**Author**: Verdolini, Silvia
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# I

# Introduction

High mass stars dominate the mechanical energy injection into the interstellar medium (ISM), through stellar winds and supernova explosions, and thus the turbulent pressure which helps support clouds against galactic- and self-gravity. Stars with masses larger than 10 $M_{\odot}$ end their lives in powerful supernova explosions, which release large amounts of energy and momentum and inject most of the metals (elements heavier than hydrogen and helium) contained in a galaxy back into the ISM. Thus, massive stars are responsible of the chemical enrichment of galaxies. They are also the source of intermediate mass elements which play an important role in interstellar dust. Massive stars control the ultraviolet (UV) photon energy budget and the cosmic ray flux, which are important heating, ionization, and dissociation sources of the interstellar gas. Clearly, there is a complex feedback between stars and the ISM that determines the structure, composition, chemical evolution, and observational characteristics of the ISM in galaxies.

Despite their importance, little is known about the origin and early evolution of massive stars. One observable stage of massive star formation is when the forming star is luminous enough to emit a considerable fraction of high energy photons, and starts to ionize the gas in its neighborhood. This is what astronomers call H II region. It consists primarily of hydrogen, hence the name – the term H II refers to ionized hydrogen – and it has temperatures of around 10,000 K. Because massive stars evolve very rapidly and they do not move far from their birth site, they are good signposts of recent star formation. Hence, emission from H II regions provides a direct handle on the environment in which massive stars are formed.

Figure 1.1 – The Orion Nebula as observed by the *Hubble Space Telescope*. An example of Compact H II region. The gas is ionized by few hot, massive stars – known as the Trapezium – located at the center of the region. Credit: NASA/ESA.

One of the key questions in astronomy is what is the cosmic history of star formation, or in other words, how the early universe evolved into the beautiful collection of galaxies and stars that we can see in the sky today. It is still not clear what are the conditions for star formation and how it evolved during the lifetime of the universe. Moreover, it is under discussion how important is mechanical and radiative feedback by massive stars for the evolution of the ISM of galaxies.

## 1.1 High mass stars and the interstellar medium of galaxies

### 1.1.1 High mass star formation

Despite their very crucial role, the formation of massive stars remains poorly understood and still under debate. High-mass star formation is generally taken to be a scaled up version of the low-mass star case. However, more complex physical processes take place and complicate its formation scenario. Starting from a giant molecular cloud, a likely sequence of events that leads to the formation of massive stars is as follows (Zinnecker & Yorke 2007):

compression - a cold dense molecular core or filament forms by gravo-turbulent cloud fragmentation in a giant molecular cloud.

collapse - a protostellar embryo forms by gravitational collapse of portions of the core. For a star to form, the force of gravity must overcome the pressure, magnetic forces, internal turbulence and rotation.

Table 1.1 – Typical properties of classes of H II regions.

| Type of region | Size (pc) | Density ($cm^{-3}$) | Ionized Mass ($M_\odot$) | Number of ionizing stars$^{(a)}$ |
|---|---|---|---|---|
| HyperCompact | $\sim 0.003$ | $\gtrsim 10^6$ | $\sim 10^{-3}$ | $\sim 1$ |
| UltraCompact | $\lesssim 0.05$ | $\gtrsim 10^4$ | $\sim 10^{-2}$ | $\sim 1$ |
| Compact | $\lesssim 0.5$ | $\gtrsim 5 \times 10^3$ | $\sim 1$ | $\sim 1$ |
| Classical | $\sim 10$ | $\sim 10^2$ | $\sim 10^5$ | few |
| Giant | $\sim 10^2$ | $\sim 30$ | $10^3$-$10^6$ | $\sim 10^2$ |
| Starburst nuclei | $> 10^2$ | $\sim 10$ | $10^6$-$10^8$ | $\sim 10^3$ |

($a$) Calculated assuming $10^{48}$ photons $s^{-1}$ per star.

accretion - material accretes onto the protostellar object as it evolves towards the main sequence. For low mass objects accretion happens through a disk. Only when all the material has been accreted the star starts nuclear burning in its core. Instead, high-mass objects accretion continues as they evolve towards the main sequence, meaning that the radiation pressure of the photons coming from the star acts against the force of gravity.
disruption - as the first high-mass star forms in a complex, it influences its environment with stellar winds, outflows, UV radiation, and eventually a supernovae explosion. Such feedback eventually disrupts the birth cloud, leaving as a result a OB association or OB star cluster.

### 1.1.2 H II regions

From the moment that a newly formed massive star begins to ionize its surroundings by emitting a copious amount of UV radiation, an H II region is formed. Since the star is deeply embedded into its natal molecular cloud, the H II region stage is one of the first observable stages of the birth of a massive star. When an H II region forms around a protostar, there is a competition between the expansion of the ionized material and the accretion of gas onto the protostar that is still ongoing. As accretion stops and the expansion takes over, the H II region expands progressively into the surroundings.

Observationally, H II regions are visible at multiple wavelengths due to the variety of physical mechanisms involved in their formation. The gas that is ionized by the central star is observable at radio wavelengths due to the thermal Bremsstrahlung (free-free) emission (scattering of free electrons off ions). In the infrared (IR), the *Galactic Legacy IR Mid-Plane Survey Extraordinaire* (GLIMPSE) showed over 5,000 H II regions detected from dust emission. The dust present in the ISM absorbs the UV light from the star and re-emits it at IR wavelength. Such observations show the beautiful morphologies of different layers of the photo-dissociation region. The optical spectra is dominated by hydrogen and helium recombination lines, and collisionally excited optical forbidden line emission from trace ions such as [O II], [O III], [S II] and [N II] showing different layers of the H II region ionized gas. X-rays can emerge from such a cloud showing both the ionizing star and the characteristics of the hot plasma around it.

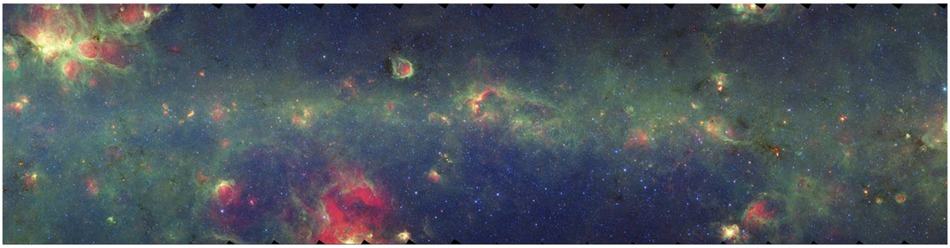

Figure 1.2 – Segment of an IR portrait of dust and stars radiating in the inner Milky Way. Blue is IRAC 3.6 $\mu$m, green is IRAC 8 $\mu$m, and red is MIPSGAL 24 $\mu$m. Credit: NASA/JPL-Caltech/Univ. of Wisconsin.

Wood & Churchwell (1989) divided H II regions into morphological classifications based on their Radio emission. The classification is summarized in Table 1.1. The smallest and densest regions observed are called HyperCompact H II region, and are bright at millimeter wavelengths. UltraCompact H II regions have sizes of $< 0.1$ pc, high electron densities and high emission measures. The Compact H II regions are still buried in their parent molecular clouds, with radii of 0.1 to few pc. The more extended H II regions reach tens of pc (Classical) up to hundreds of pc (Giant) in radius. Figure 1.1 shows the Orion Nebula, an example of a Compact H II region: powered by few massive stars, it has a radius of $\sim 1.7$ pc.

It seems natural to assume that the classification represents an evolutionary sequence of the expanding H II region: when the massive star forms, a HyperCompact H II region develops, which then expands to become an UltraCompact H II region. However, age is not the only parameter that determines the large range of H II regions. The combined effect of age, number of massive stars powering the region and environment density is at the base of the H II region classification.

### 1.1.3 Interstellar bubbles

Besides ionizing hydrogen (and other elements) in their surroundings, massive stars – with their UV radiation – excite polycyclic aromatic hydrocarbons (PAHs) in the swept up shell, lighting them up at IR wavelengths, and heat dust to moderate temperatures that radiates at mid-IR wavelengths. Large-scale surveys have been designed to identify such structures: the *Spitzer Space Telescope* with GLIMPSE at 3.6/4.5/5.8/8.0 $\mu$m (Benjamin et al. 2003) and MIPSGAL at 24/70 $\mu$m (Carey et al. 2009). Thanks to the Milky Way Project (Simpson et al. 2012), a citizen science initiative, the number of known IR bubbles in the inner Galactic plane is about 5100, an order of magnitude more than previous studies. Churchwell et al. (2006, 2007) catalogued about 600 bubbles and found a good correlation of IR bubbles with known H II regions and relatively low contamination from supernova remnants, asymptotic giant branch star bubbles and planetary nebulae reported in the literature. This demonstrate that bubbles are tracers of star formation activity (Deharveng et al. 2010).

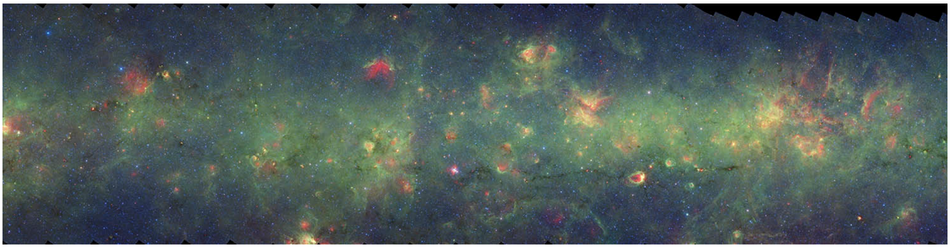

Figure 1.3 – Segment of an IR portrait of dust and stars radiating in the inner Milky Way. Blue is IRAC 3.6 $\mu$m, green is IRAC 8 $\mu$m, and red is MIPSGAL 24 $\mu$m. Credit: NASA/JPL-Caltech/Univ. of Wisconsin.

Figure 1.2 and 1.3 show two sections of the galactic plane as seen by GLIMPSE and MIPSGAL survey. The striking feature is the complexity and variety of bubbles. Some regions are spatially extended and with a intricate morphology, other are smaller and more regular circular regions. Such large number of objects allow statistical studies important to solve longstanding questions, such as triggered star formation. Kendrew et al. (2012) found a strong positional correlation of massive young stellar objects and H II regions with interstellar bubbles.

### 1.1.4 H II regions: dynamics

When a high mass star ionizes the gas around it, there are important dynamical effects on its surroundings. In a uniform medium, the ionization front expands rapidly into the surrounding medium till the Strömgren radius, where the total recombination rate integrated over the nebula equates the total number of ionizing photons. Such expansion is so fast that the gas does not have time to react dynamically. The photon flux at the ionization front drops, and the expansion changes nature. The overpressure caused by the ionization and heating of the H II region drives the expansion in the neutral medium (Spitzer 1978). A sketch of the structure of such H II region is shown in Figure 1.4 (A). Other physical mechanisms can alter the expansion of an H II region, such as the radiation pressure on the gas (Krumholz & Matzner 2009), that would create the same morphological structure as the overpressure case, but with the additional force pushing the swept-up shell due to radiation. Another mechanism proposed is the presence of stellar winds (Castor et al. 1975), that generates and onion-like structure (Figure 1.4 (B)). In the inside the free-flowing stellar wind is divided by the shocked stellar wind by the reverse shock; and the swept-up shell expands outward into the ISM.

In the case of non uniform medium, the H II region breaks open and gas inside the bubble flows outwards, giving it the name of champagne flow models (Figure 1.4 (C)). Expansion of an H II region in a non uniform medium in the presence of stellar winds has also been studied. The overall shape would be a similar cometary-like region, but the inside of the bubble would contain the same reverse shock between free-flowing stellar wind and the shocked gas. When a star moves through the medium, a similar cometary

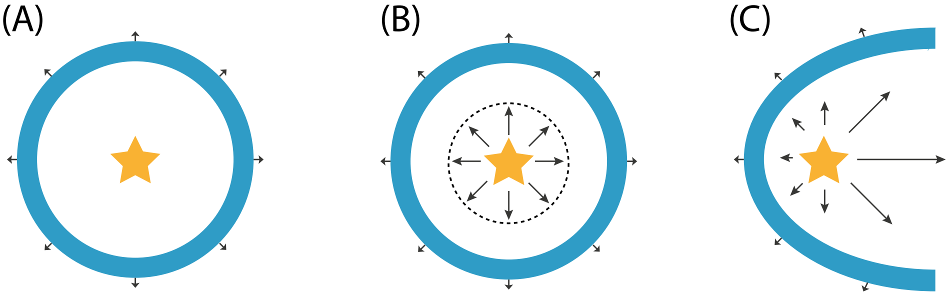


Figure 1.4 – Sketches of H II regions (A) driven by overpressure of the ionized gas (Spitzer 1978); (B) driven by stellar winds (Castor et al. 1975); and (C) in presence of a density gradient in the medium (champagne flow model, van Buren et al. 1990). Credit: Bram Ochsendorf.

shape is achieved.

Many factors contribute to the formation and evolution of H II regions. Looking at the most famous example of an H II region, the Orion Nebula (Figure 1.1), it is easy to realize that the physics involved in such source is more complicated than the simplified description given above. Indeed, non-uniformity of the medium determines deviations from sphericity; stellar winds, and supernovae explosions might trigger second generations of star formation; dynamical movement of stars also changes the morphology.

## 1.2 Star-forming galaxies

Astronomers have put huge effort in investigating the formation and evolution of galaxies. Wide-field surveys of the local Universe have provided a detailed and statistically robust description of the galaxy population today. Such results mark the endpoint of the description of the formation and evolution of galaxies. Understanding the properties of high redshift galaxies and their similarities and differences with the local galaxy population is crucial to explain the evolution of galaxies.

Galaxies are characterized according to the main source of ionization/excitation of elements. One main division of galaxies is between star-forming and active galactic nuclei (AGN) dominated galaxies. In this work, we only focus on star-forming galaxies since the light coming from these galaxies originates mainly from stars and their associated H II regions. The collective effect of H II regions affects the characteristics of the galaxy, and their emission provides a way to characterize the environment in which massive star form. Therefore, connecting detailed studies of H II regions to galaxies' studies is important to understand their properties and possibly to disentangle differences between the local and high redshift universe.

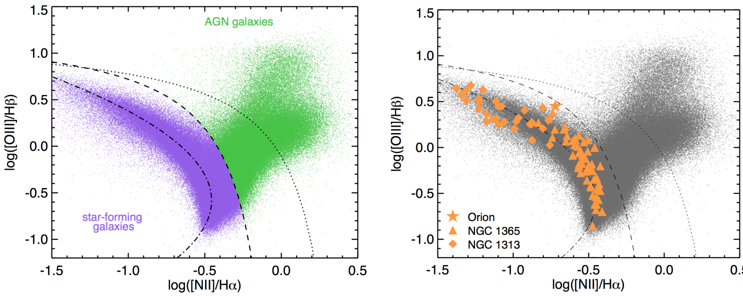


Figure 1.5 – BPT diagram for (a) galaxies from the SDSS catalog (Brinchmann et al. 2004) divided into star-forming and AGN dominated galaxies; (b) H II regions in galaxies at z = 0 with blue symbols (Roy & Walsh 1997, Walsh & Roy 1997, Sánchez et al. 2007), and galaxies from the SDSS catalog with gray dots. The dashed line is the (Kauffmann et al. 2003) line, an empirical separation of star-forming galaxies and AGNs based on the SDSS galaxies. The dotted line is the (Kewley et al. 2001) theoretical limit for star-forming galaxies. The dot-dashed line is a fit to the star-forming galaxies from the SDSS galaxies (Brinchmann et al. 2008).

### 1.2.1 Line diagnostic diagrams

Optical and IR emission lines from H II regions are an important diagnostic used to study galaxies. Line ratio of emission lines are often used as diagnostics of physical properties such as metallicity, electron density, electron temperature, and hardness of the ionizing radiation.

The Baldwin et al. (1981) diagram (hereafter the BPT diagram) is a commonly used tool to study extragalactic H II regions and their host galaxies. The most used combination is [O III] $\lambda$5007/H$\beta$ versus [N II] $\lambda$6584/H$\alpha$. In the galactic context, such plot is also used to classify galaxies since it allows a clear distinction between star-forming and AGN dominated galaxies (Figure 1.5(a)). Star-forming galaxies lie along a narrow sequence, while AGN are found offset due to their much harder ionizing spectrum.

The horizontal axis, [N II]/H$\alpha$, strongly depends on the metallicity within the star-forming region that increases with increasing [N II]/H$\alpha$. Changes in metallicity correspond to changes in the abundance of an emitting species relative to hydrogen. The results is a weaker emission in lines such as nitrogen and oxygen relative to hydrogen recombination lines such as H$\alpha$ and H$\beta$. Instead, the vertical axis of [O III]/H$\beta$ is associated with the average ionization state and temperature of the photoionized gas in the galaxy. Instead, for AGN and shocks the ionization/excitation always leads to a high value of line emission.

In the same plot, single H II regions cover a sequence that overlaps with the star-forming sequence of the SDSS galaxies (Brinchmann et al. 2004). The location on this sequence is controlled by physical properties of the H II region, such as metallicity, density of the ISM, ionization parameter, and age. Understanding how the star-forming sequence is connected to single H II regions on the BPT diagram can be helpful to assess physical properties of unresolved H II regions in galaxies.

The interpretation of emission lines requires significant modeling of both the internal structure and dynamical evolution of the emitting regions. Models of the BPT diagram, or in general any line emission, are produced using photoionization model codes such as Cloudy (Ferland et al. 2013) or MAPPINGS (Sutherland & Dopita 1993, Dopita et al. 2000). It is possible to create a set of predicted H II regions' line emission that can be compared to the observed BPT diagram for a set luminosity of the central star or star cluster, density of the ambient medium, and age. Such modeling is important in understanding H II regions' structures and in constraining their physical properties. By matching observations and a grid of models on the BPT diagram, it is possible to derive an approximate cluster age and ionization state of the region, even if the region is unresolved.

## 1.3 Thesis outlook

Key questions in star formation theory are the formation of massive stars and their feedback in their environment over cosmic time. This thesis tackles some aspects of this cosmic history of star formation and the way massive stars drive the evolution of galaxies. Specifically, we addressed the analysis of optical observations of star forming galaxies deriving the gas physical conditions of the H II regions associated with its massive star. We also numerically simulated the dynamical expansion of H II region driven by stellar winds and driven by the overpressure of the ionized gas. We carried out comparison of theories and numerical prediction with observations of both the H II region and the interstellar bubbles.

In Chapter 2 we address all aspects of UltraCompact H II regions. Focusing on a prototypical region, G29.96-0.02, we investigate the missing X-ray emission from stellar wind bubbles in H II regions. We conduct a broad study, combining X-ray observations of the hot gas with spectroscopic study of the properties of the ionizing star, and a hydrodynamical study of the dynamical evolution of these regions. We construct three-dimensional hydrodynamical model of the UltraCompact H II region including photoionization and wind effects, radiative processes, mass loading, and bow shock from stellar motion through the cloud. We find that champagne flow models are best at explaining the morphology and the gas dynamics, and that mass loading is necessary to cool the shocked stellar wind gas as the X-ray observations show.

In Chapter 3 we present a class of H II regions formed by champagne flow mechanisms to explain the cometary shape of the dust emission seen inside H II regions. Ochsendorf et al. 2013 (submitted) suggested that the arc-like structure seen at 24 $\mu$m is the result of the interaction between radiation pressure from the star with the dust contained in the flow of ionized gas photo evaporated from the birth molecular cloud. We show that in the presence of a champagne flow, the ionized gas inside the H II region reaches velocities at the star location high enough to set up the conditions for a dust wave. Such modeling can also reproduce the observed variety of morphologies of H II regions and their emission characteristics.

In Chapter 4 we step out, and look at the effects of H II regions on larger scales. Physical parameters of H II regions, such as age, radius and density of the ambient medium, are important in understanding the interaction of massive stars with their surroundings, the mechanisms driving the expansion of the ionized gas, and the link between star-forming galaxies and single H II regions. We select two well-studied H II regions in the nearby galaxy NGC 6822: Hubble V and Hubble X. We obtain well constrained physical parameters of two star-forming regions in the nearby universe and use such information to understand the star-forming sequence of SDSS galaxies in optical line diagnostic diagrams and their relation with single H II regions. We find that the emission characteristics of the star-forming galaxies are consistent with most of their light coming from the few brightest H II regions rather than the most dim ones.

Finally, in Chapter 5 and 6 we revisit the question of how H II region line emission depends on the physics of winds and radiation pressure. The emission line ratios [O III]/H$\beta$ and [N II]/H$\alpha$ have been adopted as an empirical way to distinguish between the fundamentally different mechanisms of ionization in emission-line galaxies. However, detailed interpretation of these diagnostics requires calculations of the internal structure of the emitting H II regions, and these calculations depend on the assumptions one makes about the relative importance of radiation pressure and stellar winds. We construct models of single H II regions including and excluding radiation pressure and winds in Chapter 5, and in Chapter 6 we describe a population synthesis code that uses these models to simulate galactic collections of H II regions with varying physical parameters. We show that the choice of physical parameters has significant effects on galactic emission line ratios, and that in some cases the line ratios can exceed previously claimed theoretical limits.