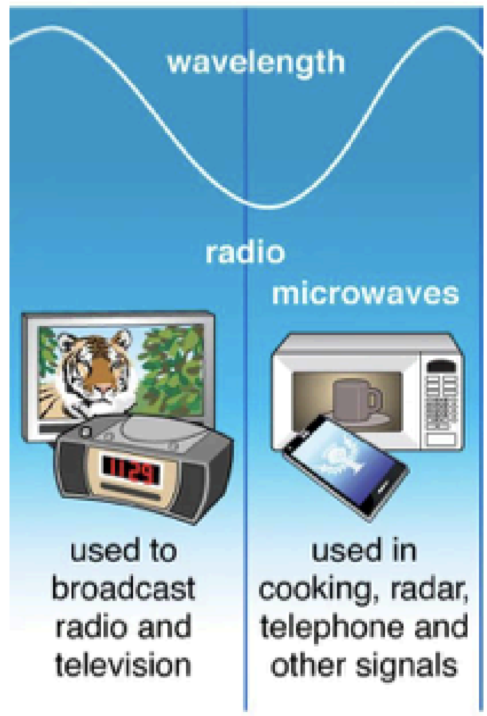
Lecture 3: Radio Astronomy and Compact Stellar Remnants [Answer Key]

Radio waves - light (electromagnetic radiation) with long wavelengths (1mm - 10m)

- The **ionosphere** reflects radio waves below 10 MHz, and the **Galactic ISM** absorbs radio waves below 2 MHz
- The **Federal Communications Commission** (FCC) and **International Telecommunications Union** (ITU) regulate the frequency spectrum and reserve specific "bands" (frequency/wavelength ranges) for communications, television, GPS, satellites, HAM radio, radio astronomy, and more.



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Rayleigh Jeans Law: $B_\nu(T) \approx \frac{2\nu^2 kT}{c^2}$ for low frequencies

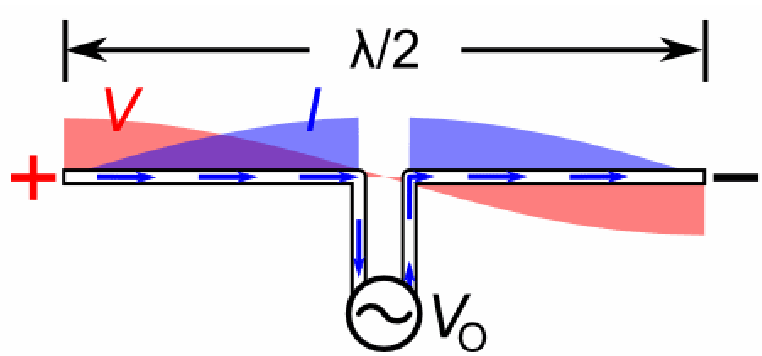
$h\nu \ll kT$

- **Brightness temperature**: $T_b = \frac{c^2}{2\nu^2 k} I_\nu$

Single-Dish Radio Telescopes

An **antenna** converts **radiation** in space into **electrical currents** and vice-versa

- **Superposition principle** - when two waves add together, they create a **resultant** wave equal to the sum at each point
- **Wave equation:** $y(x, t) = A sin(\frac{2\pi x}{\lambda}) sin(\frac{2\pi t}{\lambda})$
- **Standing wave** - incident and reflected wave on a string length L superimpose so it appears stationary in space for



any wave **modes** with $\lambda_n = \frac{2L}{n}, \nu_n = \frac{2L}{n}$

- A **Circuit** connects a conductive **wire** to a battery that generates a **voltage**, or potential, which causes electrons to flow creating a **current**
  - **Ohm's law:** $V = IR$
  - **Current** - rate of electron flow
  - **Alternating current** - current oscillates in time, meaning that charges are **accelerating**: $I(t) = I_0 sin(2\pi\nu t)$
  - **Just like waves on a string, a wire can carry a standing wave of current!**
  - **Transmitting:** a circuit driven with an oscillating current will radiate
  - **Receiving:** light waves can **induce** an alternating current on a wire
- **Half-wave dipole antenna**: simplest antenna, two wires with lengths equal to half the desired **wavelength** will be sensitive to waves with $\lambda_n = \frac{2L}{n}$
  - Radiation pattern: $P \propto sin^2\theta$

Sensitivity - measure of how effectively the antenna converts incident/driven power to received/transmitted power

- A **dish**, like a lens, focuses radio waves towards the antenna
- **Feed -** some antennas use a waveguide to collimate waves towards the antenna
- **Gain** (K/Jy) - power transmitted per unit solid angle in each direction ('antenna pattern')
  - **Primary beam** - the main lobe of the antenna pattern
  - For a circular dish, the **primary beam** is an **Airy disk,** just like for a circular lens!
  - **Primary beam solid angle -** $\Omega_A = \frac{4\pi}{G}$
- **Effective Area** - ratio of the output power to the incident flux from a given direction
  - **Reciprocity theorem:** the effective area is proportional to the gain!
  - $A_{eff}(\theta, \phi) = \frac{\lambda^2}{4\pi} G(\theta, \phi)$ → **an antenna with a larger dish will be more sensitive!**
- **Antenna Temperature** - **noise** temperature of a resistor that **dissipates** power equal to the antenna's output power: $T_A = P_\nu/k = T_{CMB} + T_{SKY} + T_{SYS}$
  - Incident light changes the **thermal energy** of the antenna, which changes the **speed of electrons** in the wire, which changes the level of **noise** we see → **all measurements on an antenna are noise measurements!**

- **Radiometer sensitivity** - minimum noise temperature[K] (or flux density[Jansky]) that a telescope can detect: $\sigma_T = \frac{T_A}{\sqrt{2\Delta\nu t_{samp}}} = G\sigma_S$

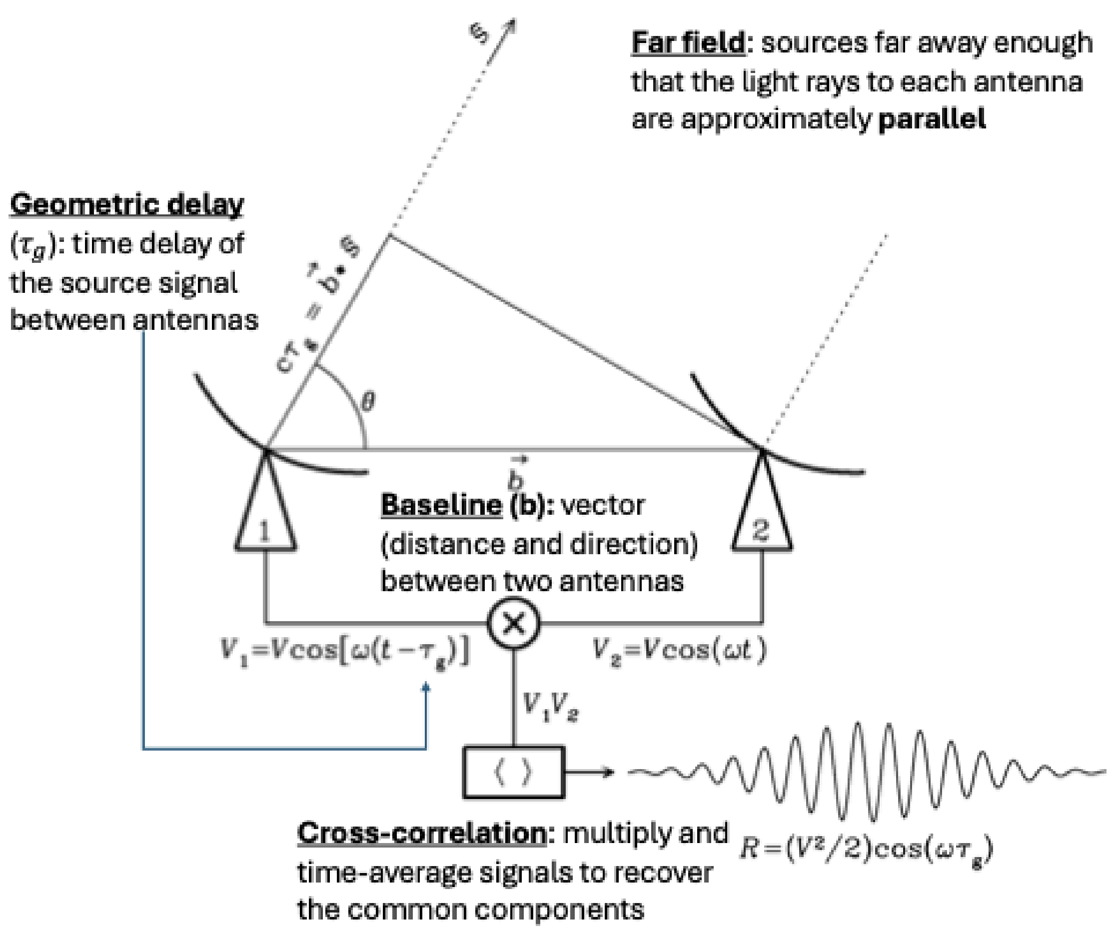
The **Green Bank Telescope (GBT; West Virginia)**, the **Parkes *Murriyang* Telescope (PMT; Australia),** and the **Five-Hundred Meter Aperture Spherical Telescope (FAST; China)** are examples of single dish telescopes.

- Single-dish telescopes are limited because they are expensive to build and the larger they're built, the less you can steer them mechanically; how can we achieve a narrower primary beam and higher sensitivity without building a bigger dish?

Radio Interferometers

Interferometry (or ‘aperture synthesis) is the process of combining data from multiple radio telescopes to increase the **effective area**

- An **interferometer** cross-correlates the voltages from each pair of antennas, accounting for the delay between them to recover the common signal
- An interferometer's **effective area** is equal to the equivalent of a single dish with diameter equal to the max baseline, $A_{eff} \approx \pi b_{max}^2$



- **Visibility** - cross-correlation of two antennas
- **Fringe pattern** - quasi-sinusoidal oscillations from constructive and destructive interference between two antenna signals
    - **Synthesized beamwidth** - spatial resolution of the antenna equal to the distance between the fringes: $\Delta\theta = \frac{\nu b}{c} = \frac{b}{\lambda}$
    - **Higher** frequencies or **longer** baselines produce more closely spaced fringes
    - Orientation of the fringes depends on the direction of a baseline
    - **Interferometers can achieve higher spatial resolution and sensitivity with multiple small dishes instead of one large dish**
- For N antennas, we can combine the visibilities using **beamforming:**
    - (1) compute visibility for each antenna pair
    - (2) apply the signal delay using a **complex exponential** (or by manually delaying) to align signals for a particular direction
    - (3) Add together the visibilities to get the total signal
    - The sensitivity of an N-antenna beamformer is $\sigma_{T,int} = \frac{T_{tot}}{\sqrt{N(N-1)\Delta\nu t_{samp}}} = \frac{\sigma_T}{\sqrt{N(N-1)}}$
    - We can repeat for different locations on the sky to form multiple "beams"
- **Radio imaging** - alternate way to combine visibilities to form "beams" (pixels) across the field-of-view all at once
    - (1) *gridding*: arrange the antenna visibilities on a grid based on each antenna pair's East-West (U) and North-South (V) separation
    - (2) *FFT:* Take the 2-dimensional **Fast-Fourier Transform (FFT)**:

      $$F[l, m] = \sum_{U=0}^{N} \sum_{V=0}^{N} f(U, V) e^{-i2\pi(Ul + Vm)/N}$$
    - (3) *clean:* iterative convolution with the point-spread function to remove the effect of the sidelobes

The **Deep Synoptic Array (DSA-110; California), the Karoo Array Telescope (MeerKAT; South Africa) and the Very Large Array (VLA; New Mexico)** are examples of interferometers.

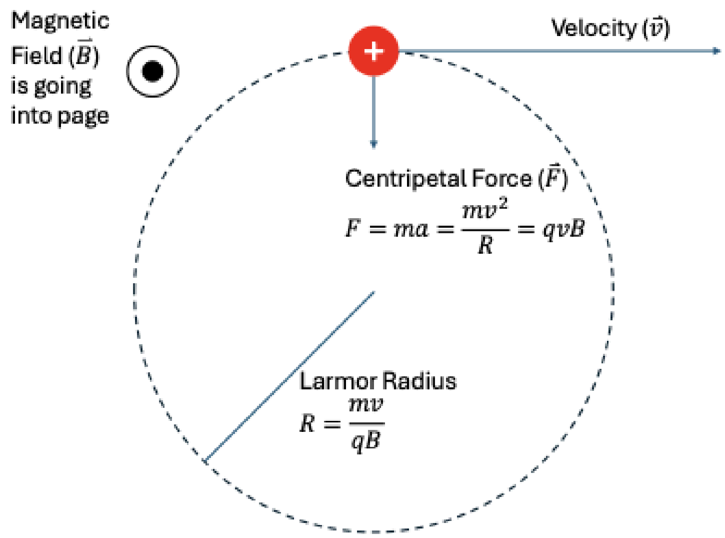
Very Long Baseline Interferometry (VLBI) - uses maximum baselines ~1000s of kilometers/miles to achieve high spatial resolutions ~milliarcseconds

- This has some added difficulties: long delay times, ionospheric calibrations, curvature of the Earth, movement of UV coordinates must be taken into account

- Examples include the **Very Long Baseline Array (VLBA)** and the **Event Horizon Telescope (EHT)**

Astronomical Radio Sources

Radio waves are produced by sources with relativistic charged particles accelerating in strong magnetic fields, in high density regions



Larmor Radiation

- **Electric field** - exerts force on charged particles in the **same direction** as the field: $F_E = qE$
- **Magnetic field** - exerts force on **moving** charged particles in a direction **perpendicular** to the field and direction of motion: $F_B = q(v \times B)$
  - In a magnetic field, charges will move in a **circle**
  - If it moves at an angle to the B field, the charge moves in a **helix**
  - **Cyclotron motion** - nonrelativistic ($\gamma << 1$)
  - **Synchrotron motion** - relativistic ($\gamma >> 1$)
- **Lorentz force -** total electromagnetic force: $F = F_E + F_B$
- **Larmor radiation** is electromagnetic radiation produced by an **accelerating** charge
  - **Cyclotron radiation** - power radiated by a **non-relativistic** charge in circular motion around a magnetic field: $P_{rad} = \frac{2q^2a^2}{3c^3}$
  - **Synchrotron radiation** - power radiated by a **relativistic** charge in circular motion around a magnetic field: $P_{rad} = \frac{2q^2a^2}{3c^3}\gamma^2$ → power is boosted when moving faster
- **Incoherent** radiation - N particles radiate separately in same region ($P_{total} = N \times P_{rad}$)
- **Coherent** radiation - N particles radiate in phase ($P_{total} = N^2 \times P_{rad}$)

- **Sources can be seen at astrophysical distances when radiating coherently and relativistically**

Diffuse Radio Synchrotron Emission

- In regions with ionized hydrogen, there are many **free electrons** which produce synchrotron emission
- **HII regions -** doubly ionized hydrogen, lots of free electrons, so we see lots of radio emission
- **Galactic plane** - in dense regions of the galaxy, we see the most synchrotron radiation

Cosmic Microwave Background (CMB) - blackbody radiation from the hot, dense early universe when it was in thermal equilibrium at 2.725 K

- **Anisotropies** (deviations from perfect blackbody) tell us about structure formation and evolution ~380 kyrs after the Big Bang

Supermassive Black Holes

- **Active Galactic nuclei -** highly magnetized SMBHs at centers of galaxies which gravitationally pull in matter that form high luminosity accretion disks
- **Jets -** infalling matter can be collimated by AGN's magnetic field and ejected near speed of light; accelerating ions and electrons produce radio emission
- **Shocks** - ejected material exceeds the local sound speed, causing rapid turbulent flow of material in forward and backward directions; charges within the shocks generate **synchrotron radiation**

21 cm Hydrogen Transition

- **Spin**- quantum mechanical property of particles
    - **fermions** (e.g. electrons, positrons) are spin-½ meaning they can have $s = \pm 1/2$
    - **bosons** (e.g. protons, neutrons) are spin-1 meaning they can have $s = 0, \pm 1$
- **21 cm line -** emission of photon when Hydrogen electron transitions from s=+½ to s=-½ ; main tracer of Hydrogen gas in galaxies which informs about star formation
- **21 cm cosmology** tries to detect an all-sky signal to learn about the evolution of galactic structure from the early universe

White Dwarf "Polars" - White Dwarf - M Dwarf binaries which produce coherent, periodic radio emission by streaming charged particles between the stars' magnetic poles.

- E.g. AR Scorpii produces radio emission at beat frequencies between the 3.6 hour orbital period and 1.95 rotation period (Geng et al., 2016; Stanway et al., 2018)
- **Long Period Radio Transients** - suspected to be magnetically locked polars (rotation period and orbital period synched) so that their pulses arrive on the orbital period (e.g. ILT 1101, GLEAM-X J0704)

Neutron Star "Pulsars" - remnants of massive stars, which often produce radio emission from their magnetic poles

- **Slow Pulsars (0.3-10 s):** produce coherent radio emission from magnetic poles via charged particle 'avalanche'
- **Millisecond Pulsars (<0.3 s):** initially lost their rotational energy, then accreted from companion to spin up to millisecond periods
- **Rotating Radio Transients (RRATs):** only detectable through single pulses because of irregular nulling
- **Magnetars (>2s):** largest magnetic fields, produce giant flares and pulses that exceed rotational energy

Fast Radio Bursts- Extragalactic radio bursts lasting <1ms with unknown source mechanism; leading candidates are magnetars

- In 2020, an FRB-like burst was detected from a Galactic magnetar, SGR J1935+54, making magnetars the primary candidates (e.g. Bochenek et al., 2020)
- First FRB (The Lorimer Burst), detected by the Parkes telescope, was determined extragalactic due to the large frequency-dependent **dispersive** delay