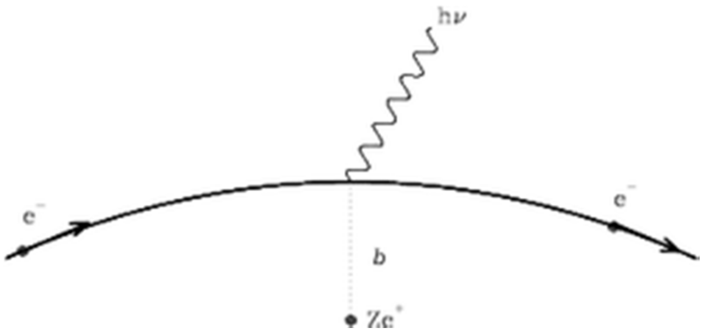
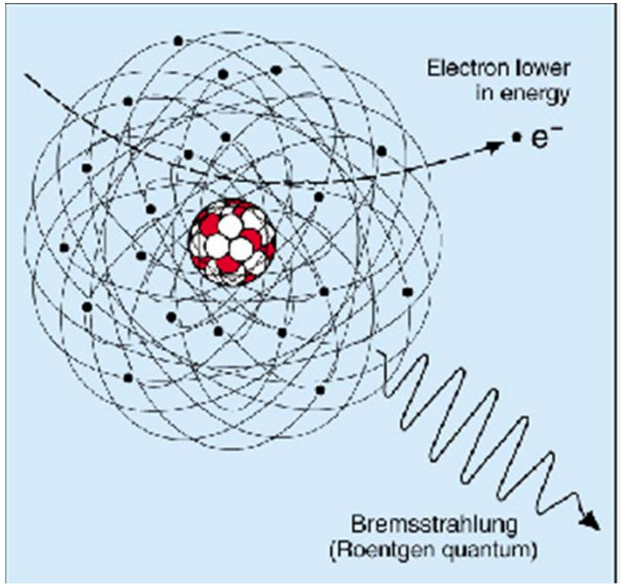
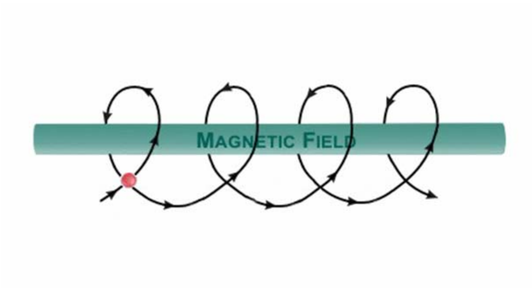
Thermal Emission

Hot, low-density plasma (e.g., HII regions, PNe, SNRs)
→ thermal radio emission



http://www.astro.utu.fi/~cflynn/





c.f.
Synchrotron
Radiation

Emission lines → $T_e \sim 10^4$ K, so in radio wavelengths

$h\nu \ll kT$ and $B_\nu \approx \frac{2kT\nu^2}{c^2}$

f-f emission $j_\nu \approx \dfrac{n_e n_i}{T_e^{1/2}} \longrightarrow \boxed{\kappa_\nu = j_\nu / B_\nu \approx \dfrac{n_e n_i}{T_e^{3/2}\nu^2}}$

Emission Spectrum

$$j_\nu^{ff} = 6.8\times10^{-38} Z^2 n_e n_i T^{-1/2}\, e^{-h\nu/kT}\, \bar{g}_{ff} \text{ ergs s}^{-1}\text{ cm}^{-3}\text{ Hz}^{-1}$$

Where $\bar{g}_{ff}$: velocity averaged Gaunt factor ~ 1

Total Emission Power (Volume Emissivity) $= \int j_\nu^{ff}\, d\nu$

$$j^{ff} = 1.4 \times 10^{-27} Z^2 n_e n_i T^{-1/2} \bar{g}_B \text{ ergs s}^{-1}\text{ cm}^{-3}$$

Where $\bar{g}_B$: frequency average of the velocity averaged Gaunt factor ~ 1.1-1.5

Considering the Gaunt factor, G ~ ln (T/ν)

$$\therefore \quad \boxed{\tau = \int \kappa_\nu \, ds = \frac{8.235 \times 10^{-2}}{T_e^{1.35} \nu^{2.1}} \, \mathrm{EM}}$$

where $\mathrm{EM} = \int n_e n_i \, ds \; [\mathrm{cm}^{-6} \; \mathrm{pc}]$, ν in GHz

That is, low ν (long λ) → τ↑

Plasma is transparent at high frequencies

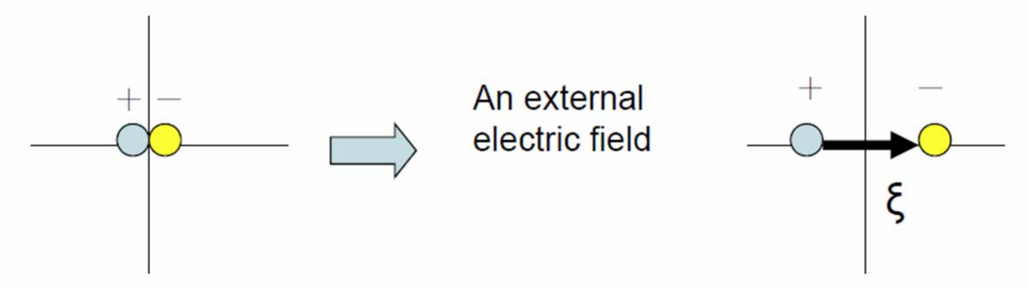
At high freq. $\tau \ll 1$,

$$I_\nu = B_\nu \tau \propto \frac{2kT\nu^2}{c^2} \frac{EM}{T^{3/2}\nu^2} \propto \frac{EM}{T^{1/2}} \quad \cancel{\longleftrightarrow} \quad \nu$$

At low freq. $\tau \gg 1$

$$I_\nu = B_\nu = \frac{2kT\nu^2}{c^2}$$ Blackbody $\cancel{\longleftrightarrow}$ n_e

Plasma Frequency



The dipole moment $\vec{P} = -n\,e\,\vec{\xi}$ points from (–) to (+); *n*: electron density

Plasma dielectric constant σ;

$$\vec{J} = \sigma \vec{E}$$

Net charge=0, so $\vec{D} = 0$

$$\vec{D} = \vec{E} + 4\pi\vec{P} \rightarrow \vec{E} = 4\pi\,n\,e\,\vec{\xi}$$

In 1-D, $E_x = 4\pi\,n\,e\,\xi$,

and the force is $F_x = -eE_x$

$$m\frac{d^2\xi}{dt^2} = -eE_x = -4\pi n e^2 \xi$$

(Taking $\frac{\hat{d}}{dt} = j\omega$) $\longrightarrow$ $-m\omega^2 = -4\pi\,n\,e^2$

$$\omega_p = \sqrt{\frac{4\pi n e^2}{m}} = 5.6 \times 10^4 \sqrt{n} \text{ rad s}^{-1}$$

or

$$\boxed{\nu_p = 8.97 \times 10^3 \sqrt{n} \text{ Hz}}$$ This is called the **plasma frequency**

Index of refraction $n_r^2 = 1 - \frac{\omega_p^2}{\omega^2}$

…for which the wave number

$$k = 2\pi/\lambda = 2\pi/(v/\nu) = 2\pi T/v = \omega/(c/n_r)$$ $$\boxed{k = \frac{\omega}{c}(1 - \frac{\omega_p^2}{\omega^2})^{1/2}}$$

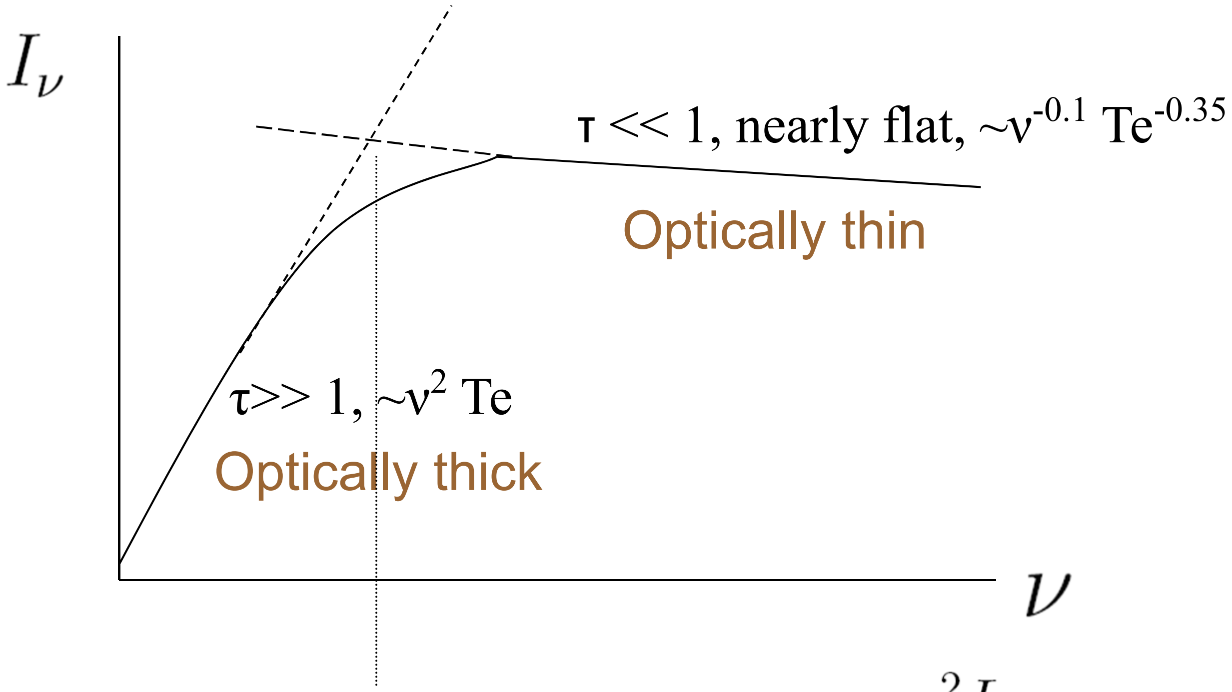
If $\omega > \omega_p$, k is real ⟶ Electrons cannot follow

If $\omega < \omega_p$, k is imaginary ⟶ Electrons follow the motion
→ absorption → no propagation

- **Metal** --- $\nu_p \sim 10^{15}$ Hz, i.e., in UV region; so metal absorbs EM waves until UV, i.e., transparent to UV radiation
- **Earth's ionosphere** --- n_e depends on height; at H=300 km, n_e~10^5-10^6, $\nu_p \sim 10^7$ Hz, λ~30 m

  cf. shortwave radio signals get reflected by ionosphere
- **ISM** --- n_e~ a few, $\nu_p \sim 10^4$ Hz (very low), so usually $\nu >> \nu_p$ ➔ transmission ok

Now back to radio thermal emission…



τ << 1, nearly flat, ~$\nu^{-0.1}$ $T_e^{-0.35}$

Optically thin

τ>> 1, ~ν^2 Te

Optically thick

$$\tau = 1, \text{at } \nu_{\text{critical}} = 0.3\left(\frac{n_e^2 L}{T^{1.35}}\right) \text{ GHz}$$

Obs at τ>> 1 → get T ⟷ Obs at τ<< 1

→ Get n_e

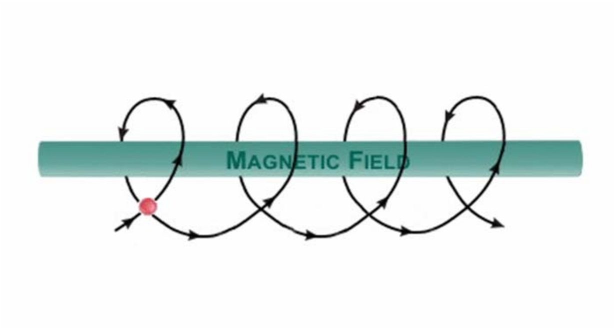
Adv. of radio observations: less extinction; measures T directly at low freq.

In general, I_v or $S_v \sim v^{\alpha}$, where α is the spectral index.

For H II regions, if optically thin $\alpha \fallingdotseq 0$

if optically think $\alpha = +2$

For synchrotron radiation, $I_v \sim v^{-0.8}$ or $T_B \sim v^{-2.8}$



http://www.nrao.edu/whatisra/mechanisms.shtml

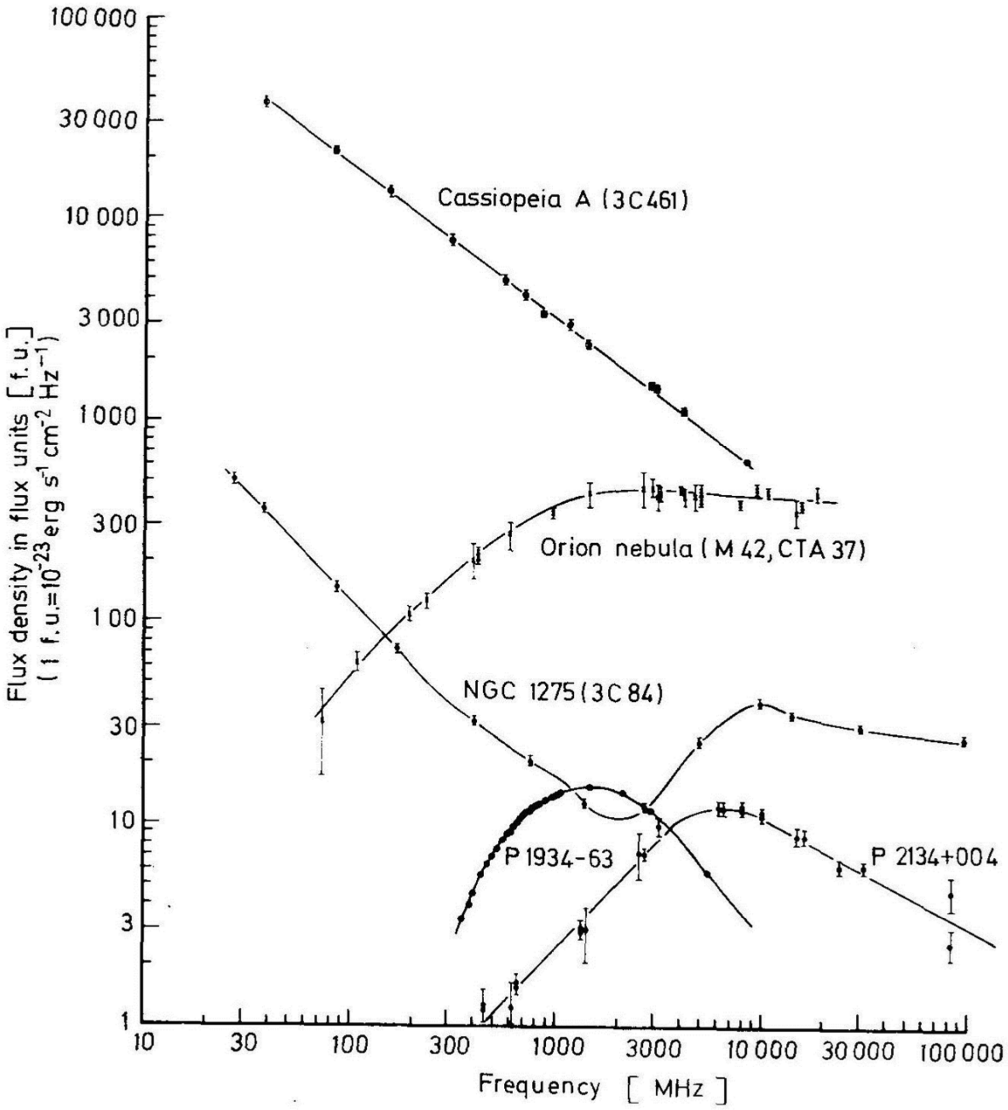
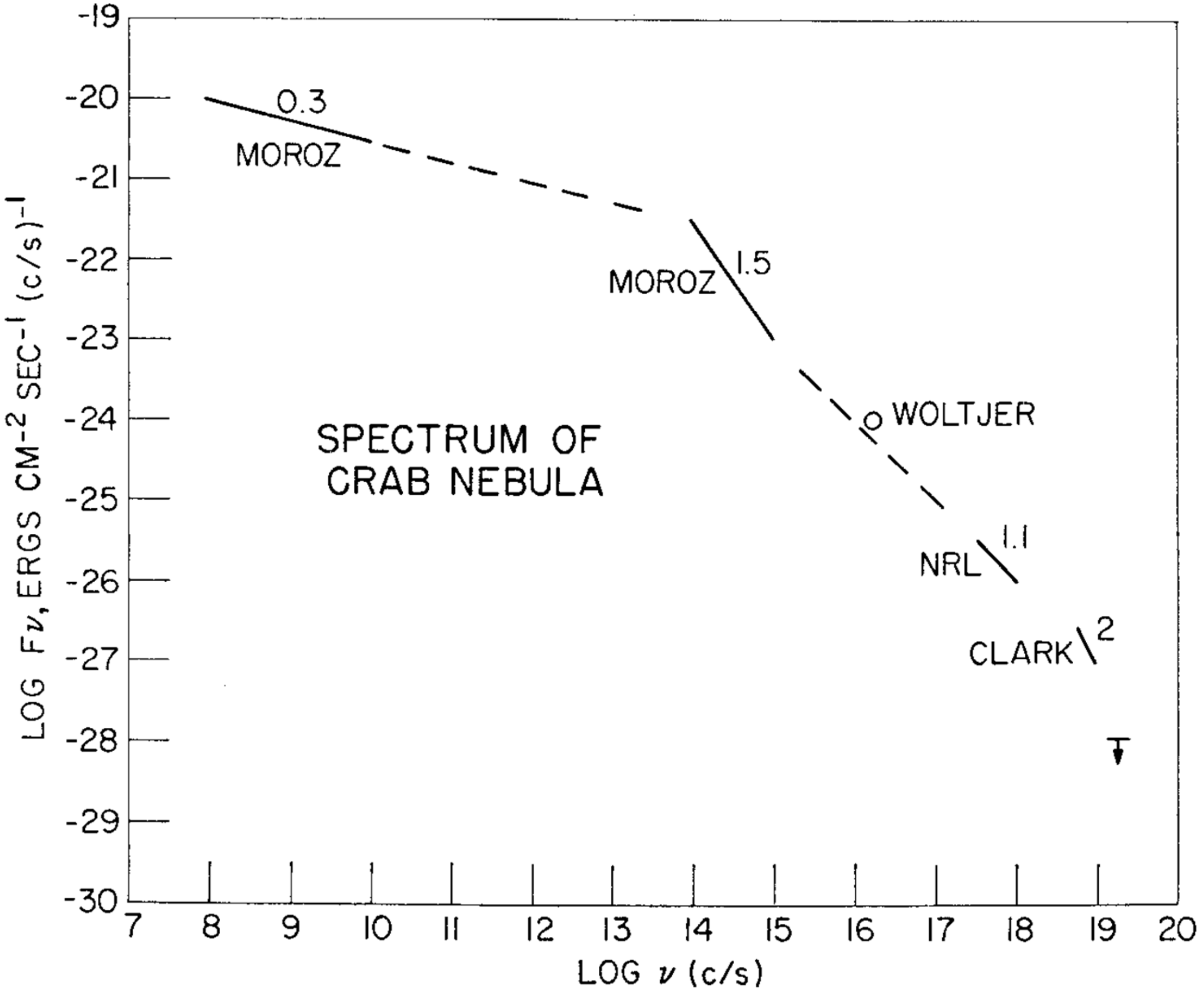
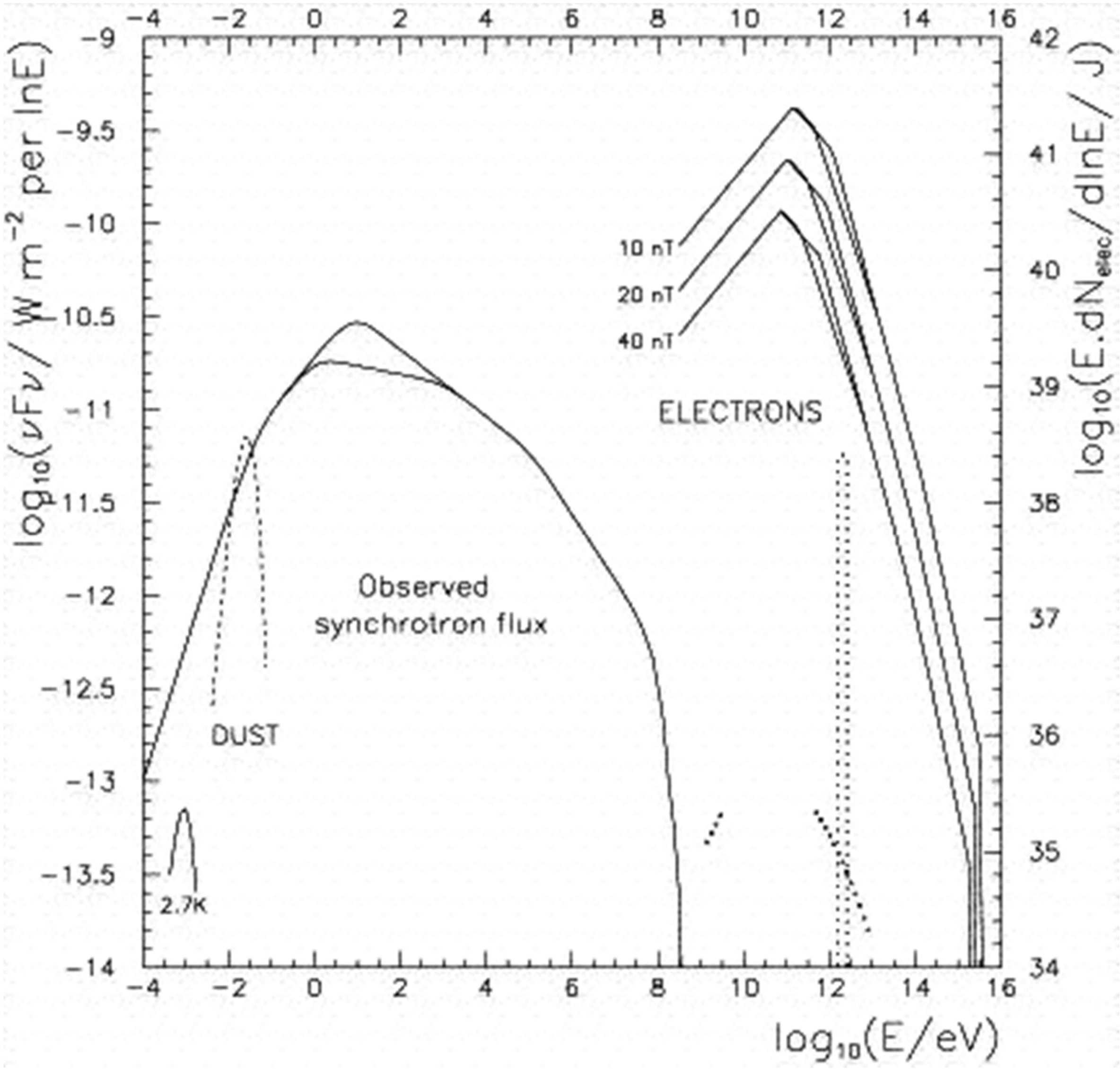


Fig. 4. Radiofrequency spectra of sources exhibiting the power law spectrum of synchrotron radiation (Casseopeia A), the flat spectrum of thermal bremsstrahlung radiation with low frequency self absorption (Orion Nebula), unusual high frequency radiation (NGC 1275), and low frequency absorption processes (P 1934 − 63 and P 2134 + 004). The data for P 2134 + 004 are from E. K. Conklin, and the other data are from Kellermann (1966), Hjellming, and Churchwell (1969), Terzian and Parrish (1970), Kellermann, Pauliny-Toth, and Williams (1969), and Kellermann *et al.* (1971)

Lang



Spectrum of Crab Nebula from radio to X-ray wavelengths
(Middlehurst & Aller)

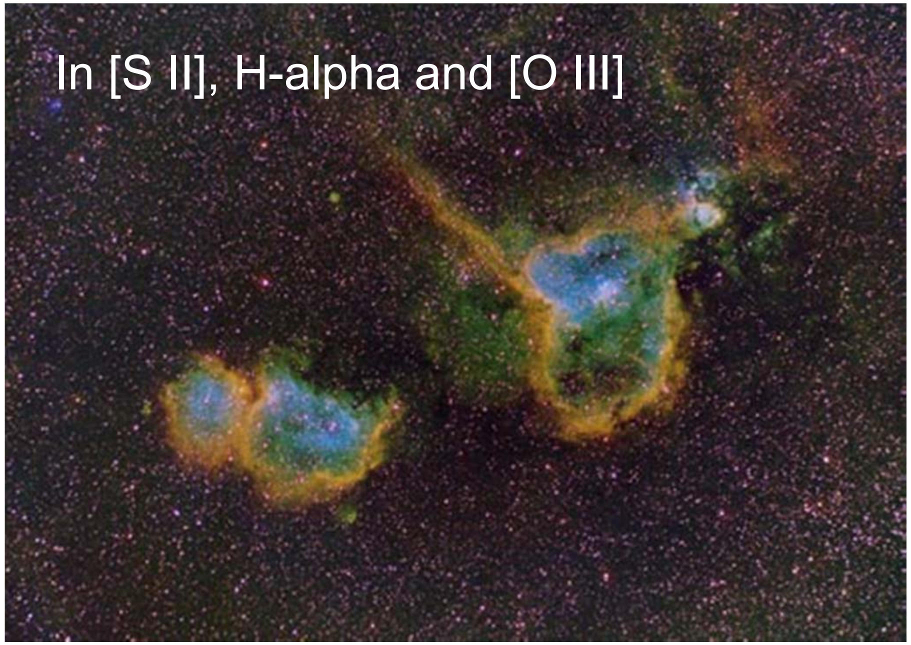


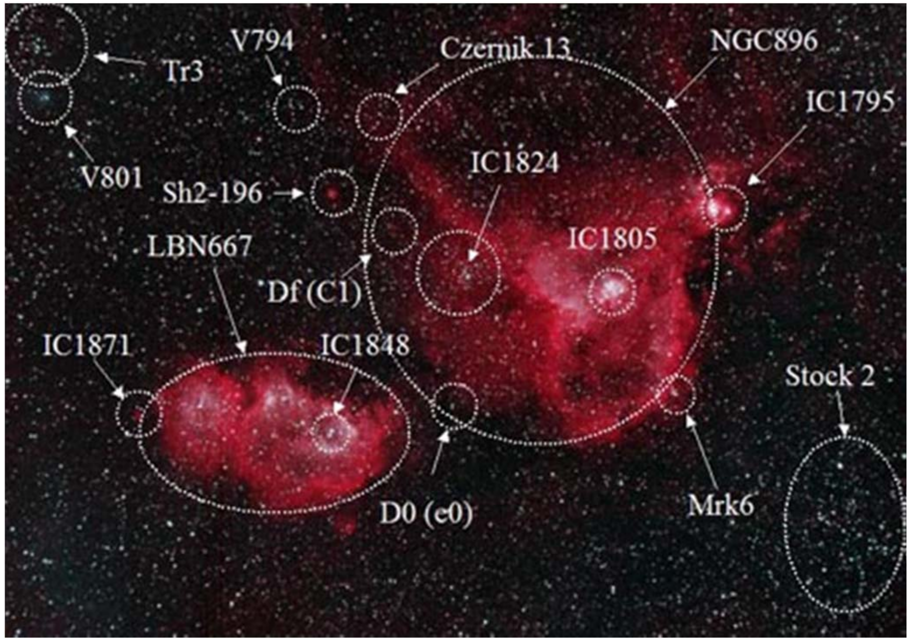
Spectrum of the Crab over a very wide range of energies. The emission is dominated by synchrotron radiation, and at at very high energies (1010-12 eV) there may be an inverse-Compton component. Source

Hillas (1998), ApJ, 503, 744

http://www.astro.utu.fi/~cflynn/astroII/l4.html

W3= IC 1795





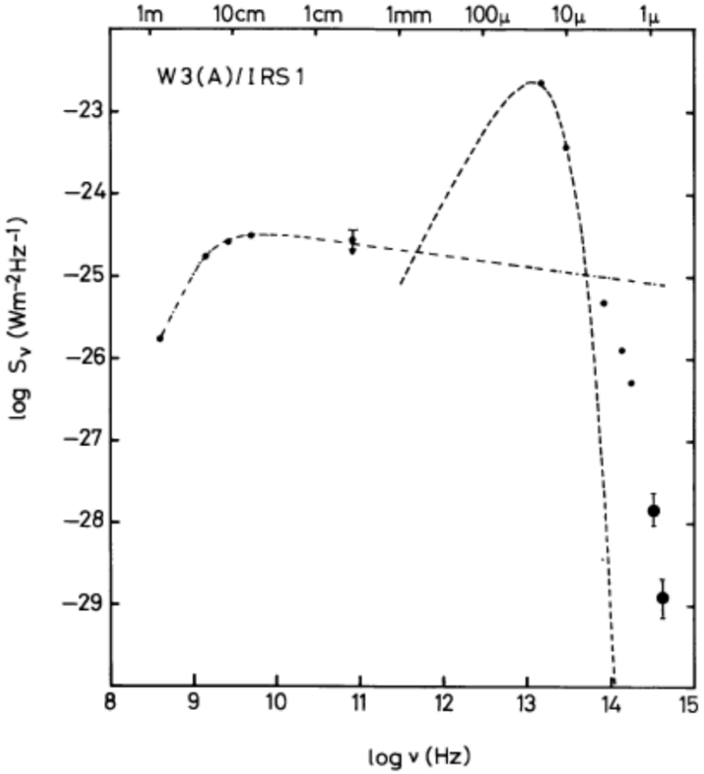
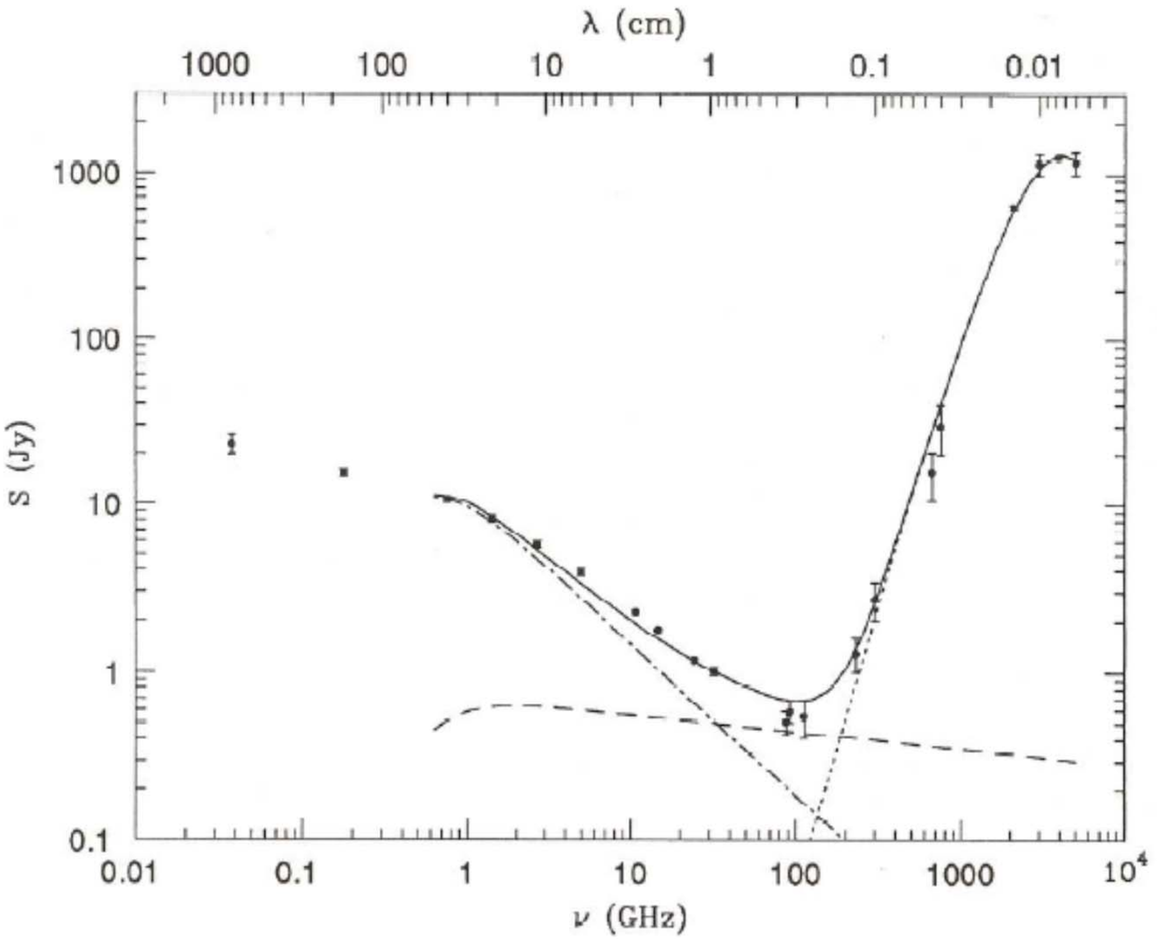


Fig. 2. Energy distribution of IRS 1 according to Wynn-Williams *et al.* (•) together with flux densities in *I* and *R* (●). Dashed lines: Predicted free-free emission from ionized hydrogen and thermal infrared radiation of dust, represented by Planck-curve with temperature $T = 200$ K

Beetz et al. (1974)
A&A, 34, 335


λ (cm)
1000
100
10
1
0.1
0.01
S (Jy)
1000
100
10
1
0.1
0.01
0.1
1
10
100
1000
10^4
ν (GHz)