Lectures on radio astronomy: 1

Richard Strom
NAOC, ASTRON and
University of Amsterdam

Introduction, history and some astronomy

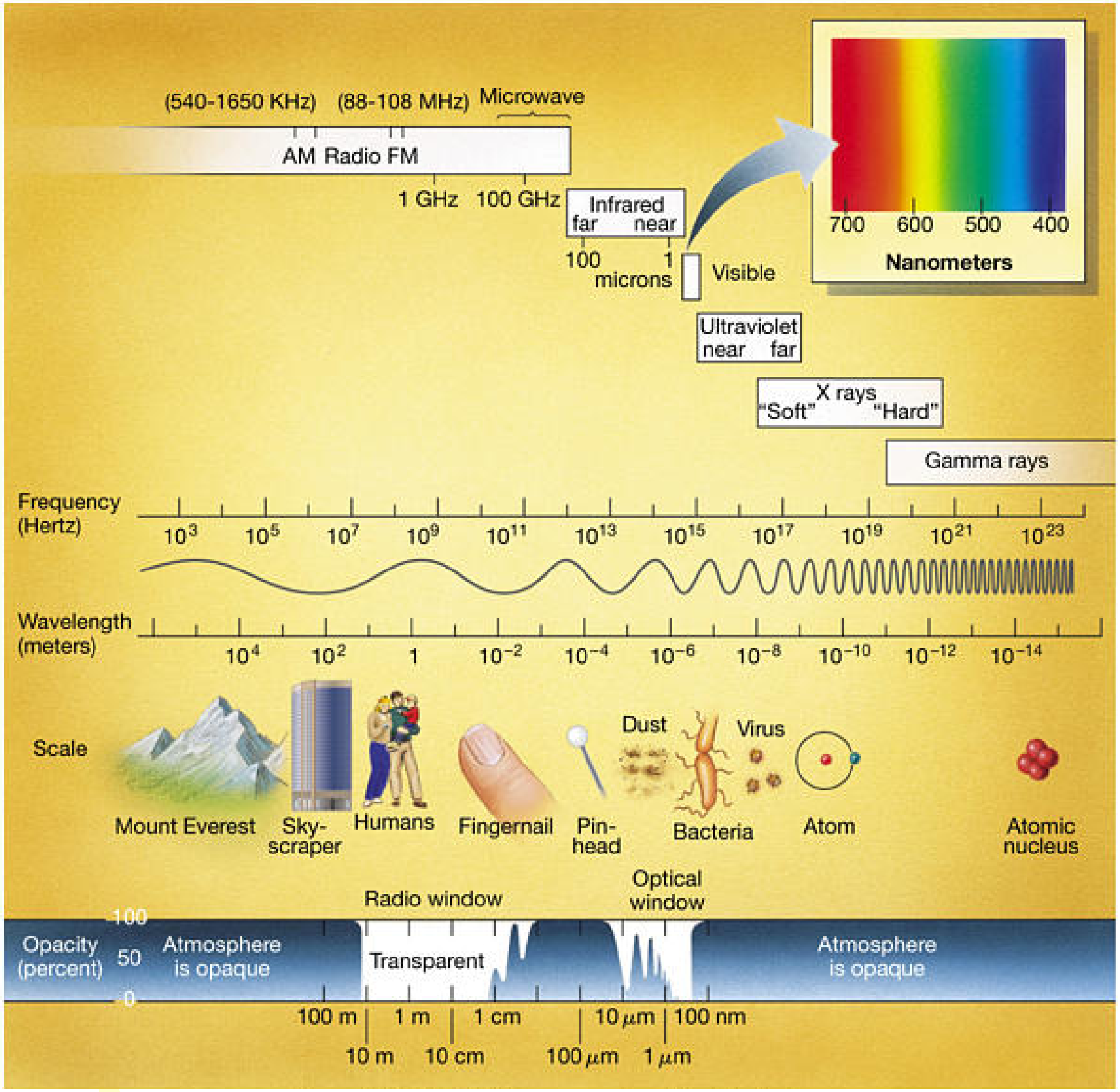
Lecture summary

1. Introduction to radio astronomy; history, examples of research
2. Single element radio telescopes; description, what they measure, data reduction
3. Interferometers: how they work, calibration and data reduction
4. Frontiers of radio astronomy and technology

What I hope you will learn from these lectures

- Some of the astrophysics involved in radio astronomy
- How radio telescopes work, what they measure.
- How to determine basic parameters (resolution, sensitivity).
- Why there are different kinds of radio telescope, what their advantages and disadvantages are.

Only optical and radio waves pass through the atmosphere



Radio astronomy:
$\lambda \geq 1$ cm

James Clerk Maxwell laid the foundations (4 “laws”)

Maxwell's equations

1. $\nabla \cdot \boldsymbol{E} = 4\pi\rho$

2. $\nabla \times \boldsymbol{E} = -\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t}$

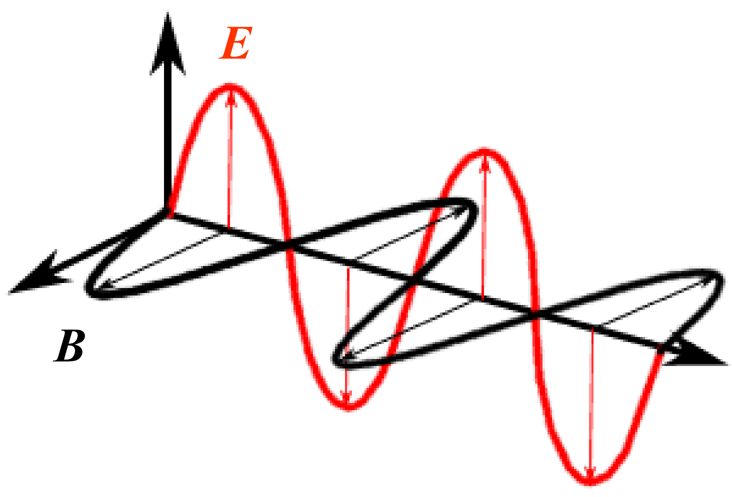
3. $\nabla \cdot \boldsymbol{B} = 0$

4. $\nabla \times \boldsymbol{B} = \frac{4\pi \boldsymbol{J}}{c} + \frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t}$

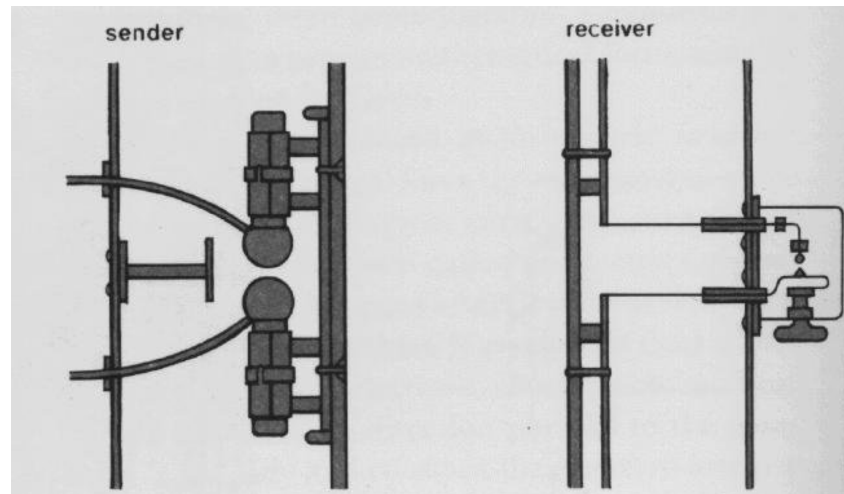
A solution to Maxwell’s equations is a wave

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

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



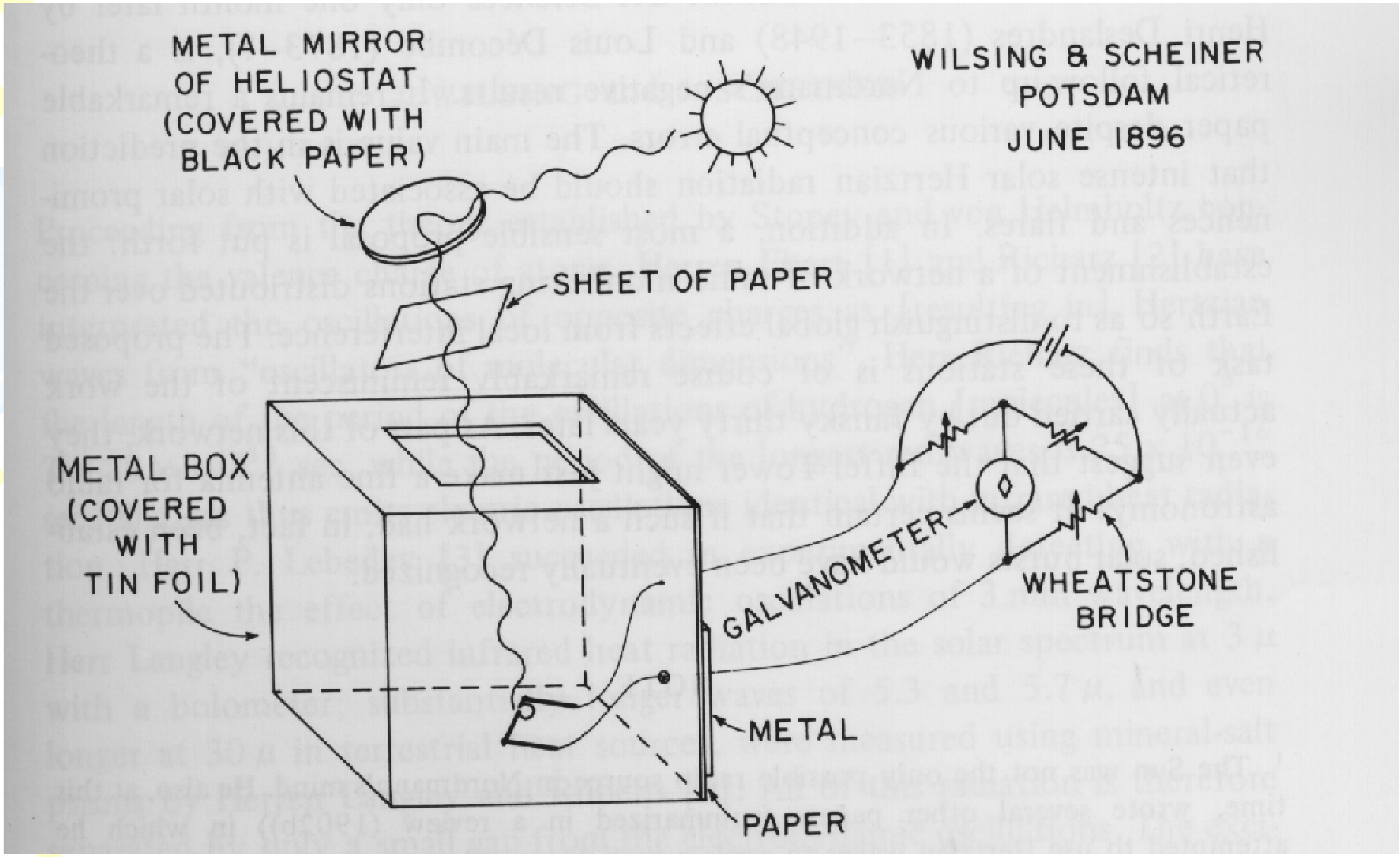
Heinrich Hertz carried out early experiments



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 wave-length from those of visible light. Above are his oscillator, or sender, and his resonator, or receiver.

Marconi was a pioneer in radio communication

Early "radio astronomy" experiment: Wilsschein



1900: experiment by Nordman – Mont Blanc

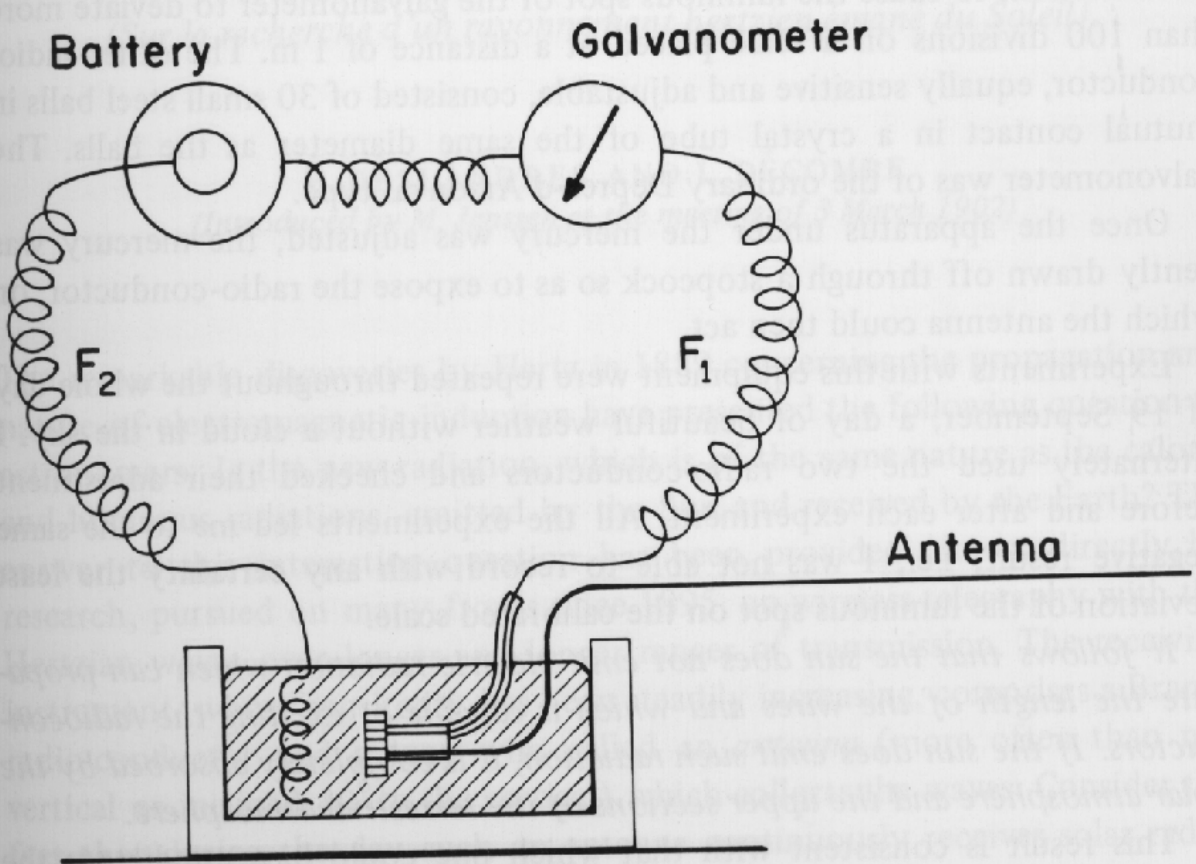
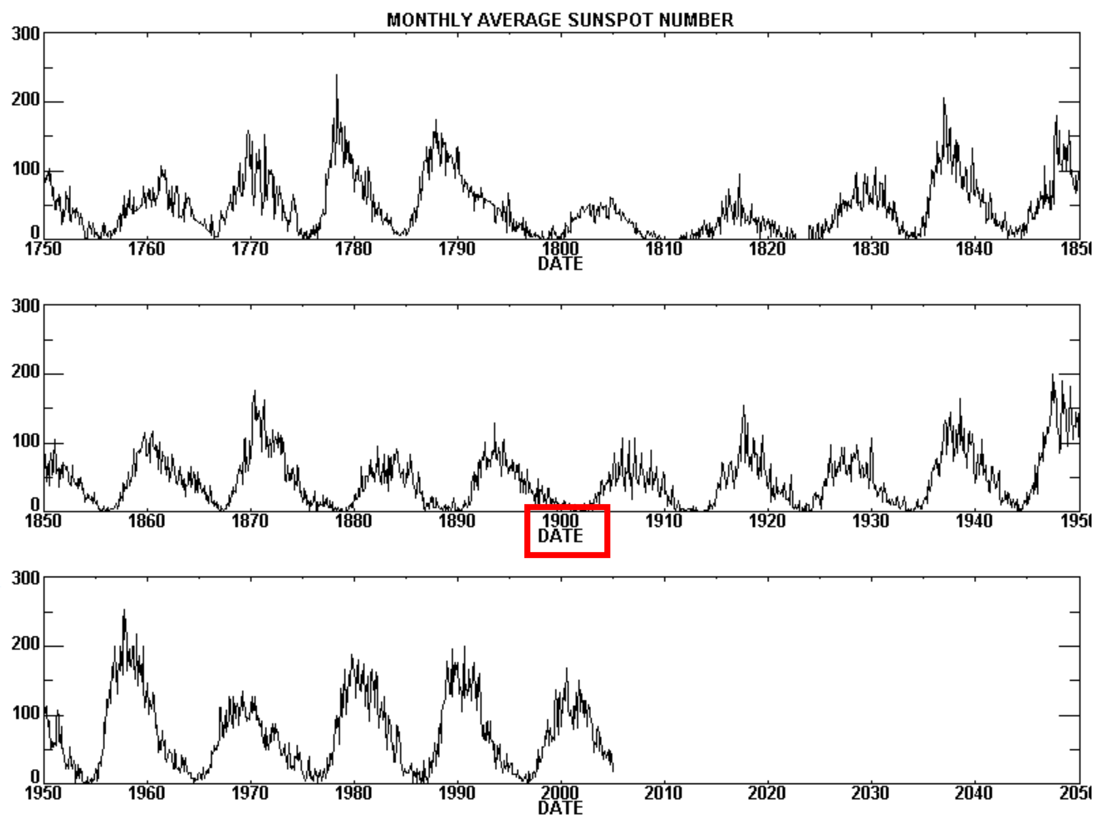


Fig. 1

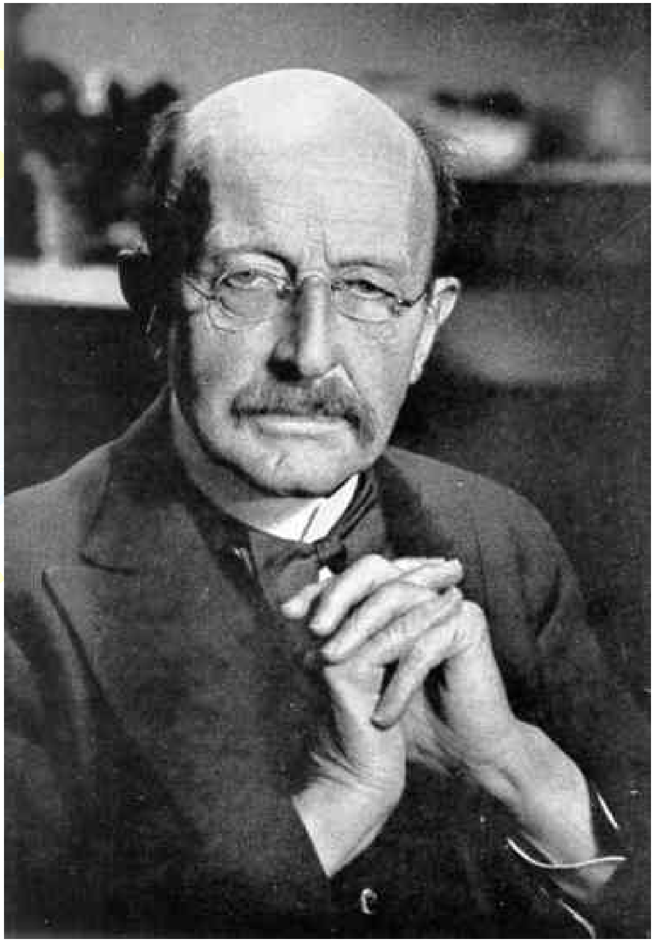
Nordman might have found a signal in a different year: bad luck, or…?

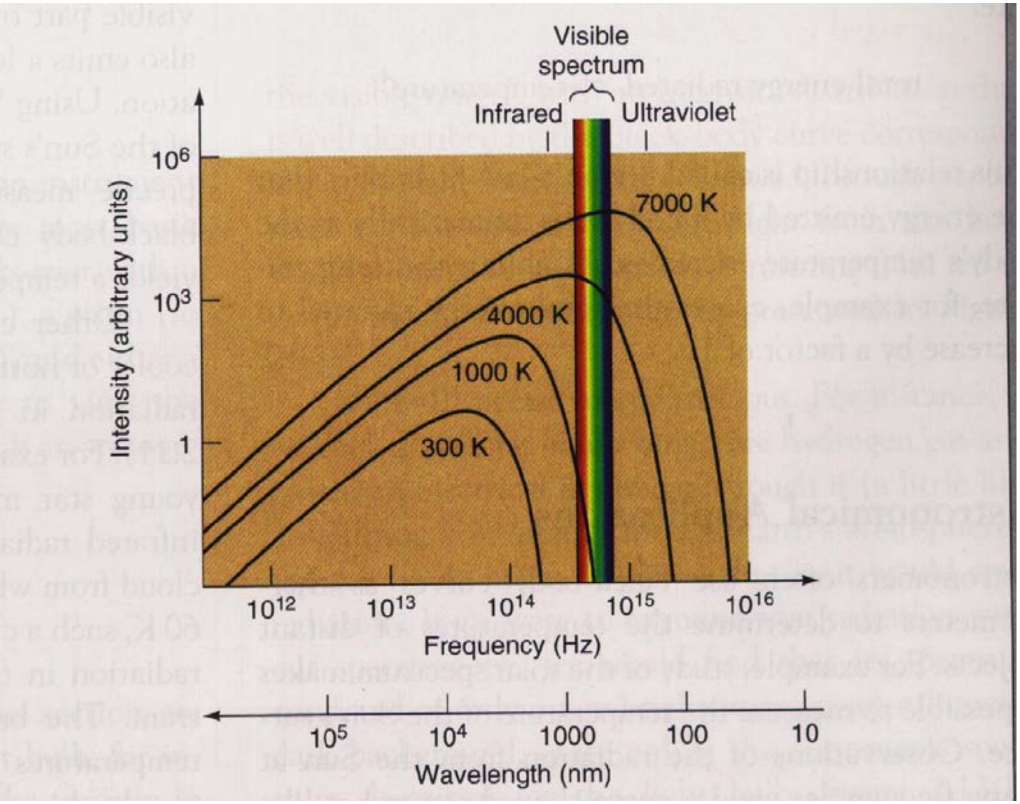


These early detection attempts were unsuccessful

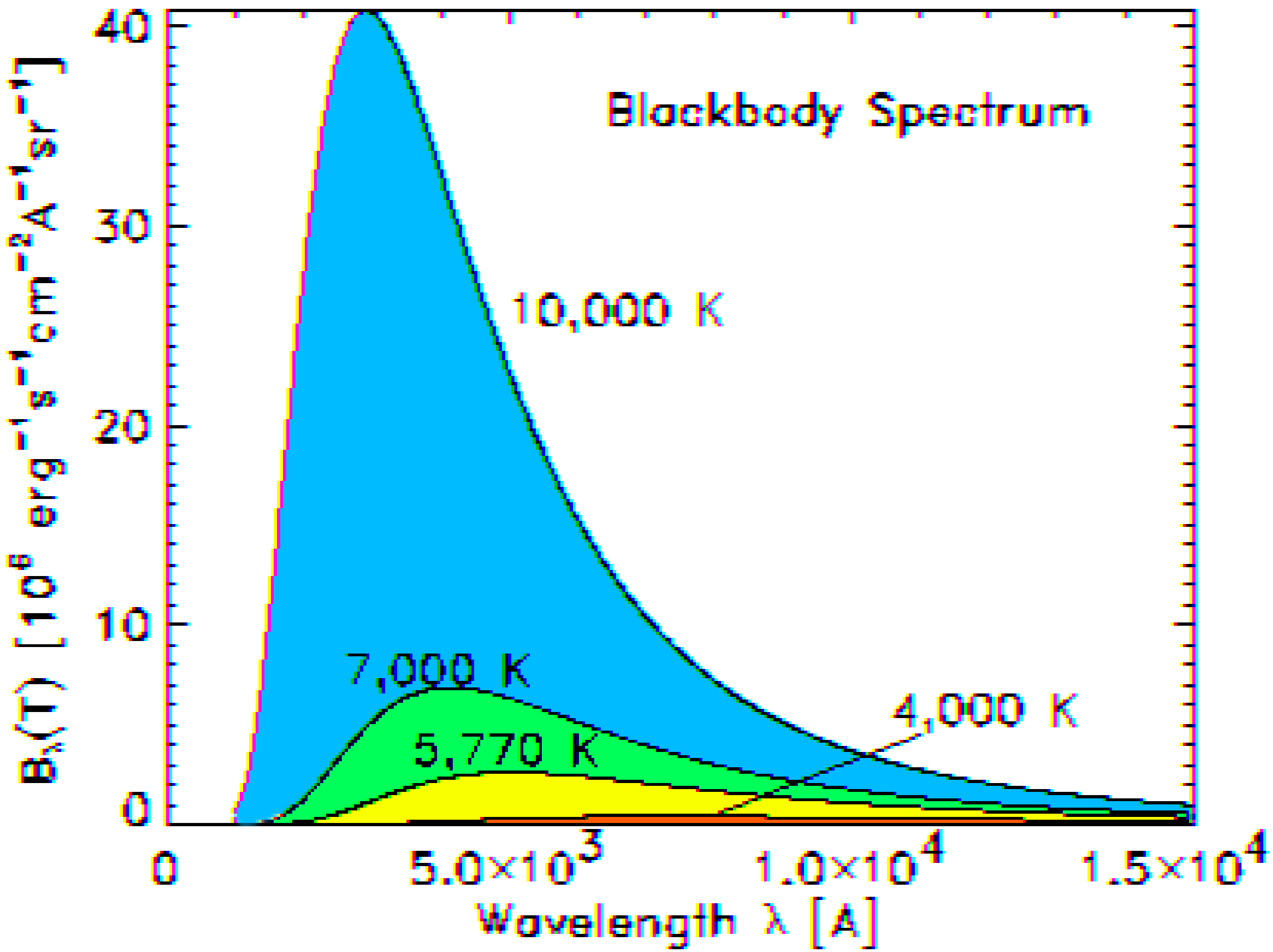
- It is felt that Wilsing & Scheiner’s equipment wasn’t sensitive enough
- Nordman’s set-up probably could have detected bursts from the active Sun
- However, 1900 was near the minimum of the 11-year sunspot cycle, so the Sun was not active
- He should have tried a few years later!

Max Planck and black body radiation





Radiation from black bodies of different temperature



The formula which Planck derived

Planck: $B = \frac{2h\nu^3}{c^2}\left(e^{h\nu/kT} - 1\right)^{-1}$ $W\,m^{-2}Hz^{-1}sr^{-1}$

Stefan-Boltzmann: $B_t = \int B\,d\nu = \sigma T^4$ $W\,m^{-2}sr^{-1}$

$\sigma = 5.7\times10^{-8}\,W\,m^{-2}K^{-1}$

Wien: $\nu_m \propto T$

Rayleigh-Jeans: $h\nu \ll kT$ ("radio")

$\left[e^{h\nu/kT} \simeq 1 + \frac{h\nu}{kT}\right] \Rightarrow B \simeq \frac{2h\nu^3}{c^2}\frac{kT}{h\nu}$

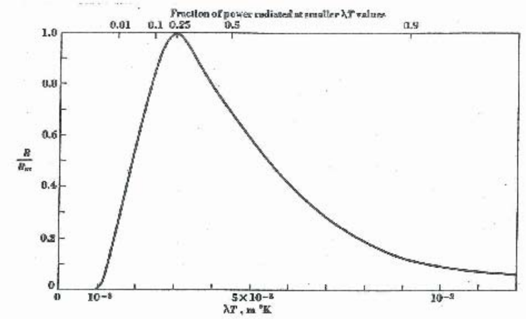
$= \frac{2\nu^2 kT}{c^2} = \frac{2kT}{\lambda^2}$

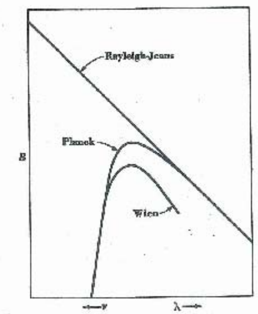
$(\lambda\nu = c)$

Wien: $h\nu \gg kT$ ("niet radio")

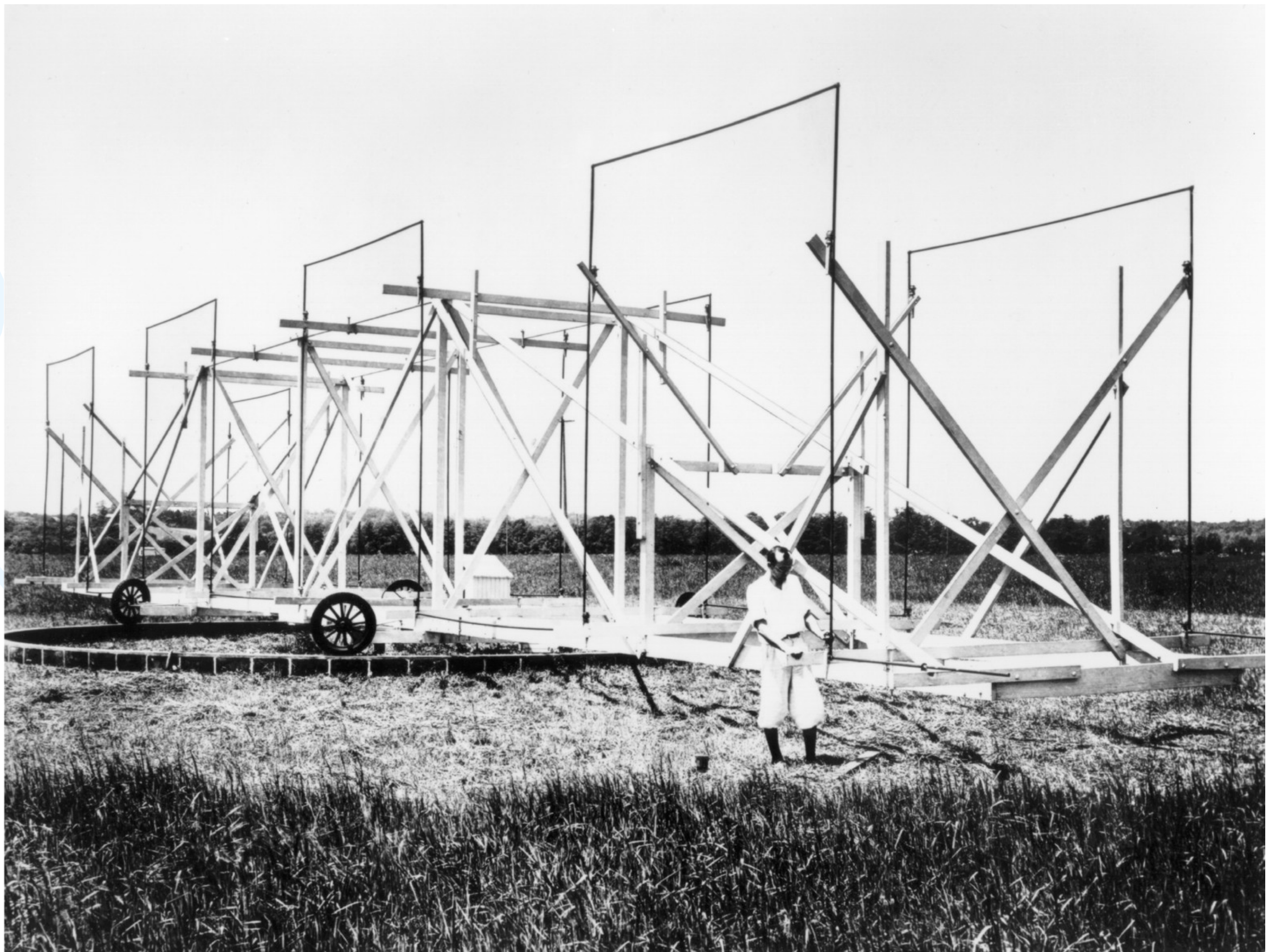
$\left[e^{h\nu/kT} - 1 \simeq e^{h\nu/kT}\right] \Rightarrow B \simeq \frac{2h\nu^3}{c^2}e^{-h\nu/kT}$

$S = \int B\,d\Omega = \frac{2kT\Omega}{\lambda^2}$

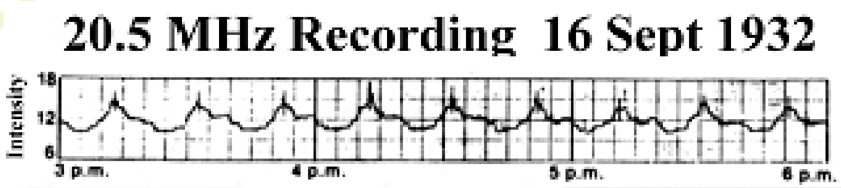


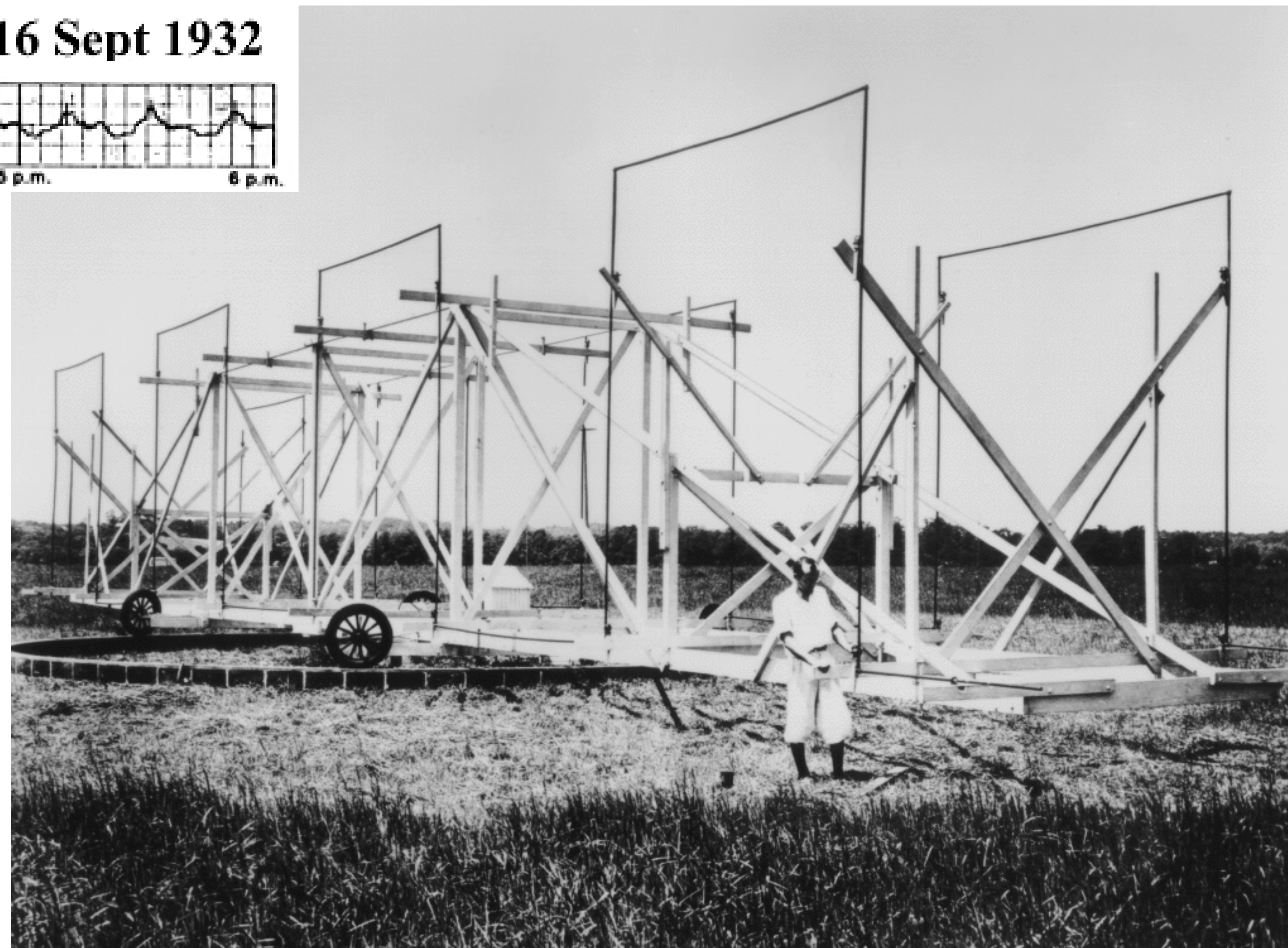


The first successful radio telescope: Jansky, 1930



1930-32: Karl Jansky investigates radio noise





Portrait of Jansky and antenna

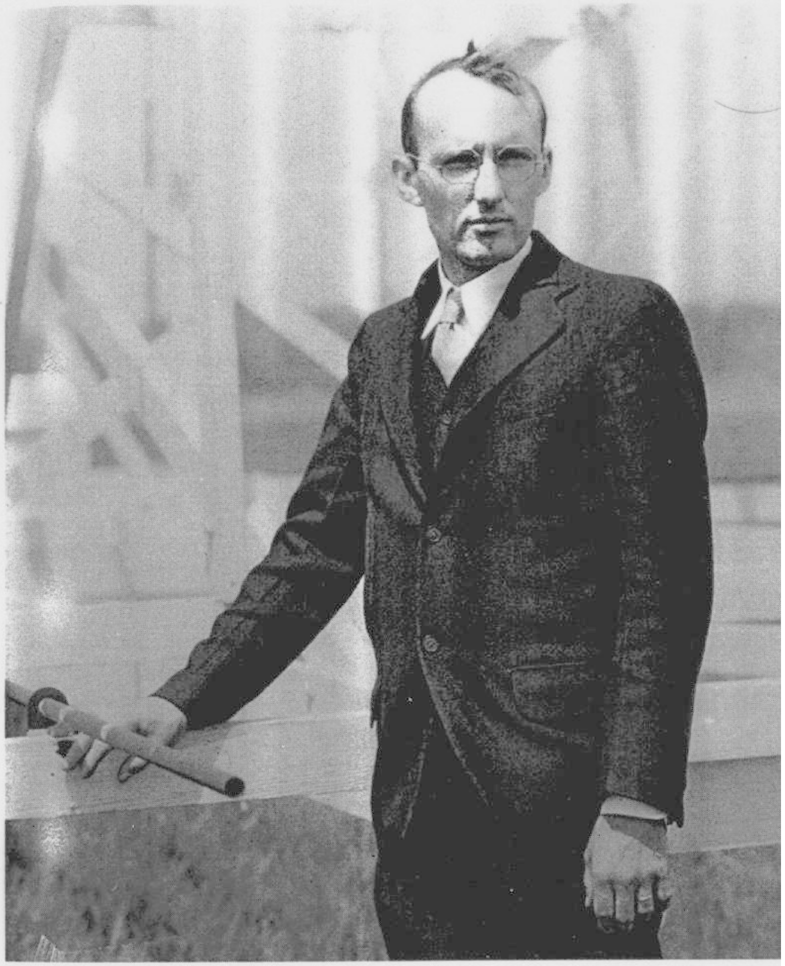
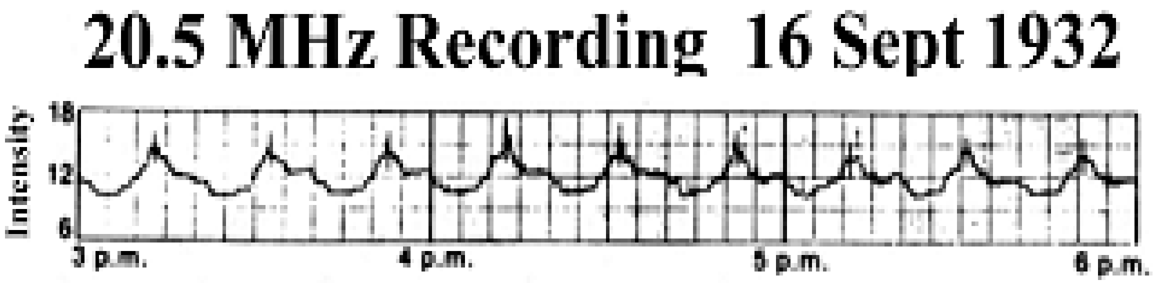


FIG. 1—Karl Guthe Jansky, about 1933.

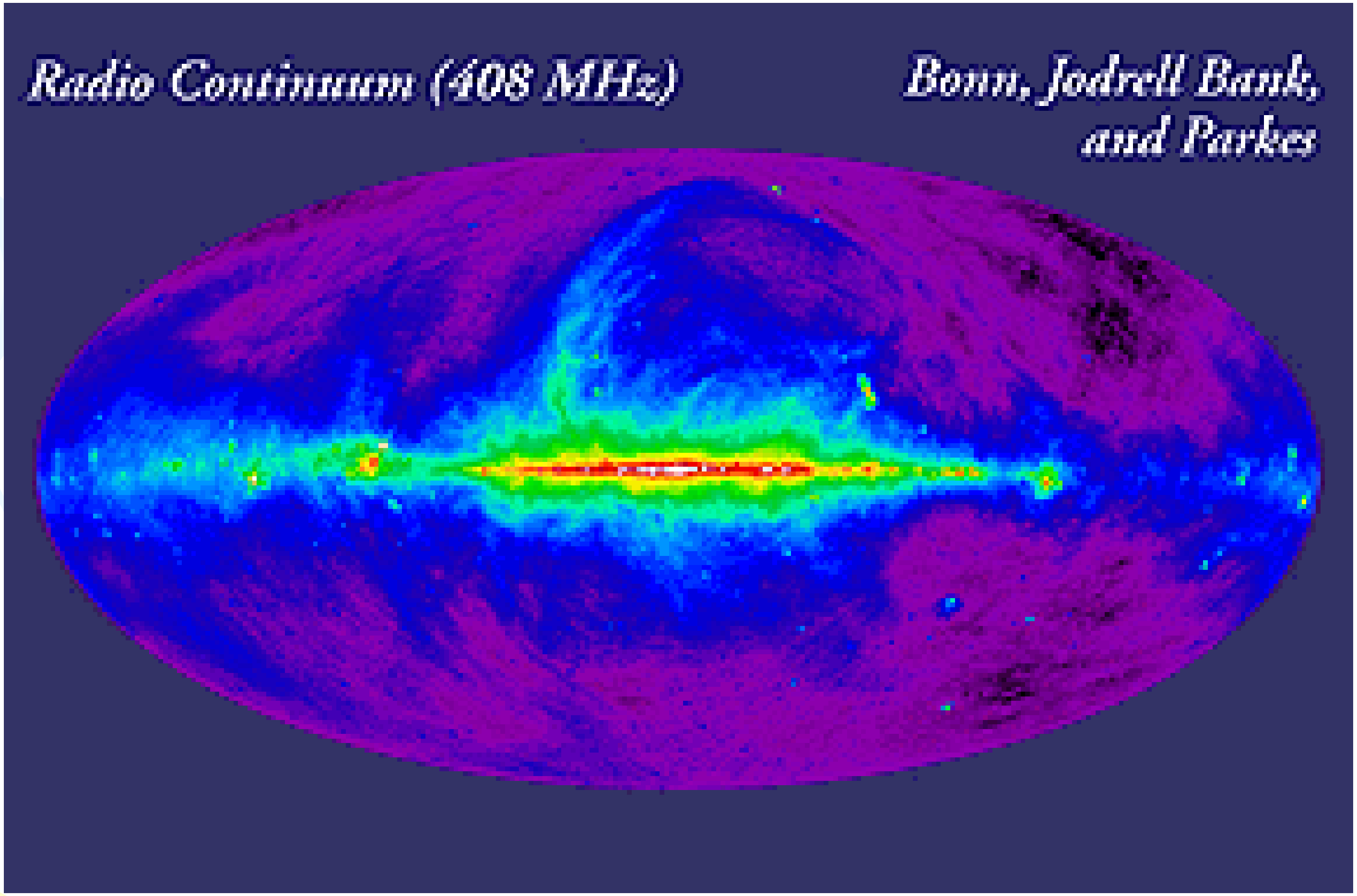
- Jansky worked for Bell Labs, who wanted to use radio for communication
- He was asked to look for radio background signals
- The background would affect quality
- He found different kinds of radio background, like from thunderstorms

There was one kind of interference always present



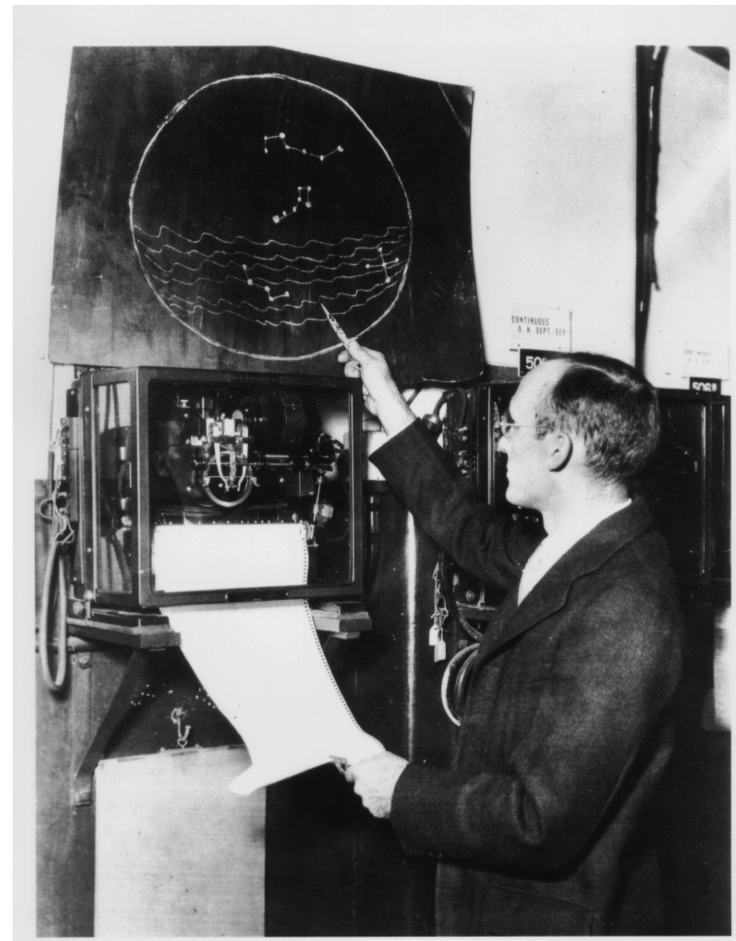
- In earphones, it was a steady hiss, pure noise
- Yet it was stronger in some directions; Jansky first thought it might be from the Sun
- But its location slowly shifted, by 4 minutes a day
- It moved with the stars, and was strongest in Sagittarius, where the center of the Milky Way is

Strongest emission came from Galaxy center



Jansky's discovery did get publicity

- He published several papers in scientific technical journals
- Did get some attention from astronomers
- But plans for a larger antenna not supported
- Article on front page of the New York Times, 1933



The New York Times

NEW RADIO WAVES TRACED TO CENTRE OF THE MILKY WAY

Mysterious Static, Reported by K.G. Jansky, Held to Differ From Cosmic Ray

Holmdel, New Jersey, May 5, 1933, Friday

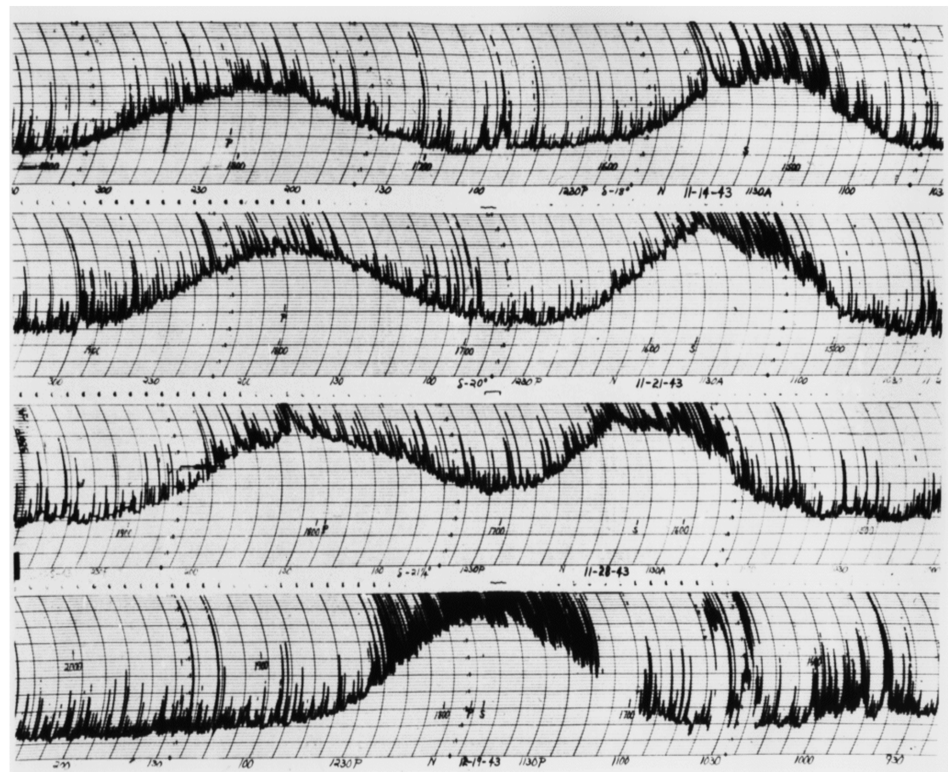
Discovery of mysterious radio waves which appear to come from the centre of the Milky Way galaxy was announced yesterday by the Bell Telephone Laboratories. The discovery was made during research studies on static by Karl G. Jansky of the radio research department at Holmdel, N.J., and was described by him in a paper delivered before the International Scientific Radio Union in Washington.

Consider, for a moment, Jansky's telescope

- Observing frequency near 20 MHz
- This means wavelength = 14.6 m
- His antenna was some 30.5 m long
- Angular resolution is, $\theta \approx \lambda/D$:
  - This is in the horizontal direction, the beam was actually like a fan
  - $\theta \approx 14.6/30.5 = 0.48$ rad $\approx 26^o$

Grote Reber: first radio astronomer (engineer and radio amateur)

Reber's telescope (in the backyard!) and results



Contour maps showing emission from Milky Way

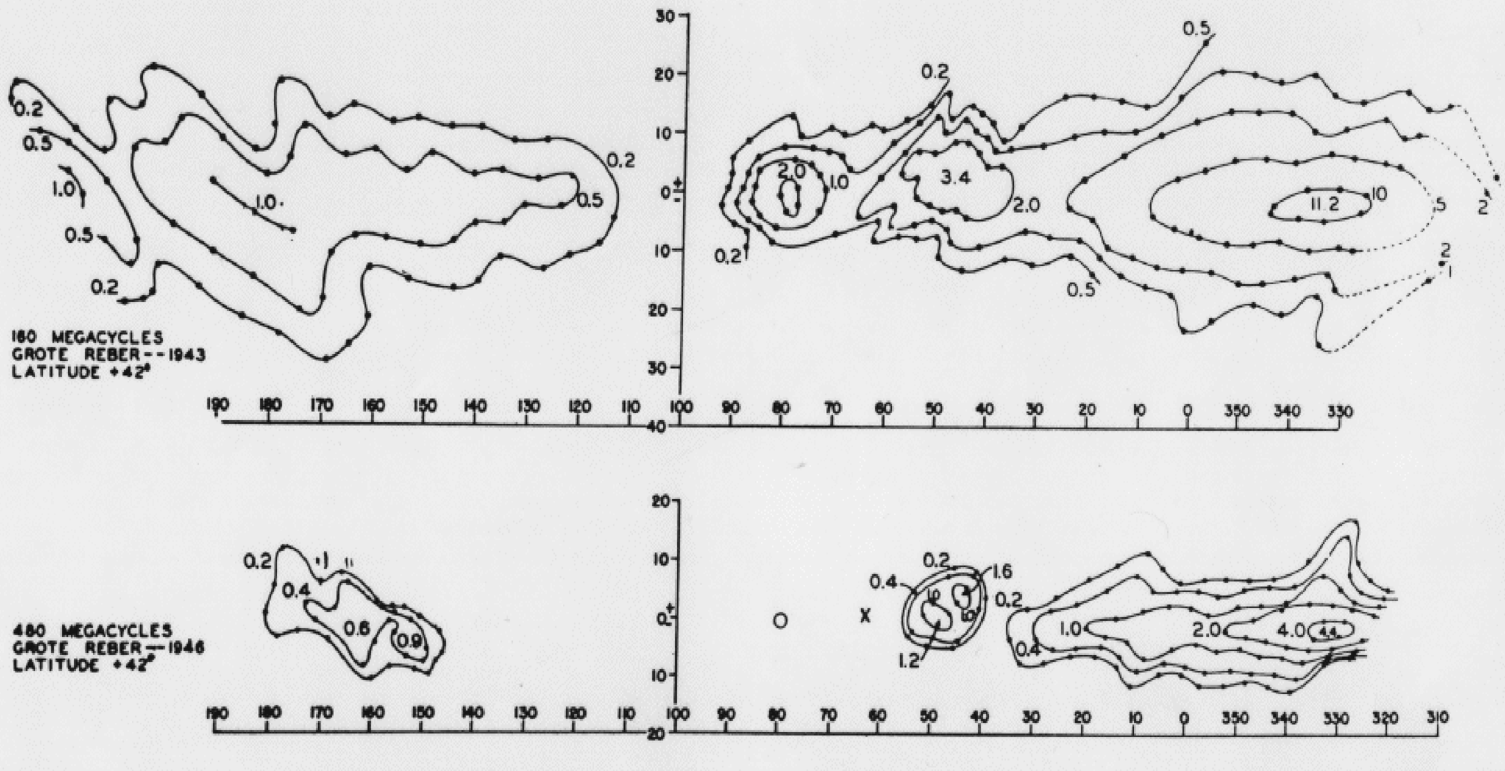


FIG. 7—Contours of constant intensity at 160 MHz and 480 MHz, taken at Wheaton, Illinois.

Let's look at Reber's telescope

- Observing frequency of 160 MHz
- This means wavelength = 1.9 m
- His antenna was about 9.6 m in diameter
- Angular resolution is, $\theta \approx \lambda/D$:
  - Reber's beam was circular like his dish
  - $\theta \approx 1.9/9.6 = 0.2$ rad $\approx 11^{o}$

Jan Oort first heard about radio from Reber's work in 1940

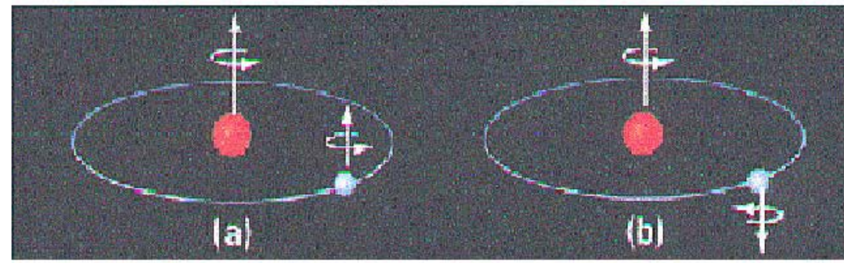
- Oort had shown that the Milky Way rotated around its nucleus in Sagittarius
- He was greatly interested in studying the central part of the Milky Way
- Practically all of the light from stars far away was blocked by dust

Jan Hendrik Oort, c. 1935

The Milky Way showing dust in the direction of the center

In 1944, Oort asked young student, Henk van de Hulst, to investigate

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*)

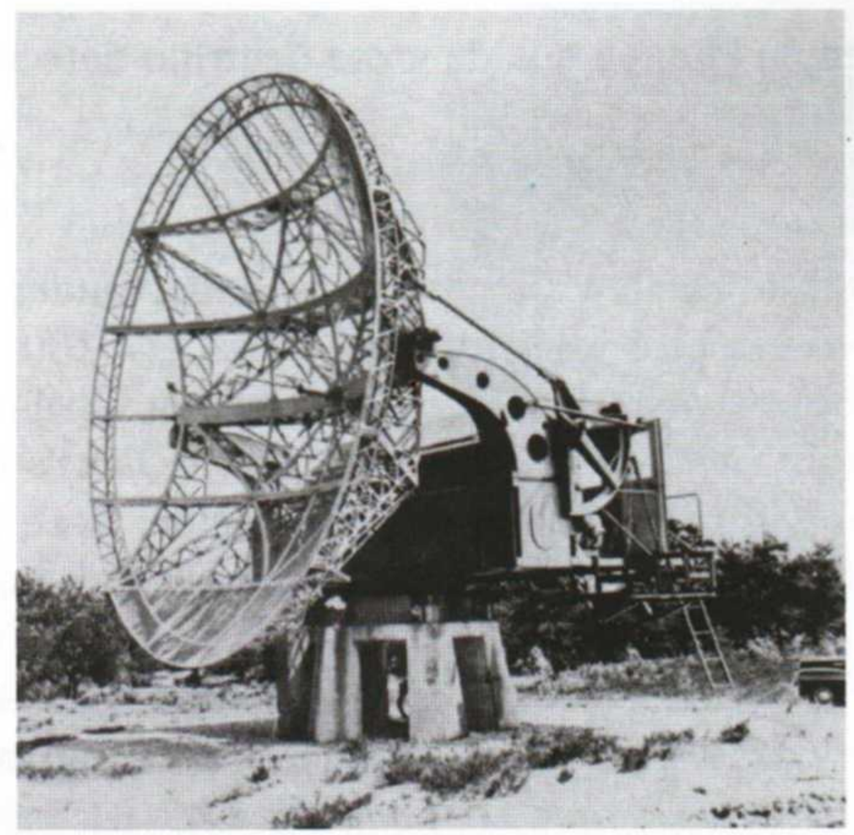


HYPERFINE STRUCTURE OF THE GROUND STATE

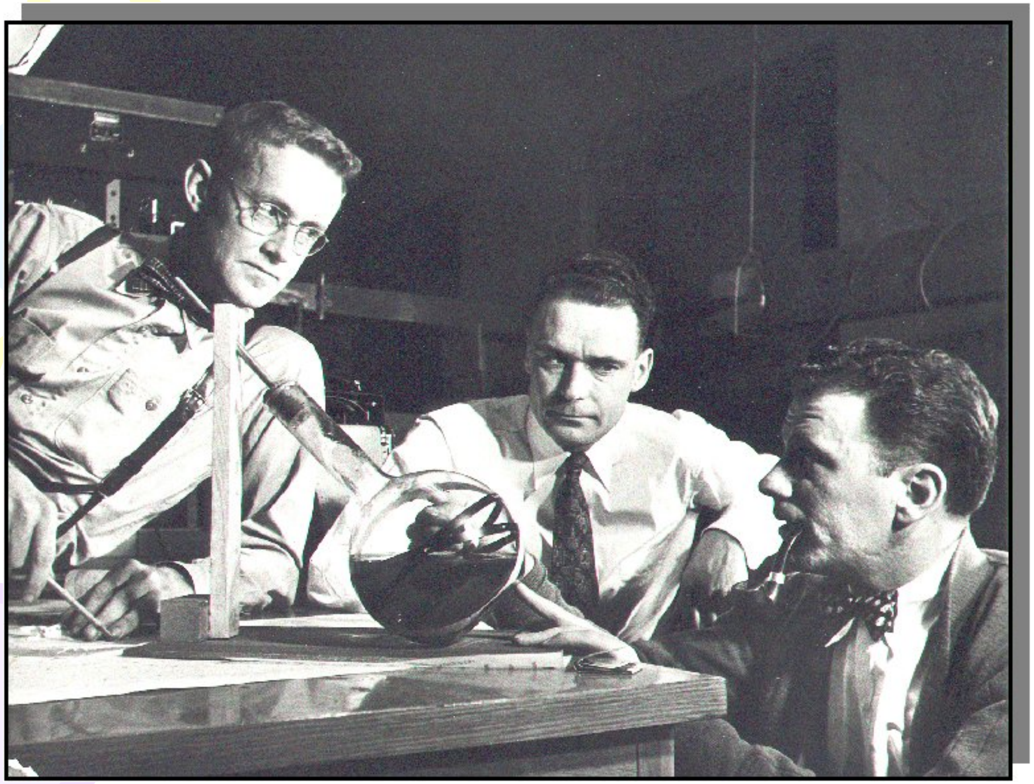
- Van de Hulst's main result was prediction that the hydrogen line at 21 cm might be observable
- Meeting of Dutch astronomy society in 1944

Oort was very keen to pursue observations of the 21 cm HI line

- Nothing could be done before end of war
- Few radio engineers in Netherlands after war
- Oort had difficulty getting funding, finding right people
- Early observations with German radar antenna



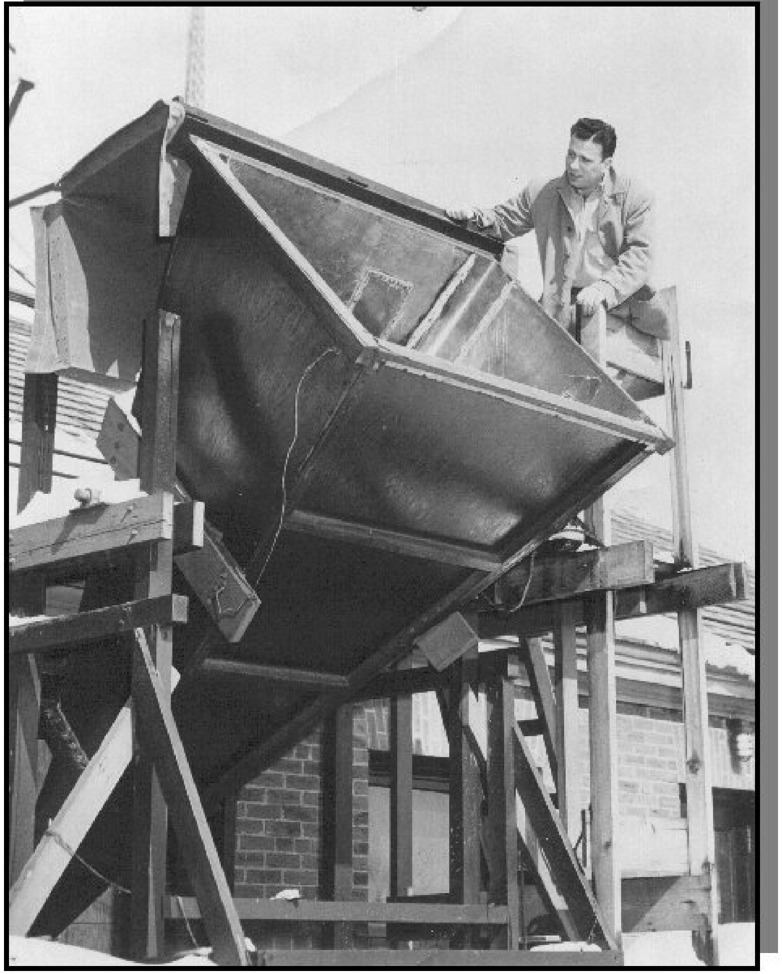
At Harvard there was interest, and the right people



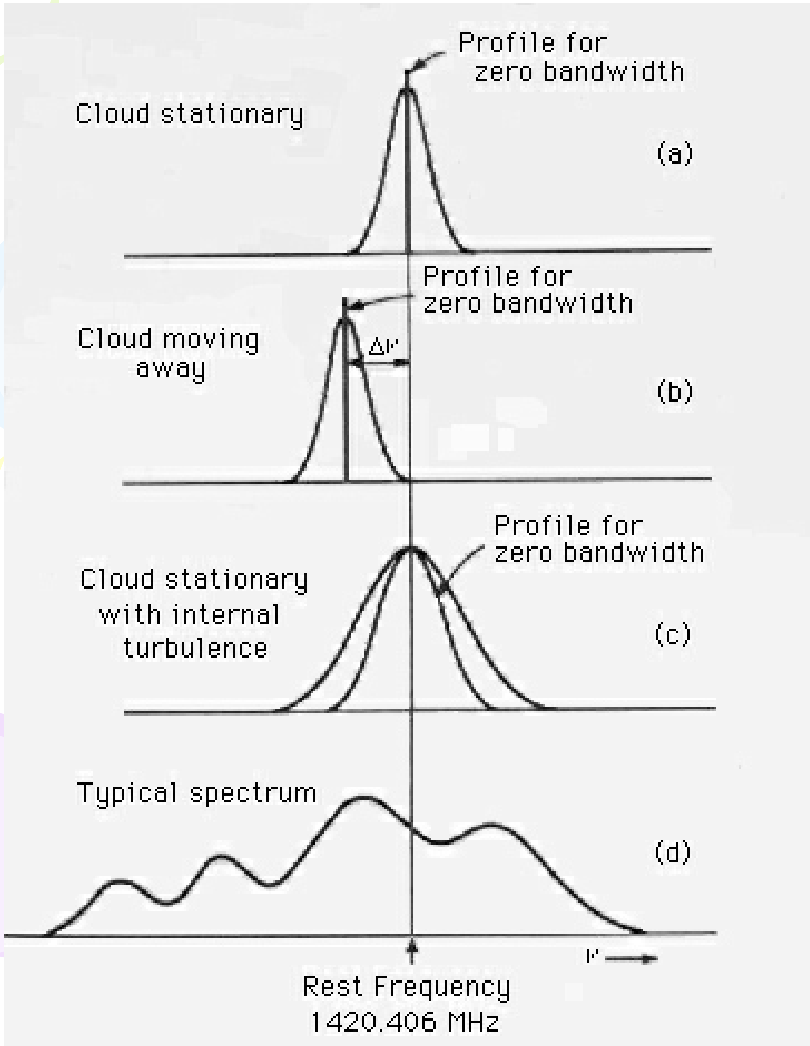
- Purcell (left) and Ewen (center) had the expertise
- Ewen built radio antenna, receiver – main problem was stability
- It was for Ewen’s PhD thesis

The antenna was a simple horn

- A large antenna wasn't needed
- The local hydrogen should be all around us, so the signal would come from all directions
- Earth's rotation would point it to different directions
- Detection in March 1951



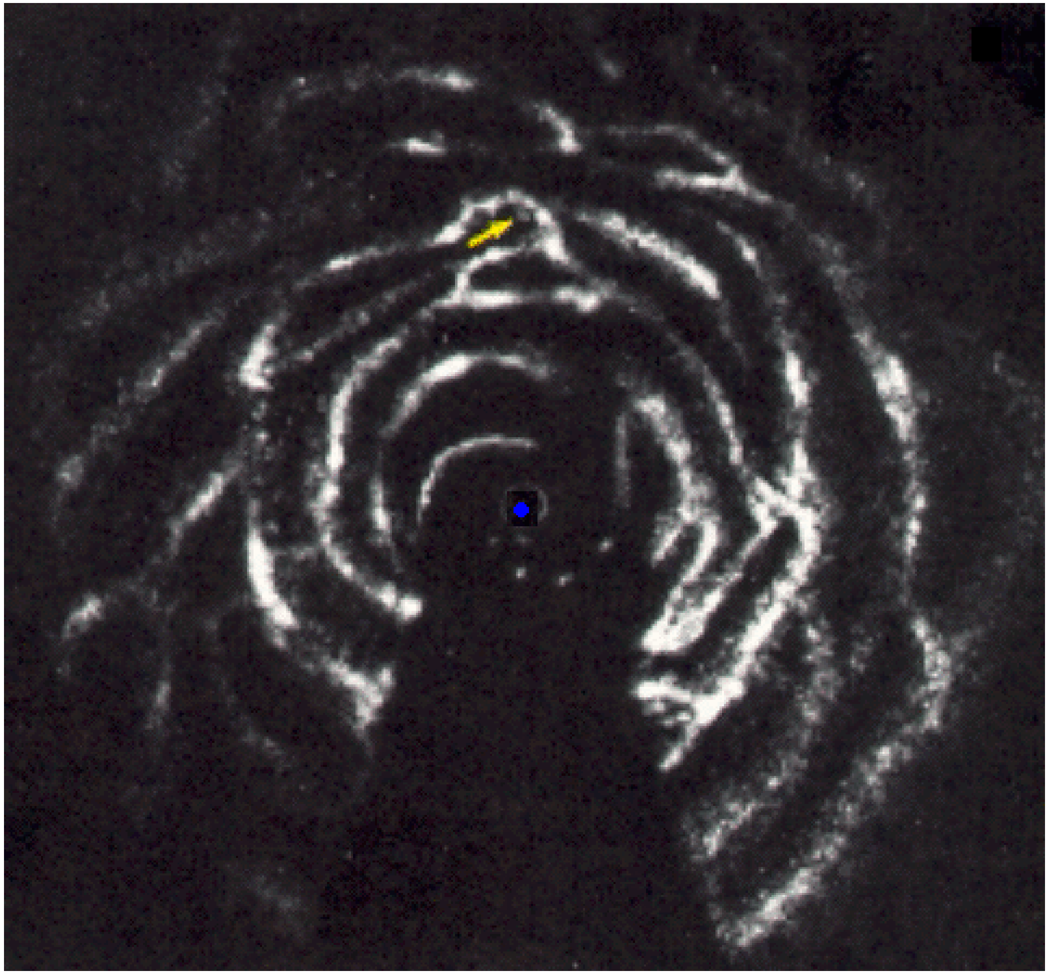
A detection in the Netherlands followed 6 weeks later



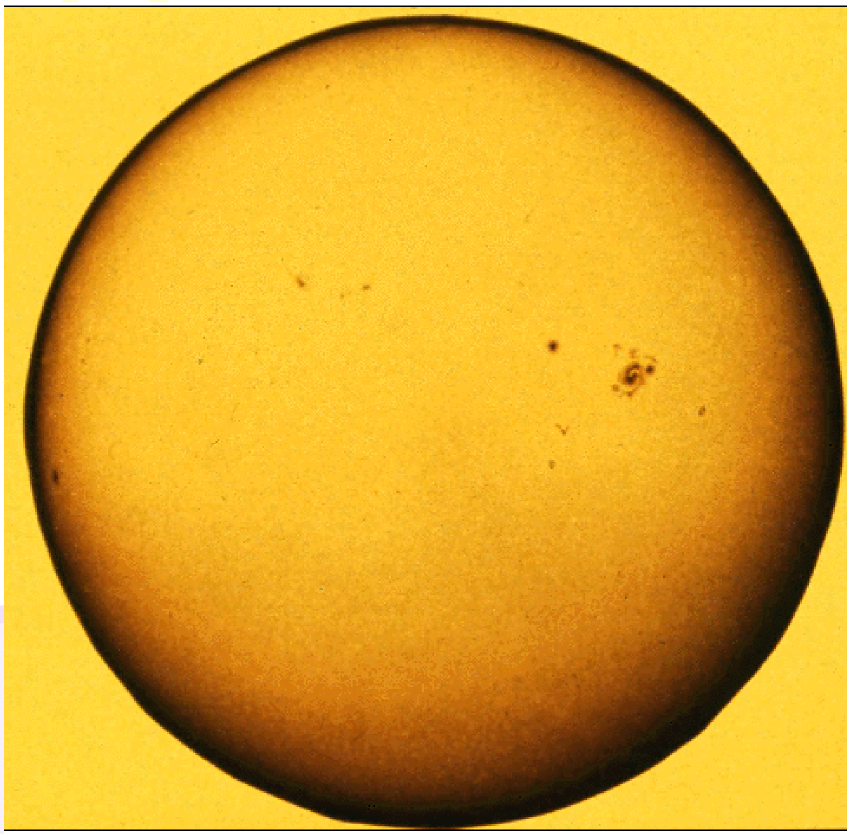
- Ewen & Purcell were interested in physics
- Oort & Muller, the engineer who built the Dutch equipment, wanted to do astronomy
- Here are examples of what the hydrogen profiles look like

From early observations, a map could be constructed

- Peaks in the spectrum were assigned to the spiral arms
- Needed model for distance
- This combines Dutch and Australian data for Milky Way

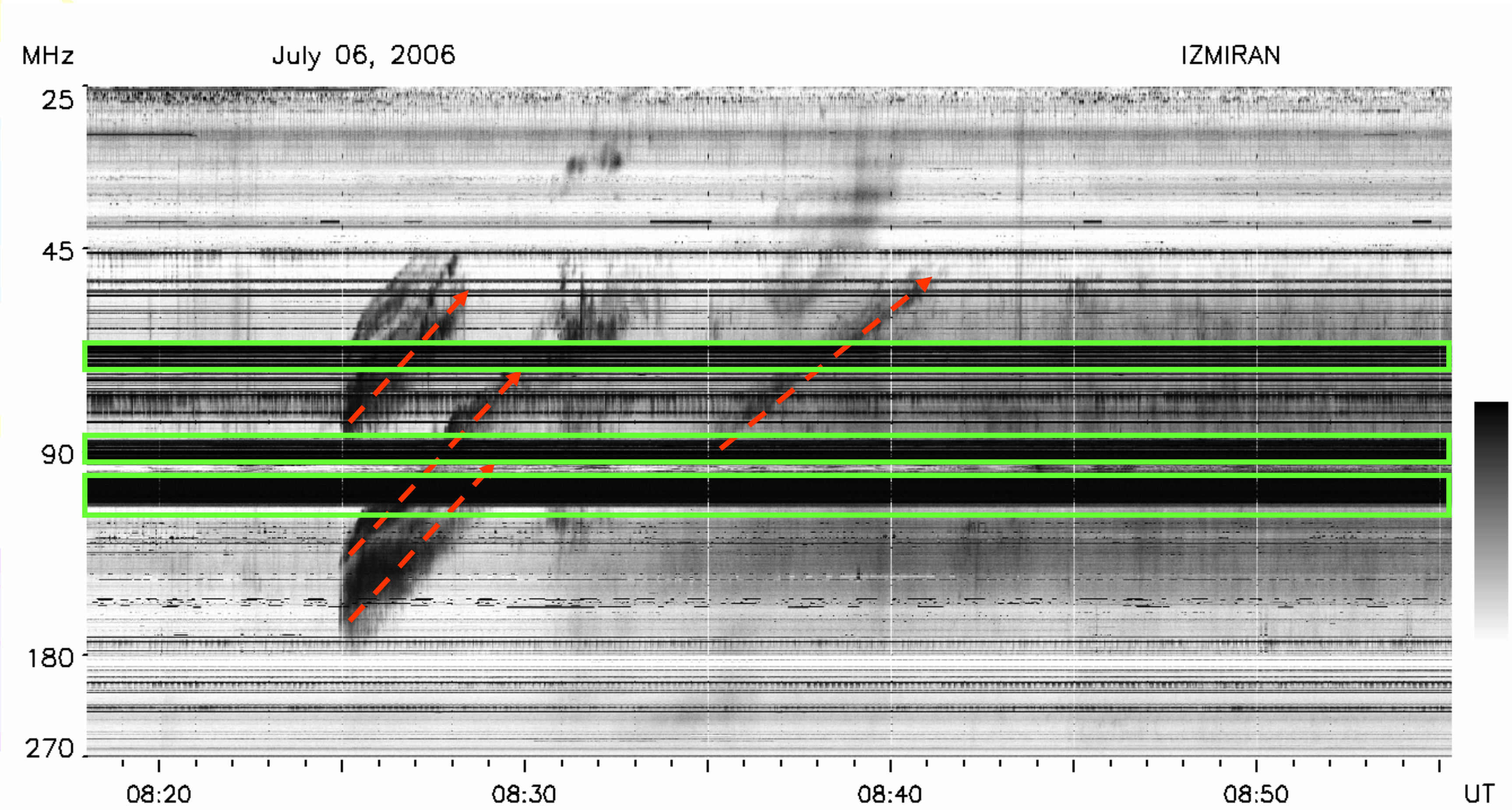


Meanwhile, during the war, radar antennas had picked up interference

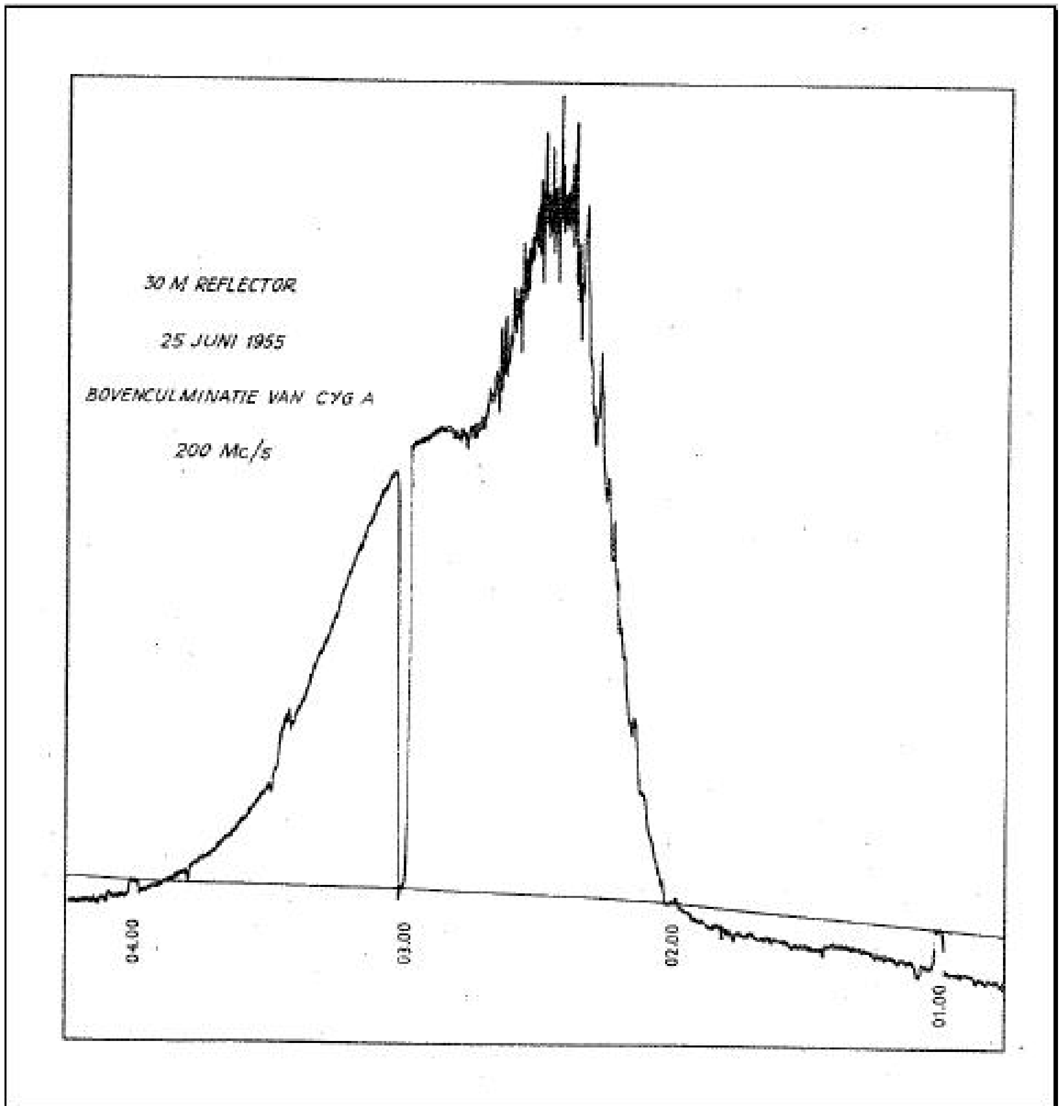


- English thought radar jammed by Germans
- J.S. Hey investigated: worst in morning, large sunspot group visible
- Conclusion: Sun was producing emission
- It was kept secret, only published after the war
- Reber also detected Sun

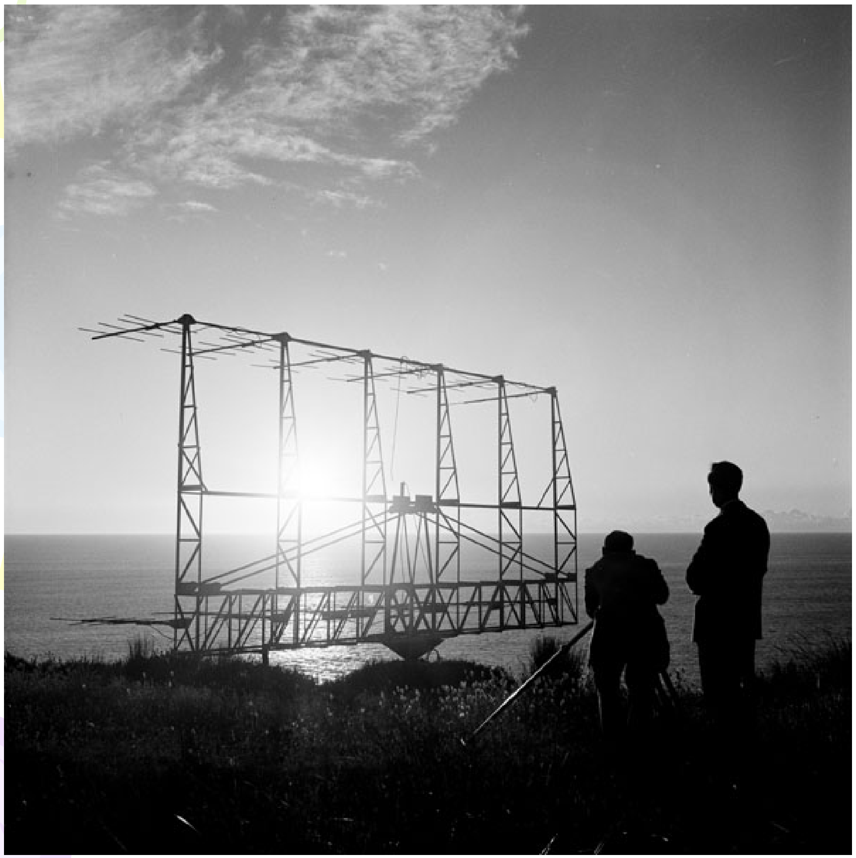
Solar radio storms: quite common (but manmade interference then and now a problem)

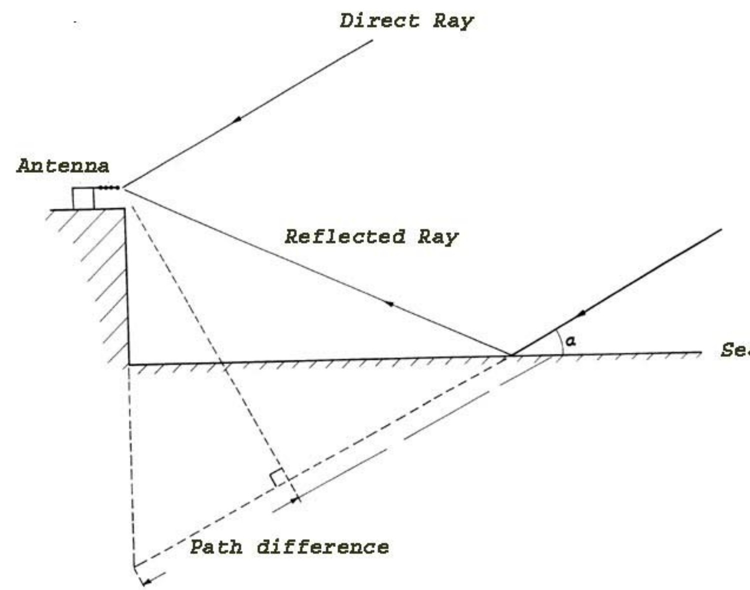


Ionospheric scintillation ⇨ some sources compact

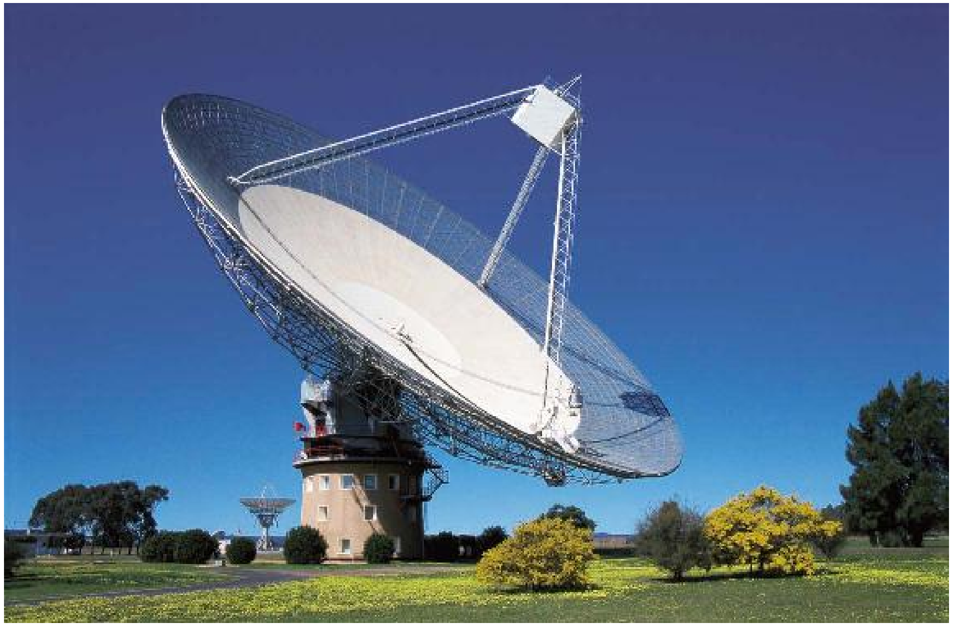


Clever ideas were used: cliff top interferometer

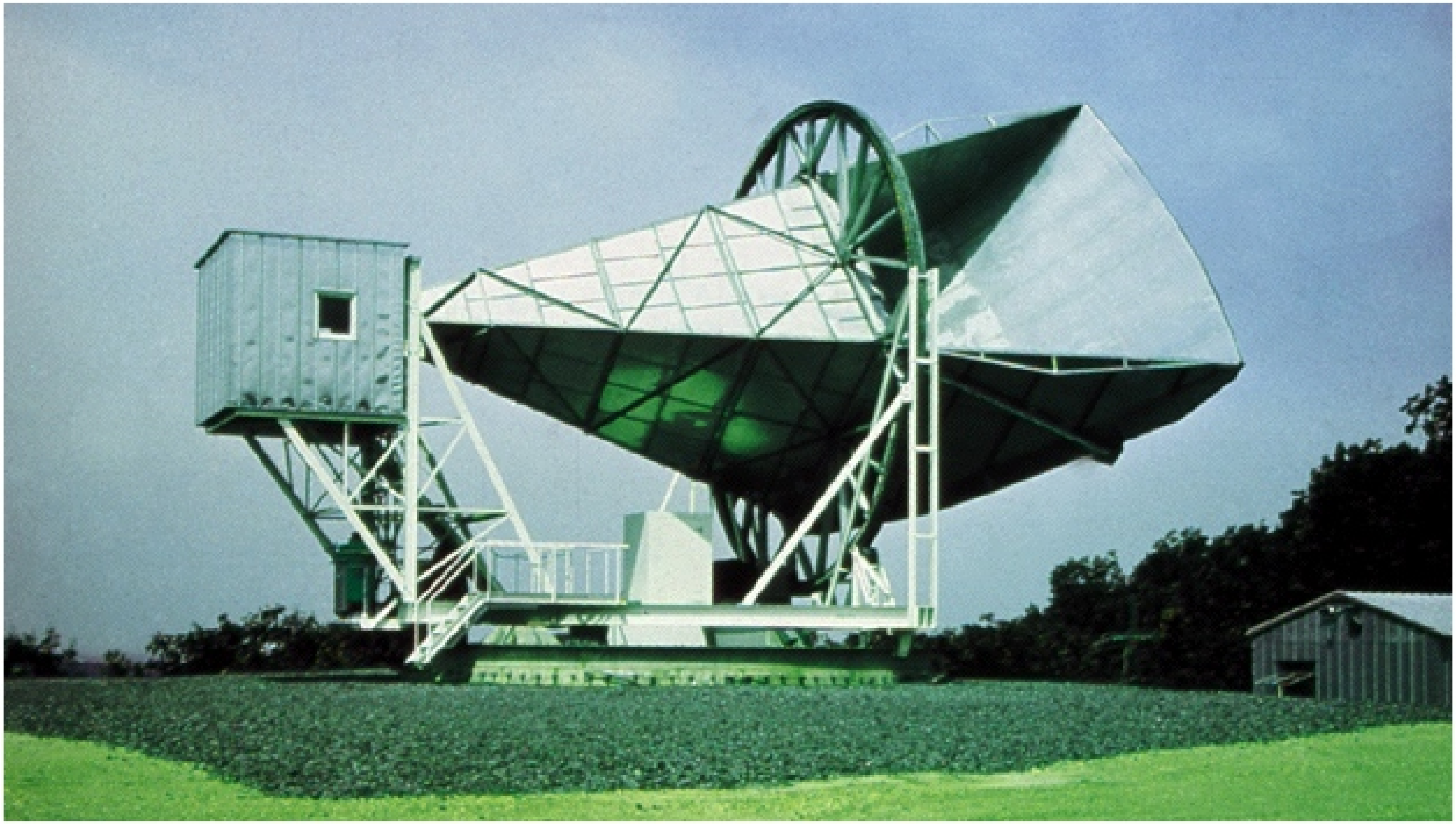




There were many kinds of radio telescope

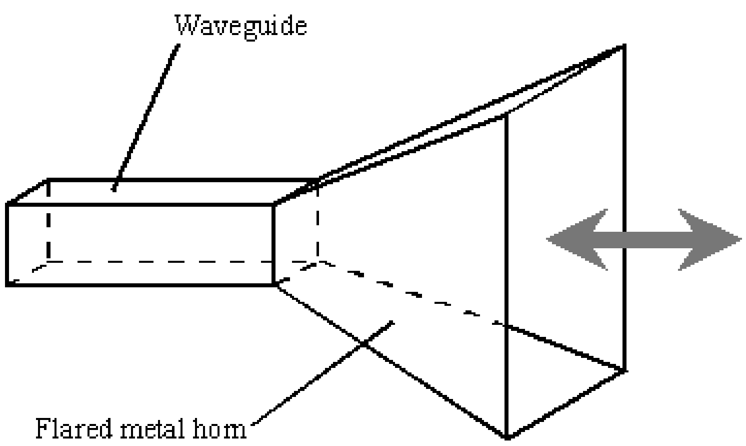


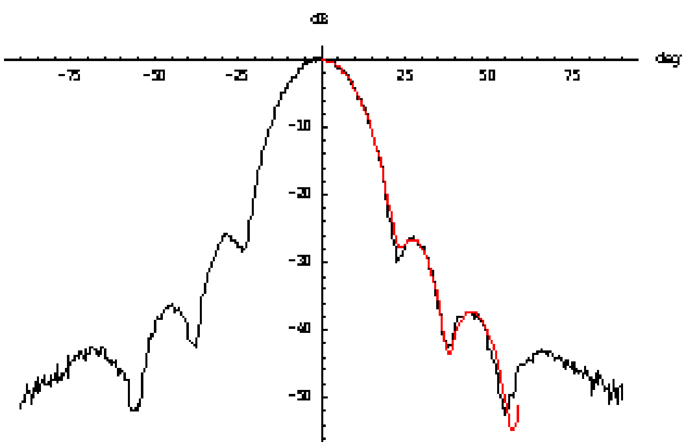
One of the strangest of all doesn't look like a telescope



This antenna, called a horn, has several interesting characteristics

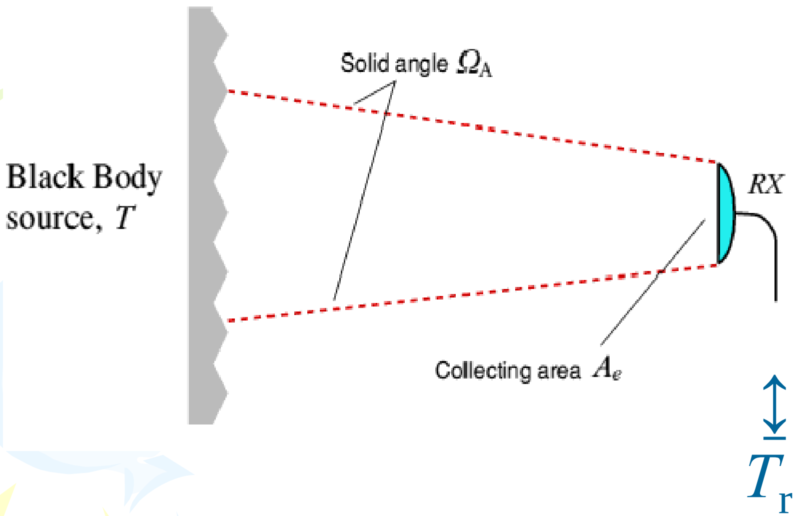
- Horn directs the signal into a waveguide, which transports it further
- Angular resolution set by size of horn
- Has good beam properties
- Effective area of a horn can be calculated, of most other antennas not

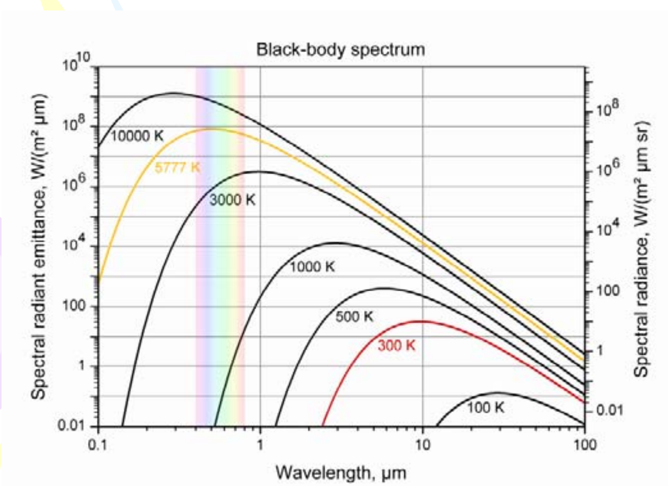




These guys just wanted to calibrate it…

What did their (or does any) antenna measure?





- The power from a source radiating over frequency range Δf can be expressed as, $P = kT\Delta f$
- This can be compared with noise source, like a resistor at some known temperature, T_r
- We say temperature of antenna, T_A, is related to source temperature

They saw temperature excess: actually was sky!

Penzias & Wilson –

"calibration" problem:

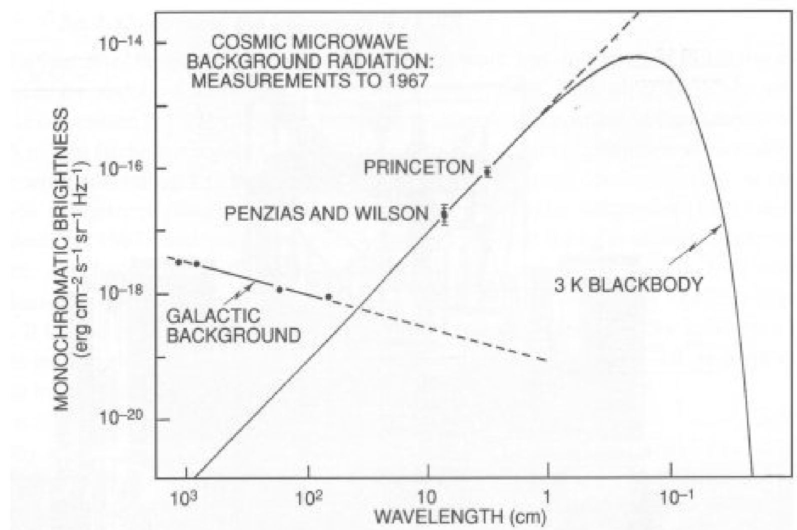
Temperature budget of instrument

Sky:	2.3 ± 0.20 K	
Antenna:	2.0	1.00
Waveguide:	7.0	0.65
Maser:	7.0	1.00
Converter:	0.6	0.15
Total:	18.90 ± 3.00 K	

Measurement: 22.2 ± 2.2 K

Excess: 22.2 − 18.9 K = 3.3 K

Microwave background: 2.7 K

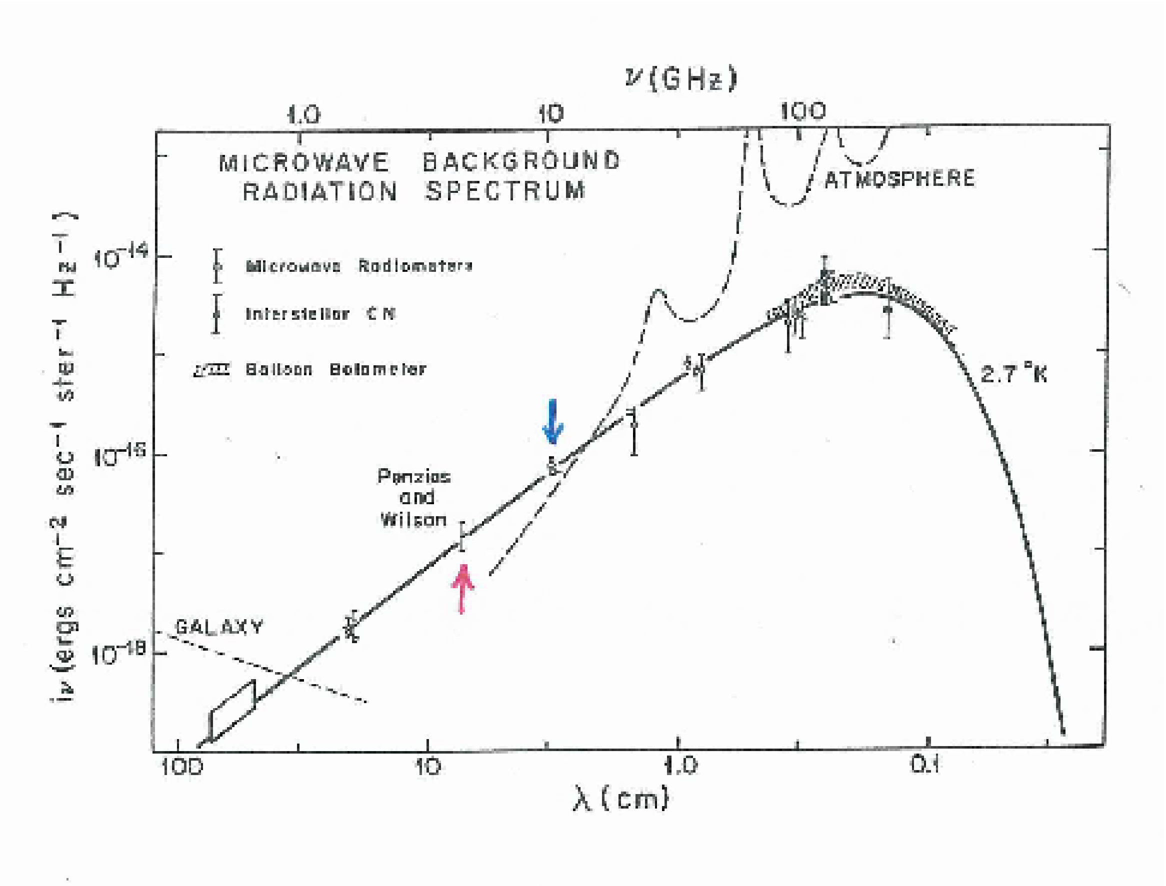


A second measurement of the CBR at 3.0 cm (Roll and Wilkinson, 1966) confirms the discovery of a thermal background and refines the value for T_0.

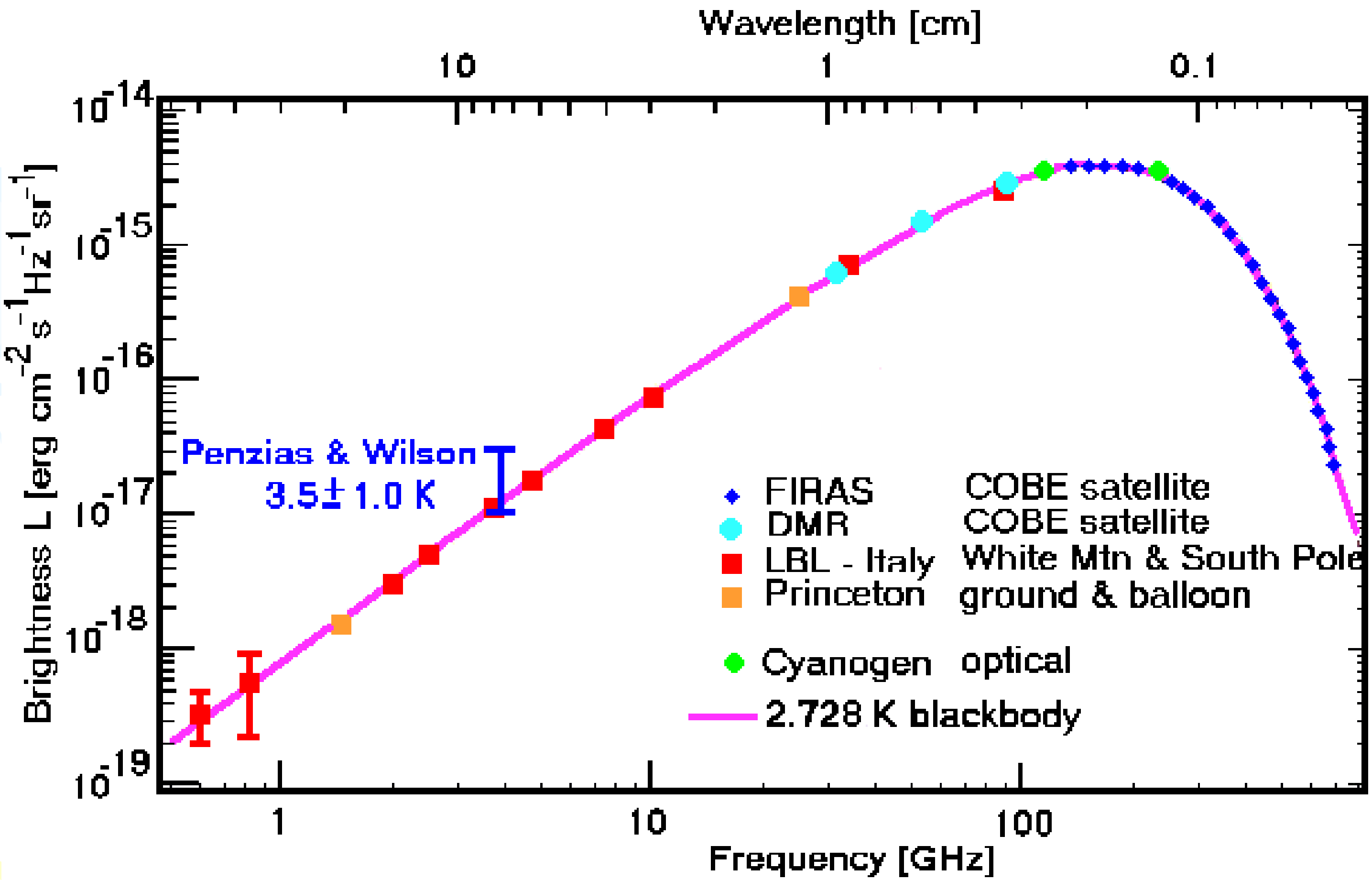
Strange thing is, another group was looking for it

R. H. Dicke and his colleagues calibrating a microwave radiometer using an ambient temperature absorber (Dicke is holding this panel, then referred to as a 'shaggy dog'. The photo dates from the mid-1940s. At about this same time (1946) Dicke *et al.* established an upper limit of 20 K on the cosmic background at microwave frequencies using similar apparatus.

What both groups found: black body spectrum

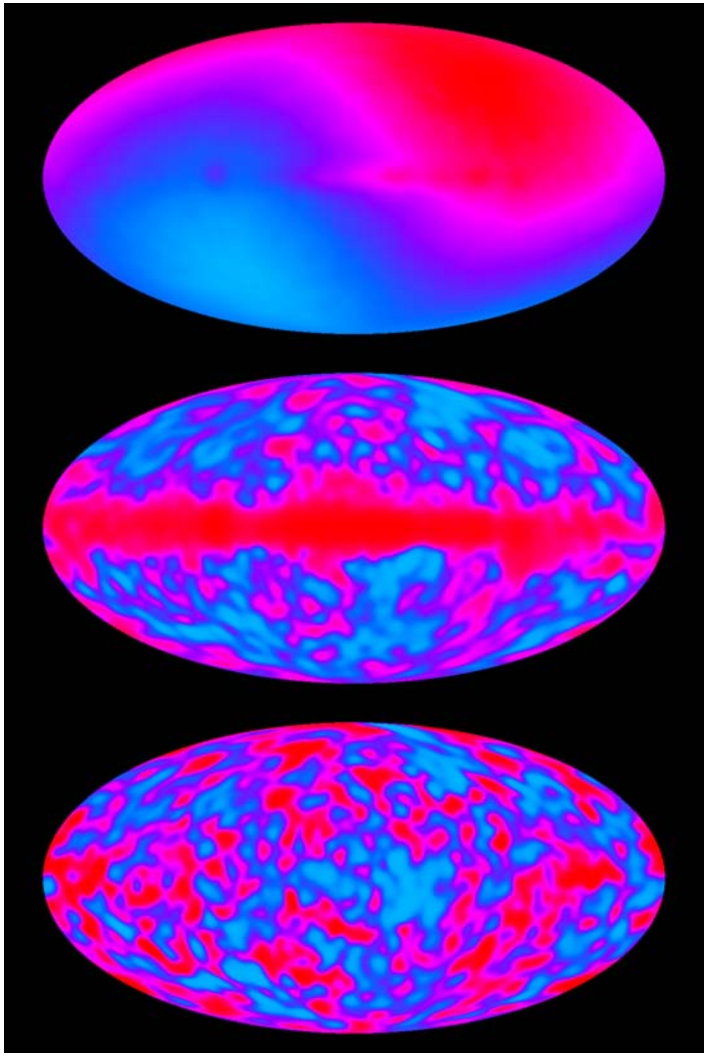


COBE and other projects show perfect black body

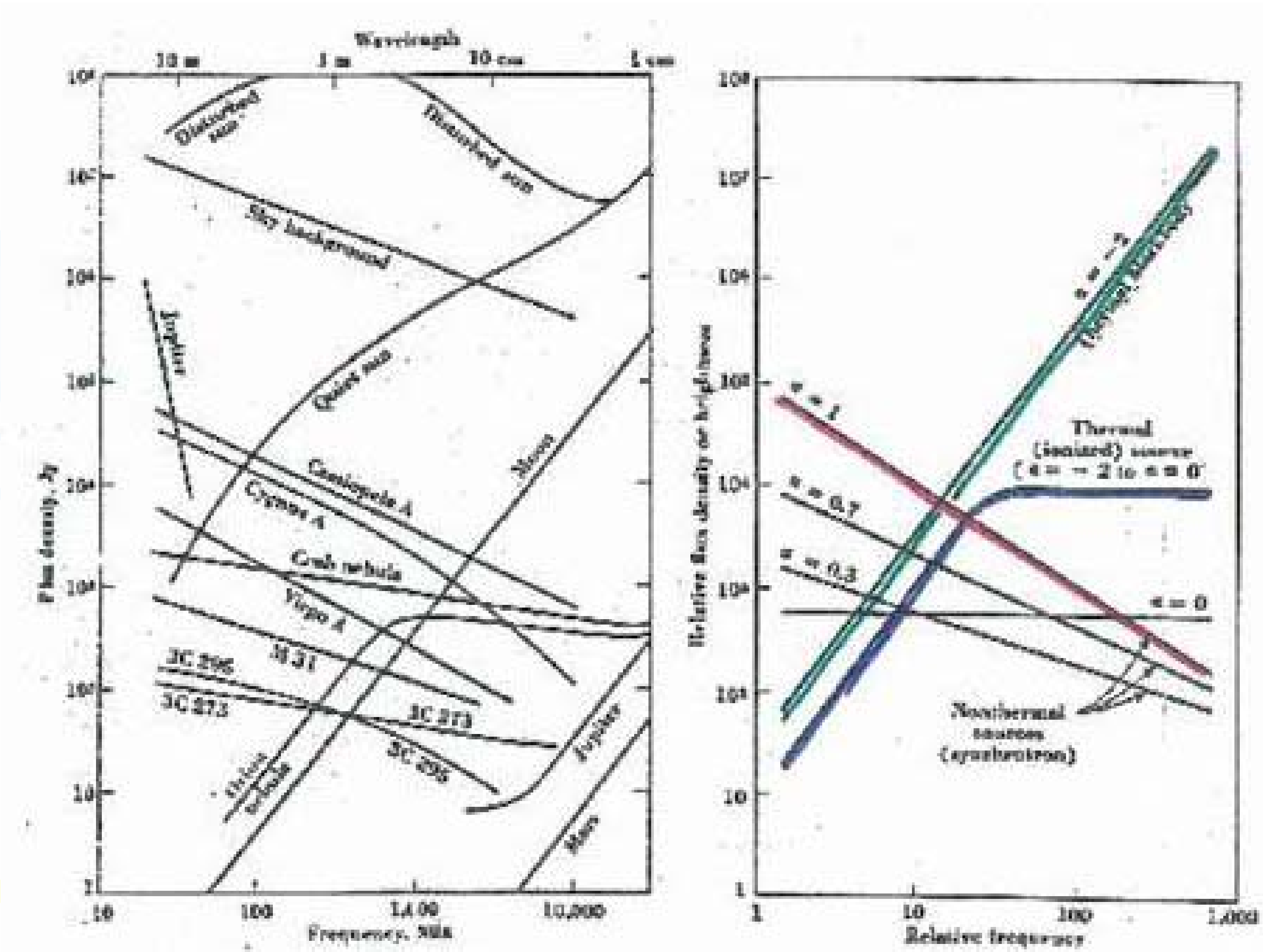


Mapped over the sky, the temperature is very uniform

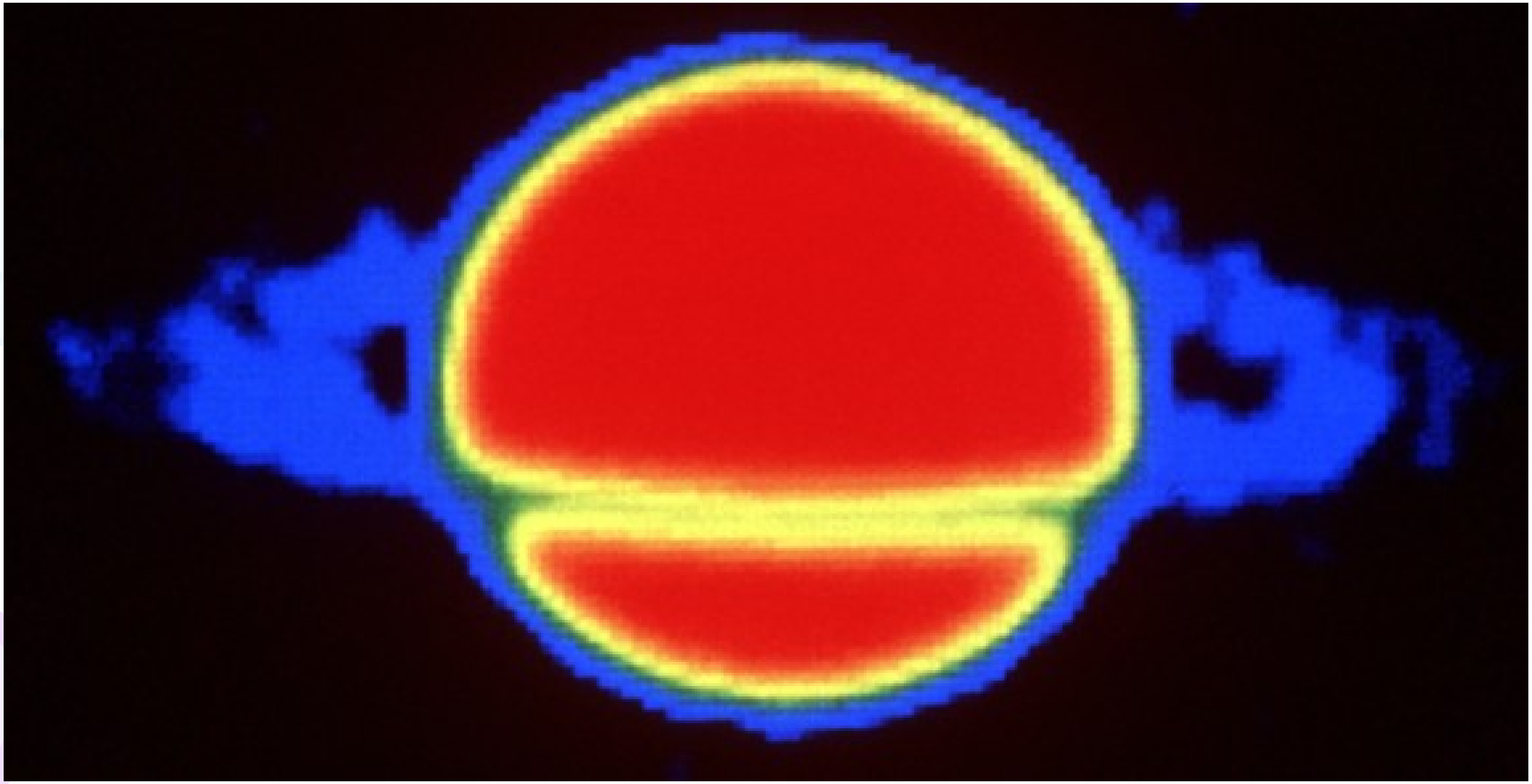
- At level of about 0.001, see dipole – our motion in space
- At ~0.00001, see Galaxy and small irregularities
- After removing Galaxy, clearly see irregularities



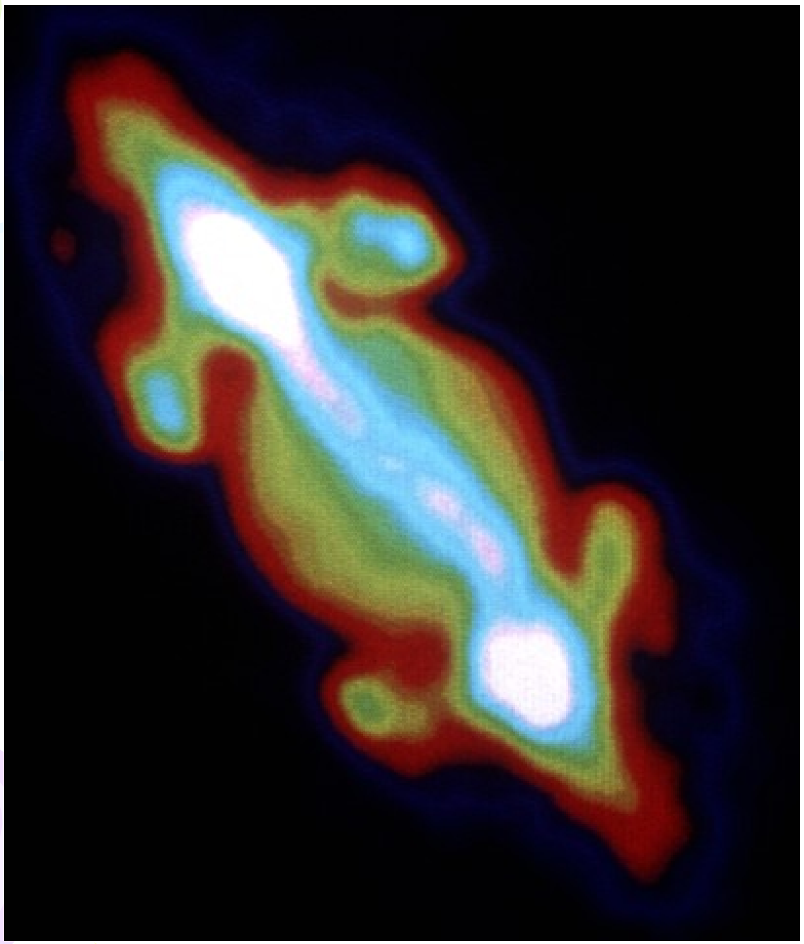
Thermal sources are not the most common type



But they do include planets like Saturn and Jupiter



They can also be used as calibration sources



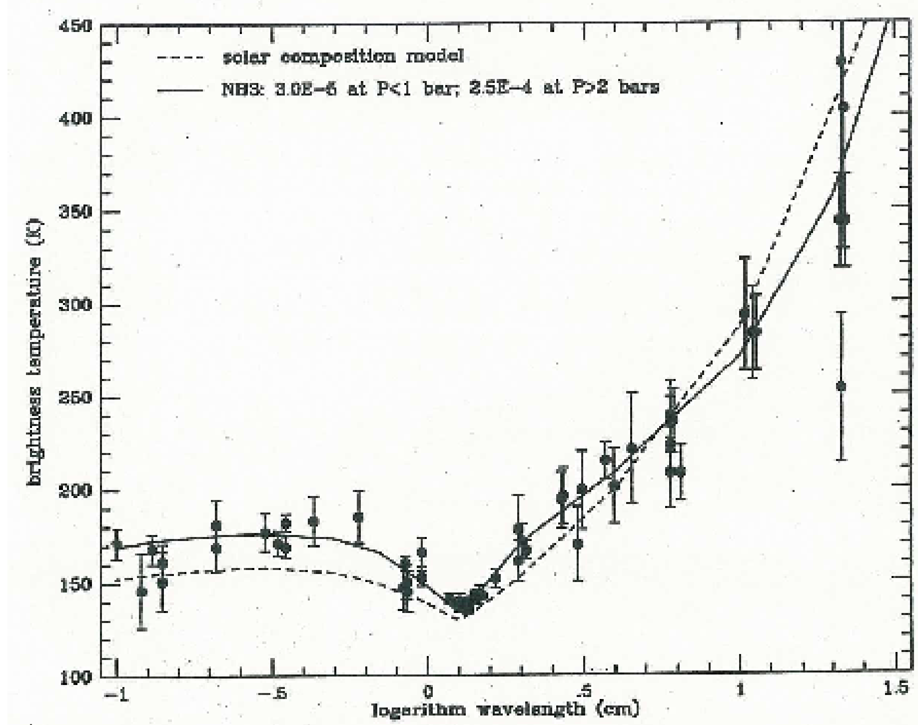
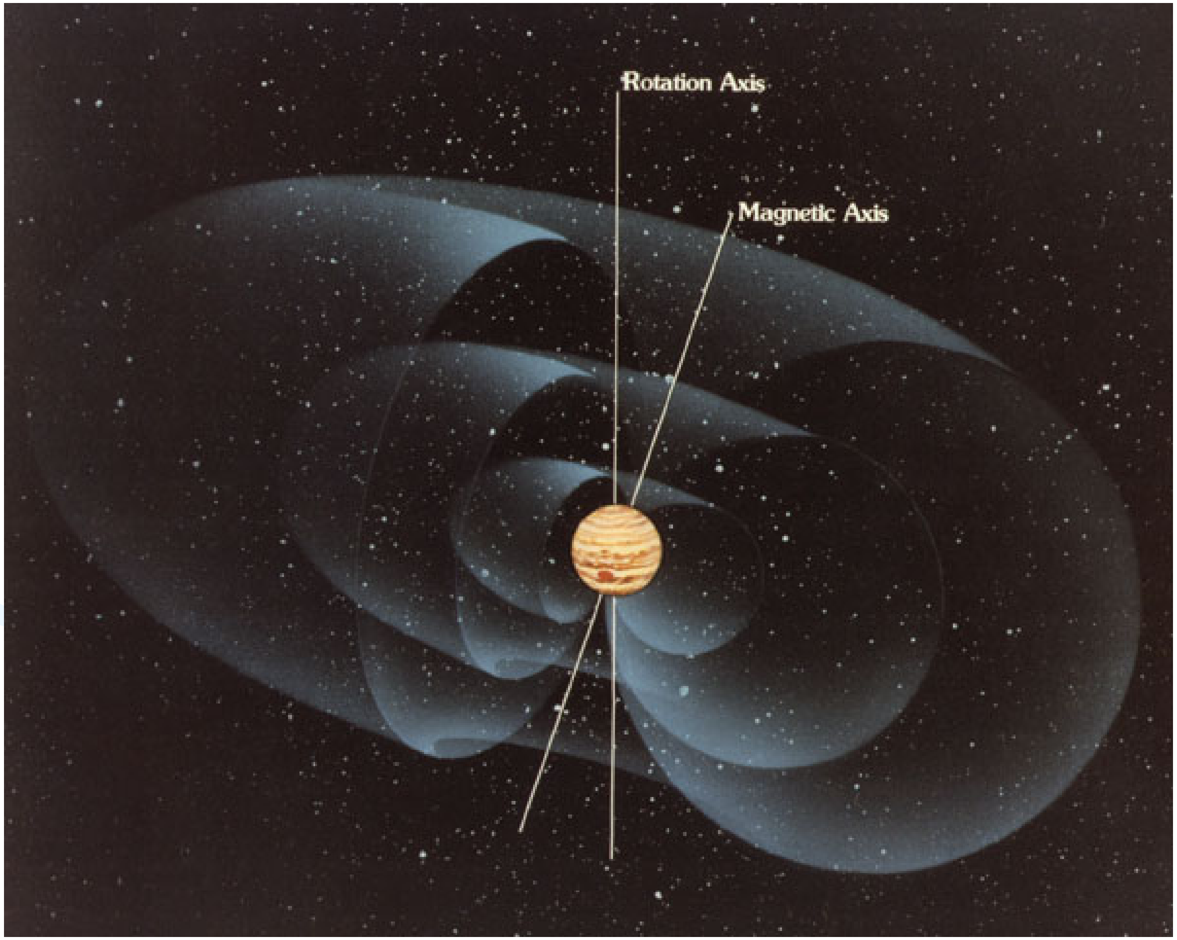


Figure 4 Jupiter's radio spectrum. Superimposed are various model atmosphere calculations. Dashed curve—solar composition atmosphere. Solid curve—NH_3: 3×10^{-5} at $P < 1$ bar and 2.5×10^{-4} at $P > 2$ bars. The gas is subsaturated at $P < 0.6$ bars.

Burke & Franklin detect strong outbursts from Jupiter

Slowed down, this is what a Jupiter S-burst sounds like

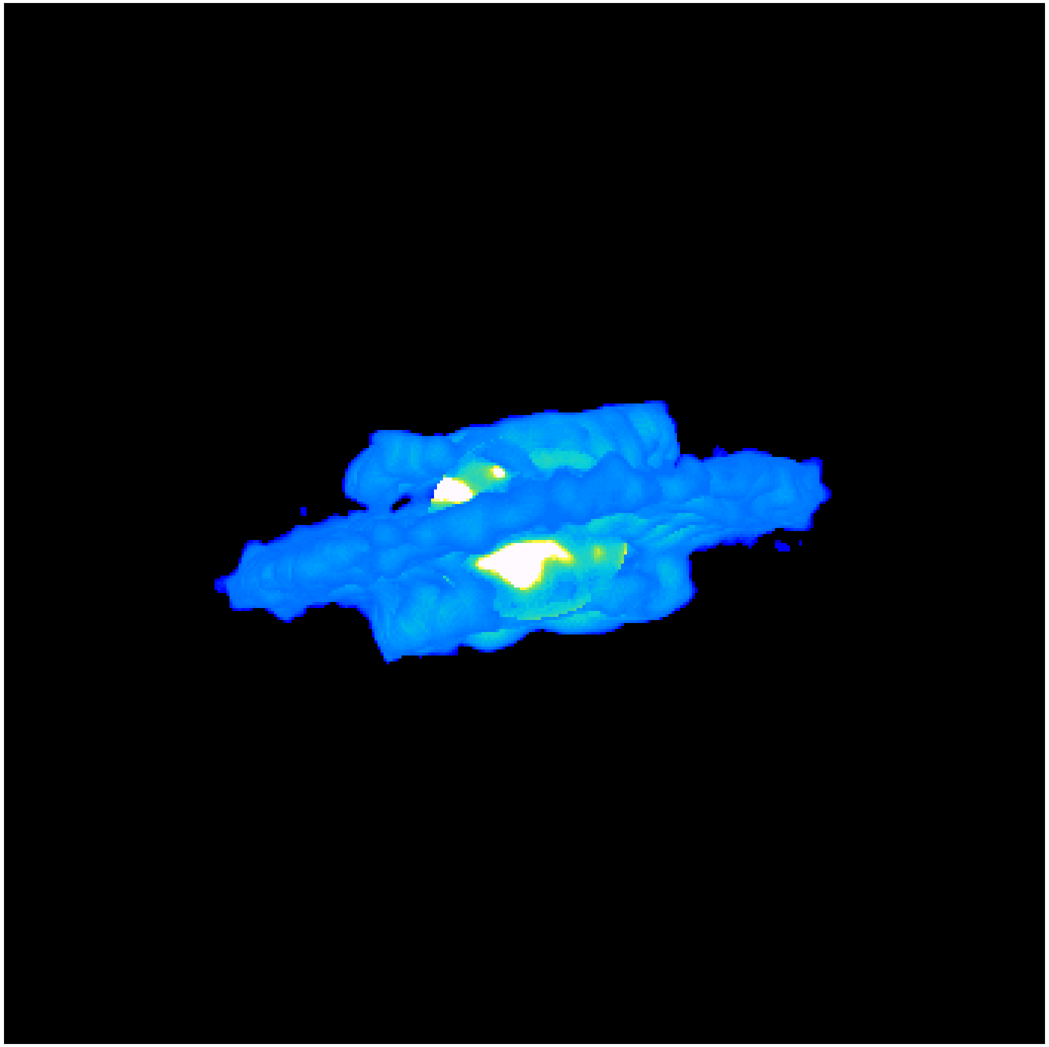
Mysterious emission from Jupiter's magnetic field at low frequencies



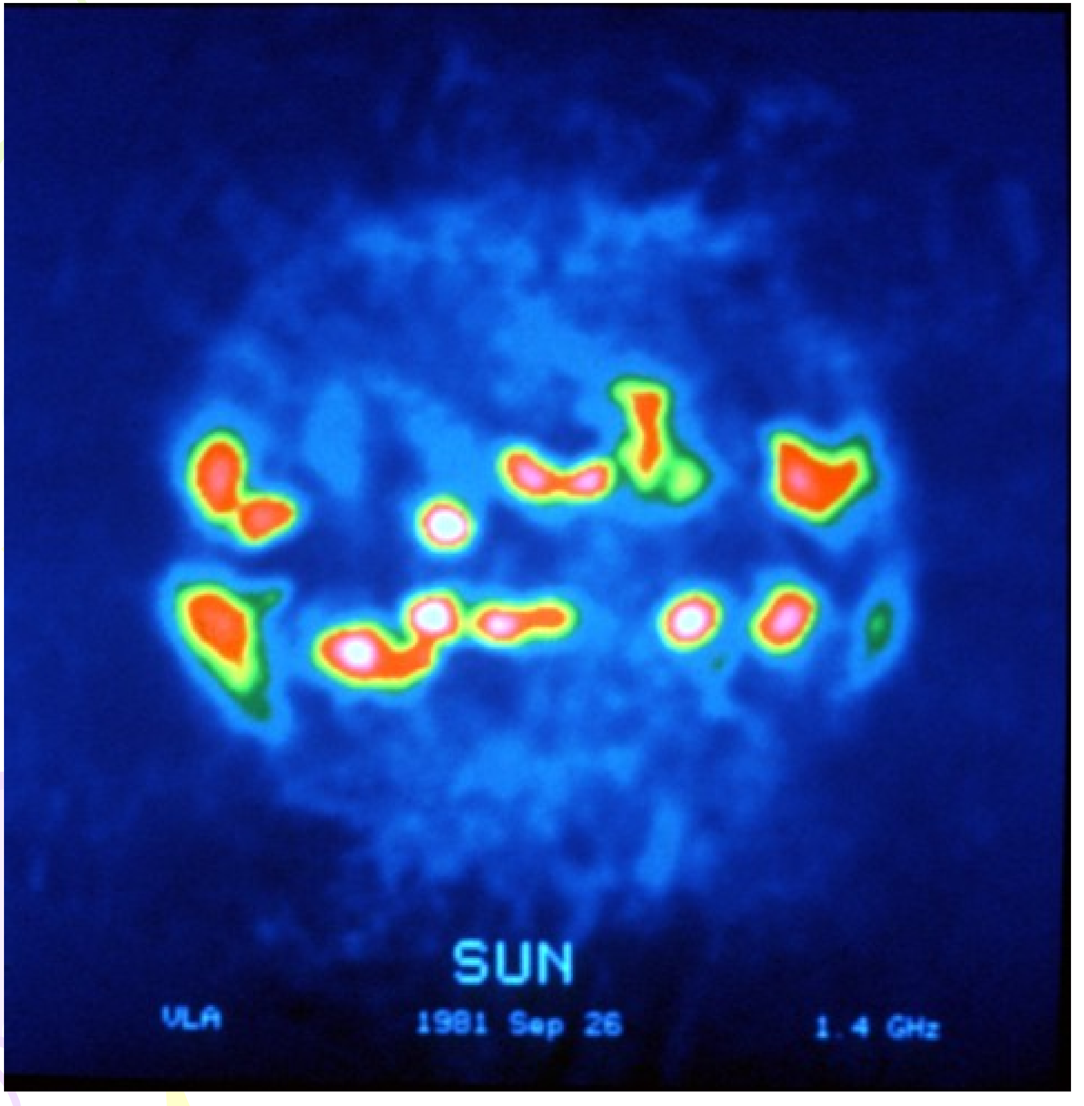
These bursts seemed to repeat with Jupiter’s rotation period

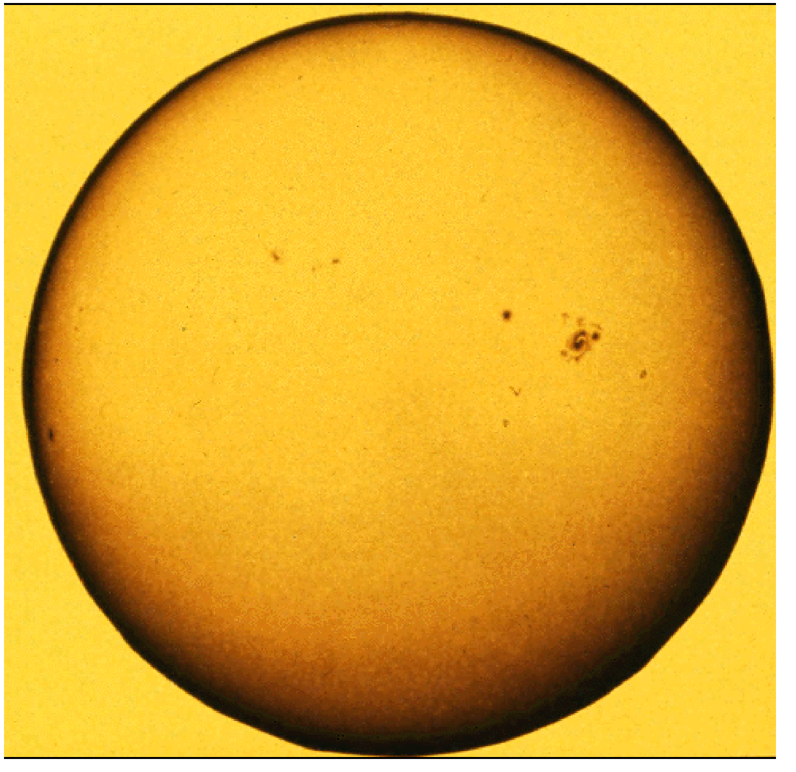
- Since Jupiter’s magnetic field is tilted with respect to the rotation axis, a link would certainly be possible
- The bursts gave a more stable rotation period than visible features (clouds), and were soon adopted: field would be anchored in planet’s core, unlike the atmosphere
- Later, emission from radiation belts found

Jupiter’s radiation belts shown rotating & in 3-dimensions



The Sun emits both thermal and nonthermal radio waves

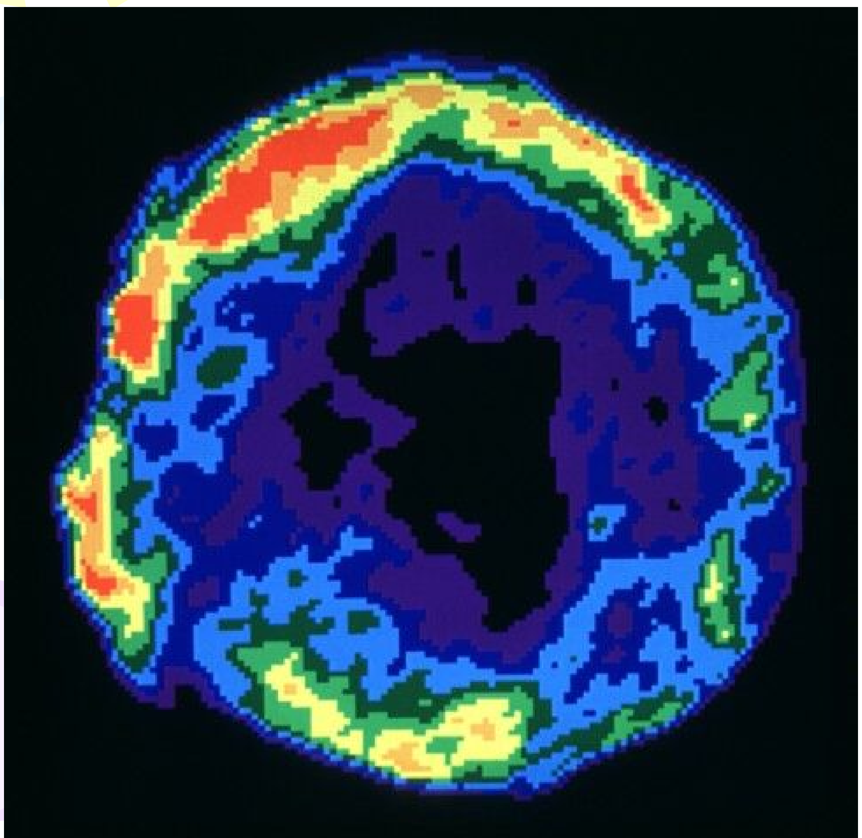


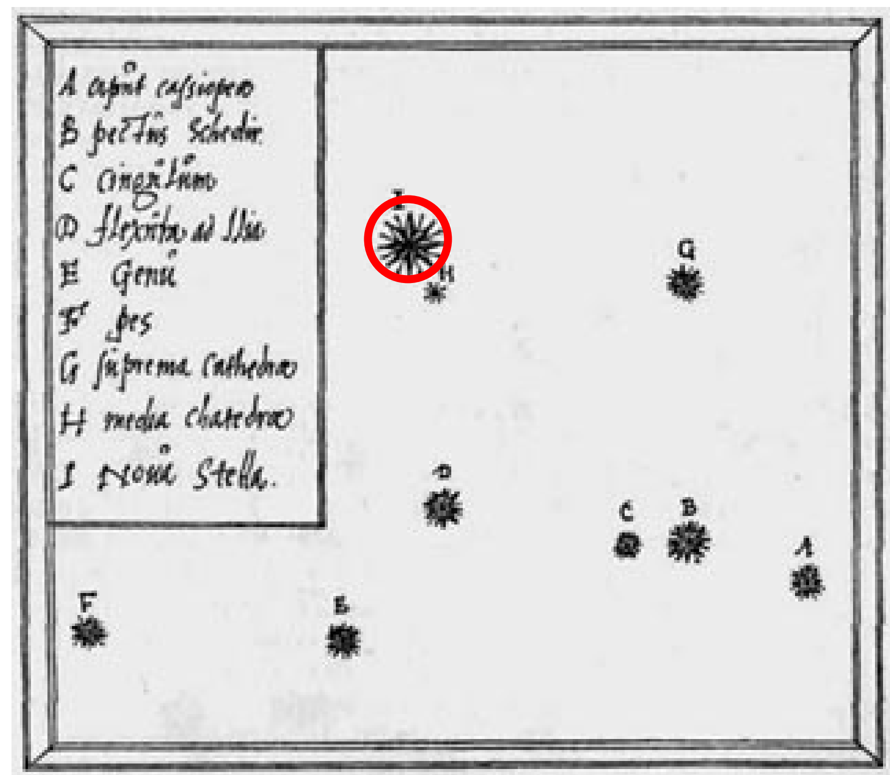


Tycho Brahe and the beginnings of modern science

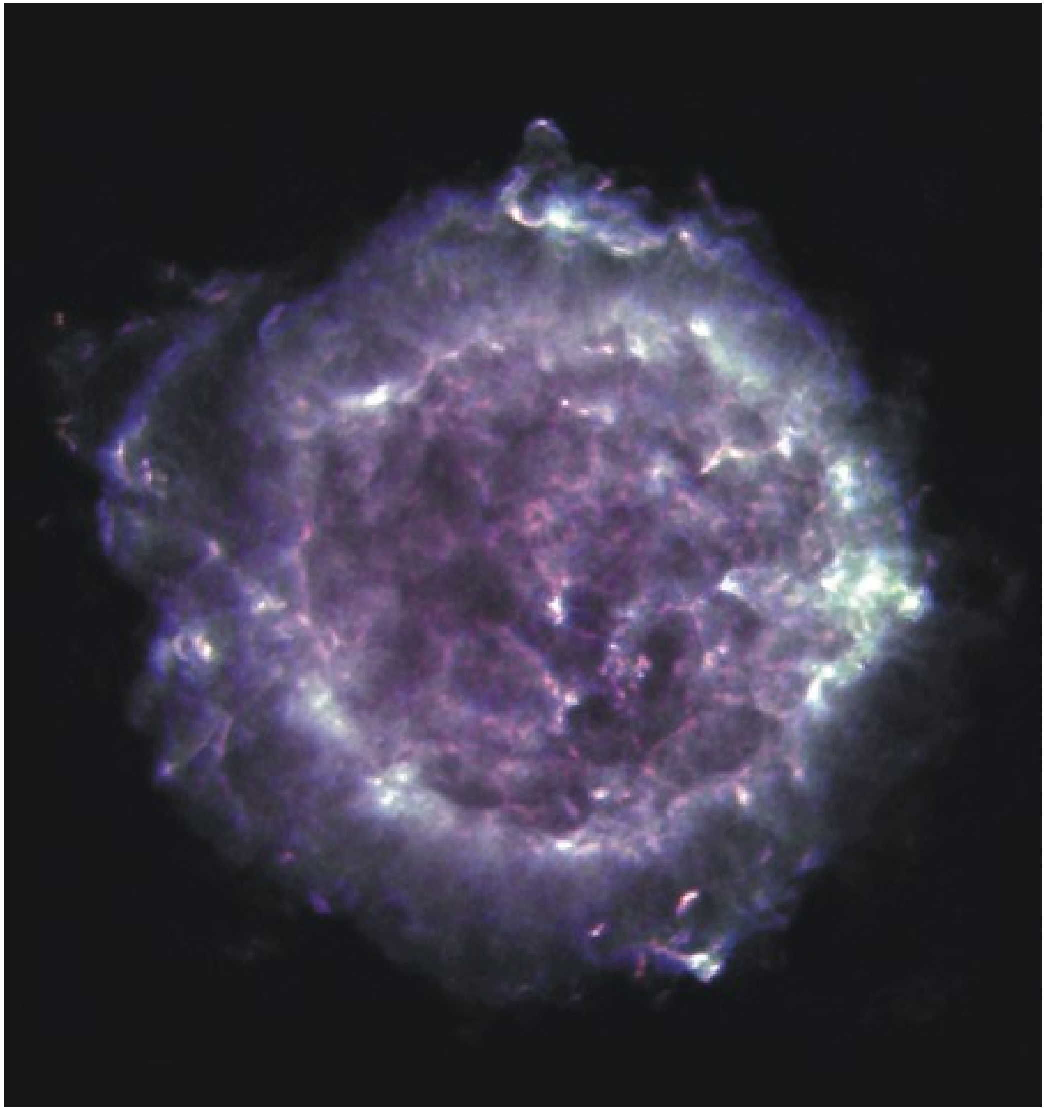
- Brahe (1546 – 1601), a Danish astronomer: made the most precise measurements of stars and planets (naked eye sightings), see if system of Ptolemy was correct
- This huge quantity of data would later be used by Kepler for his studies
- Observed nova in 1572

At Tycho's position for the 1572 nova: a strong ring-like radio source – a supernova remnant

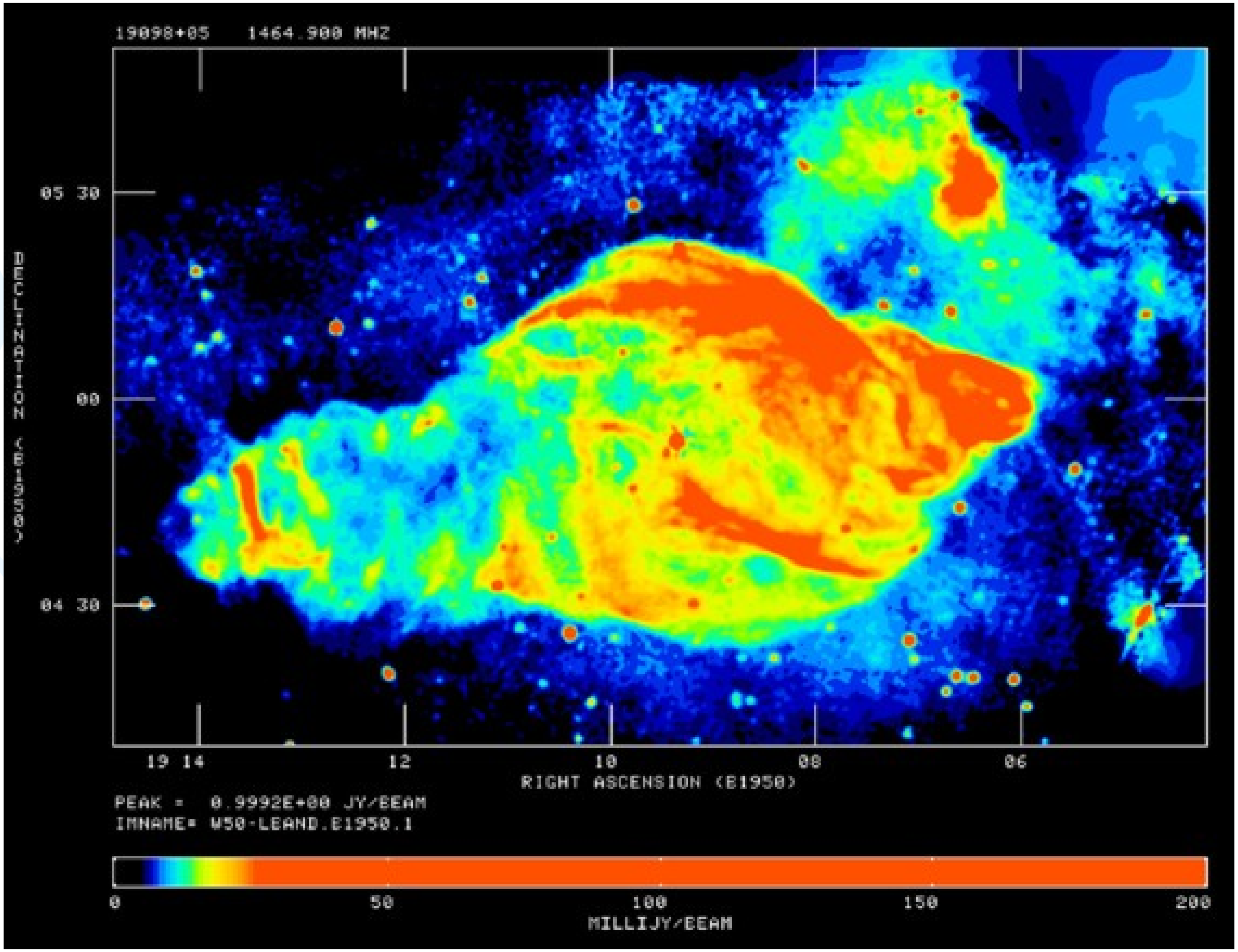




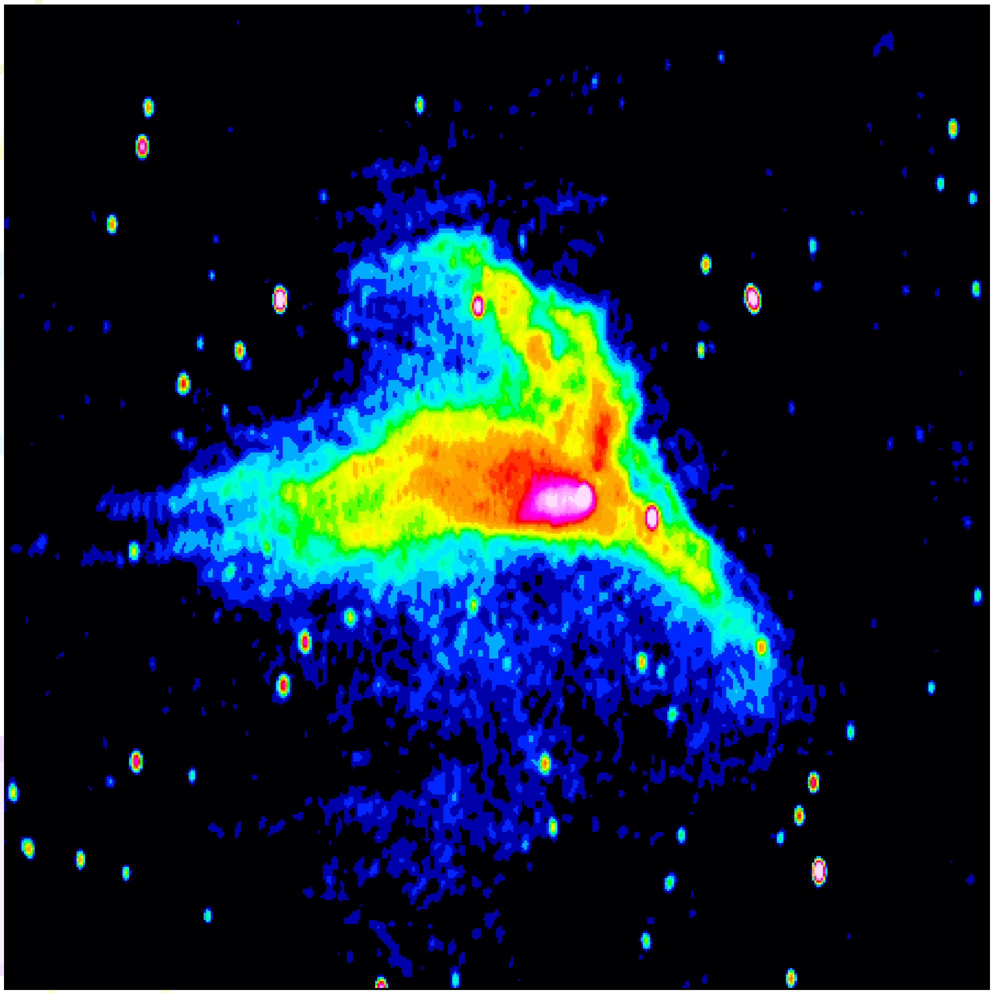
In our Galaxy we also find other supernova remnants...

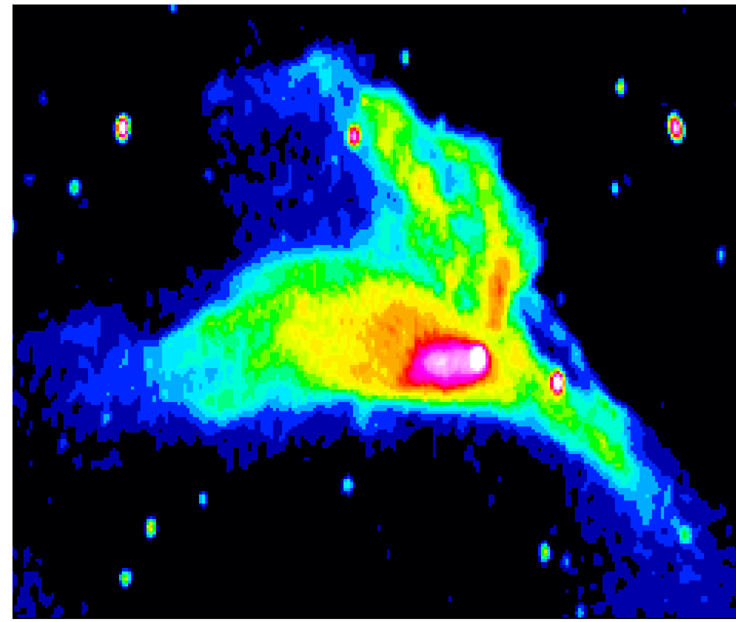


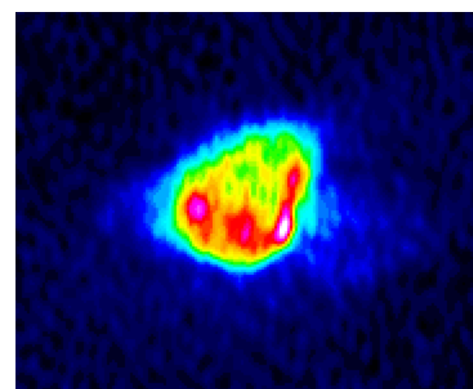
...and some have very strange structures



WSRT observation of CTB80 at 92 cm, 49 cm & 3.6 cm

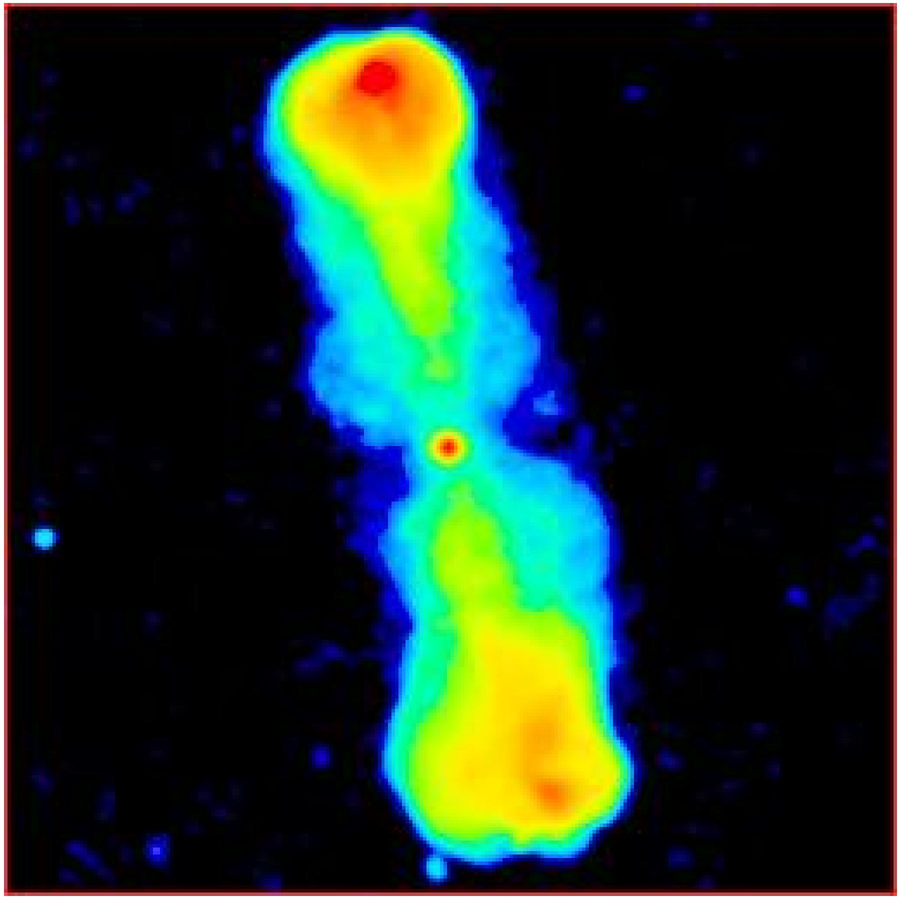




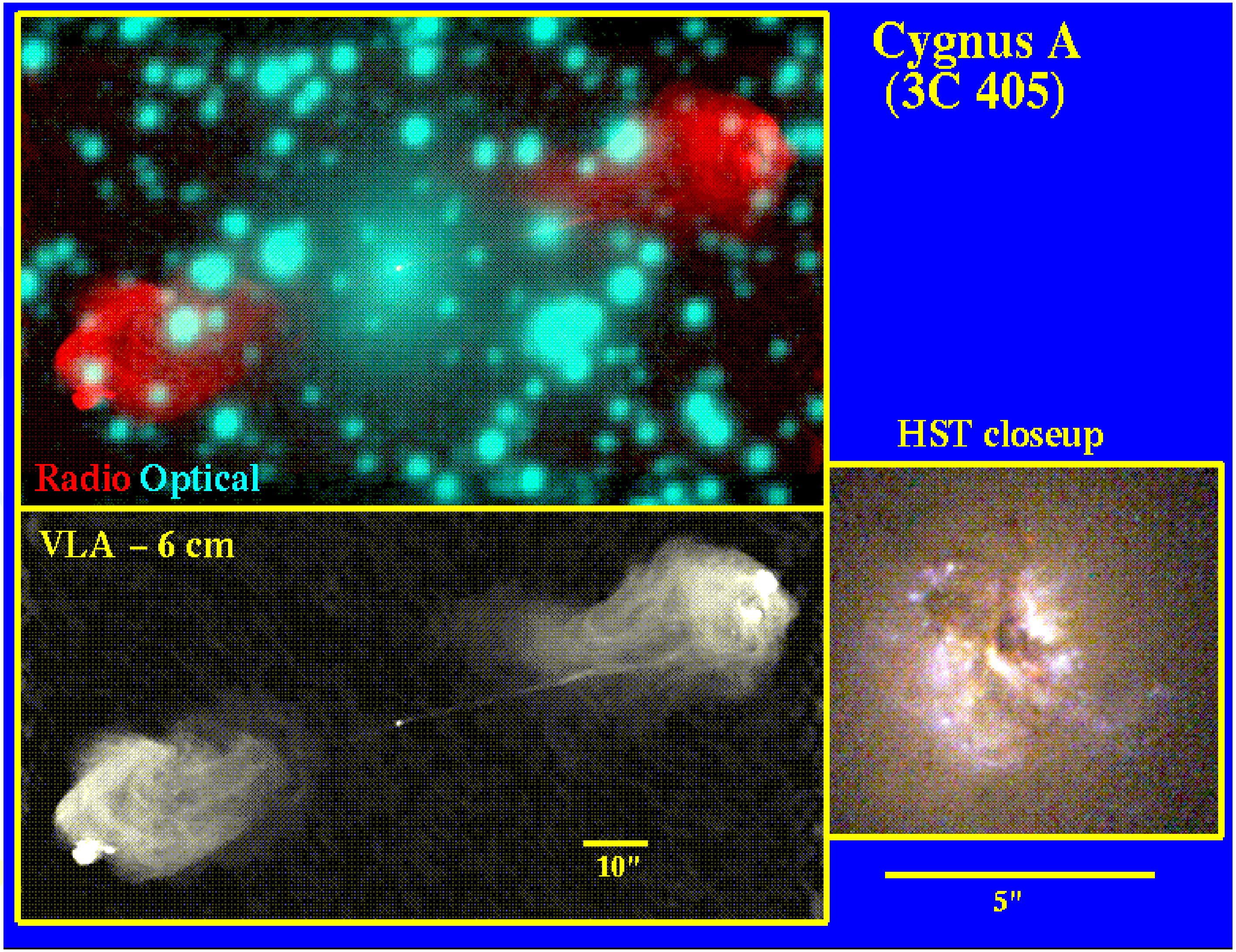


By 1960: clear that many types of objects can be radio sources

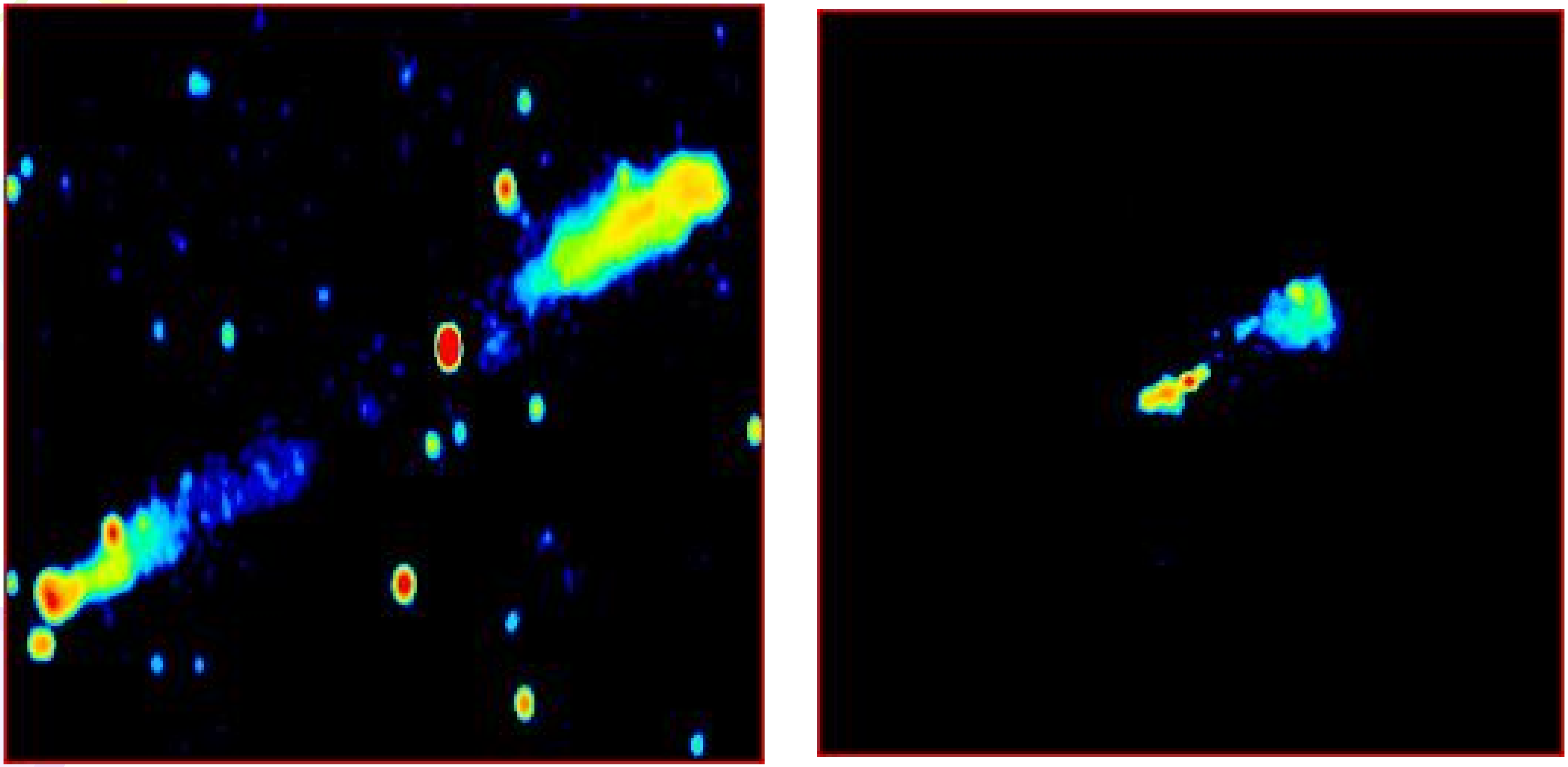
- In the solar system: the Sun and Jupiter
- In the Milky Way: stellar explosions and interstellar gas clouds
- But most common of all were the double sources associated with distant galaxies



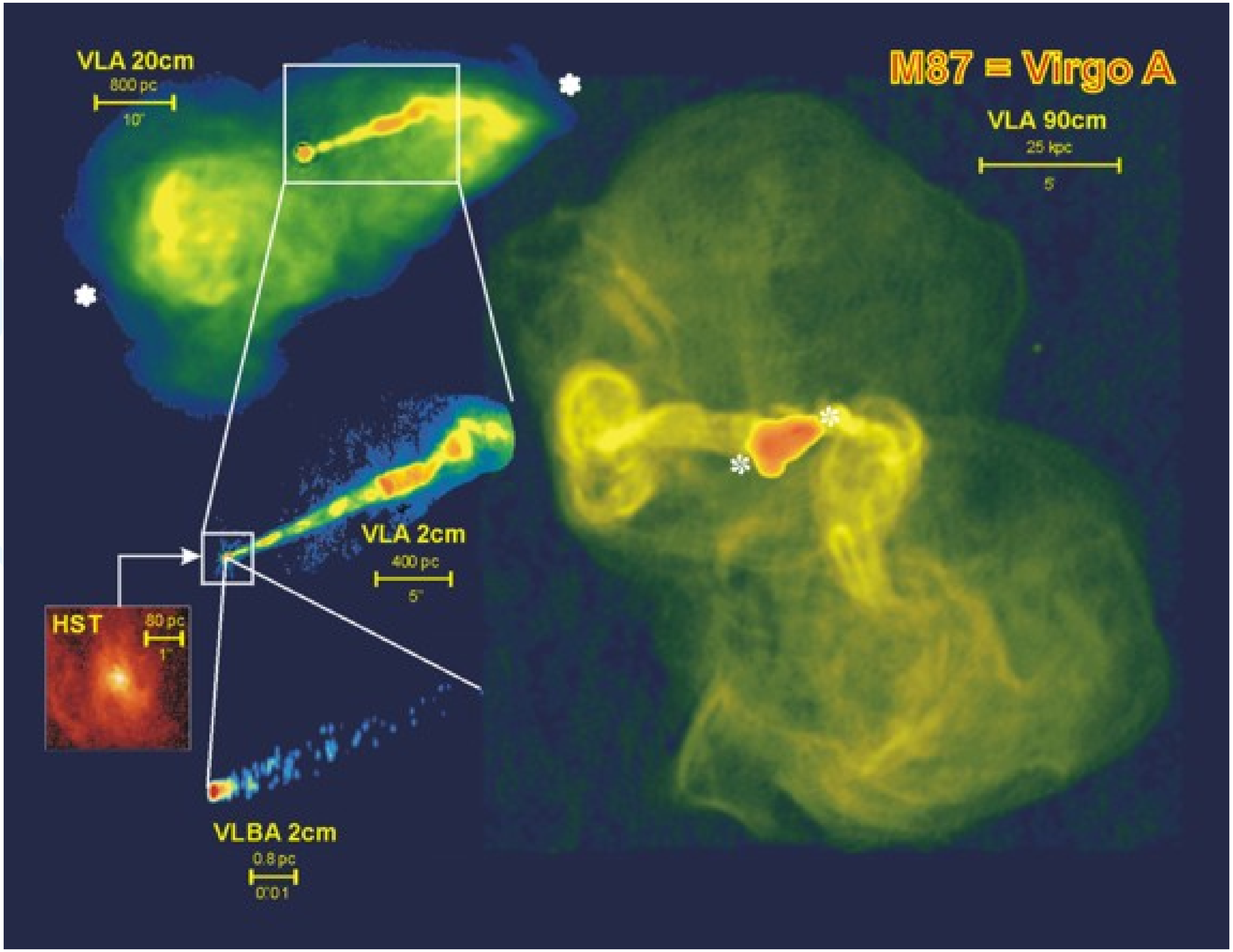
Other galaxies can also produce strange sources



WSRT and VLBI observation of giant radio galaxy 3C236



Emission from Vir A gives a clue to what happens



Maps are made with telescopes like this (VLA)

How they work we will see in the next two lectures