Effects of Massive Stars

•Classical HII Regions
•Ultracompact HII Regions

Stahler & Palla: Sections 15.1, 15.2

HII Regions

The salient characteristic of any massive star is its extreme energy output, much of which is at UV wavelengths.

Energetic photons dissociate H_2 and ionize HI. Atomic H is also created via p-e^- recombination. Each ionization event deletes a photon from the beam ➔a star with a fixed output in UV radiation can only ionize a limited region in the surrounding cloud (the Strömgren sphere, if uniform medium).

The Orion Nebula

The Rosette Nebula

The Strömgren Sphere

Ionization balance holds at each location within the region:

volumetric ionization rate = p-e⁻ recombination rate

Integrating over the sphere:

total number of ionization events per unit time ($\mathcal{N}_*$) = total recombination rate

$\mathcal{N}_*$ is the rate at which the star emits ionizing photons, i.e. those with with E > 13.6 eV. The corresponding minimum frequency is the Lyman limit of $\nu_1 \equiv 3.29\times10^{15}$ s^{-1} or λ_1=912 Å.

$\mathcal{N}_{FUV}$ is the star's far-UV output (6 < E < 13.6 eV).

Spectral Type	Mass ($M_\odot$)	log $\mathcal{N}_*$ (s^{-1})	log $\mathcal{N}_{FUV}$ (s^{-1})
04	70	49.9	49.5
06	40	48.8	48.8
09	20	47.8	48.2
B0	18	47.1	48.1
B2	10	44.8	47.1

The volumetric rate at which free electrons and protons combine to produce atomic hydrogen can be written as:

$$\mathcal{R} = n_e n_p \alpha_{rec}(T)$$

Recombination coefficient (cm^3 s^{-1})

$$= n_e^2 \alpha_{rec}(T)$$

using charge neutrality in the ionized plasma

The total rate of recombinations within the sphere follows by integrating $\mathcal{R}$ over the volume. If n_e and T are spatial constants, after balancing total ionizations and recombinations:

$$\mathcal{N}_* = \frac{4\pi}{3} n_e^2 \alpha'_{rec}(T) R_s^3$$

Strömgren Radius

α'_{rec}(T) neglects recombinations to the ground (n=1) state, given that those produce another ionizing photon that is promptly absorbed nearby.

We will soon demonstrate that the ionization spreads so quickly to the Strömgren radius that the original cloud density is not able to change appreciably. Thus:

$$n_e = n_H^0$$

n_H^0: the number density of H atoms external to R_s

[This simple approximation ignores electrons liberated from He]

Solving previous expression for R_s:

$$R_s = \left[\frac{3\mathcal{N}_*}{4\pi\alpha'_{rec}(n_H^0)^2}\right]^{1/3}$$

$$= 0.4\ \text{pc}\left(\frac{\mathcal{N}_*}{10^{49}\ \text{s}^{-1}}\right)^{1/3}\left(\frac{n_{H_2}^0}{10^3\ \text{cm}^{-3}}\right)^{-2/3}$$

typical value of an O6 star; this also assumes value of α'_{rec} for gas at $T \sim 10^4$ K

Within an HII region, the probability per unit time of ionizing an atom is far greater than the probability for a proton to recombine. Thus, for the *volumetric* rates to match:

$$n_H << n_e$$

$$\Downarrow$$

The interior of the HII region is nearly completely ionized

The neutral density becomes significant only when the photon flux becomes attenuated by the ionization it is creating. The transition to neutrality at the boundary thus occurs over some multiple of the photon mean free path within the fully neutral medium:

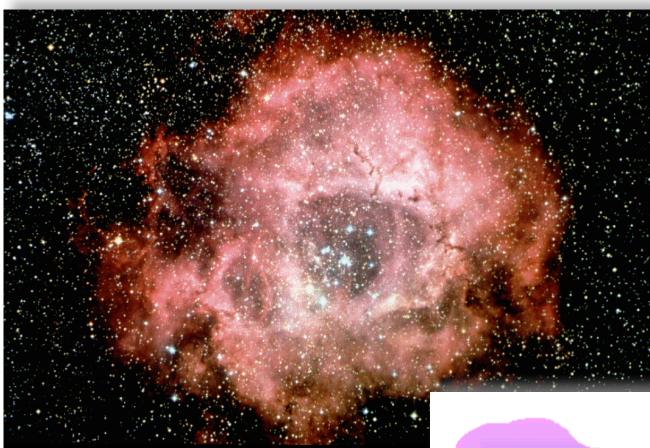
$$\Delta r = \frac{1}{n_H^0 \sigma_{\nu_1}}$$

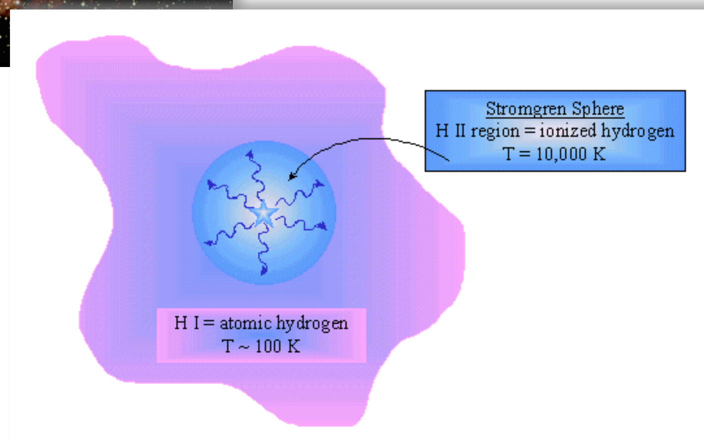
n_H^0: e.g., $\approx 2\times10^3$ cm^{-3}

σ_{ν_1} = 6.8×10^{-18} cm^2, photoionization cross section of a ground-state H atom, at the Lyman limit.

→ $\Delta r = 7.4\times10^{13}$ cm (5 AU!) = $5\times10^{-5}\ R_s$:

the HII region is very sharp-edged!





First and Second Expansion

The zone of ionization expands with time. At the earliest stages, no HII region exists. The region first quickly spreads to the Strömgren radius, and then more slowly beyond.

The moving edge of the HII region is called the ionization front. Its boundary is narrow enough to be considered a discontinuity.

When $R < R_s$, the total rate of recombinations is insufficient to match the star's output of ionizing radiation ➔ surplus photons reach the front, ionize additional gas beyond this, and the front expands.

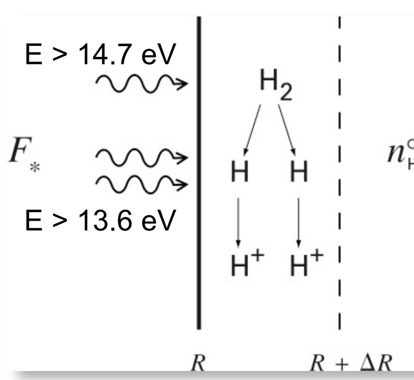
$F_*(t) \equiv$ flux of ionizing photons reaching R at time t.

After a time Δt:

$n^0_{H2} \times \Delta R$ molecules per unit area are dissociated, creating

$2 \times n^0_{H2} \times \Delta R$ atoms which are then ionized.

$F_* \times \Delta t$ is the number of photons crossing the front.

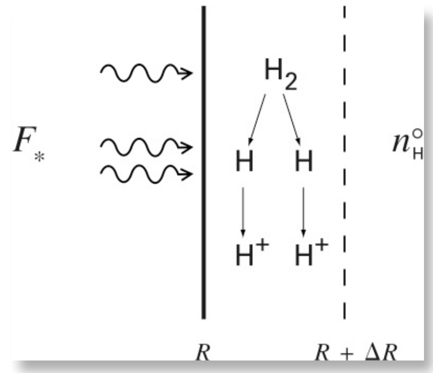


In summary, 3 photons create 2 ionizations:

$$\frac{F_* \Delta t}{2 n^0_{H_2} \Delta R} = \frac{3}{2}$$

$$\Downarrow$$

$$\frac{dR}{dt} = \frac{F_*}{3 n^0_{H_2}} = \frac{2F_*}{3 n^0_H}$$



Recombinations occurring within the spreading HII region

-Total rate: $(4\pi/3) n^2_e \alpha'_{rec} R^3$ = number of stellar photons lost to ionization per unit time (ionization balance).

-Rate at which surviving photons cross the ionization front: $4\pi R^2 F_*$

$$\Downarrow$$

$$\mathcal{N}_* = 4\pi R^2 F_* + \frac{4\pi}{3} (n^0_H)^2 \alpha'_{rec} R^3$$

Combining the equations for dR/dt and $\mathcal{N}_*$, we obtain the equation of motion for the ionization front:

$$\frac{dR}{dt} = \frac{\mathcal{N}_*}{6\pi\, n^0_H R^2} - \frac{2}{9} n^0_H \alpha'_{rec} R \qquad \boxed{A}$$

Let's define a nondimensional radius $\lambda \equiv R/R_s$ and time $\tau \equiv t/t_{rec}$, with

$$t_{rec} \equiv \frac{1}{n^0_H \alpha'_{rec}} = 61 \text{ yr} \left(\frac{n^0_{H_2}}{10^3 \text{ cm}^{-3}} \right)^{-1}$$

Equation A now becomes:

$$\frac{d\lambda}{dt} = \frac{2}{9\lambda^2} - \frac{2\lambda}{9}$$

The solution of the above equation, obeying $\lambda(0)=0$ is then:

↓

$$\lambda = [1 - \exp(-2\tau/3)]^{1/3}$$

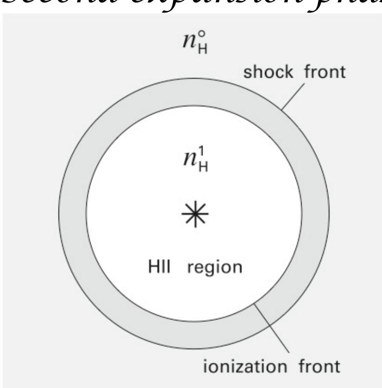
First Expansion

The front is expanding at high speed initially and than slowly creeps towards the Strömgren radius: R reaches a fraction $(1\text{-}e^{-1})^{1/3} = 0.86$ of R_s in a time $3t_{rec}/2$, or 91 yr (using previous parameters). The corresponding average speed is 6×10^3 km s^{-1}.

So far, we have assumed that the mass density within the HII region matches the exterior value. This is OK at early times, when the ionization front velocity exceeds a_1, the isothermal sound speed within the region (~10 km s^{-1}, for an ionized medium at 10^4 K).

The pressure within the HII region is ~1000 times larger than outside. Once the radius approaces R_s, the pressure difference is able to drive a *second phase of expansion*. The ionization front is preceded by a shock wave that first expands into the ambient cloud.

Second expansion phase



The second phase begins when the **velocity of the ionization** front declines to the internal **sound speed**. At this point, pressure disturbances can cross the front and create an expanding shock.

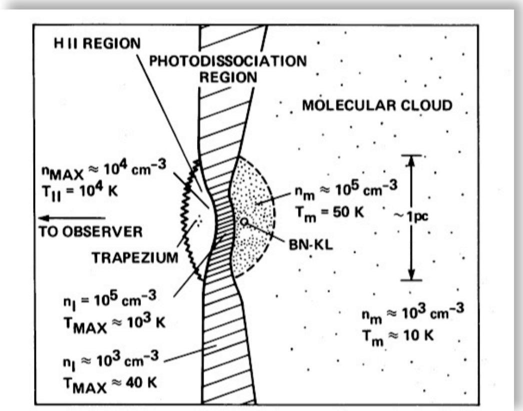
External matter traversing this shock is compressed into a relatively thin, neutral shell. The shock and the ionization fronts move out at a common speed which soon falls below a_1.

The mass of the ionized gas continues to rise (UV photons impinge on the inner side of the shell), while the interior density falls (expansion) ➔ the system gradually approaches pressure equilibrium.

Gas within the shell has the low cloud temperature at the leading edge and approaches 10^4 K toward the HII region.

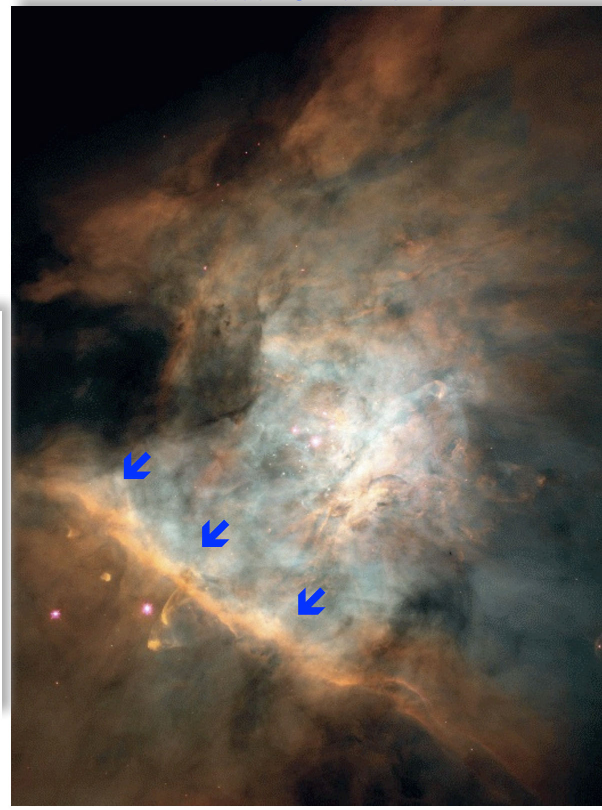
The inner surface of the neutral shell appears as a *photodissociation region*, where molecules are promptly photodissociated.

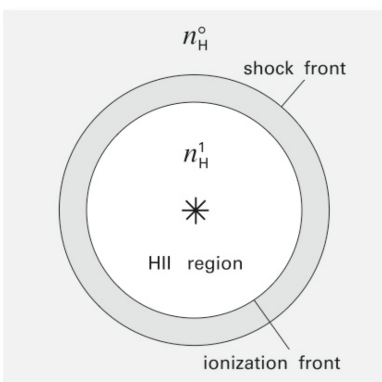
Strong lines: [CII] 158μm,
[OI] 63 μm



Tielens & Hollenbach 1985, ApJ, 291, 747

The Orion Bar





To derive the motion of the shell we assume that the shock is isothermal (efficient postshock cooling).

From the jump-conditions, the pressure inside the shell, which is also the ram pressure of the shock running into the surroundings, matches that inside the HII region:

$$n_H^0 m_H \left(\frac{dR}{dt}\right)^2 = n_H^1 m_H a_1^2$$

interior number density of hydrogen atoms < n^0_H

$$n_H^1 a_1^2 = n_H^0 \left(\frac{dR}{dt}\right)^2$$

During the expansion, nearly all the stellar ionizing photons are still consumed by the HII region, with only a small residual eroding the neutral shell. We can then modify the expression we found for the Strömgren radius to read:

$\Downarrow$

$$R = \left[\frac{3\mathcal{N}_*}{4\pi\alpha'_{rec}(n_H^1)^2}\right]^{1/3}$$

Elimination of n^1_H between the above expression and $n_H^1 a_1^2 = n_H^0 \left(\frac{dR}{dt}\right)^2$

$\Downarrow$

$$\left(\frac{dR}{dt}\right)^2 = \frac{a_1^2}{n_H^0}\left[\frac{3\mathcal{N}_*}{4\pi\alpha'_{rec} R^3}\right]^{1/2}$$

Equation of motion during the second expansion

The velocity of the shell is thus $a_1(R/R_s)^{-3/4}$. To find the radius at all times, let $\lambda \equiv R/R_s$ and $\tau' \equiv a_1 t/R_s$, so that:

$$\frac{d\lambda}{d\tau'} = \lambda^{-3/4} \quad \xrightarrow{\text{adopting the initial condition } \lambda(0)=1} \quad \lambda = \left(1 + \frac{7\tau'}{4}\right)^{4/7}$$

second expansion

Champagne Flows

In the final equilibrium state, n^1_H must fall to $(a_0/a_1)^2 n^0_H$, far below the external density. The final radius, becomes:

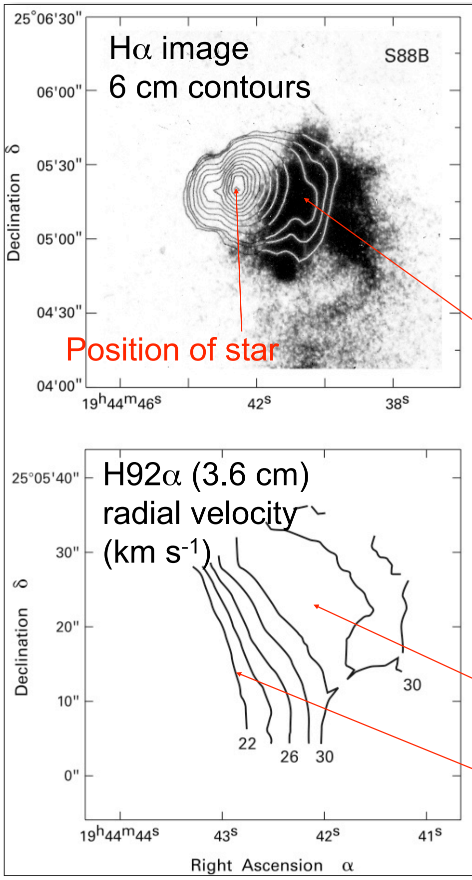
$$R_f = (a_1/a_0)^{4/3} R_s = (2T_1/T_0)^{2/3} R_s \sim 100\, R_s \;!$$

In practice, such a large inflation never goes to completion, both because it takes too long (compared to the stellar lifetime) and, more realistically, because the ionization front reaches the boundary of the molecular cloud:

the HII region is density bounded rather than ionization bounded. The pressurized HII gas burst out of the cloud into the surrounding medium, creating a *champagne flow*.

If a portion of the ionizing volume crosses the edge into the lower-density gas, the front velocity increases. This part of the HII region runs out rapidly into a plume-like structure.

There is a large pressure discontinuity within the ionized gas and a shock rushes outward, accelerating material behind it to velocities exceeding the sound speed.

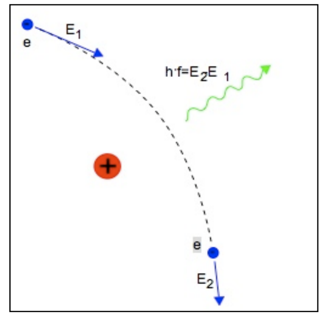


Tracers of Ionized Gas (HII Regions)

Recombination lines, e.g. Hα (recombination to n=2) in the optical. There are also recombination lines to much higher quantum levels, e.g. n=92: H92α.

Radio continuum emission from electrons accelerated by ions: "Thermal Bremmstrahlung" or "free-free" emission.

Ionized gas flows to the right, away from the dense cloud



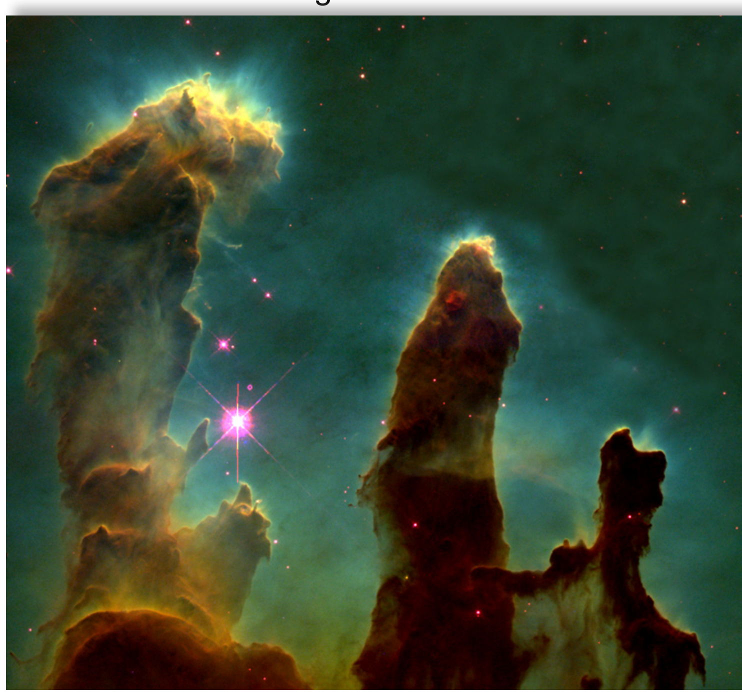
Ionized matter picks up speed as it flows to the right from the cloud

Radial velocity of the cloud

HII regions also emit continuum radiation. Some of this is in the optical and represents light from the central star scattered by dust grains. Dusty cloud gas may partially block nebular light. Long, optically thick columns (**elephant trunks**) may protrude into the HII region from the outside.

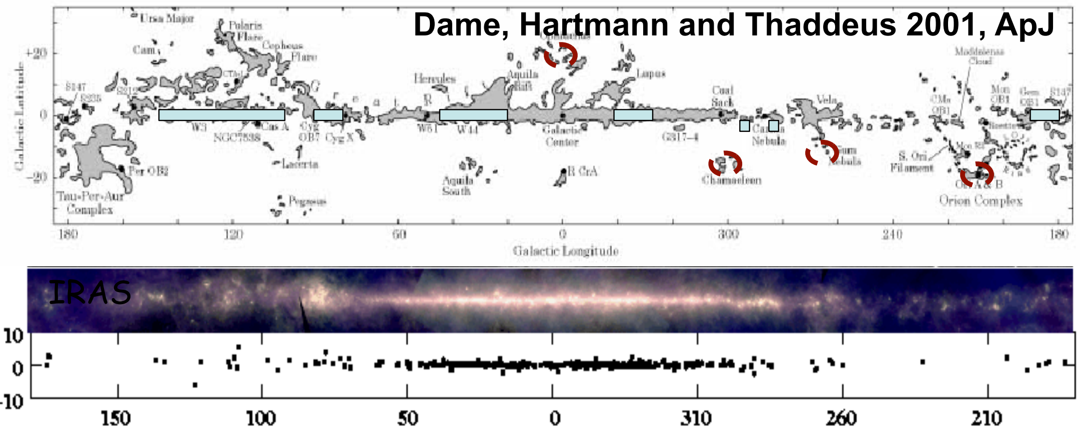
Example:

the Eagle Nebula, or M16. The columns in this optical image represent dense gas that has not yet been dissipated by UV radiation. Note the glowing ionization fronts at the top of each structure!

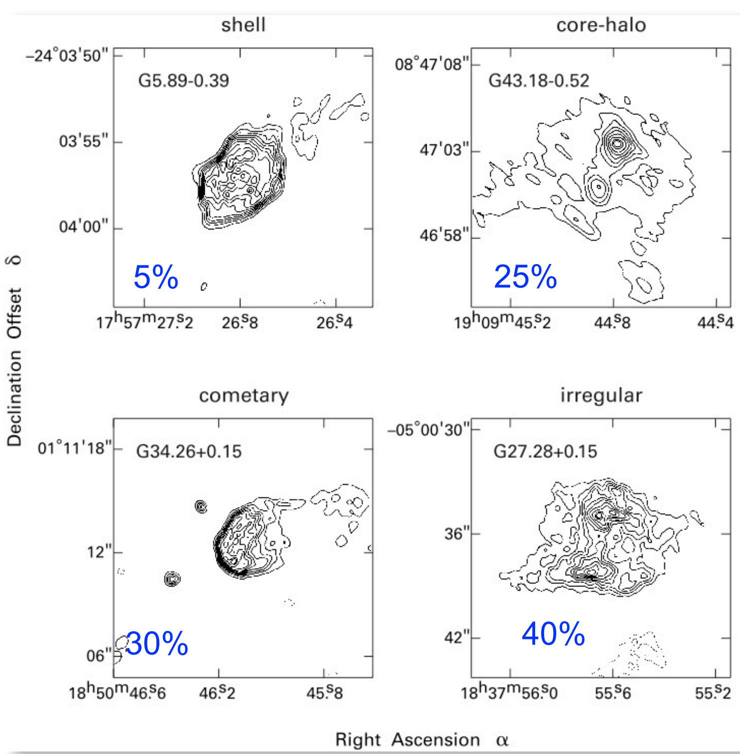


Ultracompact HII regions

Optically visible, or “classical” HII regions, such as the Orion Nebula, have $L \geq 10^{18}$ cm and $n_e \leq 10^4$ cm^{-3}. Precursors of these HII regions, are called **UCHII regions**, have $L \leq 10^{17}$ cm and $n_e \geq 10^5$ cm^{-3}. In the Far-IR they are the most luminous objects in the Galaxy (heated dust grains within the ionized gas).



Morphologies of the Radio Emission



Surveying the Galaxy, we find that about 2000 O stars are in this deeply embedded phase, or ~ 10% the **total** number of O stars.

➔

A typical O star spends ~10% of its main sequence lifetime (4×10^6 yr) as an UCHII. Thus, **an UCHII region last for ~4×10^5 yr.**

So, why the size is small ??

Assuming that the region is in its second expansion phase, then the ionization front advances at roughly the internal sound speed, or ~10 km s^{-1}. To cover the observed size of 0.1 pc would require only ~10^3 yr!

There are far too many UCHII regions for their youthful dynamical state !!

Possibilities for confining ionization

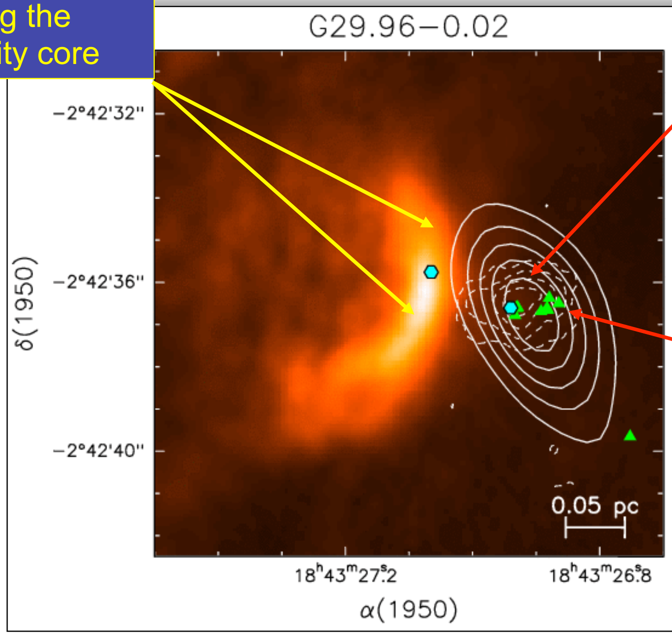
1. High pressures in surrounding medium, including non-thermal forms of pressure (turbulence and magnetic fields)

2. Ram pressure because of an accretion flow to the star.

3. Ram pressure because of motion of the star: should lead to confinement only on one side (a "cometary" UCHII region).

4. Continual replenishment of neutral gas into the UCHII regions, either from remnant material left over after formation of the star or advection of fresh neutral gas, by accretion or turbulence.

the ionization may have difficulty penetrating the high density core



Dense core

Star formation signatures

(Cesaroni et al. 1998; Olmi et al. 2003)