4.2½ Heating & Cooling in H II Regions
4.3 Ionization Fraction & Chemical Balance in PDRs

Interlude –
→ Real Spectrum of an H II Region

4.2 ½ "Thermodynamic State of H II Regions" (what is T_e?)

$\Gamma - \Lambda = 0$ for equilibrium

Recall: $n_H \int_{\nu_0}^{\infty} \frac{4\pi J_\nu}{h\nu} a_\nu(H) d\nu = \frac{\text{ionizations}}{\text{time} \cdot \text{volume}}$

Γ: Heating (due to Photoionization)

from last time

ioniz. x-sectn

$$\boxed{\Gamma_{photoionization} = n_H \int_{\nu}^{\infty} \frac{4\pi J_\nu}{h\nu} h(\nu - \nu_0)\, a_\nu(H^\circ)\, d\nu \; (\text{erg cm}^{-3}\,\text{s}^{-1})}$$

$(h\nu - h\nu_0)$ ⟷ This factor gives "x energy"

The energy above $h\nu_0$ in each ionization is $h(\nu - \nu_0)$

That extra energy → K.E. of electrons

the distribution of K.E.'s is given by a Maxwellian because the x-sectn for e-e collisions is very high

i.e. $\boxed{\sigma_{ee} \approx 10^{-13}\text{ cm}^2 \gg a_\nu \approx 6 \times 10^{-18}\text{ cm}^2}$

so ~ as soon as e^- created, it will find the pre-existing distr. of e^- which have a Boltzmann dist @ T_e ("e^- are rapidly thermalized")

(initially it depends on $J_\nu a_\nu / h(\nu - \nu_0)$ but that information is quickly lost)

Recall J_ν = mean intensity of radiation field $= \frac{1}{4\pi}\int I_\nu d\Omega$

$4\pi J_\nu - 4\pi J_\nu \frac{\nu_0}{\nu} = 4\pi J_\nu\left(1 - \frac{\nu_0}{\nu}\right)$
$4\pi J_\nu\left(\frac{\nu - \nu_0}{\nu}\right)$

Λ : Cooling inside H II Regions ... radiation by...

a) Recombination b.) free-free c.) line cooling

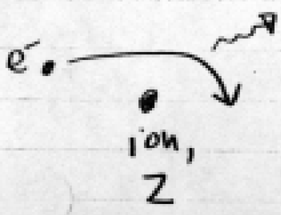
a.) $$\boxed{\Lambda_R = n_e n_p k T_e \, \beta_2(H^\circ; T)}$$

β_2 = recomb coeff averaged over Boltzmann v-dist @ T_e
(counting only recomb to $n \geq 2$)

note: for $n_e = n_p = 1$ & $T = 10^4$ K $\left[\Lambda_R \cong 10^{-25} \text{ erg cm}^{-3} \text{s}^{-1} \right]$

b) $$\Lambda_{ff} = 4\pi \underset{\substack{\uparrow \\ \text{emissivity for ff}}}{j_{ff}} = 4\pi \int_0^\infty j_\nu \, d\nu$$

(From analyzing interaxn energy as we did for ion-heat)



$$= \frac{2^5 \pi e^6 Z^2}{3^{3/2} h m c^3} \left(\frac{2\pi k T}{m} \right)^{1/2} g_{ff} \, n_e n_p$$

$$\boxed{\Lambda_{ff} = 1.42 \times 10^{-27} Z^2 T^{1/2} g_{ff} \, n_e n_p}$$ $\propto T_e n_e^2$

g_{ff} ← gaunt factor

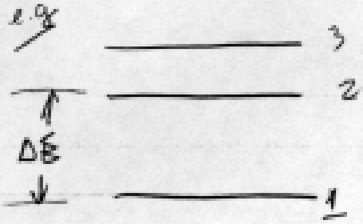
note: for $n_e = n_p = 1$ & $T = 10^4$ K $\left[\Lambda_{ff} \cong 10^{-25} \text{ erg cm}^{-3} \text{s}^{-1} \right]$
(see handout fig 5.8)

c.) Cooling by Line Radiation from Collisionally Excited Atoms ← Most Important!!

(next page)

c.) cont'd (line cooling)

e.g.



$\swarrow$ @ $T \sim 10^4 K$

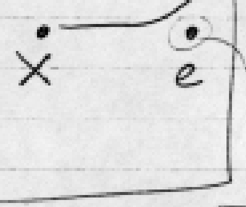
this is too big for H & He, usually smaller for other elements

Basic Idea! Convert KE of e^-/ion gas into escaping radiation.

Some atom w/@ least one bound e^- = "X"

$$X^* \longrightarrow X + h\nu$$

photon escapes H II region & thereby radiates away energy



e^- loses KE in collision

collison → Radiation

X-sectns for collis 10^5 x grtr than for radiative capture

TOO HIGH!!

For H, $\Delta E_{21} = 13.6 eV = k(1.6 \times 10^5\ K)$

For certain impurities (eg. O^+, O^{++}, N^+) $\boxed{\Delta E \approx kT_e}$

important coolants (scarce: if more abundant, H II reg would cool off fast)

∴ each excited state for each element has its own e^--collision x-sectn & detailed calculations are needed...

But as an example (see Spitzer 1978 Fig 6.1)

Λ_{OII} @ $T = 10^4 K$ is $\sim 10^{-24}$ erg cm^{-3} s^{-1}

for $n_e = n_p = 1$ this is $\gg \Lambda_{ff}$ or Λ_R

for just 1 line!

Note: w/o line cooling $T_{H II\ reg} \sim 2.6 \times 10^4 K$

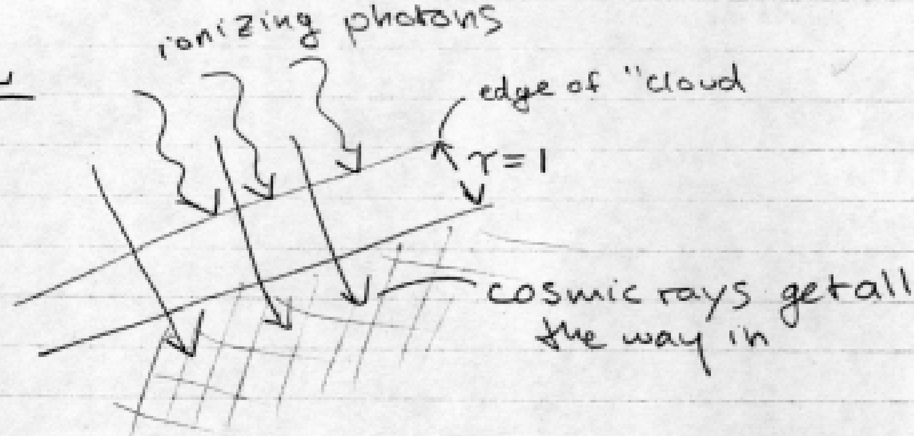
actually more like $\gtrsim 10^4 K$

So, this means ultimately T_e is determined by

$$\boxed{\Gamma_{photoioniz} = \Lambda_{line\ cooling} + \Lambda_{free\text{-}free} + \Lambda_{R(recomb)}}$$

4.3 —One Point Moot— Ionization Fraction & Chemical Balance in PDRs

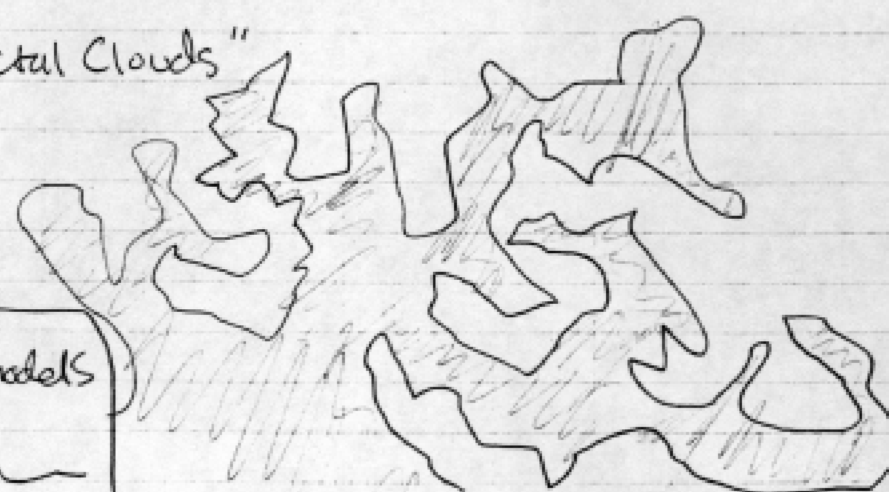
Old View



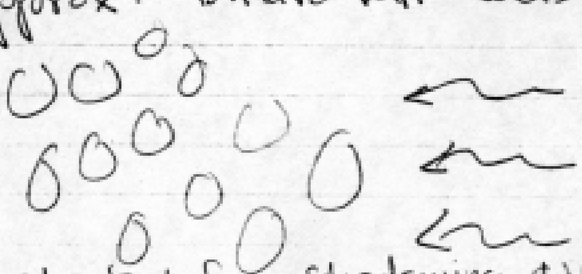
So, ionization in "exterior" layers (& hence chemistry — recall importance of ion-neutral reaxns) is "photon-dominated" — interior ionization from cosmic rays only.

New View "Fractal Clouds"

Where is $\tau = 1$ surface??



1st approx: Billard Ball models

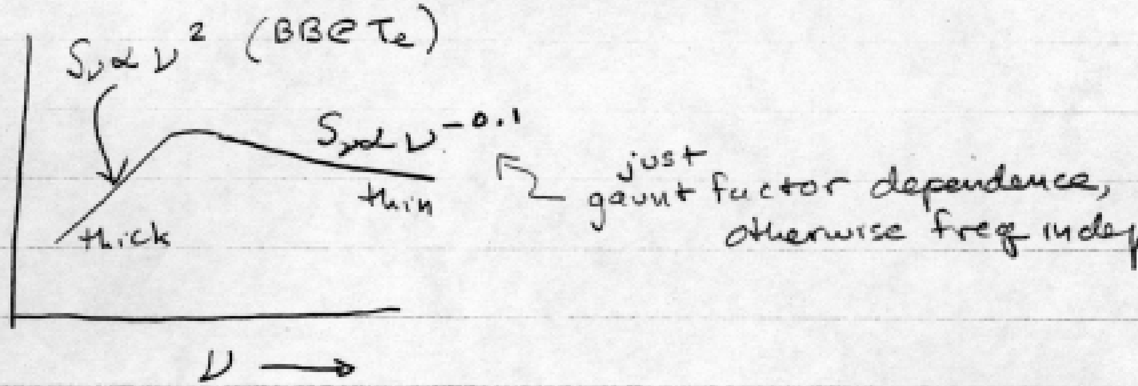


τ gets to 1 from shadowing & in densest balls

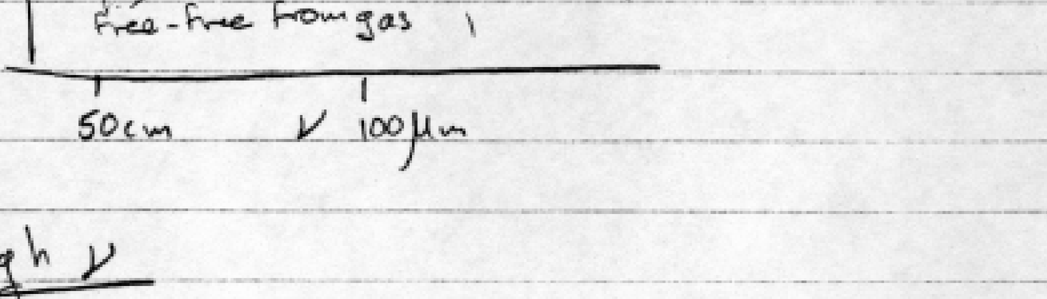
"Real" Spectrum of an H II Region

(Problem Set 4) / ... hints / handouts ...

Lowest ν dominated by free-free (Radio)



Medium ν : Dust re-radiation important

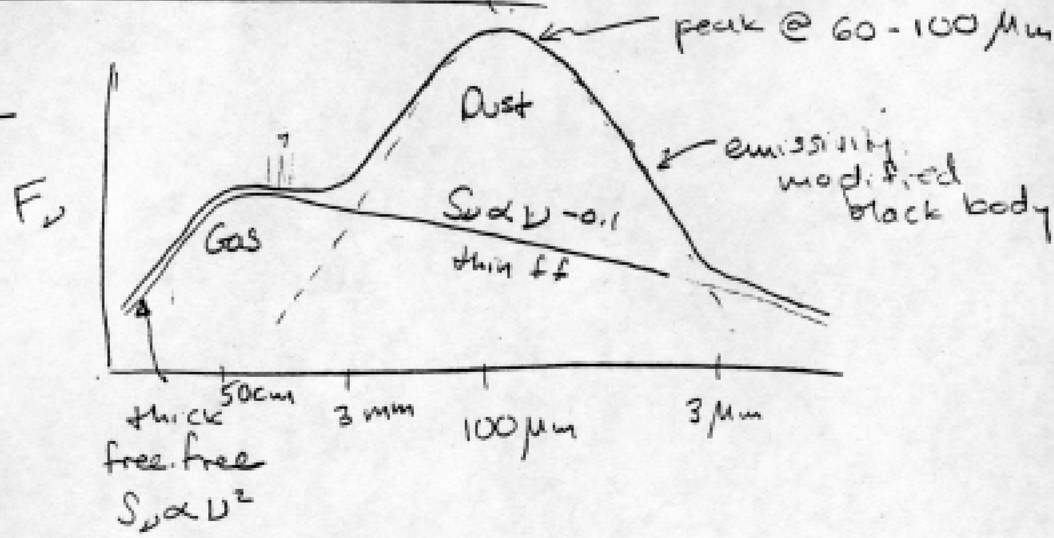


High ν

Lots of spectral lines... dominant coolants...

Real "Spectrum" of HII Region:

Last time:



This time: What about spectral lines superimposed on this? (consider today only those w/ origin <u>in</u> HII region, e.g. NOT abs lines due to foreground neut. material)

"Recombination Lines"

$\dot{e}^- + \dot{p}^+ \rightarrow$ excited H $\rightarrow$ less excited H

$\downarrow$

LINES from each step in ladder

Note on notation:

<u>Radio</u>

H76α

hydrogen line

principal quantum # of <u>lower</u> state

$\Delta n = 1$

(Recomb Lines, cont'd.)

Unfortunate optical notation

		Radio	Optical
Balmer line of H (optical)	$n=3 \rightarrow 2$ ($\Delta n = 1$)	H2α	"Hα" → "pink" glow of HII regions
Lymon line of H (ultraviolet)	$n = 2 \rightarrow 1$ ($\Delta n = 1$)	H1α	"Lyα"

When $n \sim 100$ & $\Delta n = 1$ frequencies are "radio"

At $n < 40$ → "optical recombination lines"

see: Spitzer 1978 § 3.3a

calculations complicated by: ① $\Delta\nu_{ul}$ > Doppler width

calc. level populations hard

② What happens to Lyα

Case A: HII reg opt thin to Lyα; $h\nu$ escapes w/o reionizing anything

Case B: thick to Lyα; Lyα abs'b'd & converted to longer λ

Significance of Recombination Lines

- ratio of $\frac{\text{energy radiatied in line}}{\text{energy in underlying continuum}}$

like a ~ "partition function"

giving ratio $\frac{\text{bound}}{\text{free}}$ electrons

$\rightarrow T_{gas}$

where pressure broadening is significant, also get n_e

where Doppler profile interesting also get $T_B(v)$

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Spitzer 1978

more than an order of magnitude greater. Collisional excitation of the former levels, which produces radiation in the infrared, is quite insensitive to temperature for T greater than 1000°K. Excitation of the latter, however, increases quite sharply with increasing T, since only the electrons in the tail of the Maxwellian distribution have the 1.9 to 3.3 eV of energy required, and the number of these rises sharply with T. Hence these transitions to different spectroscopic terms provide a thermostatic mechanism that tends to keep the temperature in the neighborhood of 10,000°K.

Values of $\Lambda/n_e n_p$ for low-density H II regions ($n_e < 10^2\,\mathrm{cm}^{-3}$) are shown as a function of temperature in Fig. 6.1 [4], computed on the arbitrary assumption that O, Ne, and N, the only three radiating elements considered, are each 80 percent singly ionized and 20 percent doubly ionized. The abundances relative to H are essentially those in Table 1.1. At n_e significantly above $10^2\,\mathrm{cm}^{-3}$, collisional deexcitation reduces Λ below the

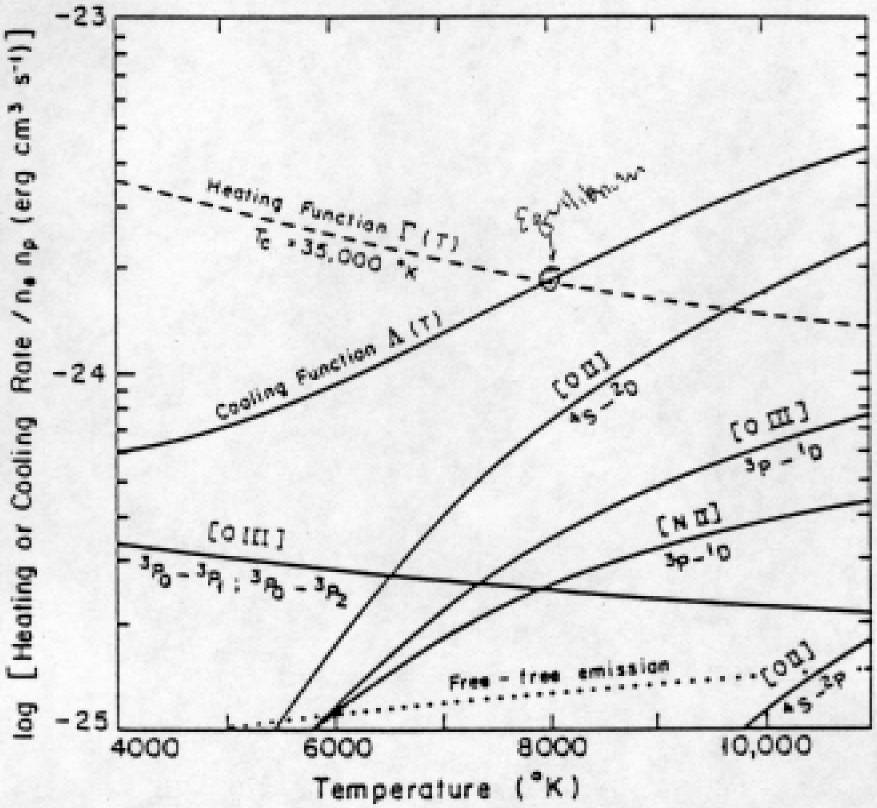
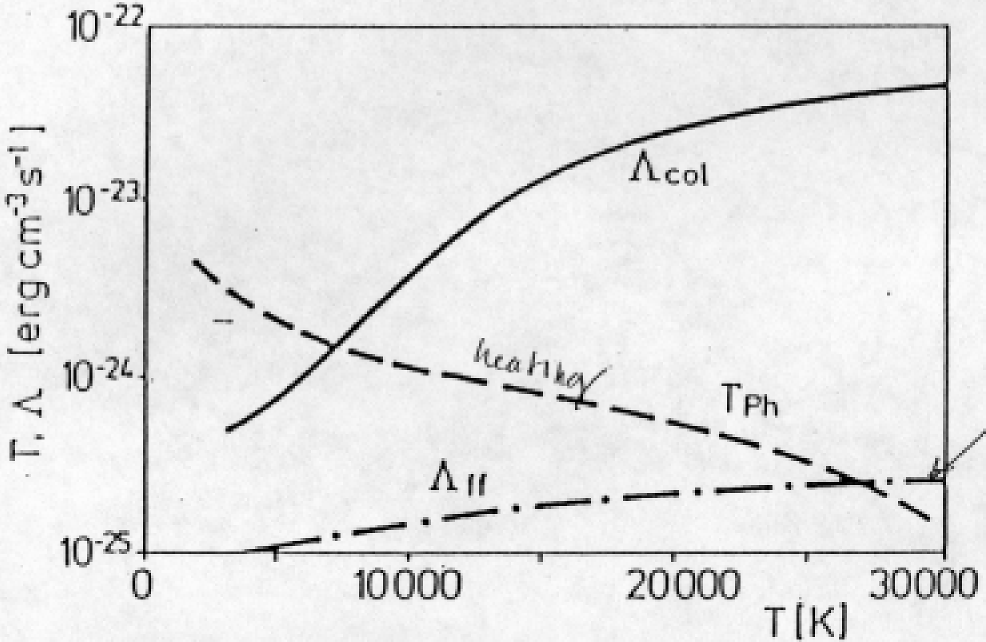


Figure 6.1 Heating and cooling functions in H II regions. Both $\Lambda/n_e n_p$ and $\Gamma/n_e n_p$ are shown as functions of the temperature T. In addition, the contributions to $\Lambda/n_e n_p$ from individual transitions in O and N ions are plotted for the low-density limit ($n_e < 10^2\ \mathrm{cm}^{-3}$) [4]. The dotted line shows $\epsilon_{ff}/n_e n_p$. The heating function represents an average for the H II region as a whole (see text), for a central star of color temperature, T_c, of 35,000° at far ultraviolet wavelengths.



as T rises ff cooling more important, but still << line radiation cooling

Fig. 5.8. Heating and cooling rates for an H II region with $N_e = N_p = 1$, caused by a st with surface temperature $T_* = 32\,000$ K, as a function of the gas temperature T. For oth values of N_e and N_p ($\lesssim 10^2$ cm^{-3}) the ordinate scale denotes $\Gamma/N_e N_p$ and $\Lambda/N_e N_p$ wi dimension erg cm^3 s^{-1}. Explanation in text. [After Spitzer (1968)]

AY218 Handout of Lecture 20

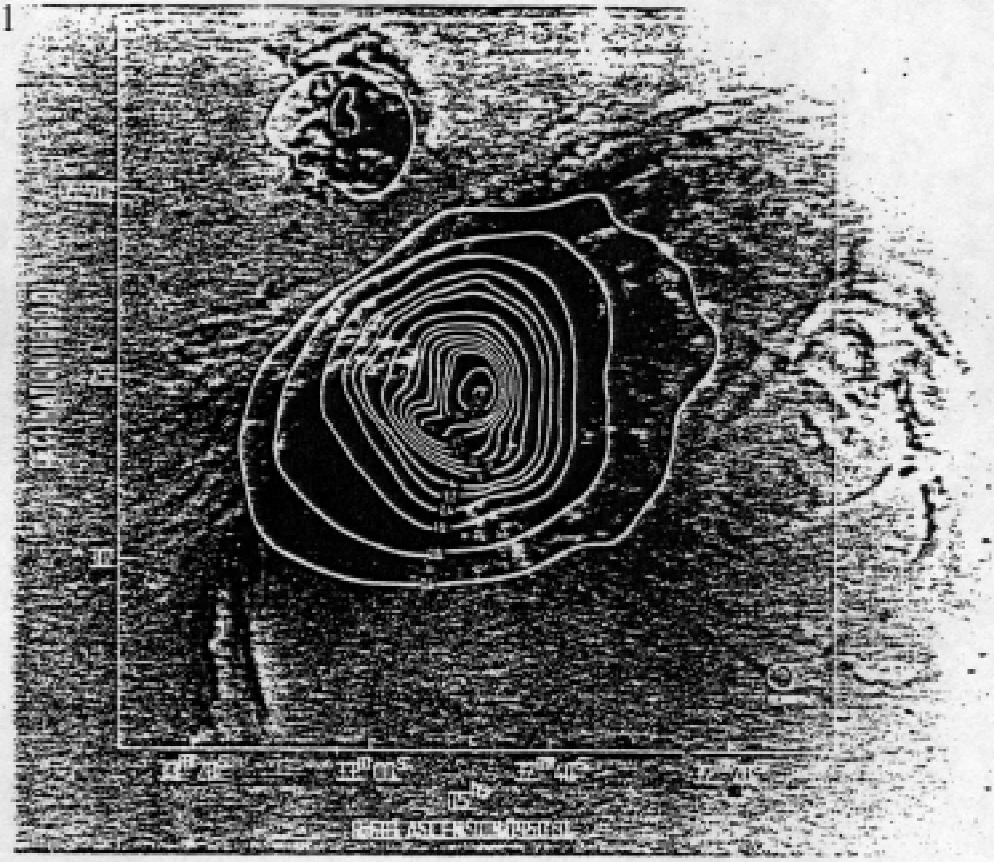


Fig. 2.3. The 23-GHz radio continuum contours, in units of main-beam brightness temperature, on an optical photo in Hα and [NII] of NGC 1976 (Orion A, M42), below, and NGC 1982 (M43), above. The angular resolution is 42", which at the distance of Orion A, corresponds to a linear resolution of 0.10 pc.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

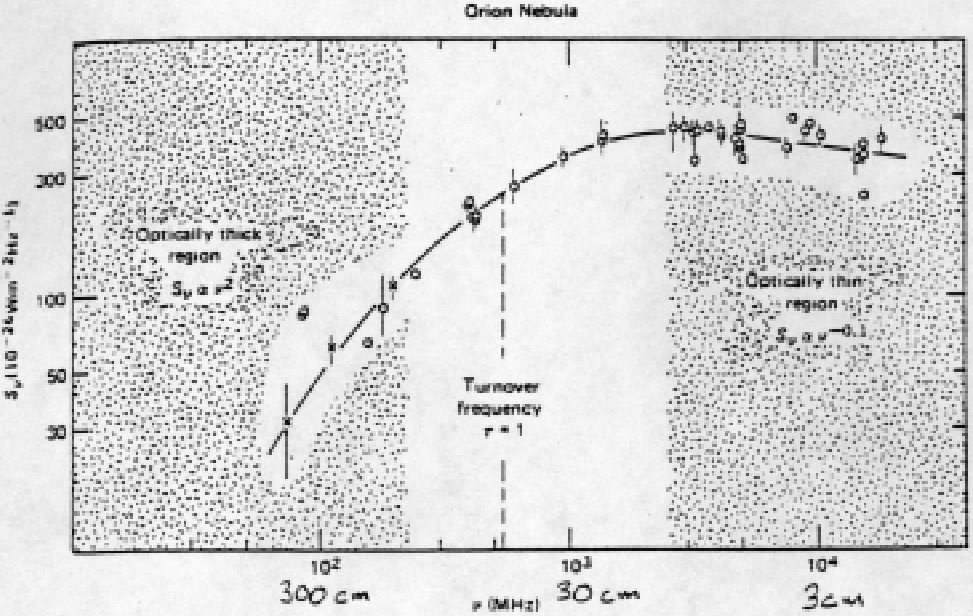


Fig. 2.2. Spectral flux density of the Orion Nebula plotted against frequency. The shaded regions mark the optically thick and thin regions of the spectrum. (Reprinted with permission by Gordon and Breach Science Publishers from: Terzian, Y. and Parrish A., *Astrophysical Letters*. Vol. 5(1970), pp.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

FROM: GALACTIC AND EXTRAGALACTIC RADIO ASTRONOMY
EDS. GL VERSCHUUR + K.I. KELLERMANN, 1974, SPRINGER-VERLAG

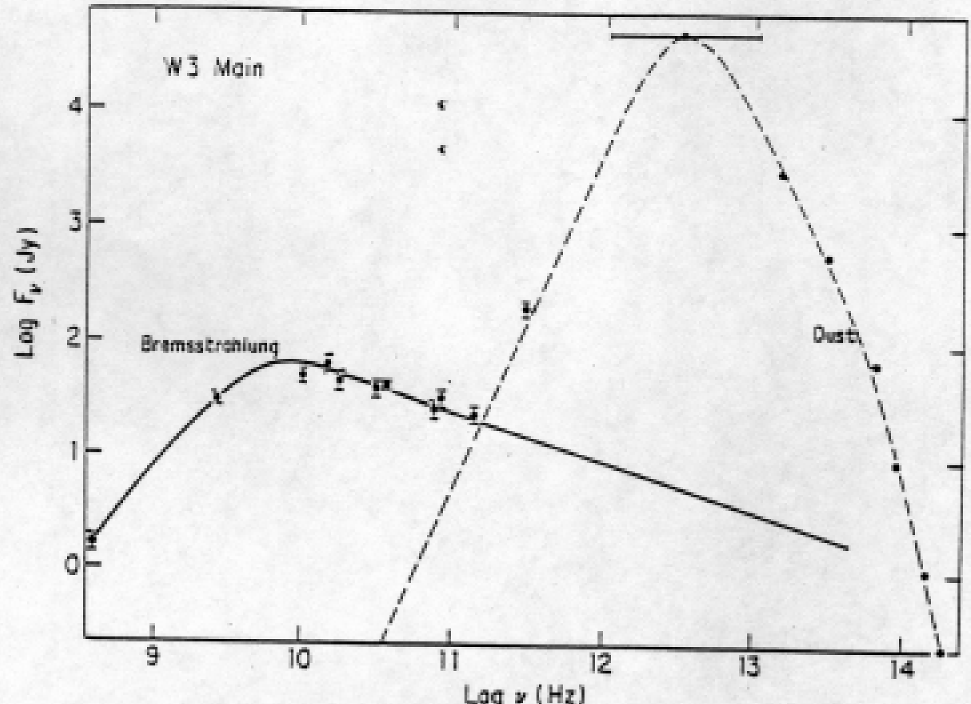


Fig. 2.4. Open circles mark observations of the integrated flux from the HII region W3 Main. Solid line: bremsstrahlung emission; dashed line: thermal emission from dust. (Malkamäki et al., 1979).

also from Gordon's contribution