Introduction

Cosmologists believe that the Universe was created about 15 thousand million years ago with the Big Bang. During the first few minutes after the Big Bang, all the hydrogen and deuterium, some $^3\text{He}$, the mayor part of $^4\text{He}$ and some $^7\text{Li}$ were created. No heavier elements, known as “metals”, were formed. Stars with masses larger than $10M_\odot$ and their associated Type II supernovae are now understood to be the dominant contributors to the abundances of metals in our Galaxy and other galaxies. They are the primary source of the elements from oxygen to calcium; these elements arise from successive stages in the stellar evolution when the exhaustion of one fuel is followed by gravitational contraction and heating enabling the previous ashes to “burn”. Massive stars also produce approximately one third to one half of the iron peak nuclei as a result of explosive charge-particle reactions in their latest stages of evolution. Finally, neutron capture processes during the supernova explosion results in the production of elements beyond the iron peak, from copper to uranium. Since massive stars live for a short amount of time ($\sim 10^7$ years), the chemical evolution of a galaxy is intimately related to the enrichment of metals over time as a result of the birth and death of successive generations of massive stars.

Apart from their rôle in the chemical enrichment of galaxies, massive stars are a dominant force in the evolution of the interstellar medium (ISM) of galaxies. Through their strong winds, ultraviolet radiation, and supernovae, massive stars are responsible for a large amount of momentum and kinetic energy input into the interstellar gas. Moreover, these hot stars emit a large part of energy at extreme ultraviolet wavelengths; these photons can couple well to the surrounding gas through ionization of hydrogen atoms. The $\text{H}\ II$ regions created this way can also influence their surroundings dynamically: the high pressure of the ionized gas drives shock waves, sweeping up the ambient molecular cloud and triggering the formation of new stars. Understanding the characteristics of massive stars and their interaction with their environment is therefore a key problem within astrophysics.

1.1 $\text{H}\ II$ regions: the nurseries of stars

The birth of stars occurs in the densest parts of molecular cloud complexes. The radiation fields and stellar winds of the newly born massive star can disrupt the surrounding molecular
<table>
<thead>
<tr>
<th>Source</th>
<th>RA*</th>
<th>Dec*</th>
<th>Date</th>
<th>TDT°</th>
<th>Galactic name</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(J2000.0)</td>
<td>(J2000.0)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sgr C</td>
<td>17 44 35.6</td>
<td>-29 27 29.3</td>
<td>5-Mar-98</td>
<td>84100301</td>
<td>G359.43-0.08</td>
</tr>
<tr>
<td></td>
<td>17 44 35.9</td>
<td>-29 27 54.3</td>
<td>11-Mar-98</td>
<td>-</td>
<td>84700220</td>
</tr>
<tr>
<td>IRAS 17455−2800</td>
<td>17 48 41.5</td>
<td>-28 01 38.3</td>
<td>29-Aug-96</td>
<td>28701327</td>
<td>G1.13−0.11 Sgr D</td>
</tr>
<tr>
<td>IRAS 17591−2228</td>
<td>18 02 13.2</td>
<td>-22 27 58.9</td>
<td>14-Apr-97</td>
<td>51500580</td>
<td>G7.47+0.06</td>
</tr>
<tr>
<td>IRAS 18032−2032</td>
<td>18 06 13.9</td>
<td>-20 31 43.2</td>
<td>14-Apr-97</td>
<td>51500478</td>
<td>G9.61+0.20B</td>
</tr>
<tr>
<td>IRAS 18116−1646</td>
<td>18 14 35.2</td>
<td>-16 45 20.6</td>
<td>13-Apr-96</td>
<td>14801733</td>
<td>G13.88+0.28</td>
</tr>
<tr>
<td>IRAS 18162−2048</td>
<td>18 19 12.0</td>
<td>-20 47 31.1</td>
<td>13-Apr-96</td>
<td>14802136</td>
<td>G10.84−2.59</td>
</tr>
<tr>
<td>IRAS 18317−0757</td>
<td>18 34 24.9</td>
<td>-07 54 47.9</td>
<td>8-Mar-97</td>
<td>47801040</td>
<td>G23.96+0.15</td>
</tr>
<tr>
<td>IRAS 18434−0242</td>
<td>18 46 04.0</td>
<td>-02 39 20.5</td>
<td>17-Apr-96</td>
<td>15201383</td>
<td>G29.96−0.02</td>
</tr>
<tr>
<td>IRAS 18469−0132</td>
<td>18 49 33.0</td>
<td>-01 29 03.7</td>
<td>26-Oct-97</td>
<td>71100888</td>
<td>G31.40−0.26</td>
</tr>
<tr>
<td>IRAS 18479−0005</td>
<td>18 50 30.8</td>
<td>-00 01 59.4</td>
<td>17-Apr-96</td>
<td>15201791</td>
<td>G32.80+0.19</td>
</tr>
<tr>
<td>IRAS 18502+0051</td>
<td>18 52 50.2</td>
<td>+00 55 27.6</td>
<td>17-Apr-96</td>
<td>15201645</td>
<td>G33.91+0.11</td>
</tr>
<tr>
<td>IRAS 19207+1410</td>
<td>19 23 02.4</td>
<td>+14 16 40.6</td>
<td>15-Apr-96</td>
<td>15001041</td>
<td>G49.20−0.35</td>
</tr>
<tr>
<td>IRAS 19442+2427</td>
<td>19 46 20.1</td>
<td>+24 35 29.4</td>
<td>15-Apr-96</td>
<td>15000444</td>
<td>G60.88−0.13 Sh 87</td>
</tr>
<tr>
<td>IRAS 19598+3324</td>
<td>20 01 45.6</td>
<td>+33 32 43.7</td>
<td>11-Apr-96</td>
<td>14601350</td>
<td>G70.29+1.60 K3-50 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4-Dec-96</td>
<td>38402466</td>
<td></td>
</tr>
<tr>
<td>DR 21</td>
<td>20 39 00.9</td>
<td>+42 19 41.9</td>
<td>17-Apr-96</td>
<td>15200555</td>
<td>G81.70+0.54</td>
</tr>
<tr>
<td>IRAS 21190+5140</td>
<td>21 20 44.9</td>
<td>+51 53 26.5</td>
<td>24-Apr-96</td>
<td>15901853</td>
<td>G93.53+1.47 M1-78</td>
</tr>
<tr>
<td>IRAS 21270+5423</td>
<td>21 28 41.9</td>
<td>+54 36 51.5</td>
<td>13-Feb-98</td>
<td>82100309</td>
<td>G96.29+2.59 Sh 127A, WB 85A</td>
</tr>
<tr>
<td>IRAS 21306+5540</td>
<td>21 32 11.4</td>
<td>+55 53 23.9</td>
<td>15-Feb-98</td>
<td>82301012</td>
<td>G97.52+3.18 Sh 128, WB 91</td>
</tr>
<tr>
<td>IRAS 22308+5812</td>
<td>22 32 45.9</td>
<td>+58 28 21.0</td>
<td>12-May-96</td>
<td>17701258</td>
<td>G105.63−0.34 Sh 138, WB 191</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30-May-97</td>
<td>56101082</td>
<td></td>
</tr>
<tr>
<td>IRAS 23030+5958</td>
<td>23 05 10.6</td>
<td>+60 14 40.6</td>
<td>24-Jun-96</td>
<td>22000961</td>
<td>G110.10+0.05 Sh 156, WB 240</td>
</tr>
<tr>
<td>IRAS 23133+6050</td>
<td>23 15 31.4</td>
<td>+61 07 08.5</td>
<td>24-Jun-96</td>
<td>22001506</td>
<td>G111.62+0.37 Sh 159, WB 261</td>
</tr>
</tbody>
</table>

(*) Units of RA are hours, minutes, and seconds; units of Dec are degrees, arcminutes, and arcseconds. (°) Target Dedicated Time.

(¹) “Sh” comes from Sharpless (1959); WB comes from Wouterloot & Brand (1989).
Table 1.1—. Types of H II regions and their characteristic physical parameters (adapted from Garay & Lizano 1999, Dyson & Franco 2000 and Kurtz & Franco 2002).

<table>
<thead>
<tr>
<th>Type of region</th>
<th>Size (pc)</th>
<th>Density (cm(^{-3}))</th>
<th>Ionized mass ((M_\odot))</th>
<th>Number of ionizing stars(^\dagger)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypercompact</td>
<td>(~0.003)</td>
<td>(\geq 10^6)</td>
<td>~10(^{-3})</td>
<td>~1</td>
</tr>
<tr>
<td>Ultracompact</td>
<td>(~0.05)</td>
<td>(\geq 10^4)</td>
<td>~10(^{-2})</td>
<td>~1</td>
</tr>
<tr>
<td>Compact</td>
<td>(~0.5)</td>
<td>(\geq 5 \times 10^3)</td>
<td>~1</td>
<td>~1</td>
</tr>
<tr>
<td>Classical</td>
<td>~10</td>
<td>~100</td>
<td>~10(^5)</td>
<td>Few</td>
</tr>
<tr>
<td>Giant</td>
<td>~100</td>
<td>~30</td>
<td>(10^3 - 10^6)</td>
<td>~10(^5)</td>
</tr>
<tr>
<td>Starburst nuclei</td>
<td>&gt;100</td>
<td>~10</td>
<td>(10^6 - 10^8)</td>
<td>~10(^6)</td>
</tr>
</tbody>
</table>

\(^\dagger\) Rough guide to the number of stars ionizing every class. This has been calculated assuming that each star produces 10\(^{48}\) photons s\(^{-1}\).

gas. Particularly important is the creation of emission nebulae known as H II regions (or regions of ionized gas). The stars that create them, of spectral type O and B, are the most massive, hot and luminous stars, with effective temperatures in the range of about 10 000 to 50 000 K.

H II regions in the Milky Way are classified in three main categories by their average sizes and electron densities: ultra-compact, compact, and extended or “classical” H II regions (see Table 1.1). The more extended H II regions can often be observed in the visible. Perhaps the most famous example of an H II region of this class is the Orion Nebula (see Figure 1.1). Compact H II regions are buried in the parent molecular clouds and can normally be detected only at radio or infrared wavelengths. They were first catalogued as a class of objects by Mezger et al. (1967). In the late 1980s and early 1990s, and based upon infrared selection criteria, radio surveys with the Very Large Array Telescope (e.g. Wood & Churchwell 1989; Garay et al. 1993; Kurtz et al. 1994; Miralles et al. 1994) revealed the existence of a new class of objects: the ultra-compact H II regions. They have higher densities and smaller sizes than compact H II regions and seem to be even deeper buried inside the molecular clouds. Of the order of 1000 actual or candidate ultra-compact H II regions have been identified so far. Finally, recently, another class, called hyper-compact H II regions, bright at millimeter wavelengths, has been added. These hyper-compact H II regions are typically one order of magnitude smaller and two orders of magnitude denser than traditional ultra-compact H II regions (e.g. Kurtz 2002).

A simple expansion scheme may connect these classes of H II region. Hyper-compact and ultra-compact H II regions are buried inside the inner, high-pressure parts of the parental clouds and probably represent the youngest stages in the evolution of H II regions. As the new O and B stars continue to power the expansion of the ionized gas still farther into the molecular cloud, H II regions can begin to be observed at visible wavelengths and appear as compact H II regions. Extended optically visible H II regions represent, in this picture, the more mature expanded state of these objects.

Even larger H II regions (called giant H II regions, see Table 1.1) can be found in external
1.2 An overview of the physical processes in H II regions

When a newly born massive star “switches on”, it begins to ionize the surrounding material. Stellar photons with energies greater than the ionization potential of hydrogen (13.6 eV) ionize hydrogen and other elements. The excess energy of each absorbed photon goes into...
Figure 1.2—Sketch of the Orion OB association adapted from Reeves (1978). The Orion association can be spatially divided into four subgroups of stars which appear to have different ages (Blaauw 1964). Subgroup OB1a (indicated by plus signs) is the oldest (12 Myr) and largest group. As we move from northwest to southeast, we find increasingly concentrated and younger subgroups: subgroup OB1b (6 Myr old) is indicated by open circles and subgroup OB1c (2 to 5 Myr old) by filled squares. The Trapezium cluster in the Orion Nebula (located within the solid circle) constitutes the youngest subgroup (OB1d), with an age less than 2 Myr. This succession in ages and locations of the subgroups indicates that star formation has propagated through the original Orion cloud in a sequential manner (Elmegreen & Lada 1977). Orion A and Orion B are two large molecular clouds, which appear to have been shaped by energy release from the OB association. The dashed semi-ring is Bernard’s Loop, the brightest part of a giant bubble of Hα emission. Between 5000 and 20 000 stars are likely to have formed in the Orion region within the last 15 Myr.

kinetic energy of the ejected (thermal) electron. Collisions between electrons, and between electrons and ions, distribute the energy and maintain a Maxwellian velocity distribution with a temperature in the range from 5 000 to 10 000 K. Collisions between thermal electrons and ions excite the low-lying energy levels of the ions. Downwards radiation transitions from these excited levels have very small transition probabilities, but at the densities of these nebulae, collisional de-excitation is even less probable and hence, almost every excitation leads to emission of a photon, and the nebula emits a forbidden-line spectrum.

Thermal electrons are recaptured by the ions, and the degree of ionization at each point in the nebula is fixed by the equilibrium between photoionization and recombination. In the recombination processes, recaptures occur to excited levels, and the resulting cascade downwards gives the recombination line spectrum.

The star cannot ionize an infinitely large amount of surrounding gas. The volume of gas that the star can ionize is limited to that volume in which the total recombination rate is just equal to the rate at which the star emits ionizing photons. This volume of ionized gas is characterized by the Strömgren radius. The transition zone between neutral and ionized gas is termed an ionization front and has a thickness equal to the mean-free-path of and ionizing photon in the neutral gas, far smaller than the Strömgren radius. Consequently, nebulae
1.3. The forbidden spectrum of H\textsc{ii} regions

In emission nebulae, many common ions such as O\textsuperscript{+}, O\textsuperscript{++} and N\textsuperscript{+} have low-lying energy levels with excitation potentials of the order of $kT_e$, where $T_e$ is the electron temperature (see Figure 1.4, which shows the energy-level diagram of the lowest terms of O\textsuperscript{++}). Hence, the electrons in the extended tail of the Maxwell distribution corresponding to about 10,000 K have sufficient energy ($\sim 2 - 4$ eV) to excite the first spectral terms of these ions. Once

bounded by ionized-neutral zones are sharp edged.

The ionization state of any particular element depends on the energy distribution of the photons to which the parent element is exposed. This energy distribution is strongly influenced by photoabsorption by helium. Hard photons are absorbed nearest the star and so ions with the highest parent ion ionization potential are found there (e.g. O\textsuperscript{++}, N\textsuperscript{++}). The radiation field is softer further out and one finds there parent ions with lower ionization potentials (e.g. O\textsuperscript{+}, N\textsuperscript{+}). This phenomenon is called ionization stratification. Figure 1.3 shows the calculated ionization structure for oxygen and nitrogen. The ionization structure of these species has a layered structure, with the highest ionization stages closer to the stars and the lower ionization stages progressively located further away. The relative distribution of these ionization stages depends principally on the hardness of the stellar energy distribution.

For a detailed description of the physics of ionized gases, we strongly recommend the book by Osterbrock (1989).

**Figure 1.3.** Calculated ionization structure of oxygen (a) and nitrogen (b) for an O4 (top) and O9 star (bottom) at a density of $10^3$ cm\textsuperscript{-3}. The sequential ionization stages show an onion-like shell structure with the highest ionization stages closer to the star.
these levels are excited, they radiate spontaneously back to the ground state via forbidden transitions (they are called “forbidden” because they are not allowed by the dipole selection rules). The emission spectrum of H II regions in the ultraviolet, optical and infrared is characterized by a large number of these forbidden lines. The emissivities of these lines are simply \( j_\lambda = N_u A_{u \rightarrow l} h c / \lambda \), where \( A \) is the Einstein coefficient of the transition taking place at the wavelength \( \lambda \) and \( N_u \) is the number density of ions in the upper level, which is essentially proportional to a Boltzmann factor which increases as the temperature increases.

These forbidden transitions represent the main paths through which the kinetic energy of the gas is converted into photon energy which finally escapes from the nebula. This cooling is compensated by heating due to photoionization. The heating rate per unit volume is proportional to the number density of neutral hydrogen, which decreases with increasing gas temperature. The equilibrium between cooling and heating fixes the electron temperature of the nebula, which is remarkably constant throughout the nebula due to an thermostating mechanism: an increased gas temperature results in a decreased heating and increased cooling, while the opposite is true for a lowered temperature.

The most efficient cooling is the one via transitions that connect fine-structure levels within the ground state \( p^0 \) terms of abundant ions, such as O ++. These transitions, which give rise to emission lines in the infrared, are illustrated in Figure 1.4. The [O III] 52 and 88 \( \mu m \) lines are the dominant cooling lines in H II regions.

The forbidden lines carry also information about the physical structure of H II regions. Studies of intensity ratios of lines with either close or very different excitation energies probe, respectively, the electron density or the electron temperature conditions. For instance, the ratio of the intensity of the 4363 Å line of O ++ to the sum of the intensities of the 5007 and 4959 Å lines is a good probe of the temperature because of the difference in excitation energy of the levels. The ratio of the intensities of the 52 and 88 \( \mu m \) lines probes, on the other hand, the density.

Forbidden lines can be used to obtain relative abundances of two elements or elemental abundances relative to hydrogen. The abundance ratio of two ions can be obtained from the observed intensity ratio of lines emitted by these ions. To derive ionic abundances relative to hydrogen, one needs the H + density, which can be obtained from hydrogen recombination.
1.3. The forbidden spectrum of H\textsc{ii} regions

Figure 1.5–. Infrared spectrum of a typical compact H\textsc{ii} region obtained with the spectrometers on board the Infrared Space Observatory (ISO). The spectrum is characterized by a large number of recombination lines of hydrogen and fine-structure lines of N, O, Ne, S and Ar.

lines or radio continuum measurements. The total abundance of a given element relative to hydrogen is given by the sum of abundances of all its ions. In practice, not all the ions present in the nebula are generally observed and one must correct for unseen ions using ionization correction factors. Ionization correction factors based on ionization potential considerations were commonly used in the 70s and 80s (e.g. Peimbert & Torres-Peimbert 1977; Torres-Peimbert & Peimbert 1977). More recently, ionization correction factors are based on grids of photoionized models of nebula (e.g. Stasińska 1990; Mathis & Rosa 1991; Gruenwald & Viegas 1992).

With respect to the determination of elemental abundances, the use of infrared fine-structure lines presents several advantages with respect to the optical lines (e.g. Rubin et al. 1988; Simpson et al. 1995b). First, they are attenuated much less due to the presence of dust. Second, they are insensitive to the precise temperature of the emitting gas (these lines are emitted from levels with very low excitation energies) and hence, provide a direct probe of the abundances of the elements. Third, the infrared range is the only wavelength regime to measure the dominant form of nitrogen in highly ionized H\textsc{ii} regions (N\textsuperscript{++}).

Figure 1.5 shows the infrared spectrum from 2.5 to 196 $\mu$m of a typical compact H\textsc{ii} region. The spectrum is dominated by recombination lines of hydrogen and fine-structure lines of carbon, nitrogen, oxygen, neon, sulphur, argon and silicon. The lines of [C\textsc{ii}], [O\textsc{i}] and [Si\textsc{ii}] are produced by ions with ionization potentials lower than 13.6 eV and are thus expected to be mostly emitted in the photodissociation region surrounding the H\textsc{ii} region. Nitrogen, neon, argon and sulphur are observed in two different ionization stages, which enormously alleviates the problem of applying ionization correction factors.

The direct observation of two different ionization stages not only facilitates the determination of elemental abundances, but probes also the ionization structure of the nebula and
constrains the stellar energy distribution (SED) of the ionizing star. Basically, the ratio of two successive stages of ionization \( X^{+i} \) and \( X^{+i+1} \) of a given element \( X \) indicates the state of ionization of the nebula, which directly depends on the shape of the SED – more specifically on the number of photons able to ionize \( X^{+i} \) (Vílchez & Pagel 1988) – and the ionization parameter. This ionization parameter, \( U \), ties together the local gas and photon density and is essentially the ratio of ionizing photons to gas particles. It is defined by the expression

\[
U = Q / (4\pi R_s^2 n c),
\]

where \( Q \) is the number of stellar photons above 13.6 eV emitted per second, \( R_s \) is the Strömgren radius of the nebula, \( n \) is the gas density and \( c \) is the speed of light. The larger the ionization parameter, the more ionized the gas.

In the infrared regime, four different ratios sensitive to the ionization structure of the nebula are available: \([\text{N}\,\text{III}]/[\text{N}\,\text{II}] \) 57/122 \( \mu \text{m} \), \([\text{Ar}\,\text{III}]/[\text{Ar}\,\text{II}] \) 9.0/7.0 \( \mu \text{m} \), \([\text{S}\,\text{IV}]/[\text{S}\,\text{III}] \) 10.5/18.7 \( \mu \text{m} \) and \([\text{Ne}\,\text{III}]/[\text{Ne}\,\text{II}] \) 15.5/12.8 \( \mu \text{m} \). Figure 1.6 shows the effect of varying the effective temperature of the ionizing star on the \([\text{Ne}\,\text{III}]/[\text{Ne}\,\text{II}] \) and \([\text{Ar}\,\text{III}]/[\text{Ar}\,\text{II}] \) line ratios in the case of a nebula with fixed ionization parameter and metallicity. Such infrared line ratios are commonly used to infer the stellar content of \( \text{H}\,\text{II} \) regions where individual stars cannot be directly observed (e.g. Oey et al. 2000; Takahashi et al. 2000; Okamoto et al. 2001; Morisset et al. 2002). Moreover, because the hardness of the extreme UV spectrum is a good measure of the spectral type of the ionizing stars, and because later spectral types live longer, the observed ionization structure is often interpreted in terms of the age of a star burst region in external galaxies (e.g. Crowther et al. 1999; Thornley et al. 2000; Spoon et al. 2000).

### 1.4 H\(\text{II}\) regions in the Galactic context

The chemical evolution of the ISM varies between galaxies and is both position and time dependent within a galaxy. Theoretical models of the chemical and dynamical evolution of a galaxy depend on many variables including the historical star formation rate (e.g. Phillipps & Edmunds 1991), the initial mass function (e.g. Guesten & Mezger 1982), radial inflows/outflows of gas (e.g. Mayor & Vigroux 1981) and the infall of metal-poor gas from the halo (e.g. Pilyugin & Edmunds 1996). The radial variations of metallicity within
the galactic disk predicted by such models are not tightly constrained. Thus, the reliable
determination of the extent and magnitude of radial and spatial variations for a wide range
of elements must be used to constrain models of disk evolution (e.g. Matteucci & Francois
1989; Edmunds & Greenhow 1995; Prantzos & Aubert 1995; Portinari & Chiosi 1999; Hou
et al. 2000).

H II regions are prime targets to derive the present-day elemental abundances of the ISM
in our own Galaxy and in other galaxies. The existence of large-scale abundance gradients
were first established by Searle (1971) in a survey of H II regions in six late-type spiral galax-
ies. Later studies of external galaxies (e.g. Vila-Costas & Edmunds 1992; Zaritsky et al.
1994) confirm that elemental abundances decrease outwards across the disks of spiral galax-
ies. These radial gradients may be fit by an exponential $R$, where $R$ is the distance from the
center of the galaxy.

Studies of abundance gradients in our Galaxy are more difficult due to the uncertainties
in the distances and the fact that many H II regions are highly obscured by dust lying close
to the galactic plane. The first determination of an abundance gradient in our Galaxy from
H II regions was made by Peimbert et al. (1978). Posterior optical studies in the optical have
been made by, for instance, Shaver et al. (1983), Fich & Silkey (1991) and Deharveng et al.
(2000). The arrival of the Kuiper Airborne Observatory (KAO) and the Infrared Astronomical
Satellite (IRAS) permitted measurements of elemental abundances from compact and ultra-
compact H II regions and gave access for the first time to the central regions of the Galaxy
(e.g. Simpson & Rubin 1990; Simpson et al. 1995b; Afflerbach et al. 1997; Rudolph et al.
1997).

1.5 In this thesis

The main questions addressed in this thesis are:

- How do the elemental abundances vary across the disk of our Galaxy?
- How does the ionization structure of H II regions interrelate to the metallicity and the
  spectral energy distribution of the ionizing stars?

The first question is directly related to the chemical evolution of our Galaxy. The second
question is coupled to the characteristics of massive stars and how they interact with their
environment.

The bulk of this research is based on the infrared spectra between 2.3 and 196 $\mu$m taken
towards a sample of 45 ultra-compact and compact H II regions using the two spectrometers
(the Short Wavelength Spectrometer, SWS, and Long Wavelength Spectrometer, LWS) on
board the Infrared Space Observatory (ISO). This sample spans a wide range in Galacto-
centric distance enabling to investigate the variations of nebular properties, and in particular,
the metal content, across the Galactic plane. The observations and the data reduction are
described in detail in Chapter 2. This chapter contains also the combined SWS and LWS
spectra for each of the sources, the fluxes of the fine-structure and hydrogen recombination
lines, and an inventory of the molecular bands, dust and ice bands present in the spectra.

Chapter 3 presents an analysis of the recombination lines of hydrogen and atomic fine-
structure lines originated in the ionized gas of the H II regions. Elemental abundances of
neon, argon and sulphur were determined for 34 nebulae out of the original sample. This
subsample spans a range in Galactocentric distance from 0 to 15 kpc. The methodology used to determine the elemental abundances is described in detail, with a particular emphasis on the advantages and disadvantages of the data set. The neon and argon abundances are found to decrease with the distance to the Galactic Center, while no significant gradient is found for sulphur. The relative abundance of nitrogen relative to oxygen is also found to decrease with Galactocentric distance.

The analysis of the line ratios \([\text{N}\text{ III}]/[\text{N}\text{ II}]\) \(57/122\ \text{\mu m}\), \([\text{Ar}\text{ III}]/[\text{Ar}\text{ II}]\) \(9.0/7.0\ \text{\mu m}\), \([\text{S}\text{ IV}]/[\text{S}\text{ III}]\) \(10.5/18.7\ \text{\mu m}\) and \([\text{Ne}\text{ III}]/[\text{Ne}\text{ II}]\) \(15.5/12.8\ \text{\mu m}\) shows that the most highly ionized objects are located at larger Galactocentric distances, while the less highly ionized objects are located at smaller distances. In line with the elemental abundance gradients, it is suggested that metallicity is somehow involved in these changes in the ionization structure and hence, in the hardening of the spectral energy distribution. The interplay between the SED, metallicity and ionization structure is investigated in Chapter 4. This is done with the inclusion of H II regions in the Large and Small Magellanic Clouds. Magellanic Cloud H II regions are characterized by rather low metal contents and high degrees of ionization. The combined Galactic and Magellanic Cloud sample provides a “natural” sample of H II regions covering a wide range in metallicity and degree of ionization. It is found that the variations in degree of ionization from the sources in the Galactic Center to those in the Magellanic Clouds are largely due to variations in metallicity. It is argued that the stellar and nebular metallicity influences the observed infrared line ratios and hence, makes the use of these line ratios difficult as diagnostic tools for the stellar content of H II regions. The implications in the study of starburst galaxies are assessed.

Chapter 5 combines the spectral infrared observations of 18 H II regions out of the original sample with radio continuum observations. The radio observations are used to determine physical properties such as the linear diameter, density and number of Lyman continuum photons. The radio observations provide, in addition, information about the distribution of the ionized gas within the ISO apertures. As a result of the combined radio and infrared observations, the elemental abundances are re-calculated and the galactic metallicity gradient revisited. The relation between metallicity and ionization structure is re-analyzed with the inclusion of a sample of H II regions in M33.

Chapter 6 presents a systematic study of the effect of metallicity on the SED of O main sequence stars, focussing on the hydrogen en helium ionizing continua and on the optical lines used for spectral classification. The observational results from Chapter 4 are tested theoretically here.

Long slit observations of the compact H II region 29.96–0.02 made with the Infrared Spectrometer And Array Camera (ISAAC) mounted on the Very Large Telescope (VLT) of the European Southern Observatory (Paranal, Chile) are presented in Chapter 7. Besides the nebular spectrum at different positions - with contains recombination lines of hydrogen and helium originated in the ionized gas of the H II region and a molecular hydrogen line originated in the ambient molecular cloud – the observations revealed the spectrum of the ionizing star. The potential of these type of observations is shown, first, to test the different models aimed at explaining the dynamics of the nebula, second, to determine physical properties such as temperature and the He\(^+\)/H\(^+\) relative abundance across the object, and third, to determine the spectral type of the ionizing star.

Finally, the results from the work presented in this thesis and its main conclusions are summarized in Chapter 8.