Growth of Strömgren Radii Within Different Density Distributions

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1 Introduction

Massive, hot stars produce ultraviolet radiation which can ionize the media in which they are embedded, creating emission nebulae called *HII regions* filled with ionized hydrogen. Temperatures of these regions average 10^4 K. They can range in size from a fraction of a pc to a few 100 pc, depending on the number of the stars radiating within, and have a correspondingly large range of densities from a few atoms cm^{-3} to 10^6 atoms cm^{-3} for the most compact regions. Nebular structure depends on the density distribution of the material surrounding hot stars. In an idealized uniform region of pure hydrogen, stellar photons create a spherical "bubble" of HII called a *Strömgren sphere*, the maximal volume at which ionizations balance the inverse process of recombinations.

HII regions have a similar distribution throughout the spiral arms of galaxies as the molecular clouds within which they originate. The impact of their feedback and evolution is important in subsequent star formation. HII regions are not static systems but have well-defined formation and expansion phases in the simplified case of uniform ambient density. In the former, the central star's photons create an ionization front which heats and ionizes surrounding the gas largely without disturbing it. This front reaches the initial *Strömgren* radius, slowing as the stellar radiation field drops off and recombinations increase. The pressure difference between the larger, cold molecular cloud and the hot HII region results in the supersonic expansion of the ionized gas, where the ionization front is preceded by a shock front which carves out cavities and compresses the surrounding material. Neutral gas accumulates and condenses between the ionization front and the shock front, and a new generation of stars may form in the collected layer.

In this paper we consider the initial formation phase of HII regions for various spectral types of O and B stars, first in a medium of constant density and then in a medium with a power-law density profile. We will consider the simplified case of a pure hydrogen medium with the same recombination coefficient for each spectral type. We discuss our results showcasing the resultant changes in HII region growth and their impact on the surrounding material. The calculations for Strömgren radii and growth are discussed in §2,

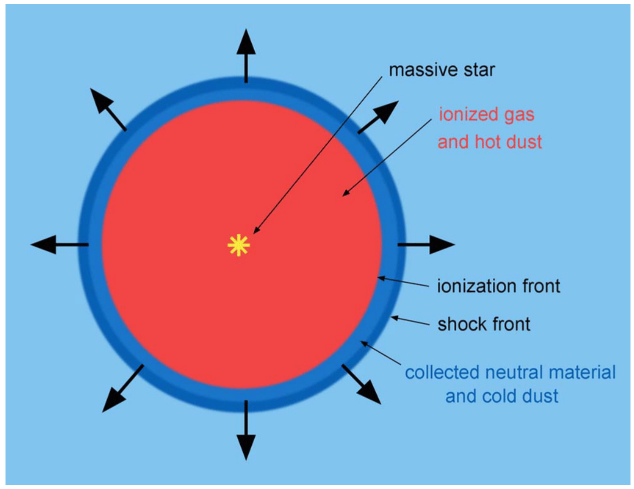

Figure 1: Model of a spherical HII region expanding into a homo- geneous medium. The ionized region is surrounded by a shell of dense neutral material collected during the expansion phase. Taken from Deharveng *et al.* (2010).

and results are shown and compared to observations in §3. We summarize the significance of studying HII region in relation to star formation in §4).

2 Modeling HII Regions

In the simple case where an HII region is expanding into a uniform medium, the boundary of the region occurs where the rate of ionizations is equal to the rate of recombinations, leading to the relation

$$Q = \frac{4}{3}\pi R_S \alpha_2 n_i n_e, \tag{1}$$

where Q is the rate of ionizing photons per second, the recombination coefficient $\alpha_2 = 2.6 \times 10^{-13} cm^3 s^{-1}$, n_i is the number density of ions, and n_e is the number density of ions [Williams (2021)]. Here we use the recombination coefficient describing recombinations down to the $n = 2$ first excited state of the hydrogen atom, omitting recombinations down to the ground state as these produce more ionizing photons. We assume that the region is fully ionized with the number density of ions equalling the number density of electrons, $n_i = n_e$.

The above equation gives the Strömgren radius,

$$R_S = (\frac{3Q}{4\pi\alpha_2 n_i^2})^{\frac{1}{3}} \tag{2}$$

and the time development of the ionized region is given by

$$R(t) = R_s(1 - e^{-t/t_r})^{\frac{1}{3}} \tag{3}$$

where the recombination time $t_r = \frac{1}{n_i \alpha_2}$.

For simplicity we make several assumptions. In the case of a constant density medium: (1) the stars are surrounded by atomic hydrogen. In reality, they form within clouds of molecular hydrogen, which must first dissociate before ionization. (2) The recombination coefficient is the same for each stellar type. In reality, the coefficient has a dependence on electron temperature, which may differ around various spectral types and throughout the ionized region. In the case of a power-law density medium: (3) the surrounding medium is assumed to have a central core with constant density n_0 and radius r_0 and a surrounding envelope with density described by

$$n_i = n_0(\frac{r}{r_0})^{-p} \tag{4}$$

[Franco *et al.* (1990)]. In the case of an inhomogeneous surrounding medium, the ionization–recombination balance is now a sum over contributions from different radial shells,

$$Q = \frac{4\pi\alpha_2 n_0^2 r_0^{2p}}{3-2p}[R_S^{3-2p} - R_*^{3-2p}] \tag{5}$$

where R_* is the stellar radius which is very small compared to R_S [Williams (2021)]. In both the uniform and inhomogeneous cases, we assume that (4) the ionizing star is fully embedded in a region of gas and not at the surface or edge (a scenario which would result in "champagne flows" of ionized gas into the surrounding material as the HII region bursts from its birth cloud). (5) We also do not account for the diffuse radiation field produced by recombinations, which is important for denser regions and increases the Strömgren radius.

Spectral Type	Q (10^{49} photons s^{-1})
O3	7.4
O4	5.0
O5	3.4
O6	2.2
O7	1.3
O8	0.74
O9	0.36
B0	0.14

Table 1: Spectral types considered in this paper and their corresponding ionization rates. Taken from Kamionkowski (2011).

We calculate the time evolution of the Strömgren radii for 8 different spectral types of hot, massive O and B stars, shown in Table 1 with their corresponding ionization rates. We do so for the uniform densities and for the exponents of the power-law densities shown in Table 2. The results are presented in §3.

n_i (Uniform Density)	n_i (Power-Law Density)
10 cm^{-3}	$n_0(\frac{r}{r_0})^{-0.8}$
10^2 cm^{-3}	$n_0(\frac{r}{r_0})^{-1}$
10^3 cm^{-3}	$n_0(\frac{r}{r_0})^{-1.2}$

Table 2: Densities of surrounding material considered in this paper. The time evolution of the Strömgren radii for each spectral type are calculated in each value of uniform density and then in each non-uniform distribution shown here.

3 Plotting the Time Evolution of Strömgren Radii

3.1 Growth Within a Uniform Medium

We first consider the growth of Strömgren radii for our chosen spectral types within uniform media with densities of (a) 10 cm^{-3}, (b) 10^2 cm^{-3}, and (c) 10^3 cm^{-3}. The results are shown in (a) Figure 2, (b) Figure 3, and (c) Figure 4. We see that for all spectral types the advance of the ionization front is initially very rapid but eventually slows, with the earliest types reaching the largest radii. This is expected as hotter stars produce more ionizing photons and therefore should be able to ionize material out to greater distances.

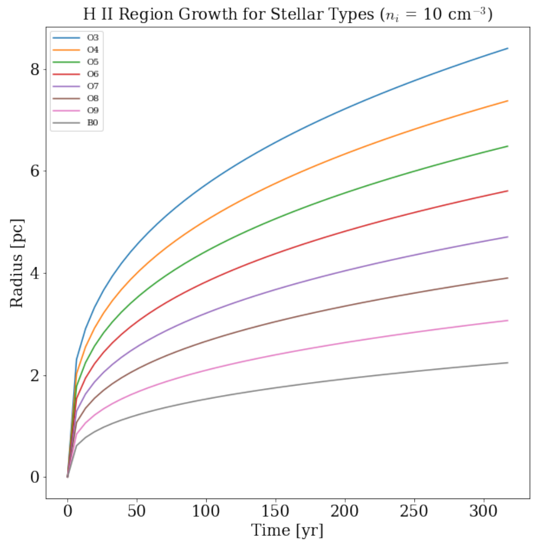

Figure 2: Plot of HII region growth in pc over time in yr for 8 spectral types (detailed in Table 1) embedded in a uniform medium of density $n_i = 10$ cm^{-3}.

As the ambient density increases, the Strömgren radii for each spectral type decrease in size. Since the recombination rate is proportional to the number density of ions, the distance at which ionizations balance recombinations will be closer in a region of higher density. For an O3 star, the earliest type considered here, inside ambient density $n_i = 10^3$ cm^{-3} (Figure 4), the Strömgren radius is only 1.29 pc, compared to 8.40 pc inside ambient density $n_i = 10$ cm^{-3} (Figure 2). For a B0 star, that is 0.34 pc compared to 2.24 pc inside those same respective densities. The higher the ambient density, the smaller in scale the Strömgren radius.

For low ambient densities, the growth of the HII region is nearly linear after an initial period of rapid growth; for high ambient densities, the initial growth is very rapid before flattening out. For stars inside ambient density $n_i = 10^3$ cm^{-3} (Figure 4), the Strömgren radius is 90% its final size at t = 136 yr. For stars inside n_i = 10 cm^{-3} (Figure 2), the radius is at 90% its final size at t = 227 yr, nearly double the time. The growth of HII regions dwindles more slowly in low-density surrounding material than in high-density material.

3.2 Growth Within a Non-Uniform Medium

Now we consider the growth of Strömgren radii for our chosen spectral types within non-uniform media. We model a setup in which the ionizing star is embedded within a dense core within a cloud, though we ignore the true molecular nature of such structures (Churchwell (2002)). We set $n_0 = 10^4$ cm^{-3} and r_0 = 0.1 pc, values for dense cores taken from Stahler & Palla (2004), and consider power-law exponents of (e) $p = 0.8$, (f) $p = 1$, and (g) $p = 1.2$. The results are shown in (e) Figure 5, (f) Figure 6, and (g) Figure 7. We see that the ionization front expansion behavior is different for different spectral types, with later types experiencing some initial growth which quickly flattens and earlier types experiencing some initial growth followed by an extended period of nearly linear expansion. This seems to indicate that cooler massive stars struggle to create large Strömgren spheres and their ionization is balanced quickly by recombination.

For higher values of p, the Strömgren radii for early spectral types are larger. This corresponds to an envelope of material with density that falls off more quickly, enabling ionizing photons to penetrate further. For $p = 0.8$ (Figure 5), an O3 star creates an HII region with a Strömgren radius of only 0.17 pc, while for $p = 1.2$ (Figure 7) it creates a region with a radius of 0.4 pc. However, for $p = 0.8$ (Figure 5) a B0 star creates

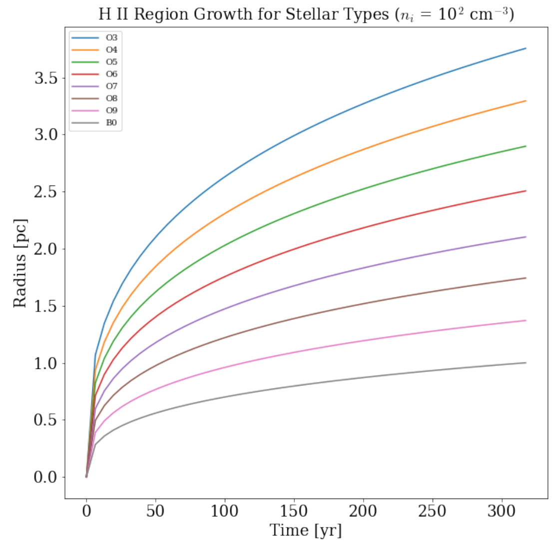

Figure 3: Plot of HII region growth in pc over time in yr for 8 spectral types (detailed in Table 1) embedded in a uniform medium of density $n_i = 10^2$ cm^{-3}.

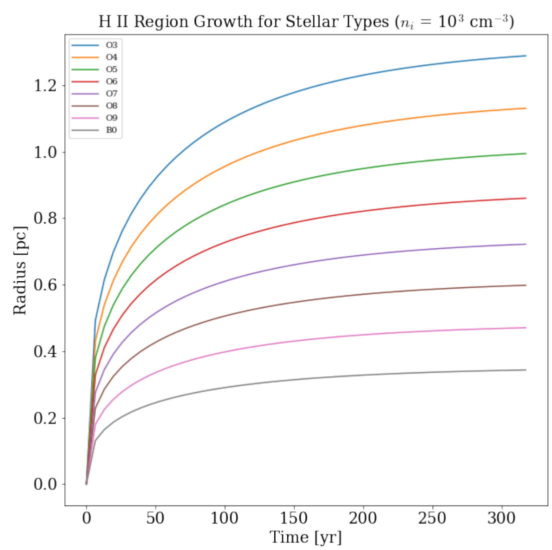

Figure 4: Plot of HII region growth in pc over time in yr for 8 spectral types (detailed in Table 1) embedded in a uniform medium of density $n_i = 10^3$ cm^{-3}.

a region with a radius of 0.01 pc, while for $p = 1.2$ (Figure 7) it creates one of 0.0005 pc. This again shows that cooler massive stars struggle to grow past the dense central core.

When calculating the Strömgren radii inside a uniform density for the spectral types, we see that the final radii are spaced nearly equally in linear space. The Strömgren radii inside a non-uniform density, however, are nearly equally spaced in logarithmic space. There is an exponential effect on the sizes of the

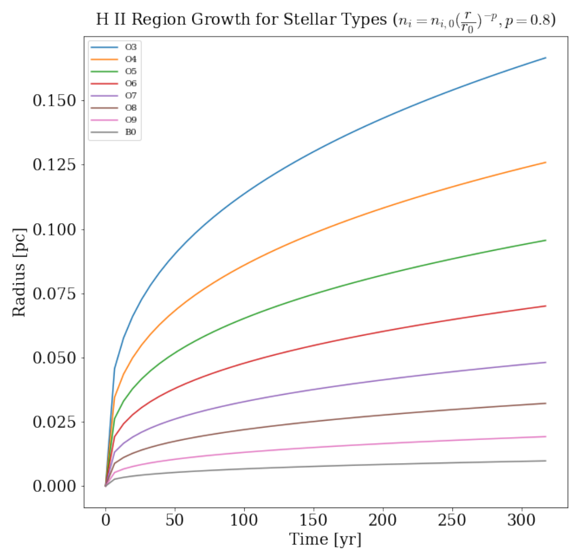

Figure 5: Plot of HII region growth in pc over time in yr for 8 spectral types (detailed in Table 1) embedded in a non-uniform medium of density (described in Table 2) with power-law exponent $p = 0.8$.

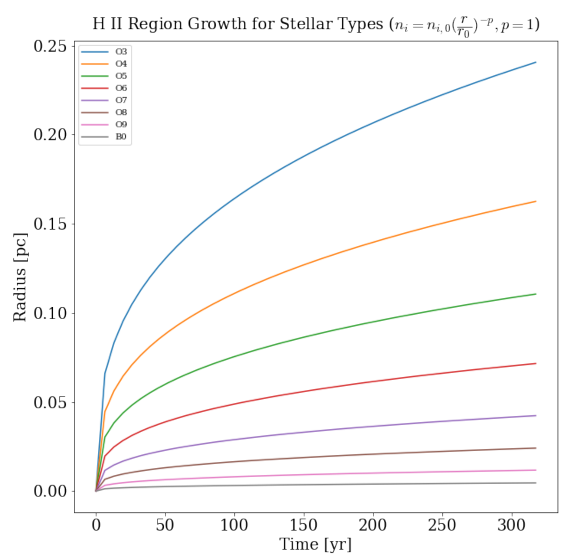

Figure 6: Plot of HII region growth in pc over time in yr for 8 spectral types (detailed in Table 1) embedded in a non-uniform medium of density (described in Table 2) with power-law exponent $p = 1$.

HII regions once a power-law density distribution has been introduced. Late-type hot stars are disadvantaged when they must first ionize a dense core of surrounding material, and the effect is worse for higher values of p. Spectral types O6 and below are in all power-laws considered here not ionizing beyond their dense cores, meaning their ionizing flux may not be able to significantly alter their surroundings.

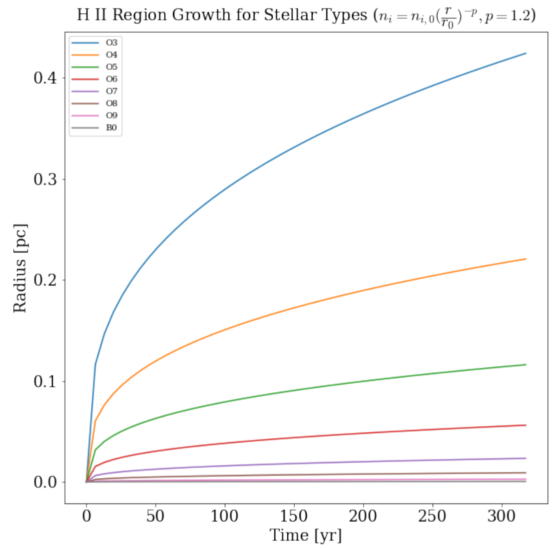

Figure 7: Plot of HII region growth in pc over time in yr for 8 spectral types (detailed in Table 1) embedded in a non-uniform medium of density (described in Table 2) with power-law exponent $p = 1.2$.

4 Connecting HII Regions to Observations

In Deharveng *et al.* (2010), the authors showcase a number of HII regions with signatures of condensed material present near their ionization fronts, the result of neutral gas being swept up during the expansion process and compressed into potentially star-forming condensations or new star-hosting ultra-compact HII regions. Most of these are large regions (>15 pc) with a few notable exceptions ($\sim$4-5 pc) expected to form in higher density media which constrain expansion.

These findings loosely reflect the results here in that most of the HII regions which proceed to affect their larger surroundings and participate in the star formation process are regions likely formed by stars of earlier types which are able to produce larger Strömgren spheres. Though we do not follow the growth of Strömgren radii here past the initial formation phase, we see that smaller HII regions within slightly more realistic density distributions (i.e. power-law rather than uniform) produced by later-type stars have difficulty growing out of the dense cores in which they are created, likely reducing their ability to continue expanding and sweeping up gas for new star formation.

The models used here are oversimplified in that they ignore the inhomogeneity of real media surrounding HII regions which may be turbulent, have extremely dense clumps, and fail to evenly ionize, resulting in regions that are far from spherical in nature and whose expansion is more difficult to model. They also ignore the additional physics and processes shaping HII regions such as stellar winds and radiation pressure of the exciting stars, as well as the impact of magnetic fields which also break the symmetry of the regions. However, even this basic model of the early evolution of HII regions provides insight into the kind of growth we can expect from different spectral types within different media and whether they are likely to contribute to the cycle of star formation.

5 Summarizing the Impact of HII Regions

Early-type hot stars have larger Strömgren radii than late-type hot stars due to their higher temperatures and higher output of ionizing photons. When the HII regions created by these stars are growing within media of uniform density, they reach larger (smaller) sizes for lower (higher) ambient density and experience

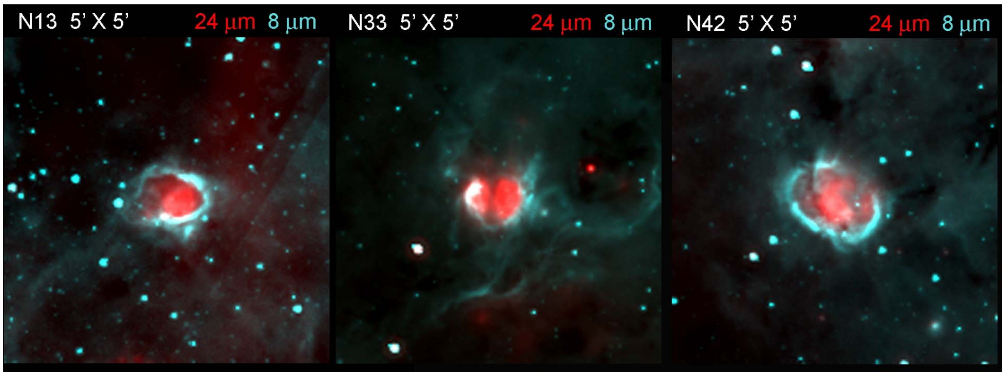

Figure 8: Examples of three bubbles that are small in angular size where turquoise (Spitzer-GLIMPSE images at 8.0 μm) defines the bubbles and red (Spitzer-MIPSGAL emission at 24 μm) is from hot dust. Taken from Deharveng *et al.* (2010).

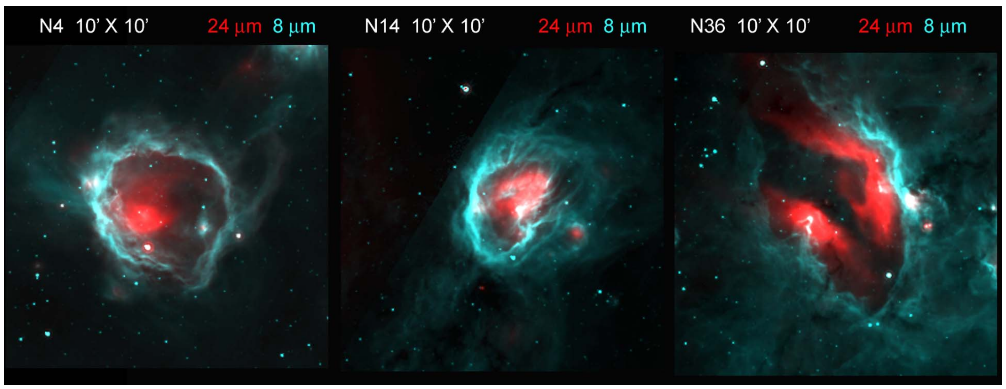

Figure 9: Examples of three bubbles that are large in angular size with the same colours as in Figure 8. Taken from Deharveng *et al.* (2010).

increasingly rapid initial growth followed by more flattened growth with increasing ambient density; the growth behavior for the regions around each spectral type are very similar.

Within non-uniform media, however, the growth of HII regions around early-type hot stars is steeper than that of late-type hot stars, which struggle to produce Strömgren spheres that expand out of the dense cores in which they are formed into the surrounding material which drops off in density. The difficulty of cooler massive stars to create large HII regions in media with more realistic density distributions indicate that perhaps the hottest stars are the most efficient at triggering new massive star formation through expansion and compression of neutral gas.

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Figure 10: Co-authors of this paper, Faust and Mephi.

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