

Lyman α , β , etc. can be absorbed; photons above "Lyman limit" ionize the electron.

13.6 eV comes to 92 nm, in the Far-UV range, so only the hottest stars supply these photons

Let's consider an O6 star (rare, very luminous).

From Carroll & Ostlie appendix, $T \sim 45,000$ K, &

$$L \sim 1.3 \times 10^5 L_\odot$$

How many ionizing photons does it produce?
From Wien's Law, $\lambda_{\text{max}} = \frac{0.0029}{T} \text{ km} = \underline{64 \text{ nm}}$

So the BB peak, & majority of photons, are above the Lyman Limit.

We assume all are at 64 nm.

Energy of 64 nm photon:

$$E = hc/\lambda = \frac{(4.13 \times 10^{-15} \text{ eV s})(3 \times 10^8 \text{ m/s})}{(6.4 \times 10^{-8} \text{ m})} = 19.4 \text{ eV}$$

or in SI, $3.01 \times 10^{-18} \text{ J}$.

The O6 star has $L = 1.3 \times 10^5 L_\odot = (1.3 \times 10^5)(3.8 \times 10^{26} \text{ W}) = \underline{4.9 \times 10^{31} \text{ W}}$

So # ionizing photons $= \frac{4.9 \times 10^{31} \text{ W}}{3.1 \times 10^{-18} \text{ J}} = 1.6 \times 10^{49}$ photons/s.

How much space does this ionize? Assume each photon ionizes one atom. In steady state, ionization rate = recombination rate.

Recombination must depend on n_e, n_H ; assume same, A_{H} .

Rate = $n_e Z \alpha(T_e)$, where $\alpha(T_e) = 2 \times 10^{-19} \left(\frac{T}{10^4}\right)^{-3/4} \text{ m}^3 \text{s}^{-1}$

\uparrow depends on composition
History

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We set N_* (ionizing photons/s) = $n_e^2 \alpha(T) \times \text{Volume}$

$$N_* = n_e^2 \alpha(T_e) \left(\frac{4}{3} \pi\right) r_s^3 \quad \begin{matrix} \text{radius of sphere} \\ \text{kept ionized.} \end{matrix}$$

Solve for r_s , $\boxed{r_s = \left(\frac{3 N_*}{4 \pi n_e^2 \alpha(T_e)} \right)^{1/3}}$ "Strongren radius"

For $n_e \sim 10^7 \text{ m}^{-3}$ (or 10 cm^{-3}), $T \sim 10^4 \text{ K}$, & O6 star,

$$r_s = \left(\frac{3 \times 1.6 \times 10^{49} \text{ photons/s}}{4 \pi (10^7 \text{ m}^{-3})^2 (2 \times 10^{-19} \text{ m}^3 \text{s}^{-1})} \right)^{1/3} = 5.8 \times 10^{17} \text{ m}$$

Since a parsec is $3.1 \times 10^{16} \text{ m}$, this is $\sim 20 \text{ pc!}$

Accurately describes Θ Orionis C, at center
of Orion Nebula.

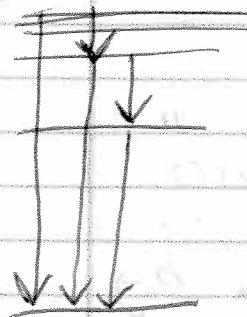
What do we see, looking at an HII region?

- Bremsstrahlung from hot ionized gas. Can find the turnover energy, for 10^4 K , $kT \sim 0.9 \text{ eV}$ so $\sim 1.4 \mu\text{m}$. This is just into the near-IR range, so strong in IR & radio, not optical.

- Diffuse reflected light from hot stars, & direct light from them; basically blackbody, at $\sim 45000 \text{ K}$.

- Recombination lines. Most H in ground state outside nebula, so very thick to Lyman photons (as these can be absorbed by H in ground state). As atoms recombine, Lyman photons are emitted, which are quickly re-absorbed, & slowly random walk through cloud, until absorbed by dust.

However, ISM is not thick to other H transitions,



Thus, photons in, e.g. Balmer series ($\rightarrow n=2$) can escape the nebula. As electron recombines, can drop direct \rightarrow ground (just a Lyman photon), or drop first \rightarrow a higher n level.

Typically each ionizing photon eventually contributes one Balmer-series photon.

H α line is excellent tracer of massive stars ionizing their environments. It's red, so gives red hue to nebulae around young, massive stars. Photos of nebulae often taken with narrow H α filter.

NGC 604, in M33

Ginga Nebula

Other recombination lines (e.g. O I, N II) available, allowing comparison of line strengths to begin gas properties.

HII regions made by young stars (few Myrs), due to short lives of O, B stars. So still in or near molecular clouds, destroying them.

M51

Can see correlation between He clouds, HII regions, & bright blue stars.

Table

HII regions have relatively high density & temp, so high pressure, & expand.

W49, ultracompact

HII

"Ultracompact" HII regions seen inside molecular clouds, confined by cloud's density. We can observe by radio bremsstrahlung radio recombination lines (e.g. H52 α).

Hillier

NGC 346: Near cloud edge, erupt into lower-density ISM.

Pismis 24: Denser cloud regions last longer in UV photon onslaught, leaving features.

NGC 3603: Clouds can also be compressed by pressure of H II region

Eagle Neb.: Strongest line emission from edges of dense cloud, where density of ionized material highest.

Angel in Eagle

Protostars in Eagle: P increase can trigger star formation, seen in infrared radiation inside "pillars".

Carina "caterpillar": Small, dense regions can be completely cut off as form stars.

Orion proplyd: Sometimes we clearly observe the forming protoplanetary disk.

Protoplanetary disk:

~~Densest thing common wherever we find~~

In addition to the spectrum, we can calculate the radiated power. Integrate $j_r(z)$ over ζ

$$j(T) = \int_0^{\infty} j_r(z) dz = C_2 \bar{g}(T, z) \zeta^2 n_e n_i T^{1/2}$$

where $C_2 = 1.44 \times 10^{-40} \text{ W m}^3 \text{ K}^{-1/2}$
and \bar{g} is freq-averaged Gaunt factor, often $\sim 1, 2$.

Note that the power increases with density?

Thus, observations of bremsstrahlung emission can tell us something about density; in terms of $\int n_e^2 dV$, called the emission measure.

(For fully ionized plasma, $n_e = Zn_i$, so $n_e^2/Z = n_en_i$)

To find total luminosity, $L(T) = \int j(T) dV$,

$$L(T) = C_2 g(T) T^{1/2} \approx \int_{\text{volume}} n_e^2 dV \quad (\text{in W.})$$

We can measure L (if know distance) and T from the spectrum, leaving our answer in terms of $\int n_e^2 dV$. If we knew the volume, & that n_e is constant in that volume, we could calculate n_e .

If the emitting object can be resolved by a telescope, then we measure intensity (as well as flux). We can also speak of surface brightness, which is identical to Intensity (basically flux per unit solid angle). Specific intensity is per unit frequency.

$$\text{Can show that } I(z, T) = \int_0^L \frac{j_r(r, z, T)}{4\pi} dr = \frac{j_r,_{av}(r, T)}{4\pi} L$$

where j_r may vary with position.

(Bradt (et al.) define emission measure along the line of sight, $\int n_e^2 dr = \langle n_e^2 \rangle L = EM_{\text{los}}$)

We can talk about $I(z, T)$ for extended sources, using the j_r expression earlier, to get (for H only)

$$I(z, T) = \frac{C_1}{4\pi} g(z, T, \xi) \frac{e^{-h\xi/kT}}{T^{1/2}} \int_0^L n_e^2 dr \quad (\text{W m}^{-2} \text{Hz}^{-1} \text{sr}^{-1})$$

where $C_1 = 6.8 \times 10^{-51} \text{ J m}^3 \text{K}^{1/2}$, as before.