Radio Science: Lecture 2

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1. The Radio Sky
2. Radio Emission Mechanisms
   - Basics
   - Line Emission
   - Continuum Emission

Table of Contents

The Radio Sky

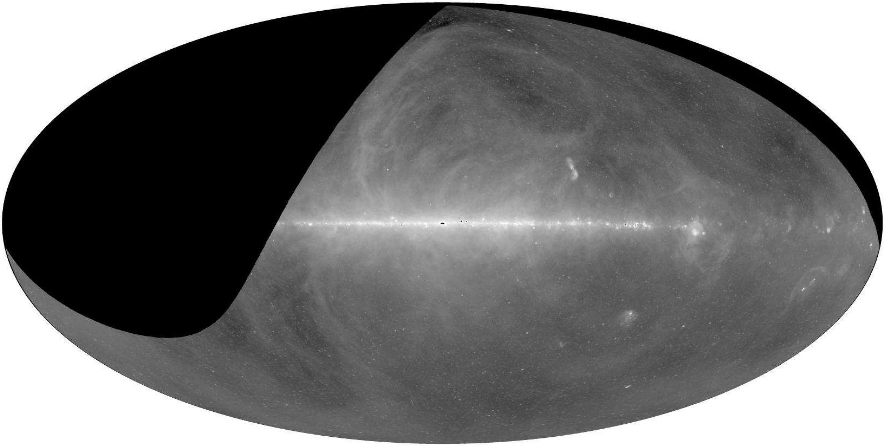


Figure : Radio Continuum Image of the Sky at 1.4 GHz, Calabretta et al. 2013

Common Types of Radio Sources

- AGN Powered Radio Sources
  - Radio Quasars
  - Radio Galaxies
  - BL-Lac Type Radio Sources
- Non-AGN powered radio sources
  - Supernova Remnants
  - Star-forming Galaxies

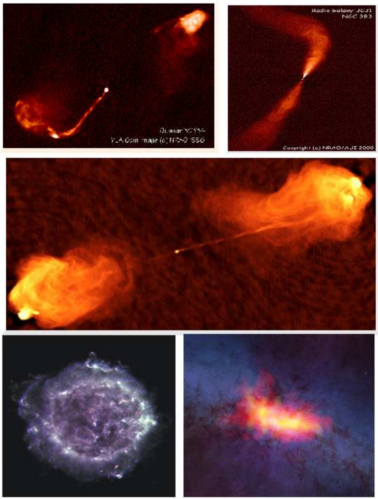


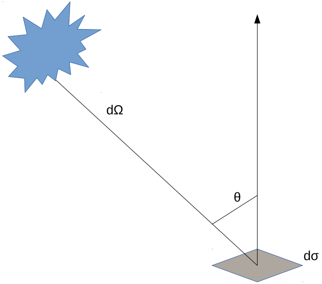
Figure : Image courtesy of NRAO/AUI,Bill Saxton (NRAO/AUI/NSF); Hubble/NASA

Units and Typical Scales

- Flux density: Jansky - 1 Jy $= 10^{-26} Wm^{-2} Hz^{-1}$
- Typical Flux density ranges $\sim 10^{-9}$ Jy to ~ 100 Jy for radio sources in the sky.
- Distance: Parsec - 1 pc $= 3.08 \times 10^{16}$ m
- Typical Observational Frequencies: ~ 10 MHz to ~ 1000 GHz

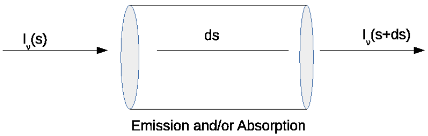
Table of Contents

Basics



- $dP = I_\nu \; cos\theta d\sigma \; d\nu d\Omega$
- I_ν, specific intensity - with units of $W \; m^{-2} \; Hz^{-1} \; sr^{-1}$
- Flux density $=$ $S_\nu = \int I_\nu(\theta, \phi) \; cos\theta \; d\Omega$

Radiative Transfer I



The change in specific intensity, or the radiative transfer equation:

$$\frac{dI_\nu}{ds} = -\kappa_\nu \, I_\nu + \epsilon_\nu \tag{1}$$

which gives, in TE, $\frac{dI_\nu}{ds} = 0$ implying $I_\nu = \frac{\epsilon_\nu}{\kappa_\nu} = B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1}$.

Radiative Transfer II

- More generally, in LTE, $I_\nu(s) = I_\nu(0)e^{-\tau_\nu(s)} + \int_0^{\tau_\nu(s)} B_\nu(T(\tau))e^{-\tau}d\tau$, where $d\tau_\nu = -\kappa_\nu\, ds$ is the optical depth
-

Radiative Transfer III

Radiation from Accelerating Charged Particles

Radio Emission Mechanism

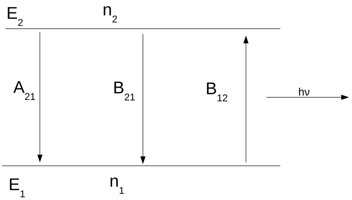
- Line Emission
  - Radio Recombination Lines
  - 21 cm Radiation
- Continuum Emission
  - Bremsstrahlung
  - Synchrotorn Emission
  - Inverse Compton

Line Emission

- Line emission - emission is confined to a narrow range in frequency.
- Arises out of energy level transitions - $h\nu = E_2 - E_1$, where h is Planck's constant, ν is the frequency of the emission and E_2 and E_1 are the energy levels.
- Examples:
  - Recombination Lines
  - 21 cm Neutral Hydrogen

Einstein Coefficients

- Line emission/absorption from any system can be characterized by the Einstein Coefficients:
  - A_{21}: The spontaneous emission coefficient
  - B_{12}: The Absorption coefficient
  - B_{21}: The Stimulated Emission Coefficient.



In case of a system in local thermodynamic equilibrium (LTE):

$$n_2 A_{21} + n_2 B_{21} U = n_1 B_{12} U \quad (2)$$

Einstein Coefficients and Radiative Transfer

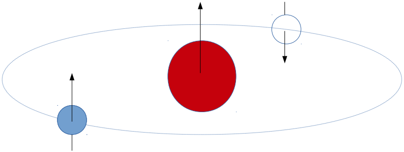
- The radiative transfer equation characterized by ϵ_ν and κ_ν.
- Relating ϵ_ν and κ_ν to Einstein Coefficients
- In general, ϵ_ν, $\kappa_\nu \equiv \epsilon_\nu, \kappa_\nu(n_1, n_2, A_{21}, B_{12}, B_{21})$.
- Simplifying scenarios - systems in TE/LTE.

Recombination Lines I

Recombination Lines II

21-cm Line for Neutral Hydrogen I

- Arises out of hyperfine transition between two states of the electron in the Hydrogen atom.
- Extremely small transition probability: $A_{21} = 2.68 \times 10^{-15} s^{-1}$.



21-cm Line for Neutral Hydrogen II

Rotation Curves

Epoch of Reionization

Continuum Emission

Bremsstrahlung

Starburst Galaxies: HII regions

Synchrotron Emission I

Synchrotron

Radio Galaxies

Starburst Galaxies: Supernova Remnants

Summary