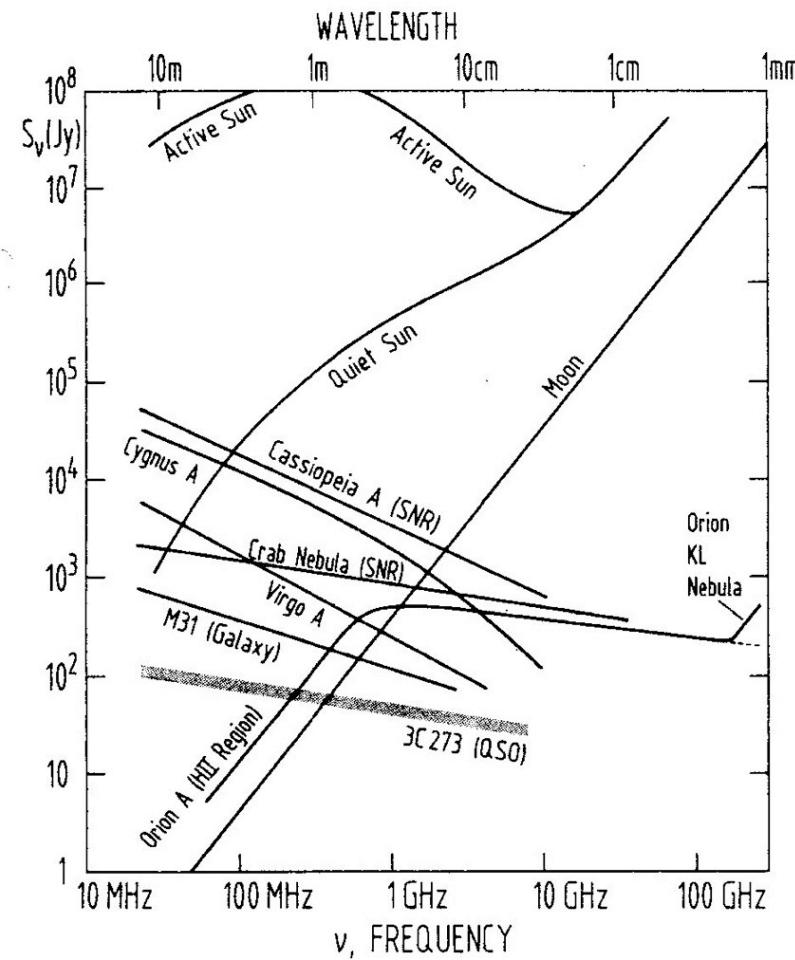


# Radio Astronomy

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  - NCUIoA S4-914/ASIAA Rm716

# The Radio Sky

- Surveys
  - spatial distribution of radio emission
    - smooth or discrete
  - spectral distribution of radio emission
  - observation bias intensity v.s. resolution

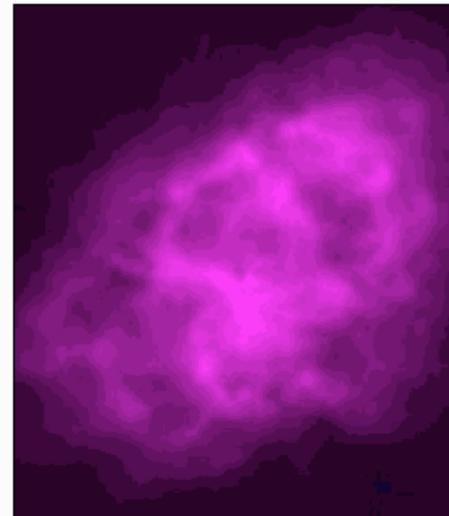


# Galactic Radio Astronomy - SNR

- Observations of supernovae :The Crab

Crab Nebula: a star that died in 1054

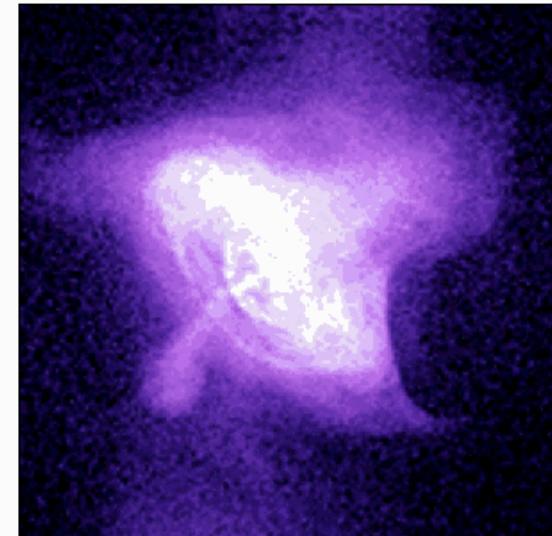
RADIO



OPTICAL



XRAY



# Galactic Radio Astronomy - SNR

- Observations of supernovae : Cassiopeia A (Cas A)

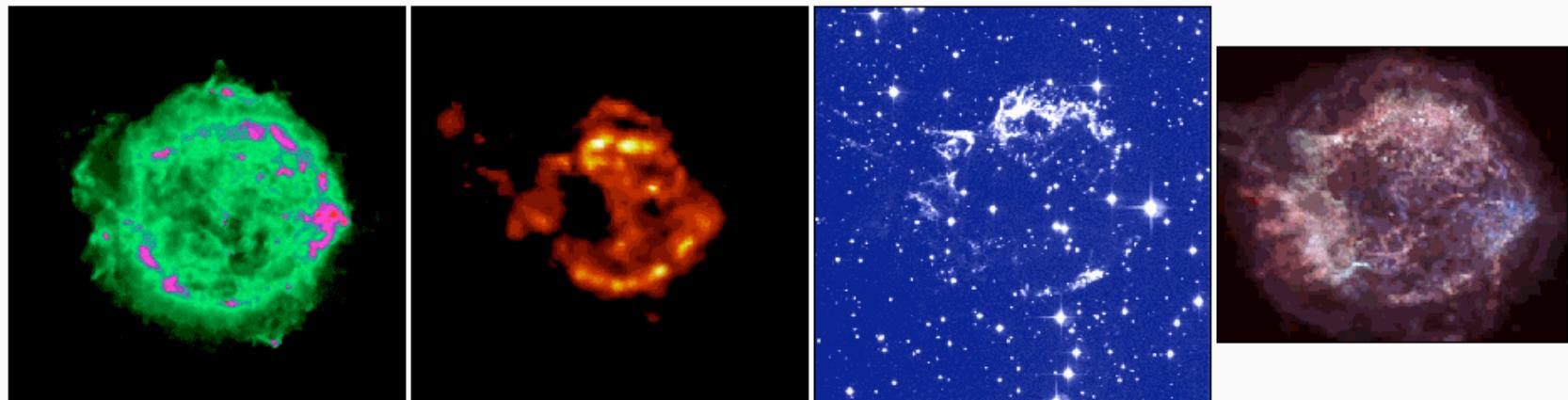
Cassiopeia A: a star that died in  $\sim$ 1700

RADIO

INFRARED

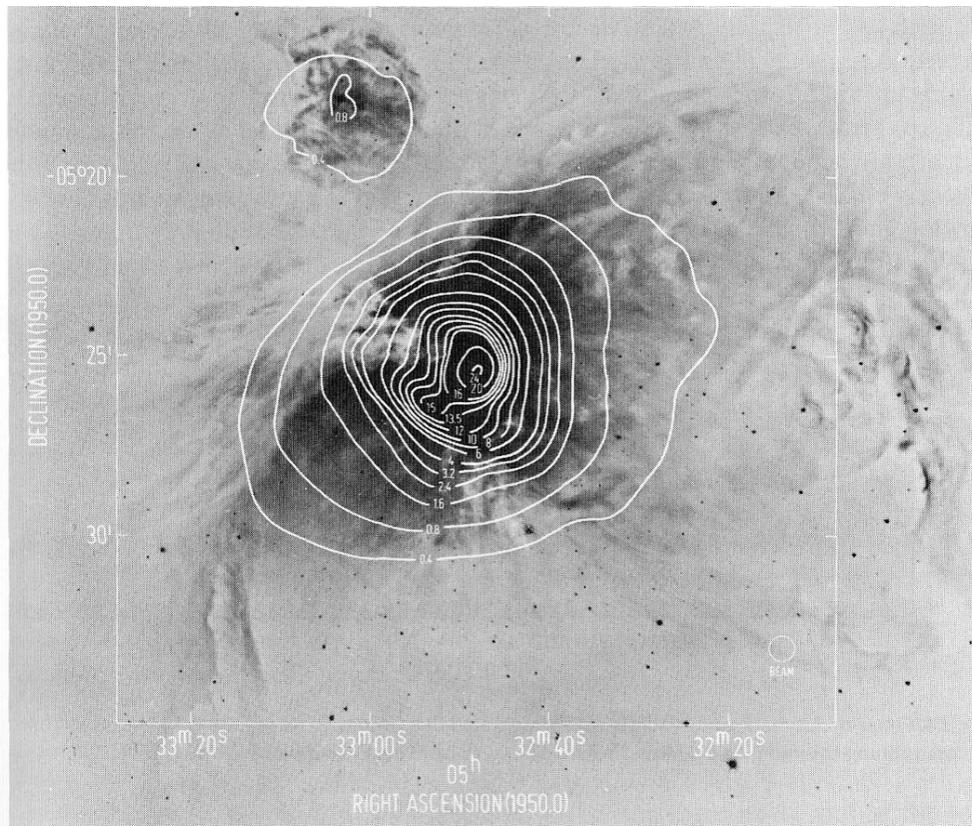
OPTICAL

XRAY



# Galactic Radio Astronomy - HII Regions

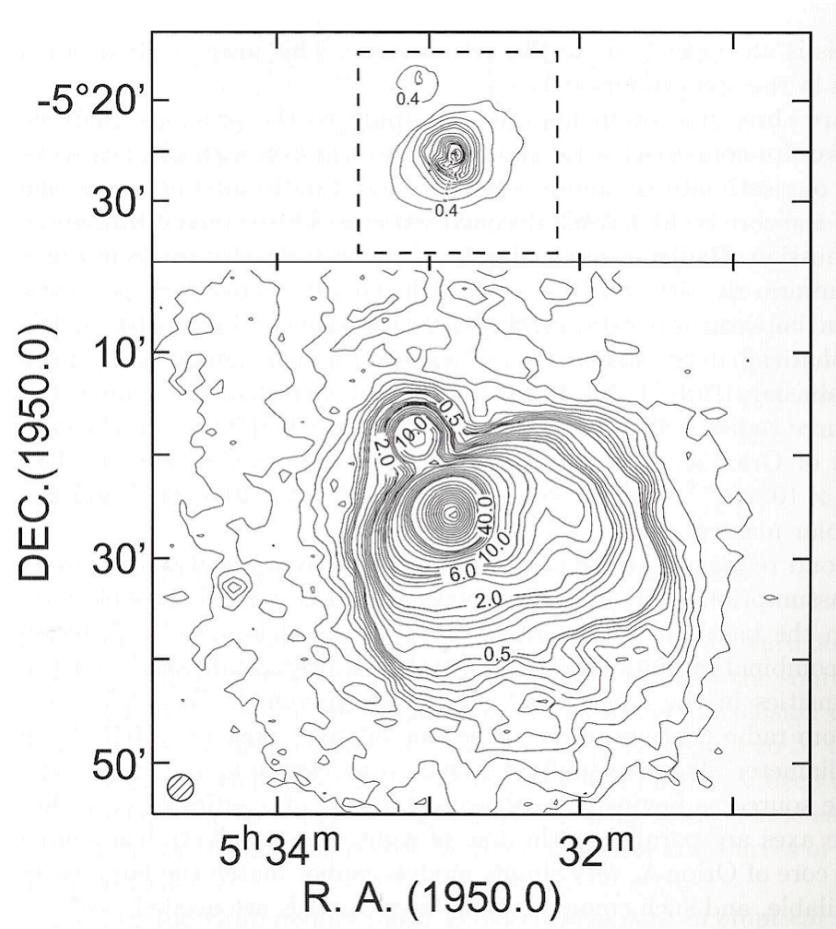
- Observational Results:



**Fig. 2.3.** The 23-GHz radio continuum contours, in units of main-beam brightness temperature, on an optical photo in H $\alpha$  and [NII] of NGC 1976 (Orion A, M42), below, and NGC 1982 (M43), above. The angular resolution is 42'', which at the distance of Orion A, corresponds to a linear resolution of 0.10 pc (Wilson and Peale 1984).

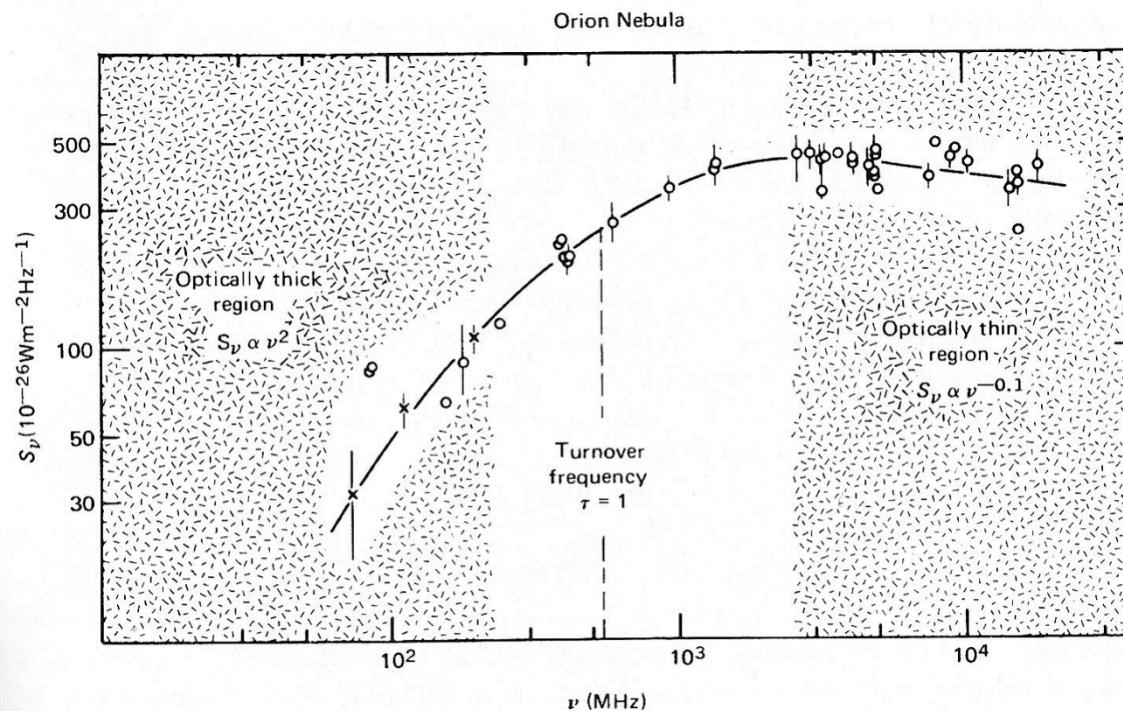
# Galactic Radio Astronomy - HII Regions

- Observational Results:



# Galactic Radio Astronomy - HII Regions

- Observational Results:

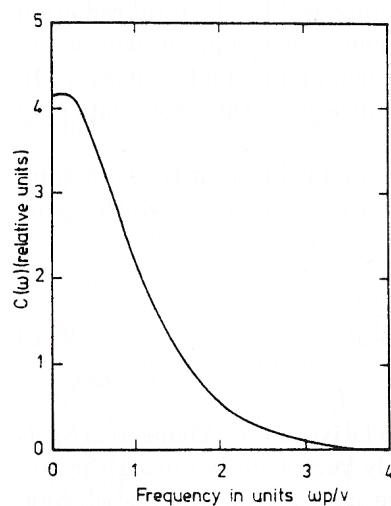


**Fig. 2.2.** Spectral flux density of the Orion Nebula plotted against frequency. The shaded regions mark the optically thick and thin regions of the spectrum. (Reprinted with permission by Gordon and Breach Science Publishers from: Terzian, Y. and Parrish A., *Astrophysical Letters*. Vol. 5(1970), pp. 261.

# Galactic Radio Astronomy - HII Regions

- Emission Mechanism - Bremsstrahlung Radiation
  - single charge

radiation spectral energy distribution for single electron

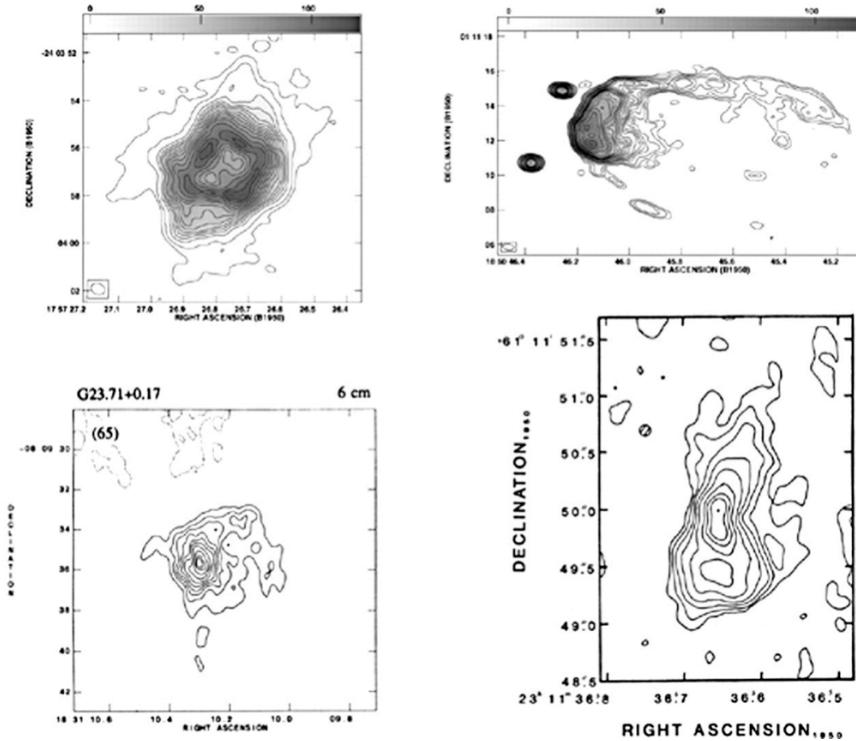


$$P_v(p, v) = \begin{cases} \frac{8Z^2e^6}{3c^3m^2} \frac{1}{p^2v^2} & \text{for } v < v_g = \frac{3\pi v}{32p} \\ 0 & \text{for } v \gtrapprox v_g \end{cases}$$

velocity      impact parameter

# Galactic Radio Astronomy - HII Regions

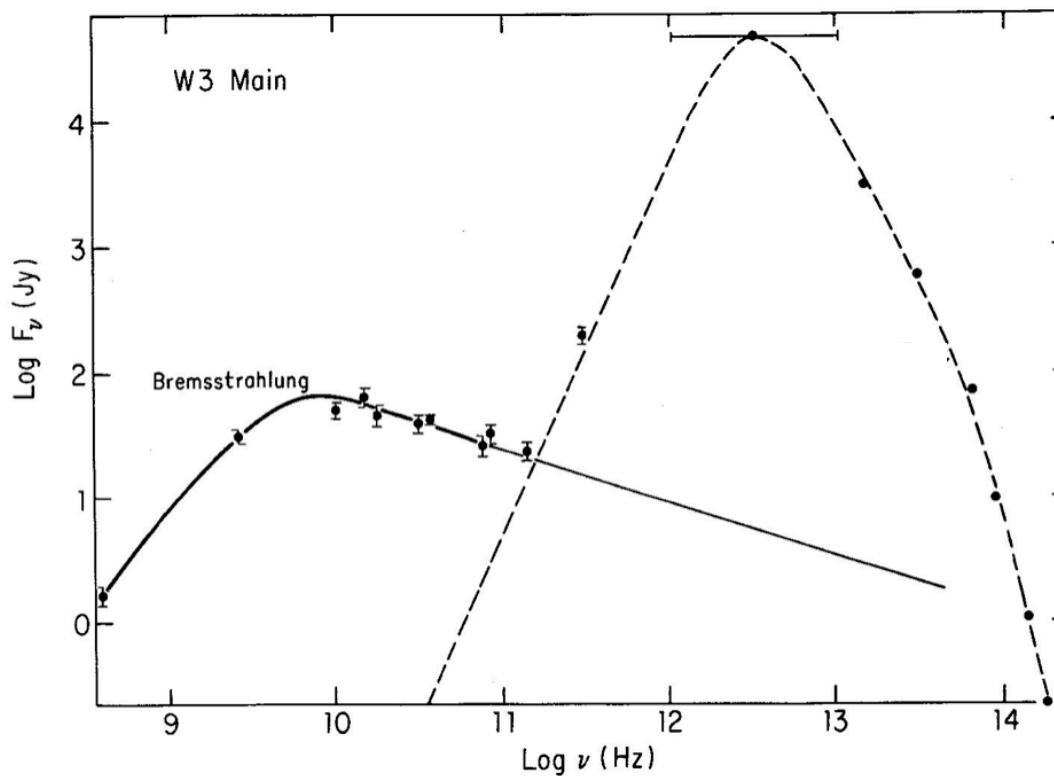
- Observational Reality I : Morphology and Lifetime
  - Morphology



- Lifetime for UC HII regions
  - observationally estimated 1e5 yrs v.s. expected 1e4 yrs

# Galactic Radio Astronomy - HII Regions

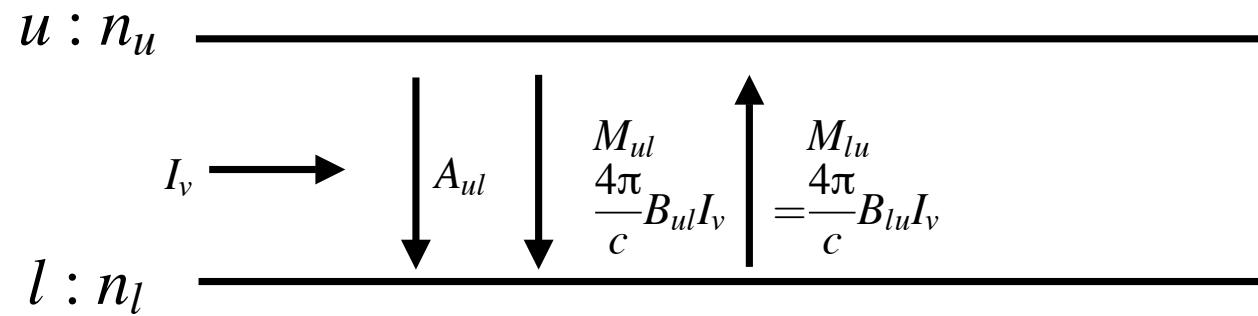
- Observational Results:



**Fig. 2.4.** Open circles mark observations of the integrated flux from the HII region W3 Main. Solid line: bremsstrahlung emission; dashed line: thermal emission from dust. (Malkamäki et al., 1979).

# Radio Astronomy - Line Emission

- Line Emission Mechanism : consider two-level system with only radiative processes



# Radio Astronomy - Line Emission

- Line Emission Mechanism : consider two-level system with only radiative processes
  - macroscopic

$$dE_e(\nu) = h\nu_0 n_u A_{ul} \phi_e(\nu) dV \frac{d\Omega}{4\pi} d\nu dt$$

$$dE_a(\nu) = h\nu_0 n_l B_{lu} \frac{4\pi}{c} I_\nu \phi_a(\nu) dV \frac{d\Omega}{4\pi} d\nu dt$$

$$dE_s(\nu) = h\nu_0 n_u B_{ul} \frac{4\pi}{c} I_\nu \phi_e(\nu) dV \frac{d\Omega}{4\pi} d\nu dt$$

$$dE_e(\nu) + dE_s(\nu) - dE_a(\nu) = dI_\nu d\Omega d\sigma d\nu dt$$

$$dE_e(\nu) + dE_s(\nu) - dE_a(\nu) = \frac{h\nu_0}{4\pi} [n_u A_{ul} + n_u B_{ul} \frac{4\pi}{c} I_\nu - n_l B_{lu} \frac{4\pi}{c} I_\nu] \phi(\nu) d\Omega d\sigma ds d\nu dt$$



$$\frac{dI_\nu}{ds} = -\frac{h\nu_0}{c} [n_l B_{lu} - n_u B_{ul}] I_\nu \phi(\nu) + \frac{h\nu_0}{4\pi} n_u A_{ul} \phi(\nu)$$

$$\begin{aligned} \kappa_\nu &= \frac{h\nu_0}{c} [n_l B_{lu} - n_u B_{ul}] \phi(\nu) \\ &= \frac{h\nu_0}{c} n_l B_{lu} \left[ 1 - \frac{g_l}{g_u} \frac{n_u}{n_l} \right] \phi(\nu) \end{aligned}$$

$$\frac{dI_\nu}{ds} = -\kappa_\nu I_\nu + \varepsilon_\nu$$



$$\epsilon_\nu = \frac{h\nu_0}{4\pi} n_u A_{ul} \phi(\nu)$$

# Radio Astronomy - Line Emission

- Line Emission Mechanism : consider two-level system with only radiative processes

- microscopic

$$\bar{I} = \int I_\nu \phi(\nu) d\nu \quad \int \phi(\nu) d\nu \equiv 1$$
$$\bar{U} = 4\pi \bar{I}/c$$

- if equilibrium

$$n_u A_{ul} + n_u B_{ul} \bar{U} = n_l B_{lu} \bar{U}$$

- if (local) thermodynamical equilibrium

$$\frac{n_u}{n_l} = \frac{g_u}{g_l} e^{-h\nu_0/kT}$$

- from the above two

$$\bar{U} = \frac{A_{ul}}{\frac{g_l}{g_u} e^{\frac{h\nu_0}{kT}} B_{lu} - B_{ul}} \quad \bar{U} = \frac{4\pi}{c} B_\nu(T) = \frac{8\pi h\nu^3}{c^3} \frac{1}{e^{\frac{h\nu_0}{kT}} - 1}$$

- from the above two

$$A_{ul} = \frac{8\pi h\nu_0^3}{c^3} B_{ul} \quad g_l B_{lu} = g_u B_{ul}$$

# Radio Astronomy - Line Emission

- Molecular Line Emission Mechanism : consider two-level system with only radiative processes
  - A quick look of Einstein A
    - check the simple electric dipole case

$$d(t) = e \ x(t) = e \ x_0 \ \cos(\omega t)$$

$$P(t) = \frac{2}{3} \frac{e^2 \dot{v}(t)^2}{c^3}$$

$$\begin{aligned}\langle P \rangle &= \frac{64\pi^4}{3c^3} \nu_{ul}^4 \left( \frac{e x_0}{2} \right)^2 \\ &= h\nu_{ul} A_{ul}\end{aligned}$$

$$A_{ul} \equiv \frac{64\pi^4}{3hc^3} \nu_{ul}^3 |\mu_{ul}|^2$$

- What about magnetic dipole transitions?

# Radio Astronomy - Line Emission

- Line Emission Mechanism :
  - In general
    - multi-level
    - not only radiative, but also collisional, etc processes
    - non-LTE
    - but still,

$$\frac{dn_l}{dt} = -n_l \sum_m \sum_i R_{lm}^i + \sum_m n_m \sum_i R_{ml}^i$$

$R_{ml}^i$  : transition rate between level m and l through process i

- for equilibrium

$$\frac{dn_l}{dt} = 0$$