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RADIO ASTRONOMY

S.R. Spangler

University of Iowa, U.S.A.

These are preliminary lecture notes, intended only for distribution to participants.

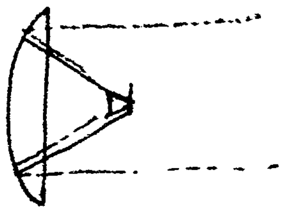
Radio Astronomy by Steve Spangler,
University of Iowa

- The universe brought to you "via the magic of Radio".

Definitions:

1. Frequency range: 5MHz — $\simeq$ 200 GHz
   (60m — 1.5mm)
2. The heterodyne technique: coherent mixing of radio wave to manageable frequencies. You can measure the complex electric field in the radio wave.

The Design of a Radiotelescope: antennas and Receivers.



antenna collects radiation and focuses it to feed + receiver.

1. Antenna collects large amount of Poynting flux and "forms a beam" on the sky.

2. Receiver amplifies signal (by $10^{10} - 10^{12}$ times) while adding minimal noise.

The Radiometer Equation

1. We measure brightness of radio sources (flux) in Janskys. $1\ Jy = 10^{-26}\ W/m^2/Hz$.

2. The sensitivity of a radio telescope is:

$$\sigma_{Jy} = \frac{2K_B}{A_e} \frac{T_{sys}}{\sqrt{B\tau}}$$

K_B = Boltzmann constant
A_e = effective area of antenna
T_{sys} = effective noise temperature of amplifier
B = bandwidth = width of spectral "window" measured
τ = averaging time.

3. Big Radio Telescopes

a. Bonn, Germany (MPI für ~~Radioastr~~ Radioastronomie: 100m, 1.4GHz — 22GHz)

b. GMRT, Pune India. (many antennas, ~ 100m collecting area (300 - 1400 MHz).

c. Arecibo, Puerto Rico (USA) 330m, (320MHz — 10GHz)

d. Senator William Byrd Radiotelescope, Green Bank, West Virginia, USA, 105m, 320MHz - 100 GHz.

4. Angular Resolution

size of diffraction pattern of radio telescope (beam pattern)

$$\Theta \simeq \frac{\lambda}{D}$$

λ = wavelength of observation, D = diameter of antenna.

Radio Astronomy [cont.]

4. [cont] $\theta = \lambda / D$

example $\lambda = 6$ cm, $D = 60$ m (large radio telescope)

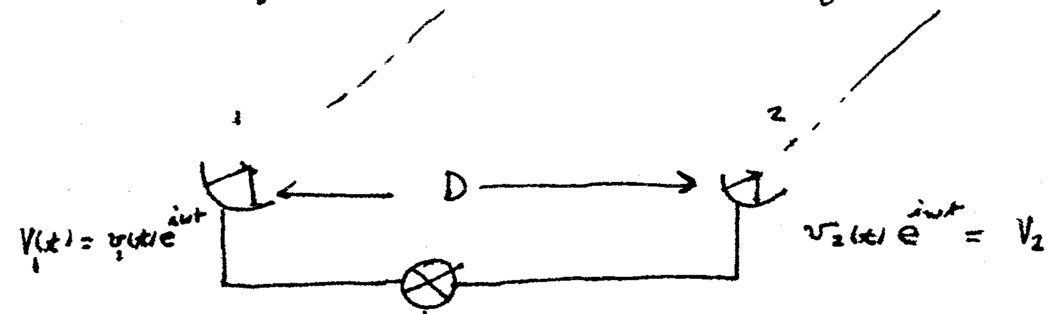
$\theta = 10^{-3}$ radians $\cong$ 3 arcminutes $=$ 180 arcsec.

Large optical telescope, $\theta \sim 1-2$ arcseconds.

without new approach, radio astronomy stuck with low resolution.

$\nwarrow \hat{e}$

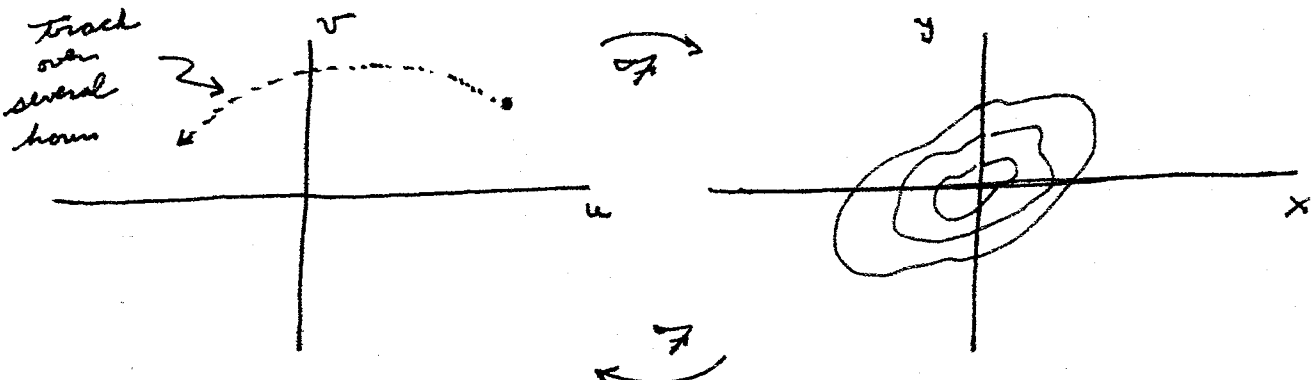
5. Interferometry and Aperture Synthesis.



$$\frac{1}{T} \int_0^T \{ v_1 v_2^* \} \, dt = V(u,v)$$

$u = \vec{D} \cdot \hat{e}_{EW}$ $\qquad$ $v = \vec{D} \cdot \hat{e}_{NS}$

Consider $V(u,v)$ as one point in a (u,v) plane



$$V(u,v) = \iint_{-\infty}^{\infty} dx \, dy \, I(x,y) \, e^{2\pi i [ux + vy]}$$

Radio astronomy [cont.]

$$I(x,y) = \iint_{-\infty}^{\infty} du\,dv\; V(u,v)\, e^{-2\pi i[ux+vy]}$$

∴ adequate coverage of (u,v) plane with measurements allows one to measure the brightness distribution.

5a — units

Janskys are units of flux, $1\,Jy = 10^{-26}\,W/m^2/Hz$

$I(x,y)$: Janskys / steradian

$V(u,v)$: Janskys.

5b — The magic of interferometry is that an interferometer with good coverage of the (u,v) plane has resolution equivalent to a radio telescope of diameter ≃ D, the length of largest baseline.

$$\theta_{int} \simeq \lambda/D \qquad \text{again.}$$

Examples: 1. VLA, $D = 35\,Km$, $\lambda = 3.5\,cm$

$\theta = 10^{-6}$ radians $= 0.''2$!

2. VLBI (Very Long Baseline arrays)

$D = 3500\,km$ $\lambda = 3.5\,cm$

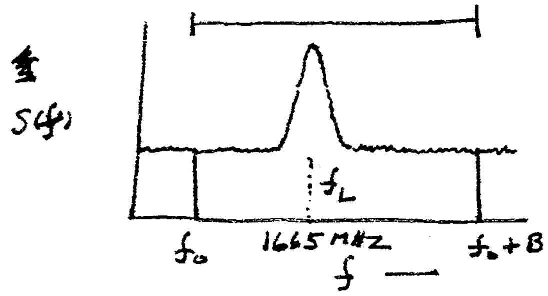
$\theta = 2 \times 10^{-3}$ arcseconds = 2 milliarcseconds

much better than Hubble Space Telescope.

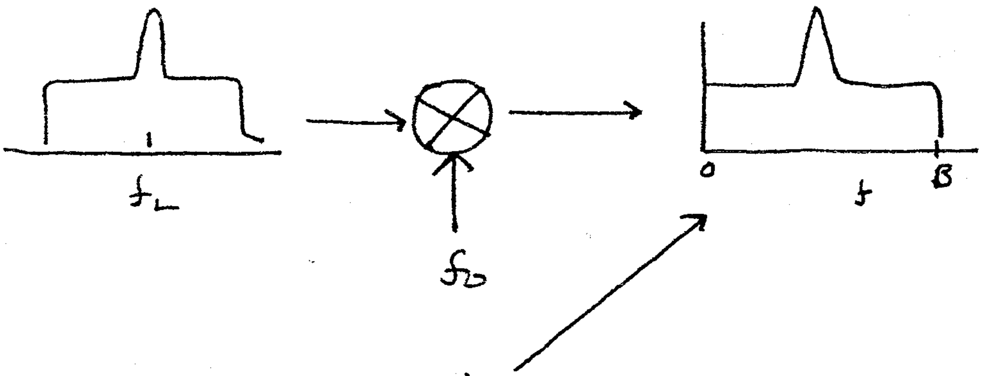
6. Radio Spectroscopy

- There are many quantum transitions of atoms and molecules in the radio wavelength range.

Radio spectroscopy:



- pass this spectrum through a filter which passes signals in range $f_0 \to f_0 + B$
- <u>mix</u> with signal at frequency f_0, and get <u>beats</u> $f \to f' = f - f_0$



- <u>sample</u> this signal for $V(t)$
- Form the autocorrelation function $g(\tau) = \langle V(t) V(t+\tau) \rangle$
- in a digital electronic instrument called an autocorrelator
- Form spectrum by result that spectrum is Fourier transform of autocorrelation function

$$P(f) = \int d\tau \, g(\tau) \, e^{2\pi i f \tau}$$

"The Wiener–Khinchine Theorem".

- Resolution can be as high as $\Delta f \simeq \frac{1}{T}$

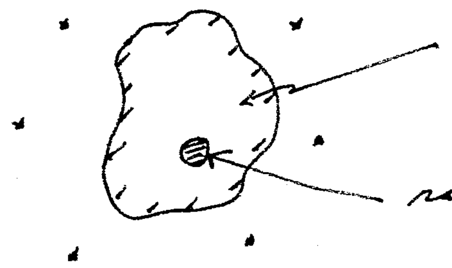
T = duration of $V(t)$ put into autocorrelator

7. What can we observe? Particular emphasis on plasma physics topics.

a. Radio wave scattering — enough said.

b. Solar radio astronomy — experts in audience

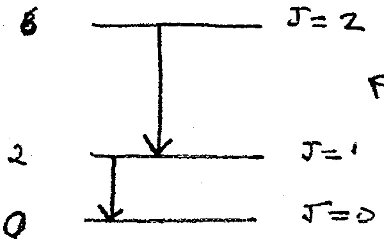
c. molecular clouds — regions of star formation



Radio telescopes see rotational molecular transitions of many ~~moleculars~~ molecules.

For linear molecules: $E = \frac{L^2}{2I}$ classical

$E(J) = \frac{\hbar^2}{2I} J(J+1)$: quantum

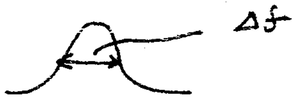


For molecules of interest, excitation temperatures ~ 5K – 50K.

ci. > 110 molecular species have been identified
CO, NH_3, H_2O, $HCOOH$, HCO^+, NH_3^+, CH_4.
organic chemistry in these clouds indicated

cii. molecular ions indicate electric charge important. Ionization fraction small ($\sim 10^{-7}$) but sufficient to insure plasma behavior according to traditional criteria.

ciii <u>Width</u> of molecular lines > thermal widths



$$\frac{\Delta f}{f_0} = \frac{\Delta v}{c}$$ Doppler widths

$\Delta v \gg \sqrt{\frac{3 K_B T}{m}}$ ← with T indicated by molecular excitation.

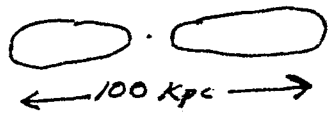
→ indicates unresolved turbulence

civ Change in centroid of line, indicating motions in the cloud, probably larger eddies in turbulence.

→ These observations show turbulence important in star formation

7d Extragalactic radio sources

→ Transparency



perhaps "blobs" of relativistic matter.

- we see these objects via synchrotron radiation by relativistic electrons

  γ_e: power law spectrum, so higher γ → higher radio frequency. For emission at cm wavelengths, $\gamma \sim 5000$

  B: estimates are $\sim 3 \times 10^{-6}$ G; comparable to ISM of our galaxy, about 10% that of solar wind at 1 a.u.

- searches for evidence of thermal matter in these objects have not yielded results, so they may be "drops" of relativistic matter.

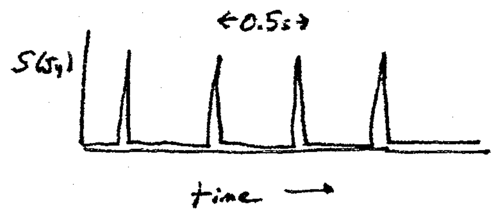
Radio astronomy [cont.]

7e **Pulsars** — rotating neutron stars — unique contribution of radio astronomy

- meditation on amazing aspects of astronomy — before 1968, neutron star considered an exotic prediction of theoretical physics.

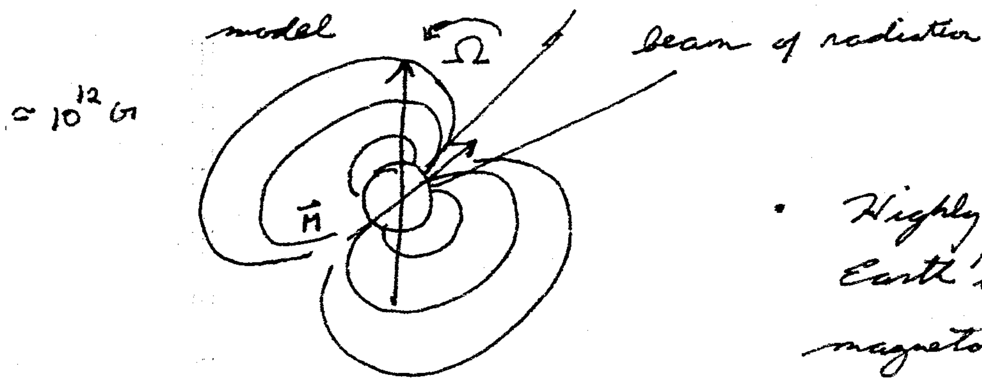
- In 1968 announcement of discovery of pulsating radio sources (pulsars) by Jocelyn Bell and Anthony Hewish.

observed →



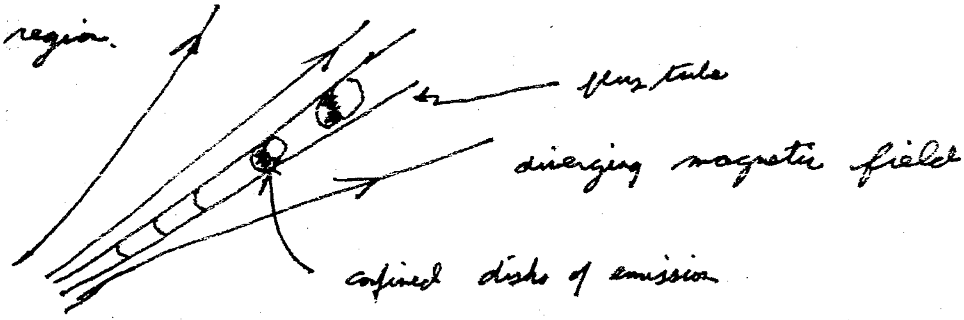
→ There are now more than 1000 of these.

Picture which has grown up: rotating neutron star model



- Highly reminiscent of Earth's magnetosphere, magnetosphere of Jupiter.

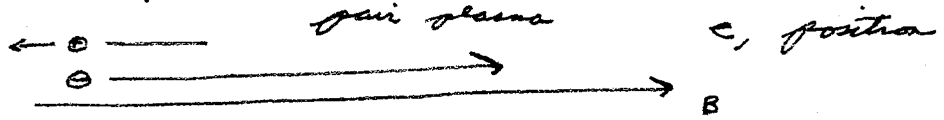
Another observational result — structuring in emission region.



7e.i — Pulsar plasma physics —

- gyromotion quantized close to pulsar surface (Landau orbitals)

- Basis of what is happening —



- Instability generated waves (Langmuir waves or generalization of Langmuir waves).

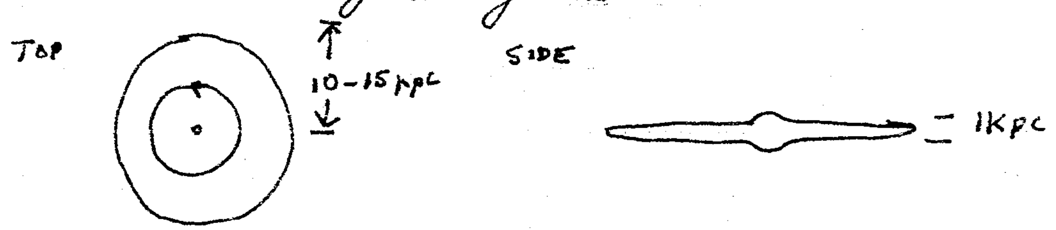
- These modes (at some point) couple into electromagnetic modes (radio waves), and are received. This is probably a nonlinear process similar to Type III solar bursts.

- The details of this are very poorly known at present. Recommendation: papers of Jonathan Arons.

7f — Galactic structure

Whole galaxies as physical systems with eigenfunctions.

- Consider spiral galaxies



Radio Astronomy

8. Opportunities in Radio Astronomy

- There are many radio observatories throughout the world, and they have programs for visitors, and have opportunities for collaboration.

- Radio astronomy primarily consists of study of diffuse gases, usually ionized, often populated with energetic particles. The theory of radio astronomy is close to that of plasma physics.

Examples of Radio Telescopes

8a — GMRT — (Giant Meter Wave Radio Telescope) Pune, India. Interferometer with large number of antennas. Observation at $f < 1.4$ GHz.

8b — ALMA — (Atacama Large Millimeter Array) Will be located on Atacama plateau in Chile. Will revolutionize study of molecular clouds.

8c — SKA — (Square Kilometer Array). Future radio telescope with huge collecting area. Would see radio emission from normal galaxies at cosmological distances.

Design studies underway in Netherlands, Australia, Canada, US, and China.

There are exciting ~~scientific~~ scientific discoveries to be made. New participants are welcome.