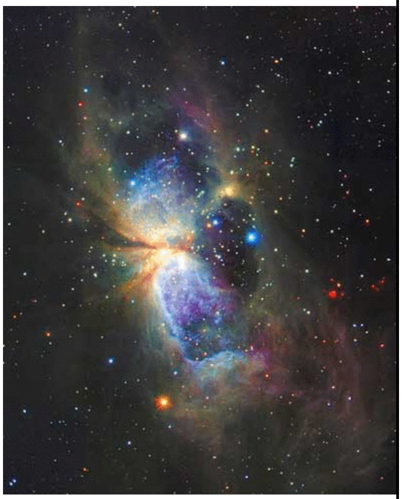
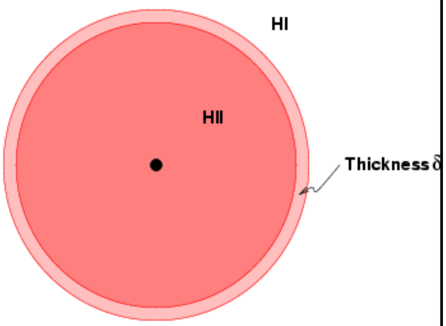
# HII Regions

- Massive (hot) stars produce large numbers of ionizing photons (energy above 13.6 eV) which ionize hydrogen in the vicinity
- Detailed nebular structure depends on density distribution of surrounding gas
- Consider an idealized picture: a star in a uniform medium of pure hydrogen
- Real situation can be much more messy: Subaru image where blue is ionized hydrogen



# Strömgren spheres

- Consider a uniform region of pure hydrogen
- Massive star turns on instantly
- Ionization cross section $\sigma \sim 10^{-21}$ m$^2$ for neutral H
- If gas density $n_H \sim 10^9$ m$^{-3}$, mean free path $\sim 10^{12}$ m before ionizing an atom $\rightarrow$ ionizing photons cannot escape
- For ionized gas, the much smaller Thomson cross section $\sim 6.7 \times 10^{-29}$ m$^2$ applies $\rightarrow$ stellar photons travel freely through ionized gas to the edge of the neutral material
- The ionized HII region around the star is called a *Strömgren sphere*
- HII region is separated from the surrounding HI region by a thin layer of thickness, $\delta \sim (n_H\,\sigma)^{-1}$



# Development of an HII region

Star emits $dN_i$ photons energetic enough to photoionize the gas in time $dt$ (atom + photon → ion + electron)

These photons serve to:

– Expand the HII region, or,

– Compensate for radiative recombinations (ion + electron → atom + photon) in the already ionized gas close to the star, i.e., to reionize atoms that have recombined to the ground state

# Ionizing photon budget

- To expand the HII region by $dR$, the star must ionize $4\pi R^2 n_H dR$ atoms.
- In the interior of the region,

$$\frac{4}{3}\pi R^3 n_e n_i \alpha(H^0, T)$$

recombinations occur per unit time. $\alpha(H^0,T)$ is the recombination rate coeff and $n_i$ and $n_e$ are the number densities of ions and electrons. $\alpha(H^0,T)$ is weakly dependent on temperature ($\propto T^{-0.5}$).

# Expansion rate

The equation for the time development of the region is then,

$$\frac{dN_i}{dt} = 4\pi R^2 n_H \frac{dR}{dt} + \frac{4}{3}\pi R^3 n_i n_e \alpha(T)$$

Rearranging, $$\frac{dR}{dt} = \frac{Q}{4\pi R^2 n_H} - \frac{n_i n_e \alpha(T) R}{3 n_H}$$

where $Q = dN_i/dt$ is the number of ionizing photons emitted per second.

Solution: with $R_S = 3Q/(4\pi\, n_i\, n_e\, \alpha(T))$, $t_r = 1/(n_H\, \alpha)$, $n_i = n_e = n_H$ for pure H

$$R(t) = R_S(1 - e^{-t/t_r})^{1/3}$$

# Properties of this model

- Volume of HII region is small at first
- Most photons ionize gas at boundary, which expands rapidly
- Expansion speed can be >> sound speed in gas, which has no time to react to the passing ionization front
- As region grows, need more photons to balance recombinations. When all photons are needed, get size of region by setting $dR/dt = 0$:

$$R_s^3 = \frac{3Q}{4\pi n_i n_e \alpha(T)}$$

- An O star with $T_{eff} = 35{,}000$ K has $Q \cong 10^{49}$ s$^{-1}$
  Taking $\alpha \sim 4 \times 10^{-19}$ m$^3$ s$^{-1}$, and $n_i = n_e = 10^9$ m$^{-3}$, we find $R_s \sim 0.6$ pc

This is a crude estimate only for several reasons…

# Complications – 1

- Only photons produced by recombinations into highly excited states will have energies low enough to escape the HII region
- Recombinations to *n* = 1 produce new ionizing photons
- Ionizing radiation field then has two parts:
  - The *stellar radiation field*, which decreases outwards due to geometrical dilution and absorption:

$$J_{\nu s} \propto F_{\nu s} \frac{e^{-\tau_\nu}}{r^2}$$

  - A *diffuse radiation field* produced by recombinations. The diffuse field is more important for denser regions. Typically, it increases the $R_s$ by a factor between 2 and 10.

# Complications – 2

- Pressure is proportional to $nT$
- Ionized gas has twice as many particles per unit volume as the neutral gas, plus it has T ~ 7000K as compared to T ~ 70K in the HI. So HII region is over-pressured compared to the HI, and will expand because of this alone. This,
  - Does not affect the *early* development, when the expansion is supersonic
  - Increases the volume at late times, and therefore *decreases* the rate of recombinations

# Calculated radii of Strömgren spheres

| Spectral type | $T_e$ /K | log Q /$s^{-1}$ | $R_s$/ pc |
|---|---|---|---|
| O6 | 40,000 | 49.23 | 74 |
| O7 | 35,000 | 48.84 | 56 |
| B0 | 30,000 | 47.67 | 23 |

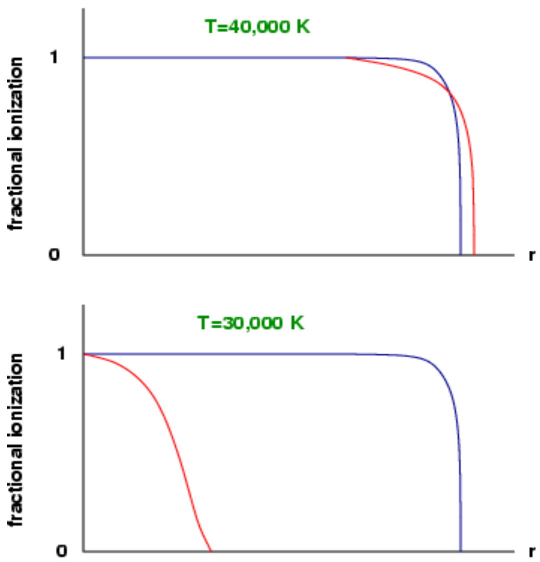
Figures include effects of diffuse radiation field.

Notes:

- Radii are for $n_i = n_e = 10^6\ \mathrm{m}^{-3}$. Scaling to the density assumed earlier using $R_s \propto (n_i\ n_e)^{-1/3}$ the agreement with the estimate is not too bad.
- $Q$ was obtained from $T_{\mathrm{eff}}$ using a model stellar atmosphere as UV flux from a very hot star is only poorly approximated by a blackbody

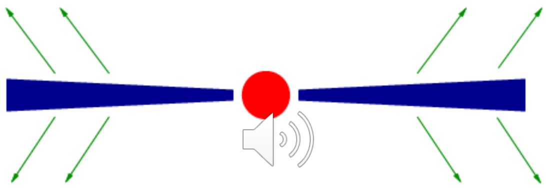
Other elements can be included in the ionization calculations. Results then depend sensitively upon the stellar temperature.

If we consider both hydrogen (blue curve) and helium (red curve) we find:



# Effect on protoplanetary discs

- Ionizing flux in an HII region can destroy protoplanetary discs surrounding lower mass stars in the region. Schematically:

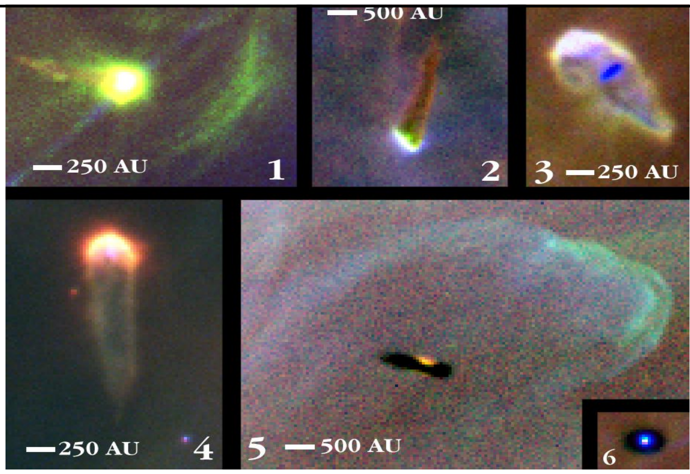


- UV flux illuminates disc, heats outer layers to $T \sim 10^4$ K
- Heated gas has a sound speed $c_s$ around 10 km/s. Where $c_s > V_{esc}$, gas escapes as a thermal wind. The critical radius is

$$R_g \sim \frac{GM_*}{c_s^2}$$

This radius is about 10 AU for a 1 $M_{sun}$ star

- Most stars may be formed in clusters (such as Orion) which contain massive stars. Therefore, this *photoevaporation* of discs may be important to consider for planet formation.




Photoevaporation has been observed in HST images of the central regions of the Orion star forming region. It is estimated that the lifetimes of these discs are less than 1 Myr, compared to the estimated 10 Myr of the disc that formed the Solar System. Thus,

- Planet formation may be easier in smaller clusters without massive stars
- May explain why no planets were found in HST search for transits in the globular cluster 47 Tuc

# Lecture 15 revision quiz

- What is the mean free path of a photon in a medium with ionization cross section $\sigma$ and gas density $n_H$ ?
- Give two reasons why the expansion of the HII region surrounding a hot young star slows down after a rapid initial expansion.
- Use the expression in slide 6 for the radius of a Stromgren sphere, to compute the radius using the values for $n_i$ , $n_e$ and $Q$ in slide 9. Compare with the tabulated values.
- Give two reasons why real HII regions are bigger than the idealised model in slide 6.
- Calculate the sound speed in hydrogen at $T=10^4$K, and the distance from the Sun at which this equals the solar escape velocity.

# Lecture 15 revision quiz

- Compute the mean free paths of ionizing photons at 13.6eV and 20eV in neutral hydrogen with density $10^3$cm$^{-3}$
- Compute the mean free path of an ionizing photon due to electron scattering in gas with density $10^3$cm$^{-3}$
- What ions of H, He, C, N, O, Ne, S will exist in an HII region excited by a star which emits photons less than 54eV?
- Derive the formula for the radius in a protoplanetary disk where ionized gas may escape as a thermal wind.