\boldsymbol{r},t) = \boldsymbol{B}_0 \sin(\omega t - \boldsymbol{k}\cdot\boldsymbol{r} + \varphi_0)$$

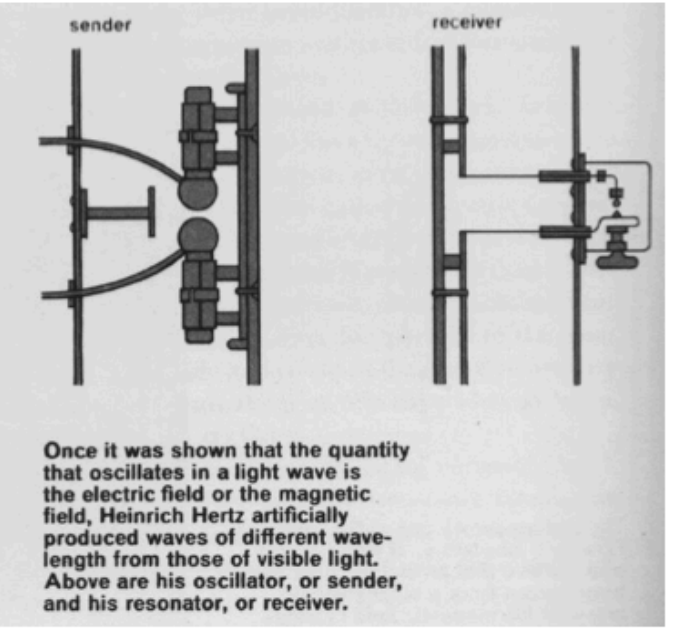




Solution is a wave

Heinrich Hertz

(1857-1894)



Once it was shown that the quantity that oscillates in a light wave is the electric field or the magnetic field, Heinrich Hertz artificially produced waves of different wavelength from those of visible light. Above are his oscillator, or sender, and his resonator, or receiver.

- First observation of electromagnetic waves ("Hertzian" or "aetheric" waves).
- In 1888 built a system for sending and receiving 5-m radio waves.

Guglielmo Marconi

(1874 - 1937)

- Italian (also heir to Irish/Scots Whiskey distillery *Jameson & Sons*).
- Improved transmitter and receiver designs and made communication practically possible (Nobel Prize 1909).
- 1901: communication between Newfoundland, Canada and Cornwall, UK (though some skepticism about exact first detection).
- Father of long-distance radio communication.
- Mussolini was his best man at second wedding

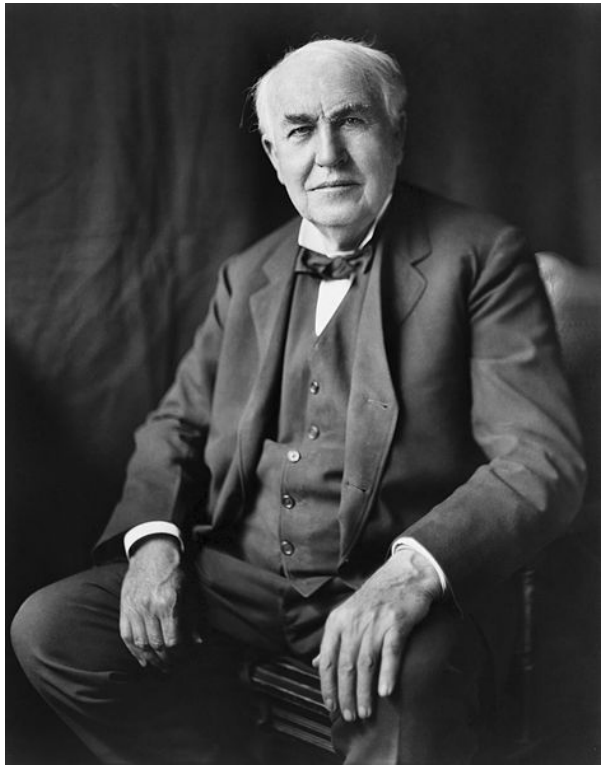
Nobel Prize Physics 1909

Guglielmo Marconi & Karl Ferdinand Braun

"in recognition of their contributions to the development of wireless telegraphy"

Thomas Edison

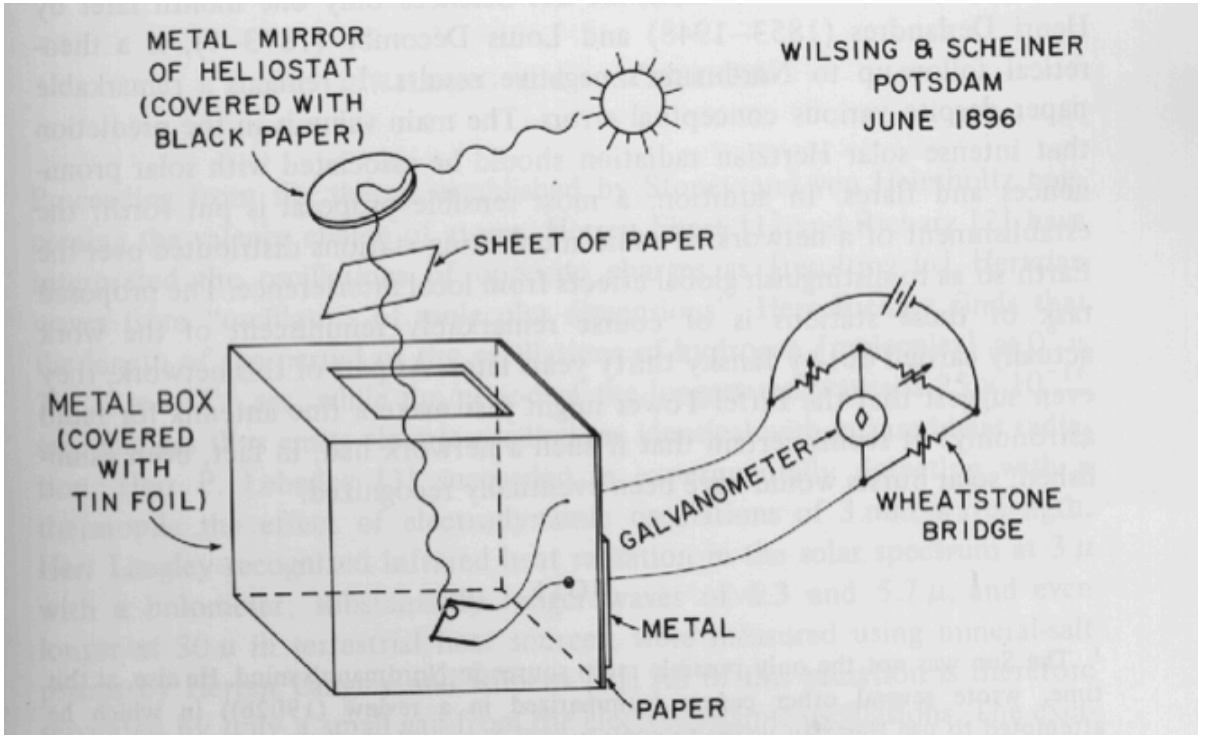
(1847 - 1931)



- First recorded suggestion of looking for astronomical sources of radio waves (1890).

Johannes Wilsing & Julius Scheiner

(1856 - 1943) (1858 - 1913)



- Astrophysicists.
- First to properly publish their attempt to detect the Sun in radio (Ann. Phys. Chem. 59, 782, 1896; in German).
- Atmospheric absorption to blame?

Charles Nordman

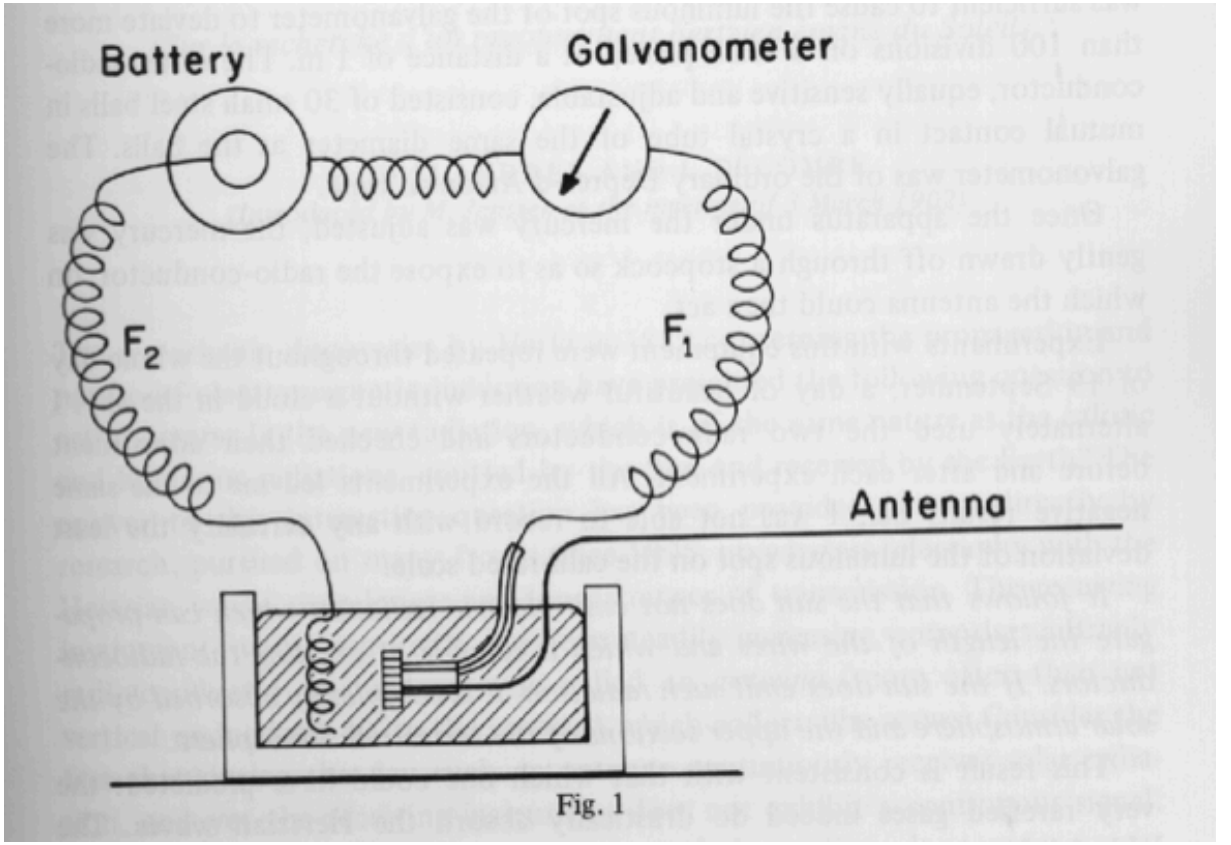
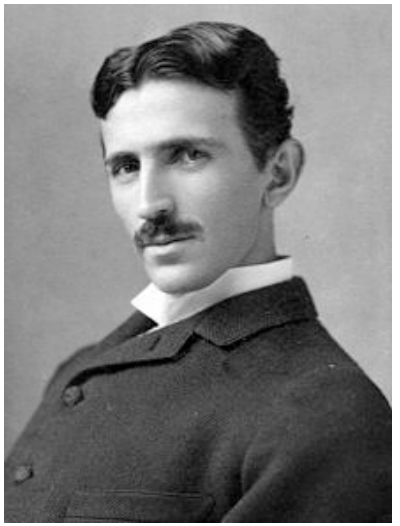
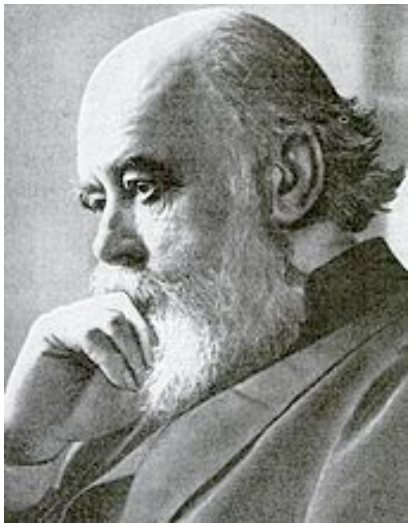


Fig. 1

- French graduate student.
- Took experiment to top of Mont Blanc (avoid absorption).

Still more attempts...

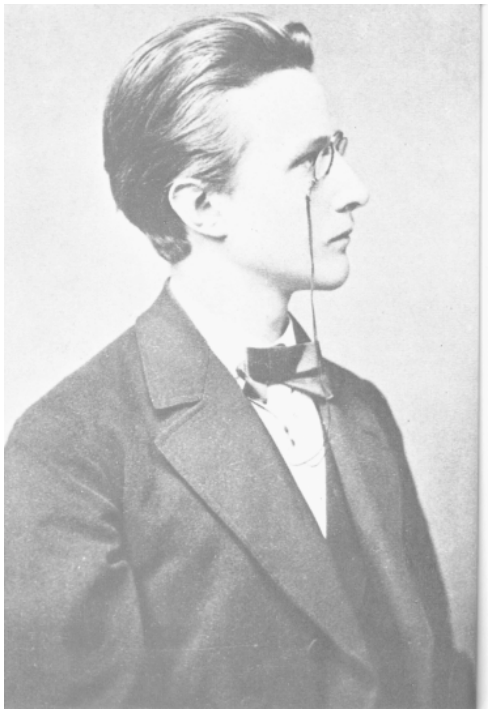




- Nikola Tesla & Oliver Lodge also tried to detect Sun, unsuccessfully.

Max Planck

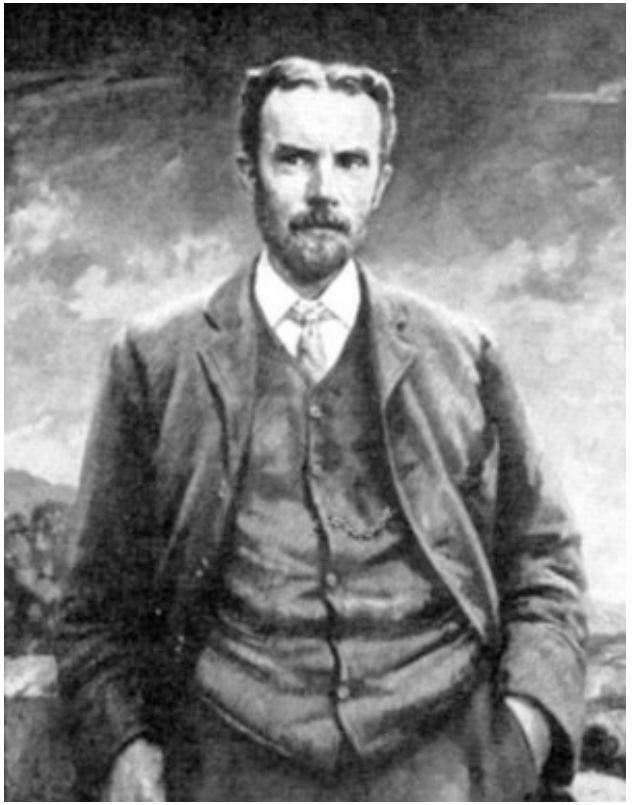
(1858 - 1947)



- Explanation of black-body spectrum using "quanta" of energy.
- Prediction for the Sun was very little thermal radio emission.

Oliver Heaviside

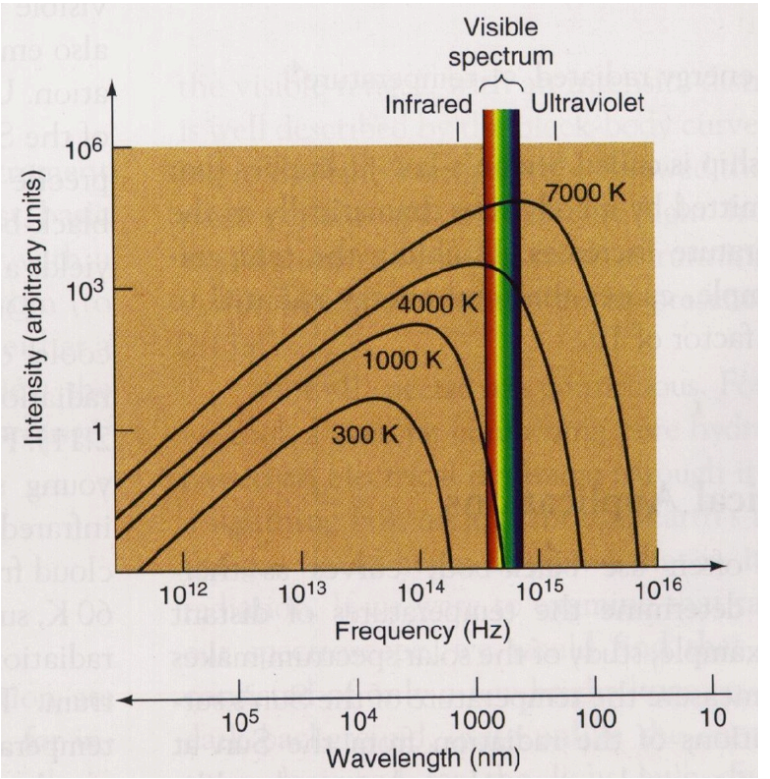
(1850 - 1925)

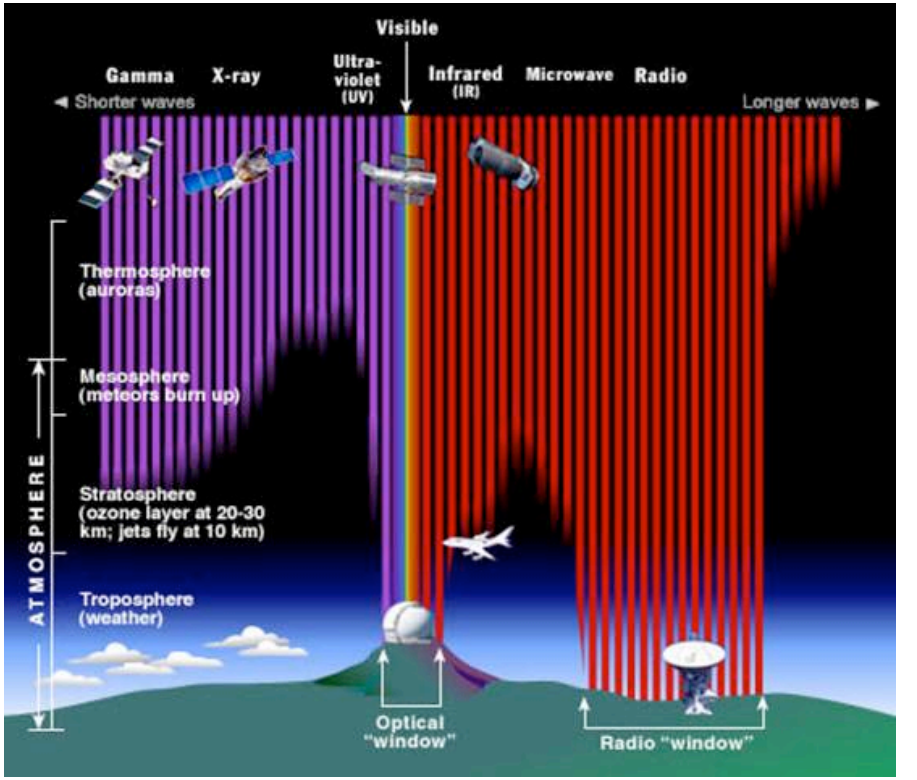


- British.
- Ionized ionospheric layer will reflect low-frequency radio waves (< 10-20MHz).
- Ionosphere predicted in 1902, observed in 1920.
- The "Kennelly-Heaviside" layer.

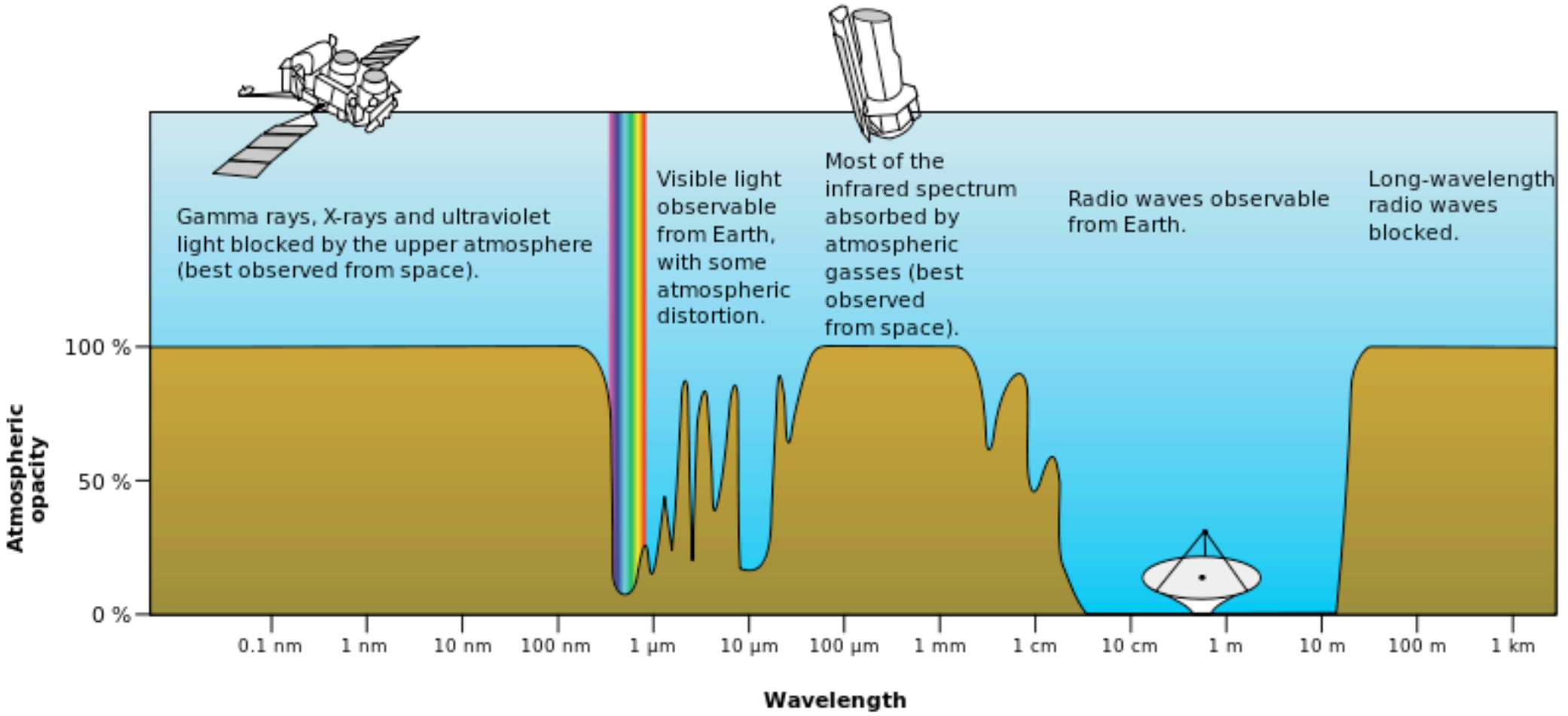
1902-1932

- People discouraged by Planck's prediction of low thermal brightnesses.
- Attempts also discouraged because of the ionosphere.





EM Spectrum



- Only optical/IR and radio pass through the atmosphere.
- Radio window: 1cm - 30m / 10MHz - 30 GHz (or more)

Key figures in early radio astronomy

Karl Guthe Jansky

(1905-1950)

- American
- Engineer at Bell Telephone Laboratories.
- Investigating interfering static in wireless communication.
- Directional antenna (at 20MHz).
- Repeating signal at the 23h56m siderial rate.

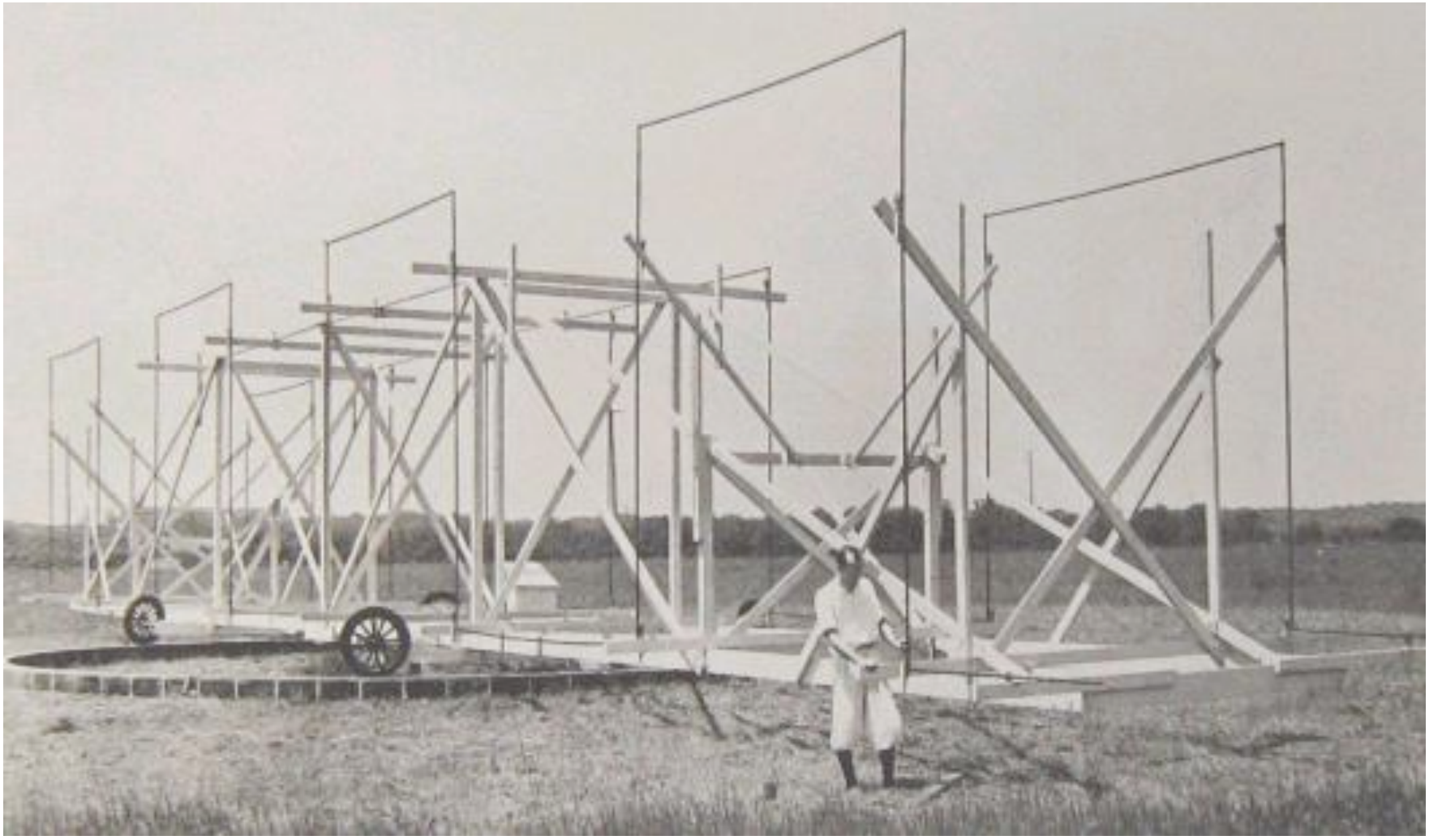
Karl Guthe Jansky

(1905-1950)

- Direction of Sagittarius.
- First detection of radio waves from an astronomical source (the Milky Way) announced in 1933.
- Proposed a 30-m dish, but...
- Re-assigned to another project by Bell Labs.
- Namesake of the flux density unit the "Jansky" (1Jy = 10-26 W/m2/Hz).

No Nobel Prize because he died too young?

Jansky's telescope 1933



Discovery during the Great Depression bad timing?

Radio astronomy did not immediately take off...

Jansky's telescope today

One of the three historic radio telescopes in Green Bank, West Virginia (replica).

Grote Reber

(1911 - 2002)

- American.
- Amateur inspired by Jansky's pioneering work.
- Couldn't get a job at Bell Labs (height of Great Depression).
- Built 9-m parabolic reflector in 1937 (in his own backyard!).
- Only successful on third attempt (3300MHz, 900MHz, 160MHz).
- Conducted first sky survey at radio frequencies.

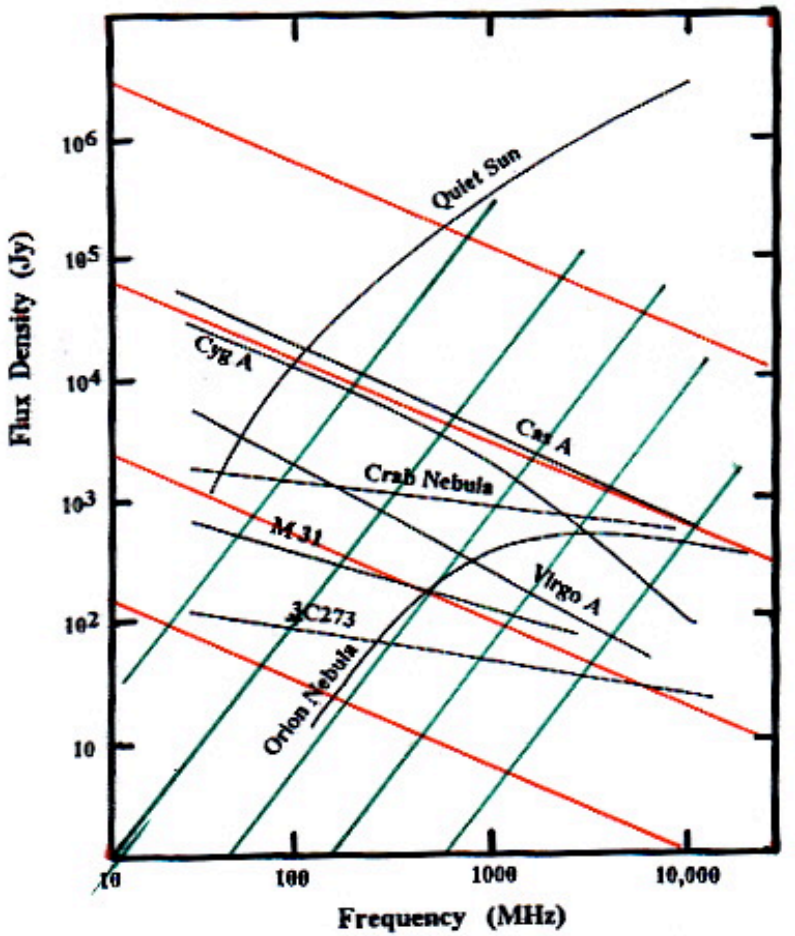
Grote Reber

(1911-2002)

- First true radio astronomer.
- Sole radio astronomer for nearly a decade.
- Mystery of low-energy (non-thermal, synchrotron) emission.
- Set the stage for the explosion in radio astronomy that followed WWII.
- Some of his ashes at ASTRON and at other major radio institutes.

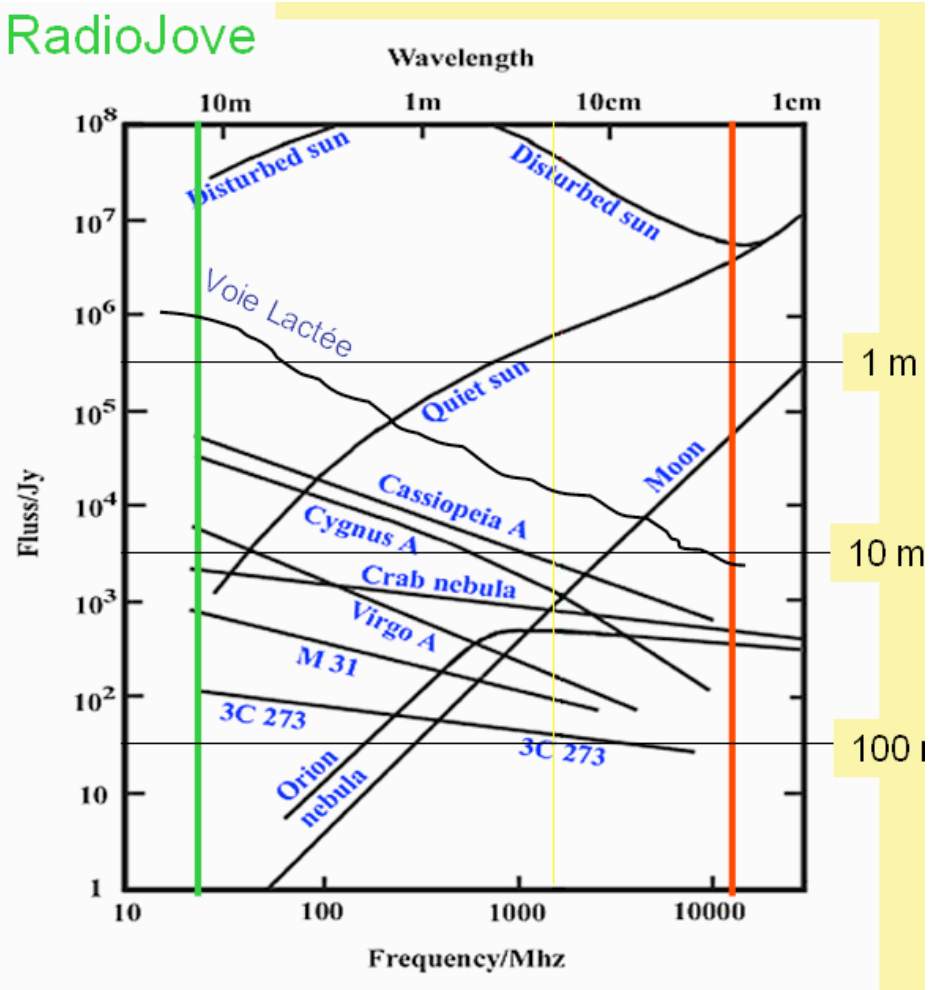
Thermal / non-thermal

$S \propto \nu^{-0.8}$ (synchrotron with $N(E) \propto E^{-2.6}$)

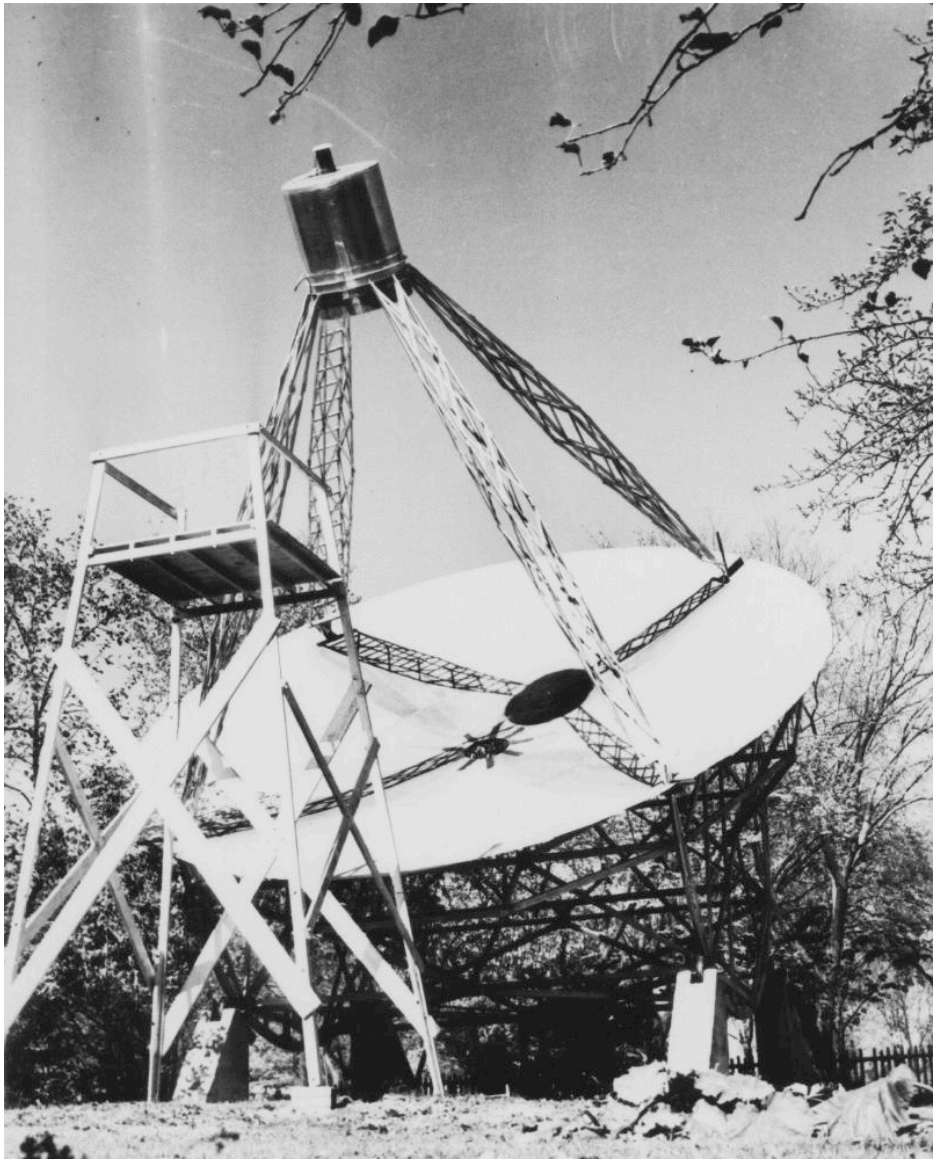


$S \propto \nu^2$ (blackbody)

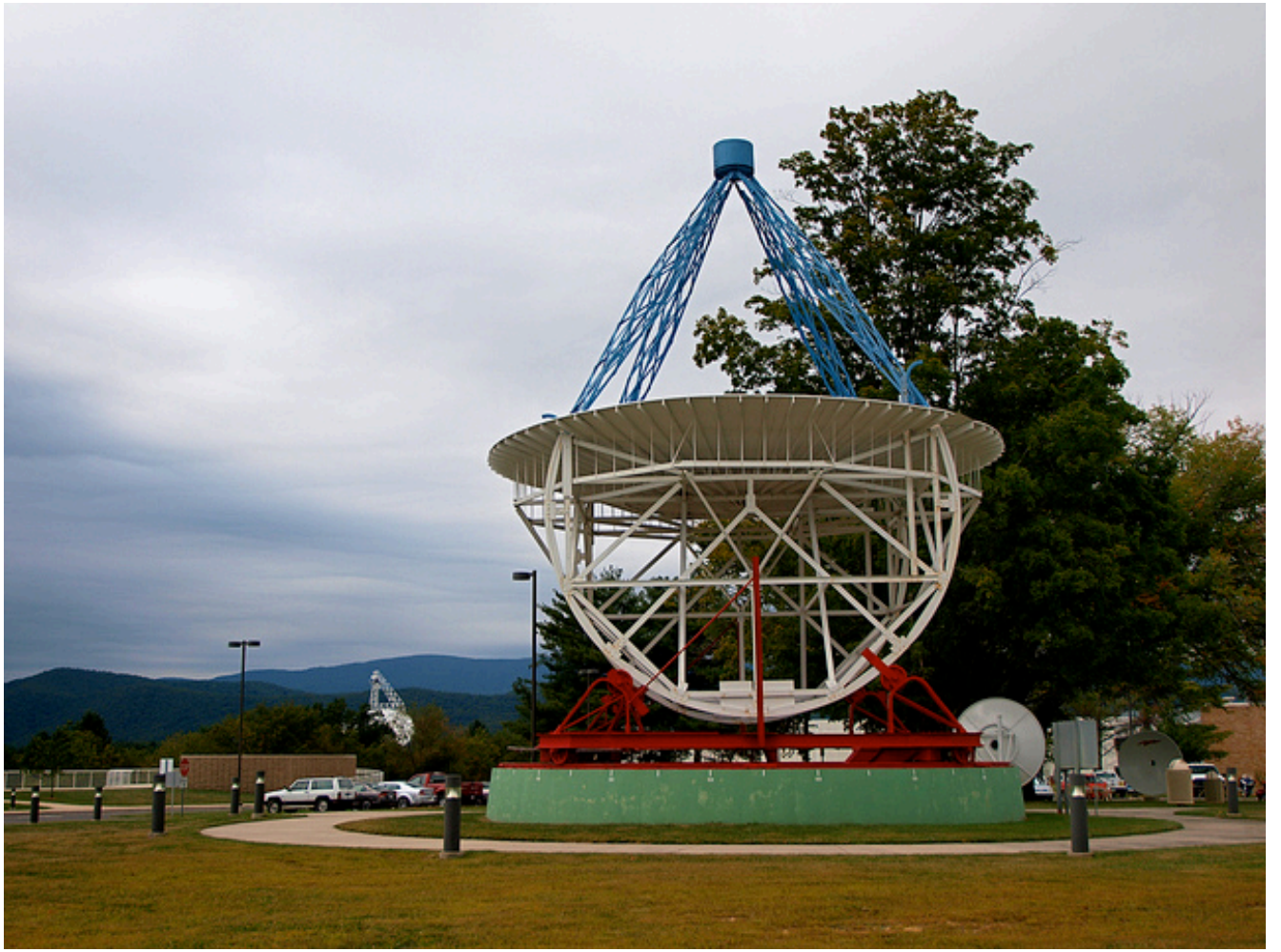
RadioJove



Reber's telescope 1937

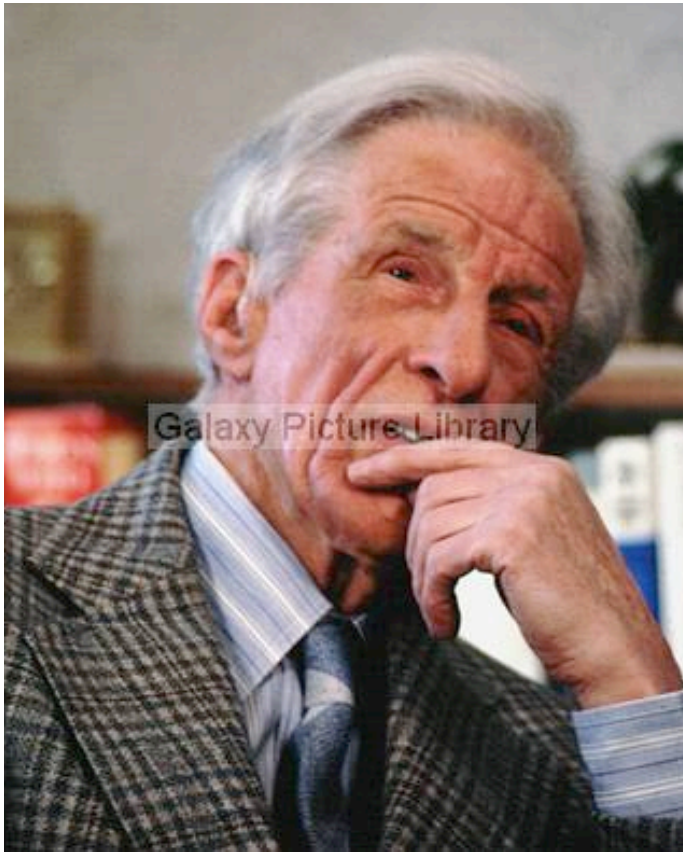


Reber's telescope today



One of the three historic radio telescopes in Green Bank, West Virginia (reconstructed).

J.S. Hey



- British Army research officer (radar WWII).
- First detection of radio waves from the Sun in 1942.
- First localized an extra-galactic radio source in Cygnus.
- Set stage for explosion of radio astronomy research in UK after WWII.

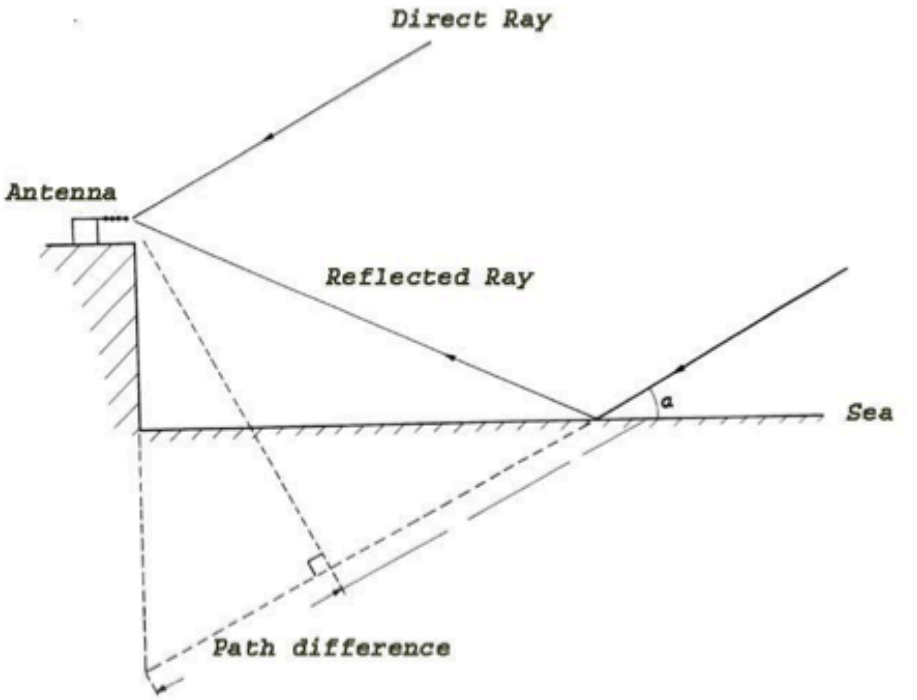
Joseph Pawsey

(1908 - 1962)

- Australian.
- Early studies of irregularities in the ionosphere.
- Developed microwave technology for the Australian Navy during WWII.
- Introduced interferometry to radio astronomy.
- Used "sea interferometry" at Dover Heights to resolve sunspots.
- Father of radio astronomy in Australia.

“Sea” interferometry

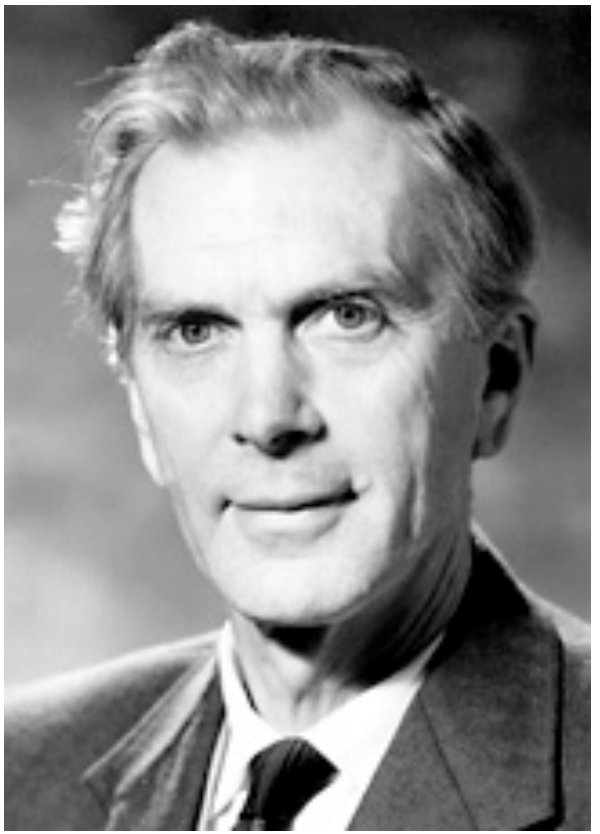
(mid 1940s)



Dover Heights near Sydney

Martin Ryle

(1918 - 1984)



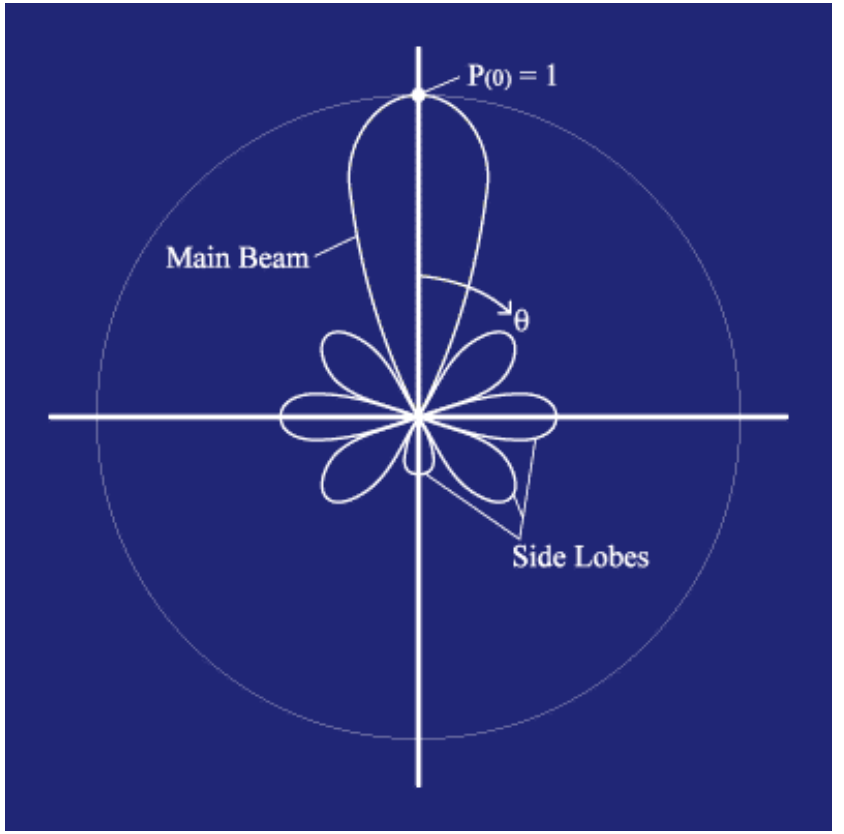
- British
- Worked on airborne radar antennas during WWII.
- First *published* interferometric observations (see Pawsey).
- Introduced (Earth-rotation) aperture synthesis to radio astronomy (1974 Nobel Prize).
- Built first multi-element interferometer in 1946.
- Led 3C catalog in 1959.

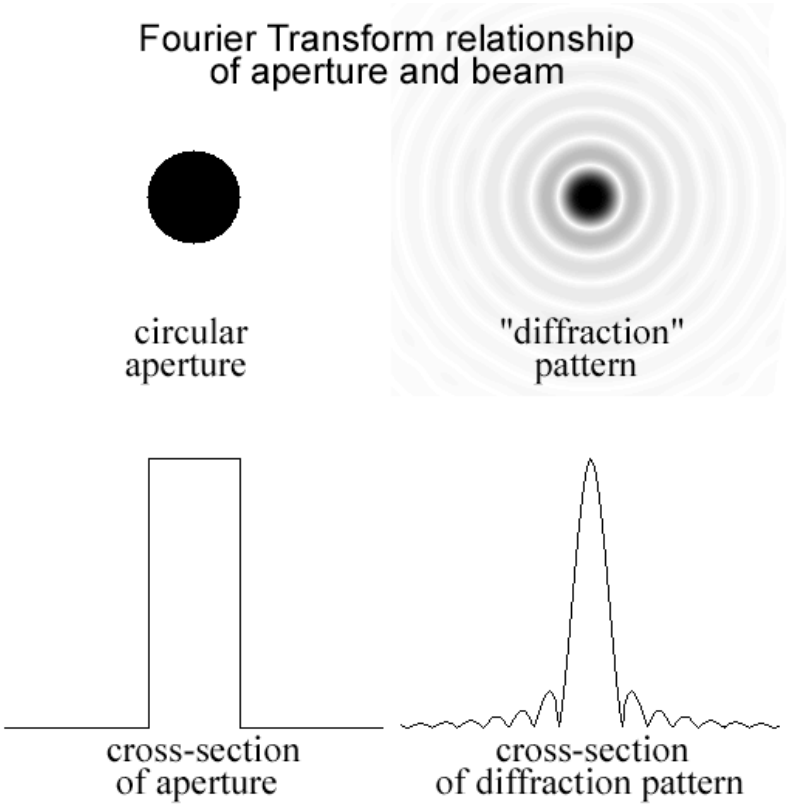
Cambridge radio catalogs

e.g. famous "3C" catalog

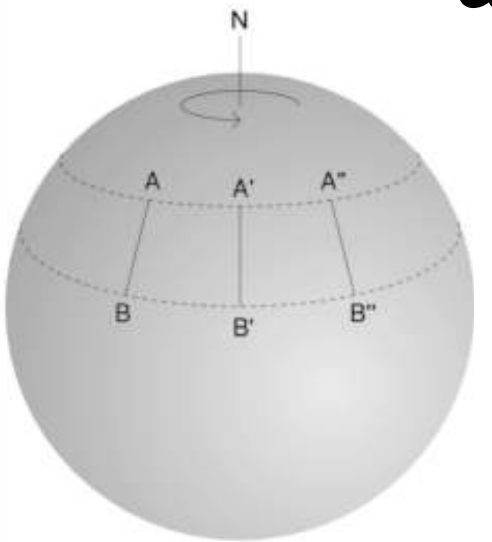
- Various Cambridge interferometers at 80 - 200MHz.
- 1C, 2C First sample of quasars.
- 3C published in 1959.
- Many of the brightest, most famous sources are "3C" sources.

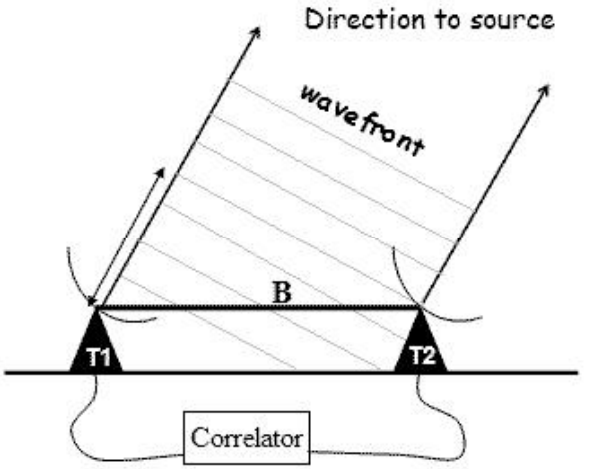
Radio telescope FoV

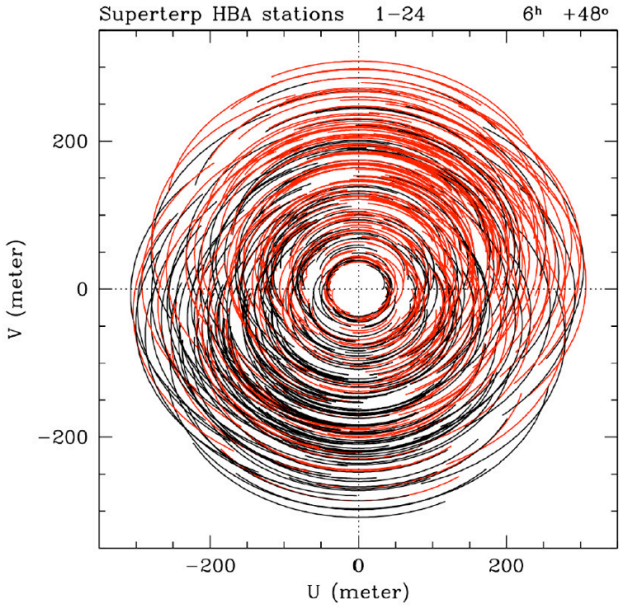




Development of interferometry and aperture synthesis

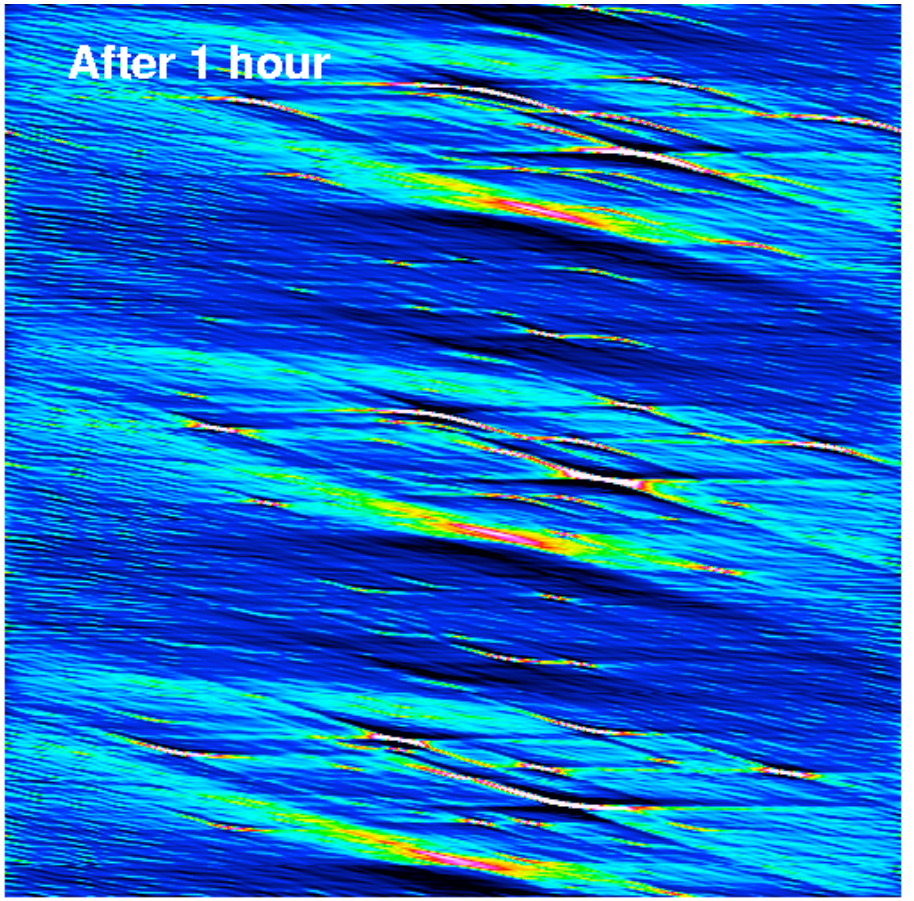




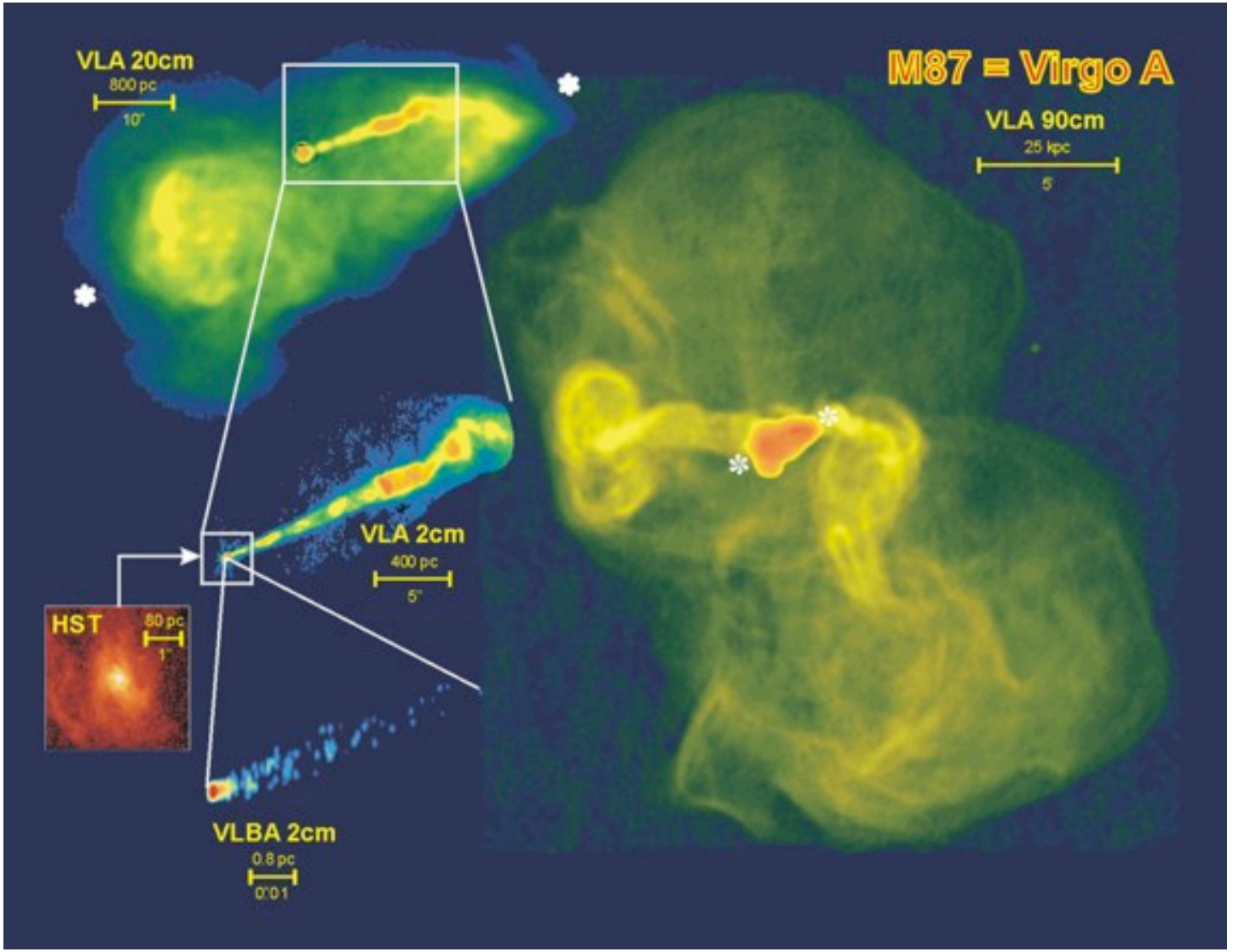


- Need for resolution.
- Earth rotation fills in the image.
- Sky brightness is the 2D Fourier transform of the spatial frequencies.

Development of interferometry and aperture synthesis



The quest for resolution



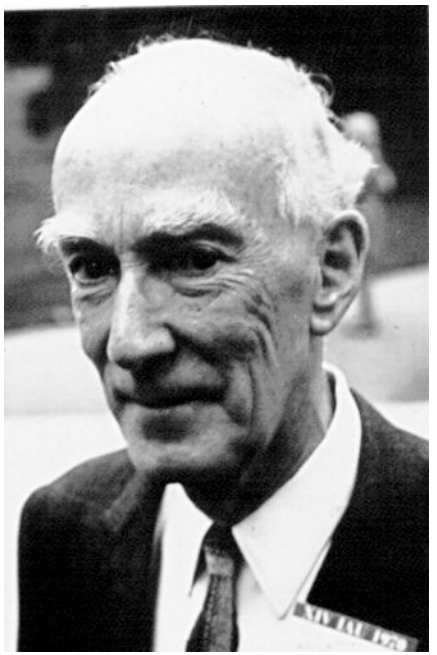
Bernard Lovell

(1913 - 2012)

- British
- Director Jodrell Bank Observatory 1945 - 1980.
- Worked on airborne radar systems during WWII.
- Led construction of the 76-m Lovell Telescope.

Jan Oort

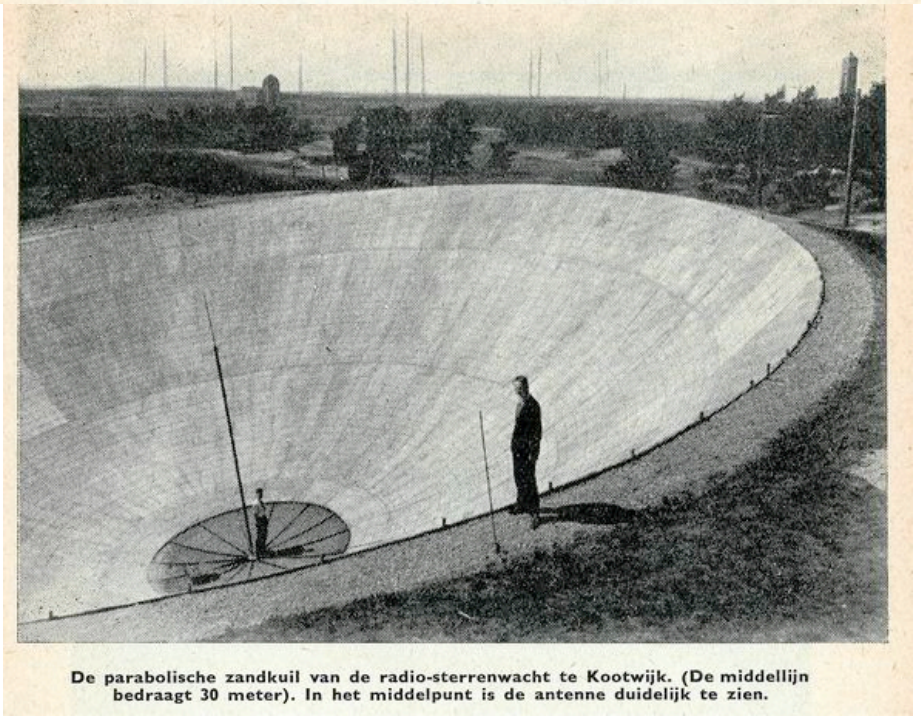
(1900-1992)



- Professor Leiden and father of Dutch radio astronomy.
- Expert on Milky Way structure.
- Kootwijk radar dish used after WWII (start of Dutch radio astronomy).
- Built Dwingeloo telescope and later Westerbork.
- Upon his death, Nobel Prize winning astrophysicist Subrahmanyan Chandrasekhar remarked, "The great oak of Astronomy has been felled, and we are lost without its shadow."

Beginnings of Dutch radio astronomy

De radio-telescoop te Kootwijk (zie ook de voorplaat). De middellijn van de spiegel is $7^1/_2$ m. Het gevaarte kan op zijn voetstuk draaien. De spiegel zelf kan omhoog en omlaag gericht worden.



De parabolische zandkuil van de radio-sterrenwacht te Kootwijk. (De middellijn bedraagt 30 meter). In het middelpunt is de antenne duidelijk te zien.

- Presided over by Jan Oort.
- Kootwijk radar antenna leftover from WWII by Germans.
- First (Dutch) detection of 21-cm line.

Hendrik van de Hulst

(1918-2000)

- Student of Oort
- In 1944 first predicted the 21-cm hyperfine line of neutral interstellar hydrogen.
- First reveal spiral structure of Milky Way.

Prediction of the 21-cm Line

(1944)

Plate 1.6 Van de Hulst reading his paper on the 21 cm hydrogen line. (This photograph taken in 1955 is a reconstruction of the 1944 meeting). (*By courtesy of H. C. van de Hulst, Leiden*)

(re-enactment)

- Astronomers still meeting in the Netherlands during WWII.
- ApJ still reaching Leiden Observatory.
- Excited by Reber's findings, Oort realized that a radio spectral line could be used to map the Milky Way's structure (optical is absorbed).

Prediction of the 21-cm Line

Plate 1.6 Van de Hulst reading his paper on the 21 cm hydrogen line. (This photograph taken in 1955 is a reconstruction of the 1944 meeting). (*By courtesy of H. C. van de Hulst, Leiden*)

(re-enactment)

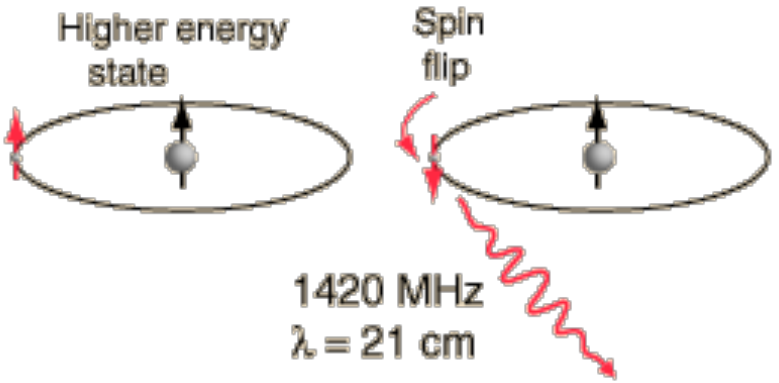
(1944)

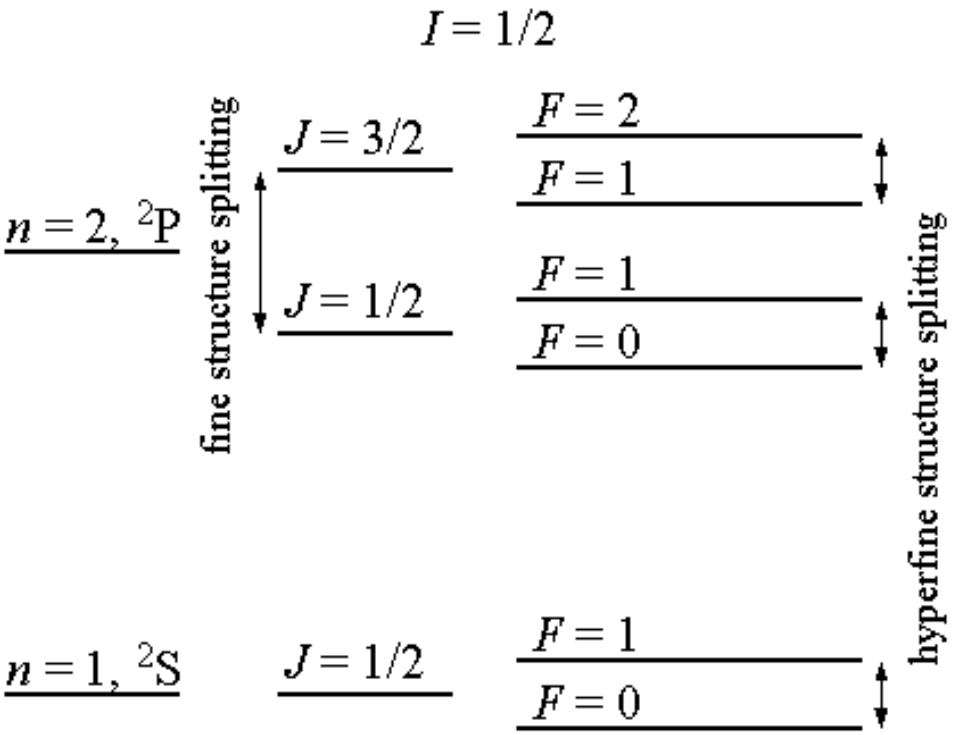
- Oort asked van de Hulst to investigate what lines there might be.
- van de Hulst discovered that a 21-cm line would result from an electron flipping its spin in the ground state of hydrogen.
- Published in Dutch in the Ned. Tijdschrift voor Natuurkunde.

Prediction of the 21-cm Line

(1944)

frequency of 1420.40575177 MHz, which is equivalent to the vacuum wavelength of 21.10611405413 cm in free space.



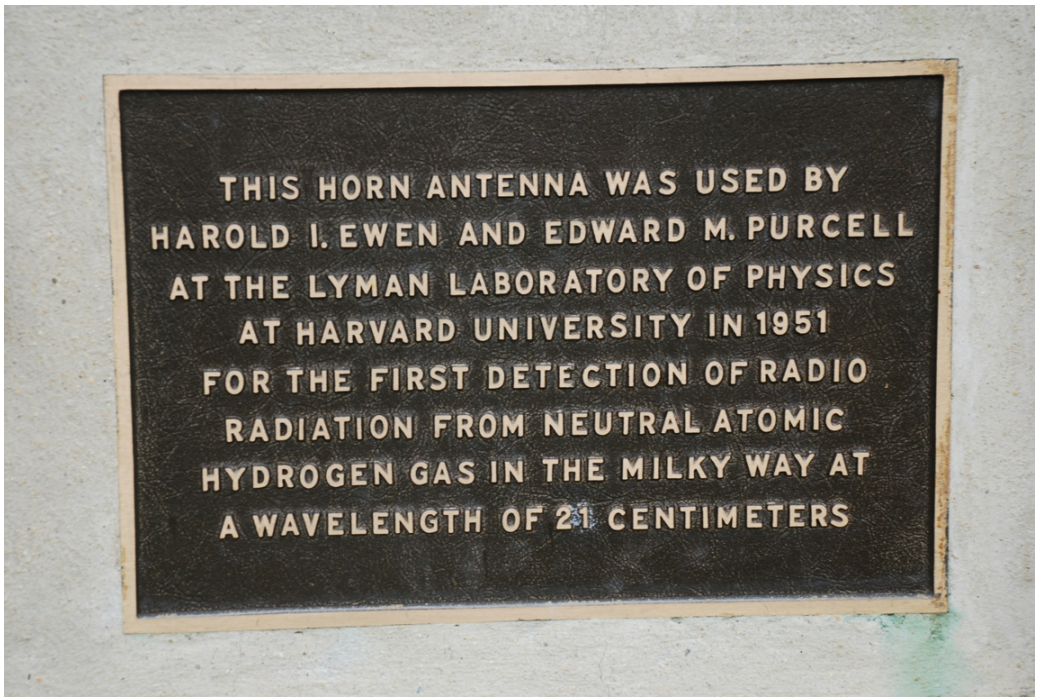


Detection of the 21-cm Line

(1951)

- Building a good receiver proved challenging.
- Reber started work but moved on.
- Ewen & Purcell at Harvard made first detection on March 25th, 1951.
- van de Hulst visiting Harvard at that time.
- Talked to Oort on phone for an hour.
- American and Dutch results were published in the same issue of Nature

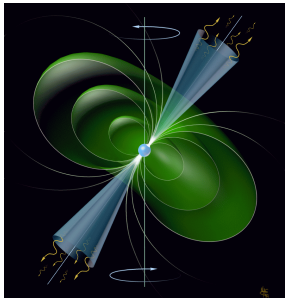
Ewen & Purcell Feed Horn Today



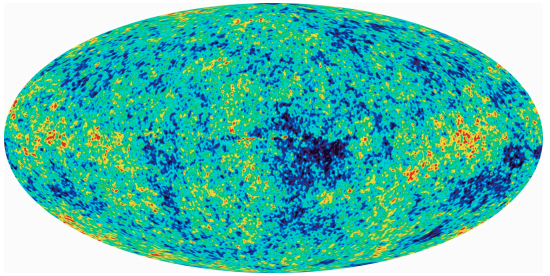
One of the three historic radio telescopes in Green Bank, West Virginia (original).

Seminal discoveries and Nobel prizes

Seminal Discoveries

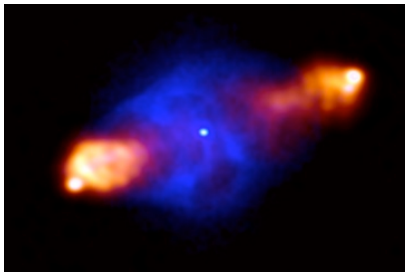


Pulsar - Jocelyn Bell & Antony Hewish (1967)



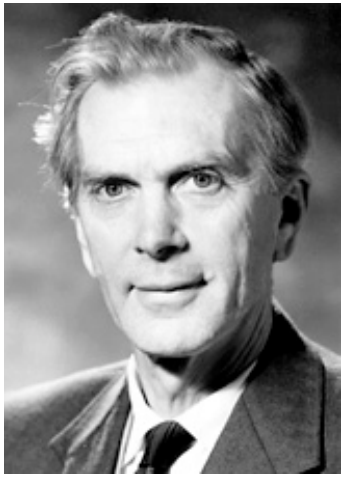
Cosmic Microwave Background - Arno Penzias & Robert Wilson (1965)

Quasars - Martin Ryles et al. (late 1950s)

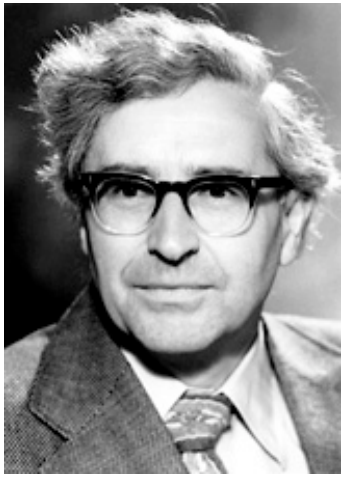


Radio Galaxies - Grote Reber, Bolton, Stanley, et al. (1940 - 1950s)

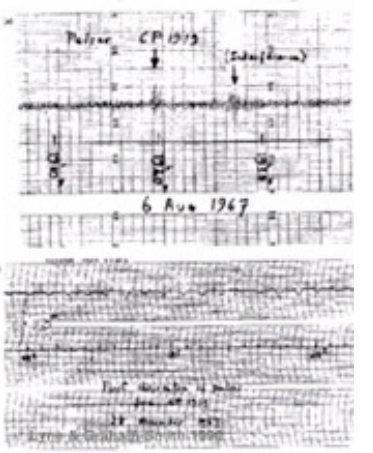
Nobel Prize Physics 1974



Martin Ryle & Antony Hewish

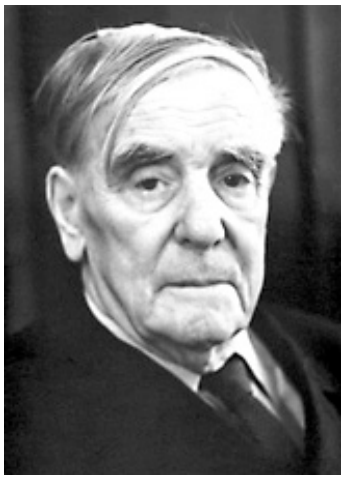


"for their pioneering research in radio astrophysics: Ryle for his observations and inventions, in particular of the aperture synthesis technique, and Hewish for his decisive role in the discovery of pulsars"



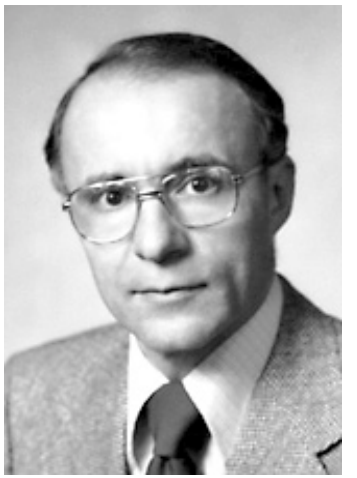
Jocelyn Bell-Burnell

Nobel Prize Physics 1978

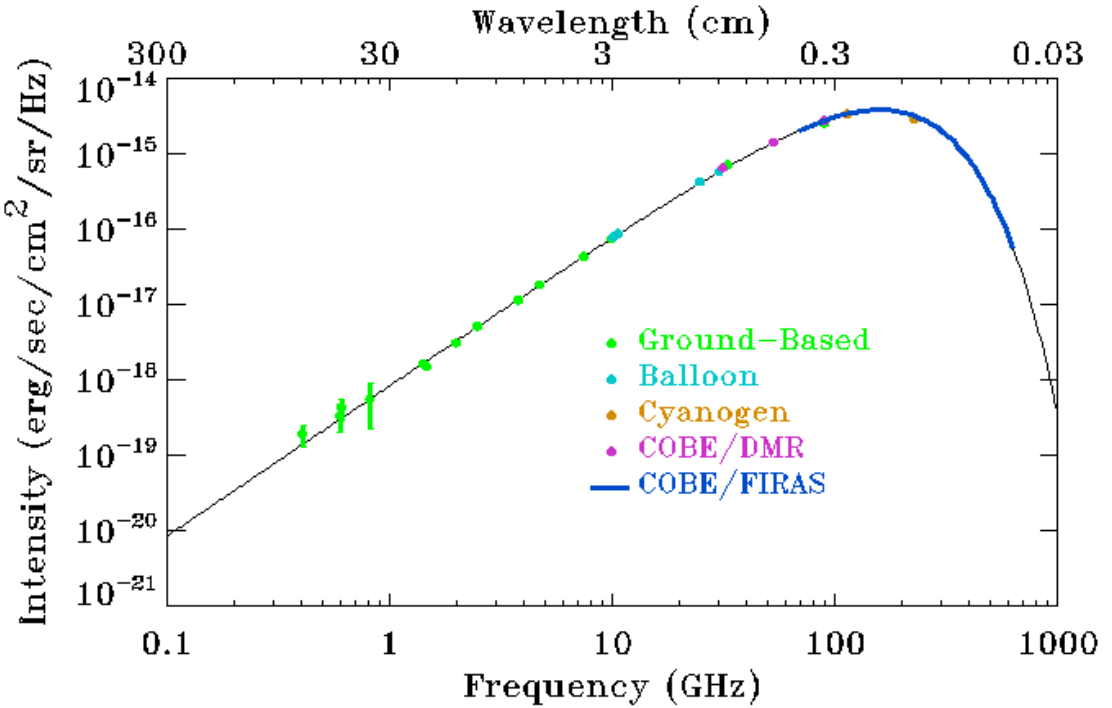


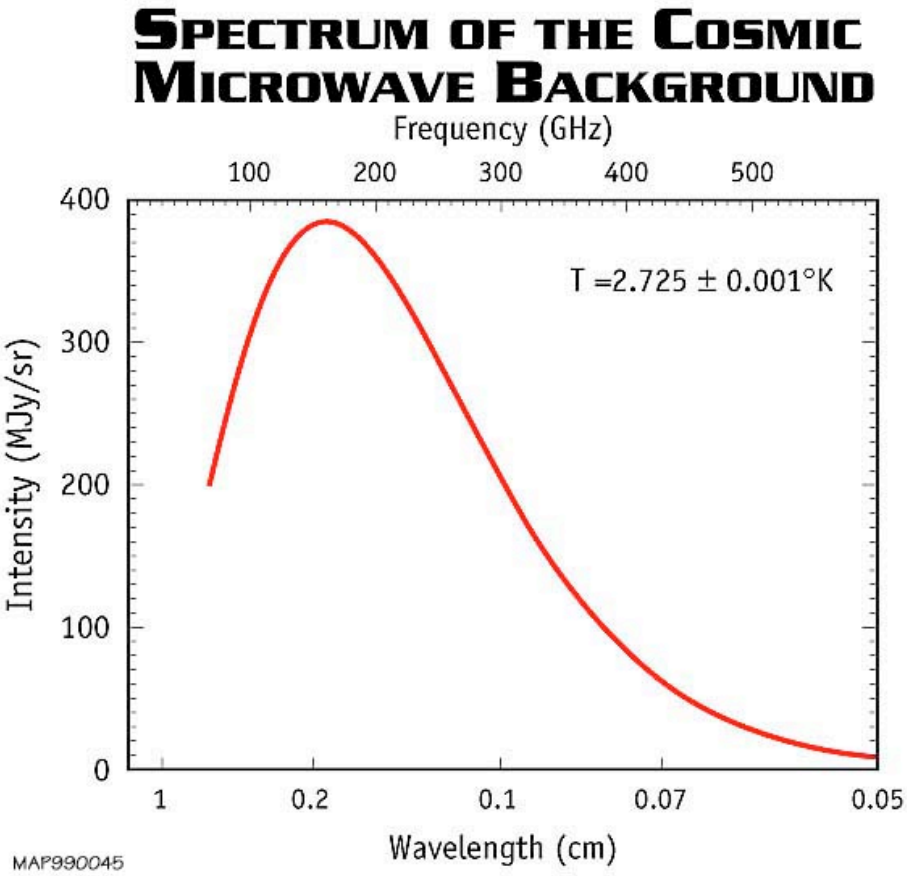
Pyotr Kapitsa, Arno Penzias & Robert Wilson

"for their discovery of cosmic microwave background radiation"



Universe's temperature

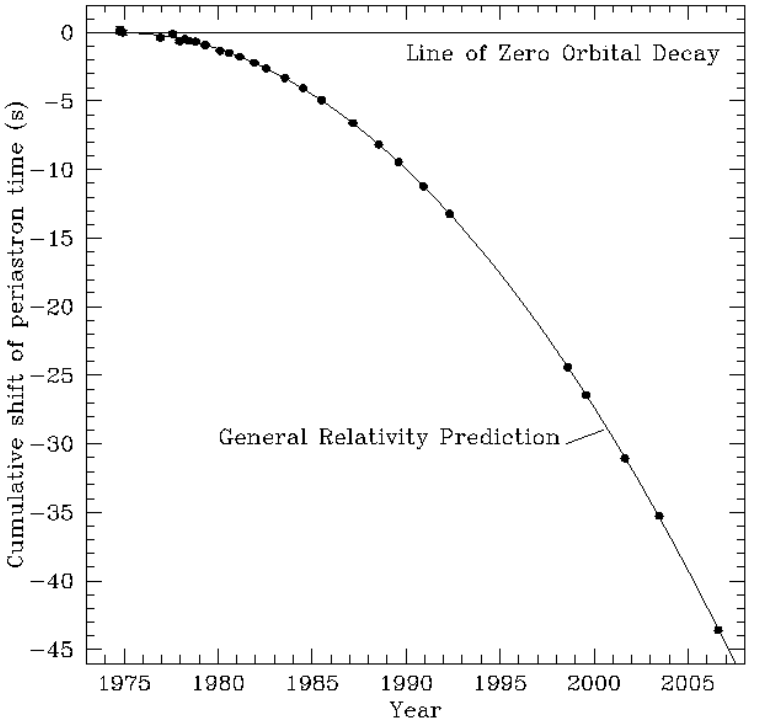




Nobel Prize Physics 1993

Russell Hulse & Joseph Taylor

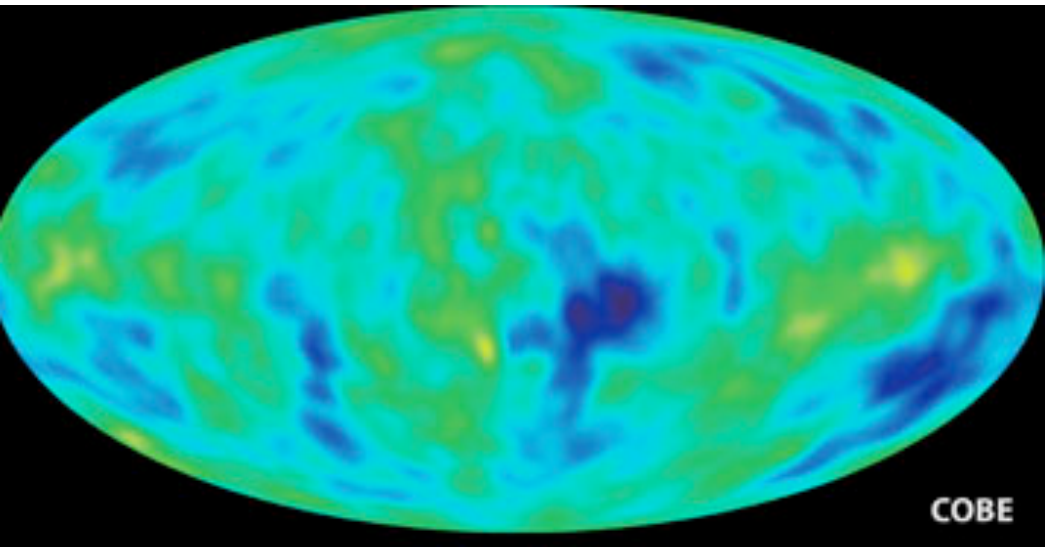
"for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation"

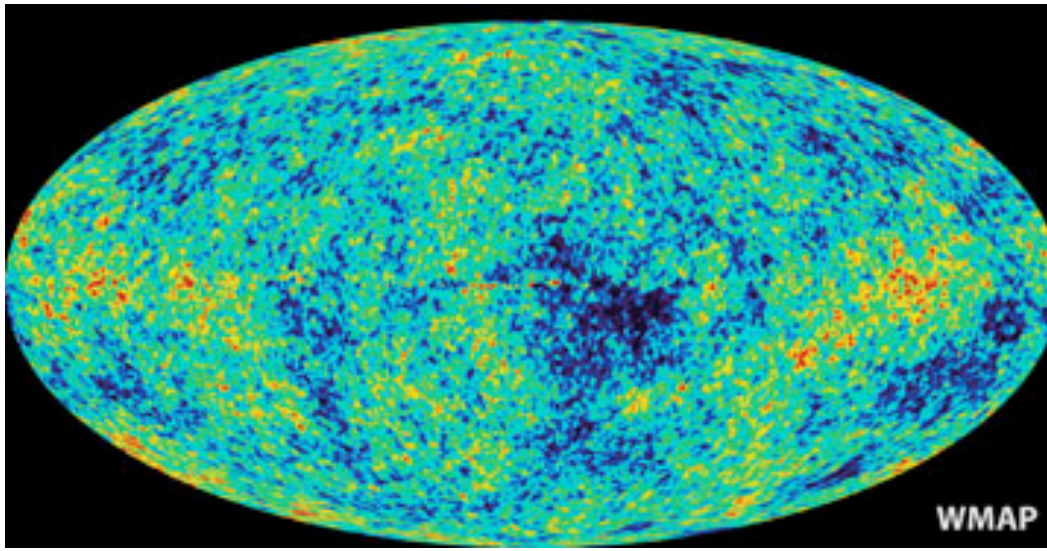


Nobel Prize Physics 2006

John Mather & George Smoot

"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"





Key instruments

Historic Radio Telescopes

http://en.wikipedia.org/wiki/Timeline_of_telescopes,_observatories,_and_observing_technology

1930 - Karl Jansky builds a 30-meter long rotating aerial radio telescope This was the first radio telescope.
1937 - Grote Reber builds a 31-foot (9.4 m) radio telescope
1946 - Martin Ryle and his group perform the first astronomical observations with a radio interferometer
1947 - Bernard Lovell and his group complete the Jodrell Bank 218-foot (66 m) non-steerable radio telescope
1954 - Earth rotation aperture synthesis suggested (see e.g. Christiansen and Warburton (1955))
1956 - Dwingeloo Radio Observatory 25 m telescope completed, Dwingeloo, Netherlands
1957 - Bernard Lovell and his group complete the Jodrell Bank 250-foot (75 m) steerable radio telescope (the Lovell Telescope)
1959 - The 3C catalogue of radio sources is published (revised in 1962)
1960 - Owens Valley 27-meter radio telescopes begin operation, located in Big Pine, California
1961 - Parkes 64-metre radio telescope begins operation, located near Parkes, Australia
1962 - Green Bank, West Virginia 90m radio telescope
1963 - Arecibo 300-meter radio telescope begins operation, located in Arecibo, Puerto Rico
1964 - Martin Ryle's 1-mile (1.6 km) radio interferometer begins operation, located in Cambridge, England
1965 - Owens Valley 40-meter radio telescope begins operation, located in Big Pine, California
1967 - First VLBI images, with 183 km baseline
1970 - Westerbork Synthesis Radio Telescope completed, near Westerbork, Netherlands
1972 – 100 m Effelsberg radio telescope inaugurated (Germany)
1980 - Completion of construction of the VLA, located in Socorro, New Mexico
1984 - IRAM 30-m telescope at Pico Veleta near Granada, Spain completed
1987 - 15-m James Clerk Maxwell Telescope UK submillimetre telescope installed at Mauna Kea Observatory
1987 - 5-m Swedish-ESO Submillimetre Telescope (SEST) installed at the ESO La Silla Observatory
1988 - Australia Telescope Compact Array aperture synthesis radio telescope begins operation, located near Narrabri, Australia
1989 - Cosmic Background Explorer (COBE) satellite
1993 - Very Long Baseline Array of 10 dishes
1995 - Giant Metrewave Radio Telescope of thirty 45 m dishes at Pune
2000 - Green Bank Telescope 100x110m dish completed in West Virginia
2011 - Low-Frequency Array (LOFAR) opens in the Netherlands
2012 - Jansky VLA (upgraded array) opens in New Mexico
2012 - Long-Wavelength Array (LWA) opens in New Mexico
2012 - Australia Square Kilometer Array Pathfinder (ASKAP) opens in Australia
2013 - Murchison Widefield Array (MWA) opens in Australia

Ryle Telescope

(at Mullar Radio Astronomy Observatory, formerly the "5-km Array")

- Near Cambridge, UK.
- Opened in ???
- 8 dishes of 13-m diameter.
- East-West array.
- Adjustable baselines, between 18m and 4.8km.
- Covers the 15GHz (2cm) range.
- Now morphed into the Arcminute Microkelvin Imager (AMI) Large Array.

One-Mile Telescope

(at Mullar Radio Astronomy Observatory)

- Near Cambridge, UK.
- Opened in 1964.
- Operated by Cambridge Radio Astronomy group.
- 3 dishes of 18-m diameter (one movable).
- East-West array.
- First Earth-rotation aperture synthesis interferometer.
- Covered 400 and 1400MHz ranges.
- Resolution of 20 arcsec at 1.4GHz (3x better than unaided eye).
- Led to 1974 Nobel Prize for Martin Ryle.

Australia Telescope Compact Array

- Near Narrabri, Australia.
- Opened ???.
- Operated by ATNF.
- 6 dishes of 22-m diameter.
- 5 of the dishes can be moved along a 3-km track.

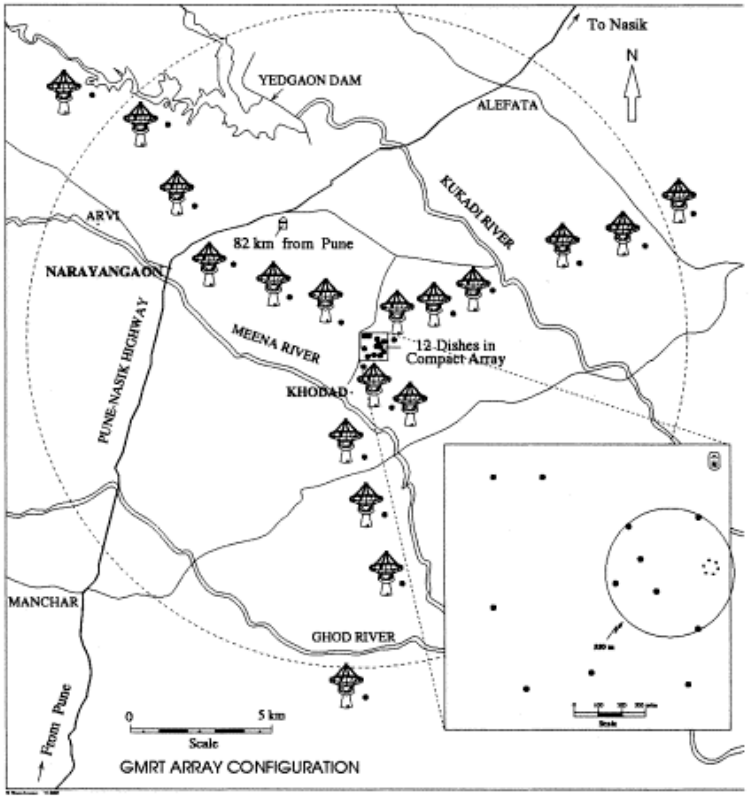
Westerbork

- Near Westerbork, the Netherlands.
- Opened in 1970.
- Premiere interferometer of its time.
- Operated by ASTRON.
- 14 dishes of 25-m diameter (two movable).
- Equatorially mounted.
- Maximum baseline 2.7km.
- East-West array (12hr for full synthesis).
- Covers 300MHz - 8GHz range.
- Resolution of ~0.5 arcsec at 1.4GHz.
- Being upgraded with "APERTIF".

Jansky Very Large Array

- Near Socorro, New Mexico.
- Opened ~1980 (and recently greatly refurbished).
- Operated by NRAO.
- 27 dishes of 25-m diameter.
- Maximum baseline of 36km.
- Covers 74MHz to 50GHz range.
- Dishes transported along rails.
- Can reach 0.05 arcsec resolution at 7mm (~42GHz).

Giant Meterwave Radio Telescope



- Near Pune, India.
- First light 1995.
- Operated by NCRA.
- Aperture synthesis interferometer.
- 30 dishes of 45-m diameter.
- Max baseline ~30km.
- Covers 50 - 1500MHz range.
- Can reach 1 arsec resolution at 1.4GHz.

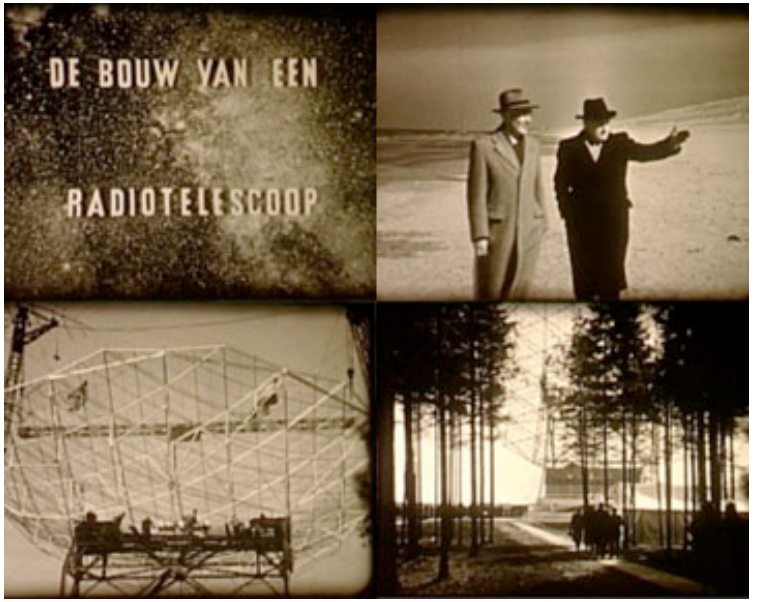
Low-Frequency Array

- Near Exloo, the Netherlands and spread across Europe.
- Opened 2011.
- Operated by ASTRON.
- Sparse digital "aperture array".
- Two types of antennas.
- Pointing achieved by delays in software.
- Covers 10-240MHz range.
- Up to 1 arcsec resolution.

Dwingeloo

- Near Dwingeloo, the Netherlands.
- Opened in 1956.
- 25-m dish (briefly the largest in the world).
- Mapped 21cm line emission in the Milky Way.
- Largest amateur radio telescope in the world (see "CAMRAS".
- Recently renovated.

Construction of Dwingeloo Telescope

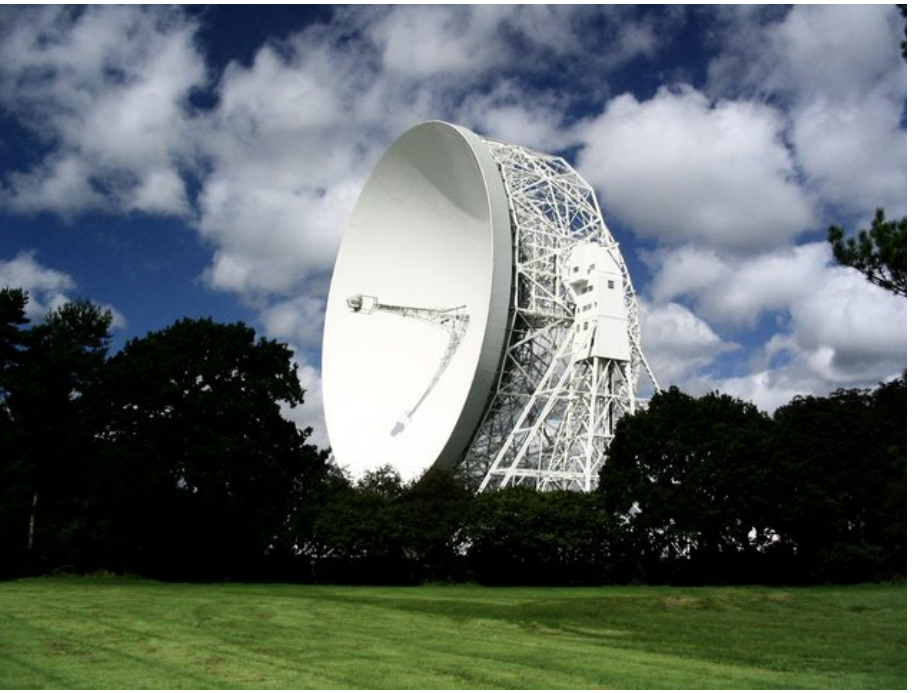


http://www.astron.nl/about-astron/history/footage/historic-footage

- Built by Nederlandse Spoorweg.
- Inaugurated by Koningin Juliana.

Lovell

(at Jodrell Bank Observatory)



- Near Manchester, UK.
- Opened 1957.
- Operated by University of Manchester.
- 76-m dish.
- Formerly the largest dish in the world.
- Covers mostly 1.3 - 1.6GHz range.
- Includes two 15-in bearings from WWII battleships.
- Resolution of 12 arcmin at 1.4GHz.

Parkes

- Near Parkes, Australia.
- Opened 1961.
- Operated by ATNF.
- Second largest dish in Sourth.
- 13-beam multibeam receiver at 1.4GHz.
- Discovered ~half the known pulsars.
- Small master equatorial in center of telescope.
- Covers primarily 0.6 - 3GHz range.
- Resolution of 15 arcmin at 1.4GHz.

Arecibo

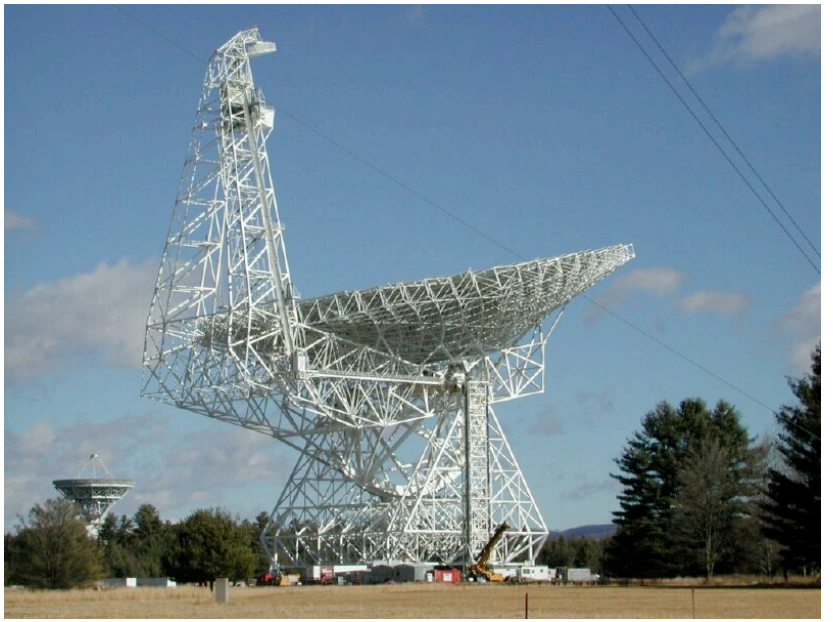
"William E. Gordon Telescope"

- Near Arecibo, Puerto Rico.
- Opened in 1963.
- Operated by NAIC.
- 305-m dish.
- Largest non-movable dish in the world.
- Built in a natural karst depression.
- Observe -2 deg < Dec < +38deg.
- Resolution of 3 arcmin at 1.4GHz.

Effelsberg

- Near Effelsberg, Germany.
- Opened 1972.
- Operated by MPIfR.
- 100-m dish.
- Largest in world for 29 years.
- Paraboloid deforms in different positions.
- Angular resolution is 10 arcmin at 1.4GHz.

Green Bank



- Near Green Bank, West Virginia.
- First light 2000.
- Operated by NRAO.
- 100x110m dish.
- Offset feed cabinet.
- Largest steerable dish (and largest man-made movable object on land).
- "Active surface".
- Covers 300MHz - 80GHz range.
- Can see ~3/4 of the sky (down to Dec = -40 deg).

The current landscape

The Culture of Radio Astronomy

- "Do it yourself" attitude still very present (both good and bad).
- Less "accessible" compared with other wavebands?
- Moving from more and more from small experiments to major facilities.
- The Square Kilometer Array will change both the science and the culture of radio astronomy.

Major Institutes

- NRAO: National Radio Astronomy Observatory
- ATNF: Australia Telescope National Facility
- ASTRON: Netherlands Institute for Radio Astronomy
- MPIfR: Max Planck Institute for Radio Astronomy
- NCRA: National Center for Radio Astronomy

URSI

Union Radio-Scientifique Internationale / International Union of Radio Science

- Commission J is "Radio Astronomy.
- Activities to protect radio-astronomical observations from interference.

Sources

NRAO: http://www.nrao.edu/index.php/learn/radioastronomy/radioastronomyhistory

Wikipedia: http://en.wikipedia.org/wiki/Radio_astronomy

Other course slides (see links on course wiki page):

http://www.astron.nl/astrowiki/doku.php?id=uva_msc_radioastronomy_2013

Questions?