Tales of Orion : the interplay of gas, dust, and stars in the interstellar medium

Ochsendorf, B.B.

Citation

Ochsendorf, B. B. (2015, September 1). *Tales of Orion : the interplay of gas, dust, and stars in the interstellar medium*. Retrieved from https://hdl.handle.net/1887/34931

Author: Ochsendorf, Bram Benjamin
Title: Tales of Orion : the interplay of gas, dust, and stars in the interstellar medium
Issue Date: 2015-09-01

1

Introduction

The constellation of Orion is one of the most discernable patterns in the northern hemisphere, and has acted as an important beacon for generations throughout history. Orion stands central in many mythological tales. One of my personal favorites describes the figure of Orion, the hunter, standing by the river Eridanus, hunting the celestial animals Taurus and Lepus together with his loyal companions, Canis Major and Canis Minor. In modern astronomy, the Orion region remains one of the best studied regions in the sky. The region is favorably placed offset from the Galactic plane, limiting the confusion with unrelated structures along the same line of sight. Furthermore, it harbors the nearest region of ongoing massive star formation, and because of its proximity, allows observations to resolve structures down to ~AU scales only to unveil a brilliant amount of detail, while stellar parallaxes can be measured to provide clues to the space motion of its stars.

Figure 1.1 offers a multi-wavelength view of the entire Orion star forming region, tracing infrared emission from cosmic dust, while ionized gas is captured through narrowband imaging at optical wavelengths. The image stretches over a magnificent extent of the sky and, moreover, demonstrates the advent of observational facilities that allow us to probe interstellar structures across the electromagnetic spectrum unseen to the human eye. The positions of the constellation's seven most recognizable stars are overplotted. By now, we know that Orion has given birth to some $\sim 10^4$ stars in the last 10 - 15 Myr, scattered in clusters and subgroups over the entire region, which in its entirety is known as the Orion OB association. The feedback from the most massive stars have left their mark on the surrounding interstellar material, creating a highly complex and chaotic environment. In this respect, figure 1.1 is striking, and captures the interaction of gas, dust, and stars on every observable scale, underlining the importance of gas- and dust dynamics in our quest to fully comprehend the physical processes that determine the formation and evolution of stars and their interaction with the interstellar medium (ISM).

In this thesis, I aim to obtain a better understanding of the interactions between gas, dust, and stars in the ISM, by using the Orion region as a benchmark model. The interplay between these constituents remains poorly understood, as results from ever better observational facilities continuously throw theorists back to the drawing board to revisit some of the most fundamental questions in ISM research. Yet, these observational opportunities offer the astronomical community with a new vantage point of the ISM that gives rise to so much new research fields. Still, to advance our understanding of the ISM of galaxies, in first principle, we need to acquire a deep understanding of the interplay between stars and their surroundings. How do massive stars and OB associations shape the neighboring ISM? How much energy is coupled to the ISM through their supernovae, stellar winds, and UV radiation, and how does this reflect on the phase structure of the ISM? How are molecular clouds formed and destroyed? How does stellar feedback regulate star formation efficiency? How are galactic outflows driven, and what is exactly the

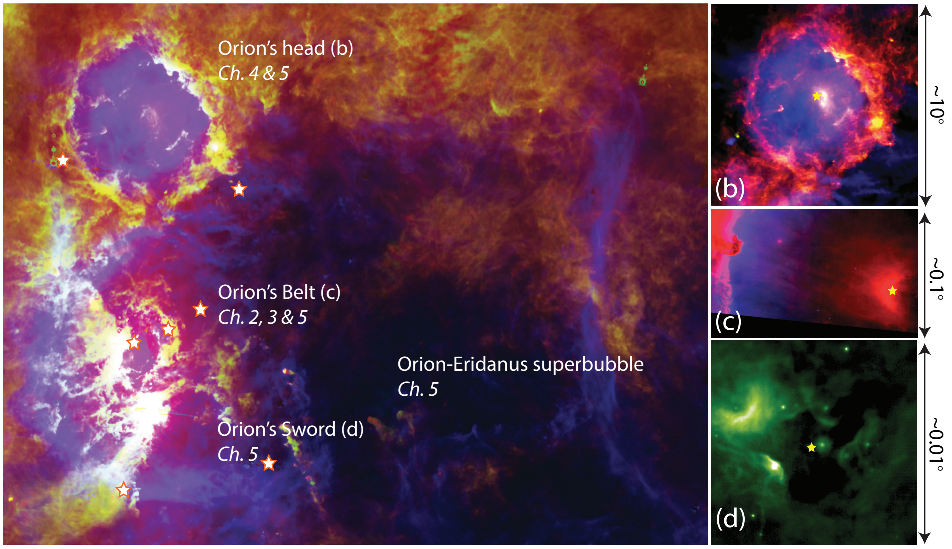

Figure 1.1: **(a)** Three-color image of part of the Orion-Eridanus region. Hα (blue) reveals ionized gas, surrounded by a layer of carbonaceous molecules (polycyclic aromatic hydrocarbons) or stochastically-heated small dust grains, traced by the 12 μm passband of the *Wide-field Infrared Explorer* (WISE; Sec. 1.1.1) shown in green. Red is 353 GHz emission detected by the *Planck* satellite, tracing columns of cold (20 K) dust. The polycyclic aromatic hydrocarbons/small grains trace the ultraviolet-illuminated edges of the clouds containing cold dust, resulting in that red and green blend to form yellow. The field of view stretches ~28° × 38° on the sky. Overplotted are the bright stars of the Orion constellation, and explicitly labelled are subregions within Orion that form the starting point and/or subject of research in the denoted chapters of this thesis. **(b)**, **(c)** & **(d)**: Infrared arc-like structures wrap around stars in Orion (yellow asterisks) on *every* observable scale. Figure (b) is a multi-degree view of the λ Ori region (Orion's head), figure (c) is an arcminute-scale picture of the σ Ori region in Orion's Belt (note the Horsehead Nebula on the left), while figure (d) is an arcsecond-scale zoom of the Trapezium region within Orion's sword. The arcs can be exploited to quantify the interaction between stars with their surroundings (Sec. 1.2.3) and exemplify the importance of dynamics within the interstellar medium.

role of the halo and the intergalactic medium (IGM) in the mass and energy budget of the ISM? In the following chapters of this thesis, I will attempt to tackle some of these questions by using novel and perhaps somewhat unconventional approaches, which are needed to evolve from equilibrium models to an ISM that is highly turbulent, filled with dynamical structures on all observable scales.

In the remainder of this introduction, some historical breakthroughs and recent development in ISM research will be highlighted. We will briefly touch upon how past infrared missions have been exploited to trace the structure and evolution of the ISM. Interstellar dust is a key player in this regard and stand central in this thesis work: we will discuss the (dis)advantages of dust as a tracer of, e.g., star formation, and the structure and physics of the ISM. Subsequently, the main dynamical effects of massive stars on the ISM will be reviewed. We will follow this somewhat chronologically, starting with the formation of H II regions and the main forces that drives the expansion of these ionized volumes, and will discuss several mechanisms that may influence the evolution of H II regions. Photo-evaporation flows of ionized gas are important carriers of mechanical energy: we will briefly discuss flow structures and how they depend on the shape of ionization fronts. We will then move towards larger scales, and discuss the formation of superbubbles through the collective efforts of radiation, stellar winds, and supernovae of massive stars. We will devote a special subsection on dust and its importance to the radiative feedback of massive stars to their surroundings, which will constitute a major part of this thesis. We will then summarize and discuss how the different mechanisms contribute to the kinetic energy budget of the ISM, i.e., how does stellar feedback couple to the dust and gas, in what way this relates to the velocity and density structure of the ISM, and how this impacts the formation of subsequent generations of stars. Finally, we set out on a journey in the constellation of Orion, and discuss its importance and usage as a benchmark to ISM and star formation studies.

1.1 The interstellar medium

Our view of the Galactic system has undergone numerous paradigm-changing discoveries since the development of astronomical instrumentation flourished. The view that the cosmos consisted of more than just stars immersed in an empty void was kick-started with observations of the Orion Nebula by Fabri de Peiresc in 1610 (Dufay 1957), Huygens (1659), and Messier (1771), who included the Orion nebula in his catalogue of nebulae and star clusters as its forty-second entry (‘M42’). Herschel (1789) described the bright patch located in the sword of Orion as *“an unformed fiery mist, the chaotic material of future suns”*. It was soon accepted that many objects in the sky could be classified as ‘nebulae’, i.e., bright bodies that appeared unresolved to the telescopes at the time. Building upon the work of Herschel (1789), the first comprehensive catalogue of nebulae was compiled by Dreyer (1888) in the *New General Catalogue*, including all types of objects that are observed in deep space, such as planetary nebula, emission nebula, H II regions, and galaxies, which often showed a spiral structure and were therefore classified as ‘spiral nebulae’. The Orion nebula is listed here as object NGC 1976. In 1904, Hartmann (1904) discovered that in the spectrum of δ Orionis, the calcium K line did not follow the periodic displacements of the photospheric lines caused by the orbital motion of the star. The narrow line profile seemed to be detached from the stellar photosphere and, therefore, Hartmann (1904) concluded that it must have originated from space located along the line of sight towards δ Orionis. Other stars revealed the same phenomenon and, in addition, more distance stars showed stronger absorption of the detached lines. Thus, gas (or matter in general) was shown to exist freely in space, filling the medium between the stars, much like a rarefied gas.

Early photographs of the Milky Way from 1869 onwards revealed dark, sharply defined spots of sky exhibiting a clear absence of stars. The existence of the black patches in the sky were already mentioned by Herschel (1785), which he described as ‘Openings in the Heavens’. Barnard (1919) examined these apparent openings, but concluded that they must constitute clouds or structures of opaque material that stand out strong and black against the light of many unresolved stars behind them. Trumpler (1930) then showed through a study of open clusters in the Milky Way that their sizes and magnitudes could only be explained by a widespread absorption in space that was correlated with distance, and produced the first reddening curves by measuring the color excess between 'visual' and 'photographic' magnitude. The wavelength dependence of the starlight extinction could only be explained by small, solid particles that absorb starlight on a spectral range much broader than the discrete, narrow bands from transitions of specific atoms or molecules. In the end, these results led to the belief that solid particles must reside in space alongside the gaseous material obvious from absorption spectra.

By now, we know that the space between stars is filled with a dilute mixture of atoms, molecules, and dust grains, which we call the interstellar medium (ISM). As quoted from D. Osterbrock (1984), *"The interstellar medium is anything not in stars"*. While this is true by definition, it disregards that the ISM and stars are intimately linked. Stellar feedback through ultraviolet (UV) radiation, winds, and supernova explosions dominate the energy input into the ISM and generate shockwaves that collect gas and dust in giant shells. Atomic and molecular clouds collapse and condense in these shells and, once they become gravitationally unstable, may form a new generation of stars of which the most massive constituents will, in their turn, end their lives as a supernova. After the lifetime of each stellar generation, the material of the ISM will become enriched with heavy materials created through nucleosynthesis.

The physics of the ISM is a crucial part in many areas of astronomy, such as the formation and evolution of stars and entire galaxies. It regulates molecule- and dust grain synthesis, which together constitute the very building blocks of planetesimals required to form planetary systems and, ultimately, life itself. The first global models of the ISM consisted of a two-phase medium (e.g., Field et al. 1969), in which a cold cloud phase and a warm intercloud phase could co-exist through thermal and pressure equilibrium set by the relevant heating and cooling processes. This was later extended to a three-phase model by implementing a third hot coronal phase created by shock waves from supernova explosions (McKee & Ostriker 1977). While these early models have had their success in explaining many of the basic principles of the ISM, neither picture has proven to be complete. Observations from, e.g., the *Spitzer Space Telescope* and the *Herschel Space observatory*, revealed that a significant fraction of the interstellar medium is dynamic, clumpy, and filamentary (Fig. 1.2), likely caused by an interplay between stellar feedback and the ISM. However, additional sources of pressure may contribute, such as magnetic fields, cosmic ray heating, and turbulent motions that stir the phases of the ISM in a non-linear fashion. Indeed, the existence of large volumes of gas at temperatures that are traditionally thought to be thermally unstable (Heiles 2001) prove that our knowledge of the ISM may be far from complete. Besides the phase structure of the ISM, the mysterious origin of the diffuse interstellar bands (Herbig 1995) and the 2175 Å extinction bump (Draine 1989) imply that we do not have a complete census of the constituents of the ISM. Nonetheless, tremendous progress is being made both observationally and computationally, with observational facilities pushing the boundaries of both sensitivity and spatial resolution, and computational facilities that are able to incorporate an ever increasing amount of 'realism' into simulations, such as fully self-consistent hydrodynamics including gas-phase transitions, chemical networks, dust physics, and star formation- and feedback.

1.1.1 Infrared missions

Infrared astronomy has classically been hampered by the fact that the Earth's atmosphere is largely opaque in this wavelength region. While in the wavelength range 1 μm - 30 μm

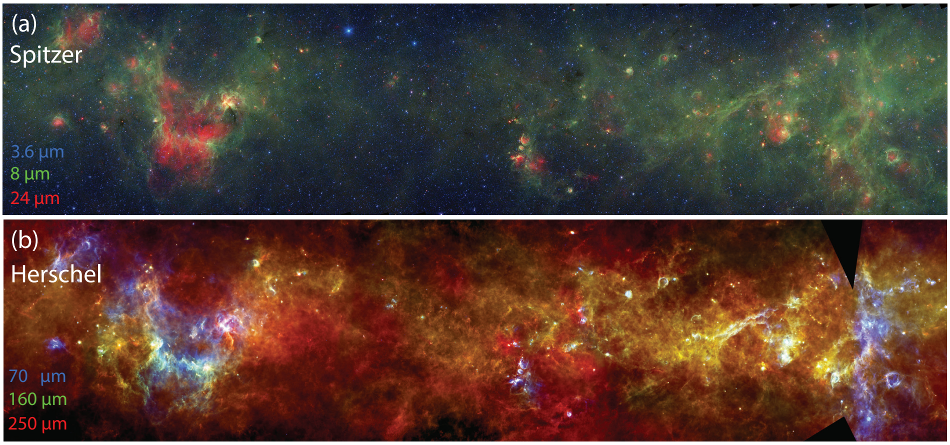

Figure 1.2: Panoramic view of the Galactic plane, stretching between $318 > l > 310$ degrees longitude that crosses the Circunus and Centaurus constellations. In visible light, this area of the Galactic plane is nearly featureless, obscured by dust that figures prominently in the infrared images from *Spitzer* (a) and *Herschel* (b). These observatories introduced a paradigm shift in our view of the interstellar medium, which appeared to be highly dynamic and turbulent. As this figure illustrates, dust is a unique tool to trace the structure of the ISM on all resolvable scales. Image credit *Spitzer*: NASA/JPL-Caltech/Univ. of Wisconsin. Image credit *Herschel*: ESA/PACS & SPIRE Consortium, Sergio Molinari, Hi-GAL Project.

several windows still exist where the atmosphere is (partly) transparent, for wavelengths between 30 μm and 400 μm the atmosphere is fully opaque. In order to allow infrared studies of astronomical objects in this wavelength range, one must get above as much of the Earth's atmosphere as possible. People thought of mountains, flying balloons, aircrafts, and even space. In this regard, infrared missions literally took off in the 1970's with the launch of the *Kuypers Airborne Observatory* (KAO; 1974), which was later followed-up by the first infrared space mission, the *Infrared Astronomical Satellite* (IRAS; 1983), marking the beginning of a golden era in infrared space observatories that included *the Infrared Space Observatory* (ISO; 1995), the *Spitzer Space Telescope* (2003), the *Herschel Space Observatory* (2009), *Planck* (2009), and the *Wide-field Infrared Survey Explorer* (2009). Finally, in 2010 the *Stratospheric Observatory for Infrared Astronomy* (SOFIA) aboard a heavily modified 747 airplane saw first light. Each of these missions had its own specific features and goals, pushing the boundaries of infrared astronomy in either spatial resolution, sensitivity, and/or sky coverage.

The contents of this thesis largely revolve around observations taken with most of the aforementioned infrared observational facilities. Here, we particularly mention the large-scale, high-resolution surveys of the Galactic plane, Spitzer/GLIMPSE (Fig. 1.2a; Benjamin et al. 2003), Spitzer/MIPS-GAL (Fig. 1.2a; Carey et al. 2009), and Herschel/Hi-GAL (Fig. 1.2b; Molinari et al. 2010). The GLIMPSE survey at 3.6 μm primarily traces the stellar content of the Galaxy, while at 8 μm Polycyclic Aromatic Hydrocarbons (PAHs) are probed that are located within photo-dissociation regions where UV photons penetrate, making the 8 μm band a robust tracer of PDRs and (massive) star formation activity. Heated by starlight, warm dust at $\sim$100 K emits within the 24 μm mid-IR wavelength channel of the MIPSGAL survey. The Herschel/Hi-GAL survey extended the high-resolution coverage of the Galactic plane towards longer wavelengths, providing spatially resolved emission maps of the cold component (~20 K) of interstellar dust. Together, these missions reveal an incredible richness of detail in the intricate interactions between gas, dust, and stars that drives the evolution of the ISM (Fig. 1.2).

1.1.2 Interstellar dust

The infrared studies discussed in Sec.1.1.1 revealed that interstellar dust is a ubiquitous component of the cosmos that pervades the Milky Way (Fig. 1.2) and other galaxies. Dust acts as a blanket that extinguishes the light from background sources in a way that is directly related to the intrinsic properties of the grains. Dust is a minor (~1% in mass of the ISM), yet crucial component of the ISM. It is the dominant source of opacity of the ISM at wavelengths above 912 Å, and by this controls the appearance of galaxies at these wavelengths by absorbing visual and ultraviolet light, and re-emitting it in the infrared. Dust stands central within interstellar chemistry by providing a surface that acts as a catalyzer for reactions between species, by shielding molecular regions from dissociating stellar radiation fields, and by controlling gas phase densities through the accretion and release of gas species onto/from their mantles. Dust grains control the temperature of the ISM as they account for much of the enriched elements that provide cooling through gas emission lines, while the photo-electric effect is considered to be the most important heating mechanism of (neutral) interstellar gas. In short, dust can be used as a tracer of gas masses and star formation rates, while probing the structural, physical, and evolutionary conditions of the ISM.

The above emphasizes the key position that dust holds within the physical and chemical processes that govern the ISM of galaxies. However, many of these details on interstellar dust are based on empirical grounds, as the precise composition or physical properties of dust grains remain largely unknown. A coherent picture of dust composition and physical characteristics in the various phases of the ISM can only be accomplished by confronting theory and laboratory work with observations. In the last few decades, dust models of increasing sophistication have been constructed, often incorporating polycyclic aromatic hydrocarbons, graphite, and ‘astronomical silicates’. These models have proven to be able to model quite robustly the extinction, emission, polarization, and abundances of dust in the diffuse ISM at high Galactic latitudes (e.g., Li & Draine 2001; Draine & Li 2007; Compiègne et al. 2011). However, these models are now being challenged by present-day observations of increasing sensitivity and angular resolution from the different phases present in the ISM. One simplifying assumption often made is that dust grains are spherical, even though dust is expected to coagulate to large, fluffy aggregate structures in molecular clouds (Ossenkopf & Henning 1994; Ormel et al. 2009). It is unclear to what extend the grains retain this shape when exposed to the harsh conditions of the diffuse ISM, as the grains will be processed through UV radiation, shocks, and thermal sputtering with the gas (Tielens et al. 1994; Jones et al. 1996). Indeed, dust cycles from clouds to the diffuse phase of the ISM (Tielens 1998, 2013) and the evolution of its composition, geometry, and optical properties seem to evolve when moving from one phase to the other (Jones 2014).

1.2 The interplay of gas, dust, and stars

The Galactic ecosystem is in constant motion due to the interaction between the ISM and the stars that are immersed within it. Stars tend to form within groups or large clusters (Lada & Lada 2003), and albeit small in number compared to their lower-mass siblings, the most massive component of the stellar population dominates the thermal and velocity structure of the ISM through their intense radiation, powerful stellar winds, and devastating supernova explosions. The constant input of radiative and mechanical energy provides feedback mechanisms that results in an ISM that is, irrefutably, a sight to be seen (Fig. 1.2).

The high-angular resolution and high sensitivity of *Spitzer* revealed that the Galactic plane is dominated by structures or shells on all spatial scales that appear complete ('ring-like') or partially complete ('filamentary-like'). As practically none of these structures are associated with supernova remnants, they must be powered by stars with spectral type B9 or earlier in order to produce the radiation fields required to excite PAHs. Therefore, Churchwell et al. (2006) hypothesized that these rings and filaments represent the PDRs of dynamically formed H II regions from massive stars, and hypothesised that the rings were two-dimensional projections of spherical bubbles. Further investigation revealed that about 86% of the bubbles classified by Churchwell et al. (2006) and Churchwell et al. (2007) are associated with H II regions (Deharveng et al. 2010) and must be blown by stars of spectral type B2 or earlier. Invoking the help of the general public, some 6000 'bubbles' have now been identified (Simpson et al. 2012) that span a wide range of morphologies and sizes that relate to their stellar content, evolutionary state, and structure of the ISM in which they expand. These works, exploiting the sensitivity and resolution of *Spitzer*, clearly demonstrated the major impact of massive stars and their dominance over the global structure of the ISM. Yet, when the *Spitzer* image is compared with the *Herschel* image (Fig. 1.2), one can see that the PAHs merely trace the tip of the iceberg. The *Herschel* passbands, sensitive to dust at lower temperatures, reveal that the ISM is dynamical in regions that escaped the attention of *Spitzer*. The impact of massive stars reach far beyond the PDRs traced by the PAHs. Indeed, stellar feedback initiates shocks waves that plow through the ISM and collect mass in dense, neutral shells. Given the short lifetime of massive stars, Fig. 1.2 represents a snapshot in the evolution of our Galaxy, yet provides clues to its history that has seen numerous generations of stars, each of which must have left its imprint on the structure of the ISM seen to date.

1.2.1 Formation and evolution of H II regions and stellar wind-blown-bubbles

Massive stars generate an intense radiation field containing numerous photons with energies above 13.6 eV that are able to ionize hydrogen. Once a massive star is born, the initial evolutionary stage of the ionized volume (the H II region) occurs rapidly, as the ionization front (IF) rushes through the surrounding material until the Strömgren radius is reached (Strömgren 1939), where the total amount of recombinations equals the ionizing photon rate from the star. The photo-ionization suddenly heats the gas towards 10^4 K, and the overpressure of the photo-ionized gas with respect to the (neutral) ambient ISM will drive an expansion of the H II region. The interior density drops with time as the H II region ex-

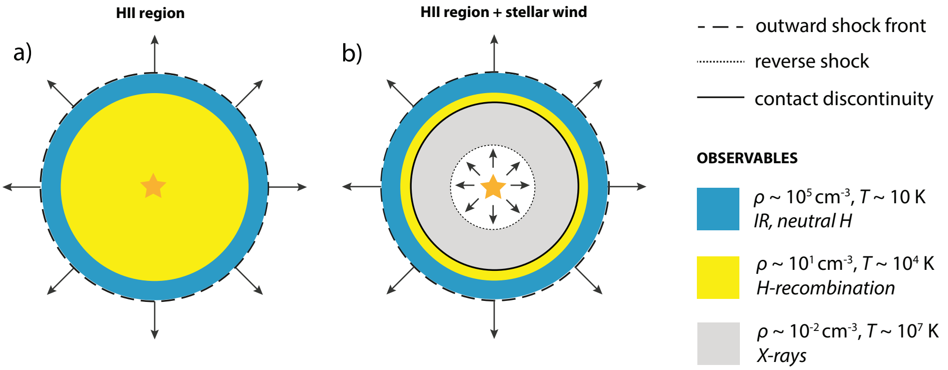

Figure 1.3: **(a)**: The structure of an H II region driven by overpressure of ionized gas (Spitzer 1978). **(b)** Same as (a), but including the effect of a stellar wind (Weaver et al. 1977). The legend denotes media separated by different temperatures and densities (parameters corresponding to a 'classical' H II region, see text), including their observational tracers.

pands in size. For example, an ultra-compact H II region such as the G29.97-0.02 region (Wood & Churchwell 1989) contains a hydrogen number density of ~10^4 cm^{-3} inside a region of radius ~0.05 pc. By the time the region has evolved to a classical H II region, such as the RCW120 region (Zavagno et al. 2007), the density has dropped to ~10^1 - 10^2 cm^{-3} within a radius of ~10 pc. If the expansion of the H II region occurs supersonic with respect to the ambient material, a shockwave will run out from from the IF on the neutral side that sweeps up the ISM and collapses into a dense (~10^5 cm^{-3}), cool (~10 K) shell, which dust component is detectable at IR wavelengths. This is the idealized view of the expansion of an H II region in a homogeneous medium (Fig. 1.3a; Spitzer 1978).

Besides the radiative feedback stemming from UV photons that ionize the surrounding gas, massive stars inject mechanical energy through powerful stellar winds that contain mass and momentum. The theory of stellar wind-blown-bubbles (WBB) stems from the seminal work of Castor et al. (1975) and Weaver et al. (1977). The stellar wind expands freely until it clashes with the surrounding medium when ram pressure equilibrium between both media is reached. From that moment on, one shock wave will move outwards, shocking and sweeping up the ambient ISM in a dense shell. This shell is ionized up to the point where ionizing photons are able to penetrate. At the same time, a reverse shock moves inwards, shocking the stellar wind and leaving behind a hot (~10^7) K, tenuous (~0.01 cm^{-3}) medium that should be detectable at X-ray wavelengths. Ultimately, part of the energy input of the stellar wind will do work on its surroundings (typically some 20%; van Buren 1986), setting the dense shocked ISM in motion to form an expanding shell, while the rest is stored as thermal energy of the hot gas. The pressure-driven expansion of an H II region, with and without the influence of a stellar wind, is depicted in Figure 1.3.

The cooling function (Dalgarno & McCray 1972) implies that radiative losses from the hot gas $\simeq 10^6$ K within WBBs is small. However, heat conduction at the contact discontinuity (Fig. 1.3) between the hot gas of the bubble and that of the swept-up shell will thermally evaporate the dense shell and initiate a mass-flux into the bubble interior (Cowie & McKee 1977; Weaver et al. 1977), a process often referred to as *mass-loading*

(Hartquist et al. 1986). If radiative losses are ignored, the energy of the hot gas will remain the same, and an increase in mass will lower its temperature. Besides the evaporation of the bubble wall, dense (molecular) clouds that are overrun by the IF that end up being enclosed in the bubble will thermally evaporate and inject mass into the hot plasma (Arthur & Henney 1996; Everett & Churchwell 2010), further lowering the temperature compared to that from idealized models. At $T \lesssim 10^6$ K, radiative losses will become important and, at this point, energy will be lost from the system.

There are a number of ways that can dramatically affect the evolution of H II regions from that described above. First, given our current knowledge of the highly dynamic ISM, the idea of spherical bubbles expanding in an homogeneous medium is, in many cases, merely an oversimplification of reality. Inhomogeneities within the surrounding ISM will lead to asymmetries of the H II region as the expansion will accelerate to media of lower density. Second, the intrinsic motion of the ionizing source may lead to a cometary shape of the bubble in its direction of movement (Wood & Churchwell 1989). Third, magnetic fields might suppress the expansion rate perpendicular to the field lines (Krumholz et al. 2007). Fourth, dust mixed within H II regions will leave its footprint on the evolution of H II regions. On the one hand, dust will absorb ionizing photons that will shrink the H II region in size. On the other hand, radiation pressure on dust grains will add momentum to the surrounding gas so as to push on it, setting it in motion. Fifth, the clouds in which the bubbles are embedded are of finite size. In this respect, Israel (1978) noticed that a large number of H II regions were located near the edges of dense clouds and adopted the term 'blister H II region', given their suggestive appearance on the 'skin' of molecular clouds. Depending on the initial location of the formation of the H II region, the star with its bubble might break out of its natal envelope towards the so-called *blister* phase allowing the (hot) gas to leak from the bubble interior.

Ionization fronts and photo-evaporation flows of gas

A massive star will ionize its surroundings and will be encircled by an IF that separates the ionized volume from the neutral material. An IF is preceded by a shock front. The conditions of the gas at either side of this shock front are markedly different, and are connected through jump conditions (Spitzer 1978; Henney 2007). Let ρ, v, and P denote the density, velocity, and pressure of the gas, and indexes 0 and 1 refer to the pre- and post-shock gas. If one assumes mass and momentum conservation, and consider C_0 and C_1 as the isothermal sound speed at both sides of the shock front, it can be shown that only two types of shock fronts can exist (Shu 1992; Tielens 2005). The first type have velocities of $v > v_\mathrm{R} \approx 2C_1$, and are called *R*-type ('rarefied gas') with $\rho_1 > \rho_0$. The second type is characterized by $v < v_\mathrm{D} \approx C_0^2/2C_1$, and are called *D*-type ('dense gas') with $\rho_1 < \rho_0$. If the velocity of the shock exactly matches v_R or v_D, the shock front is called *R*-critical or *D*-critical, respectively. The velocity of the IF traveling behind the shock front will be determined by the ionizing photon flux and the density of the neutral (shocked) medium.

The subsequent movement of the gas away from the IF has previously been studied for a few prototypical cases. The recognition of blister H II regions (Sec. 1.2.1) initiated the study of the ionized gas in terms of a *champagne flow*, after the original model of Tenorio-Tagle (1979). In this scenario, the IF of an expanding H II region reaches the edge of the natal cloud and encounters the density discontinuity between the cloud and intercloud medium. A fast, isothermal shock will move into the intercloud medium, while

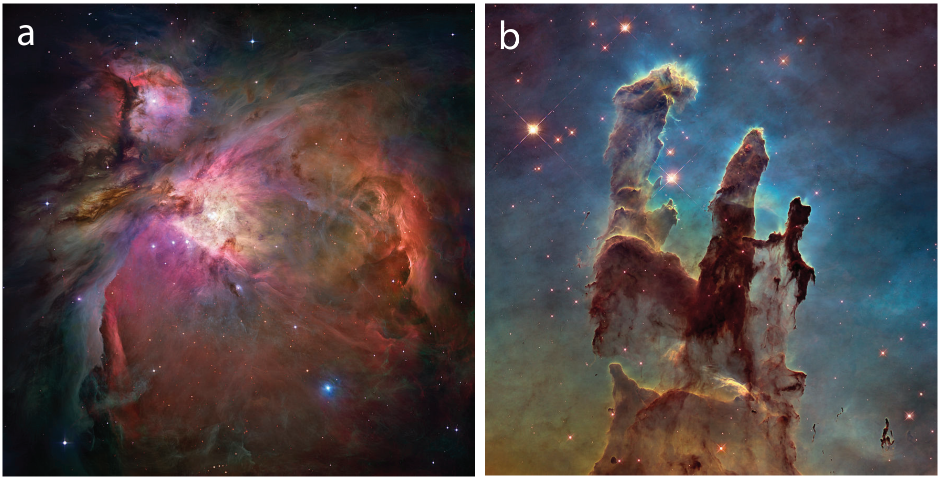

Figure 1.4: Examples of ionization fronts and ionized gas flows. **(a)** The Orion Nebula is a blister H II region that breaks out of the near-side of the Orion A Molecular cloud. The ionized gas streams away from the cloud surface (O'Dell 2001) and its structure can be viewed as the prototypical example of a *champagne flow* of ionized gas (Tenorio-Tagle 1979). Image credit: NASA, ESA, M. Robberto (STScI/ESA). **(b)** The 'pillars of creation' light up against the gaseous background of the Eagle Nebula (Hester et al. 1996). Here, the ionization front has wrapped around the condensations as dense knots of material withstanding photo-evaporation. The shape of the ionization front causes the emanating flow to differ from the champagne flow case, and is often referred to as a *globule flow* (Bertoldi 1989). Image credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA).

a rarefaction shockwave travels back through the H II region. Between the shock fronts, a champagne flow of ionized gas is set up. The pioneering studies from Tenorio-Tagle (1979) and Bedijn & Tenorio-Tagle (1981) considered a plane-parallel, non-steady case, where the gas density and velocity after break-out was described in analogy to the isothermal shock tube problem (Sod 1978), in which the ionized flow exhibits a linear velocity law and an exponential density gradient (See Fig. 1.5). Arguably, the most famous example of a champagne flow is the Orion Nebula (Sec. 1.3) bursting out of the near-side of the Orion molecular cloud (OMC): the extended blister geometry is easily detected in recombination lines, and the acceleration of the ionized gas away from the IF is traced by markers at different levels of ionization (O'Dell 2001). Another classical problem is the evaporation of dense knots or globules often observed within the (hot) ionized gas of star-forming regions (e.g., Koenig et al. 2008). Once a dense condensation is reached, the IF will slow down and wrap around the globule. In this case, the shape of the IF will become convex, and the ionized material expands and diverges as it accelerates away from the front. Early models of the globule flow problem were described in Dyson (1968) and Kahn (1969), and extended by Bertoldi (1989), in which the density of the ionized photo-evaporation flow increases sharply towards the IF, greatly exceeding that of the H II region as a whole, offering an explanation for the curved bright rims apparent as cometary globules (Koenig et al. 2008), and 'elephant trunks' (Hester et al. 1996) often observed within H II regions.

Henney et al. (2005) numerically investigated the evaporation of a cloud illuminated by a point source, and studied the structure of the ionized flow that evaporates from the cloud surface. The study unified the theories of champagne flows and globule flows in an elegant way. An IF that engulfs a flat, homogenous cloud illuminated by a point source will become concave, and the photo-evaporation flow emanating from this geometry will resemble a champagne flow structure, as the streamlines of the ionized gas do not diverge effectively (Henney et al. 2005). In practice, the ionized gas from a concave IF will accelerate more slowly compared to, e.g., the heavily divergent photo-evaporation flow from a convex-shaped globule (in analogy to Bertoldi 1989). We depict the dependence of the ionized flow structure on the shape of the IF in Fig. 1.5, assuming that the IFs are D-critical and, therefore, the gas leaves the IF at the sound speed of the ionized gas ($= C_{\mathrm{II}}$). If we consider the gas to be isothermal, which is likely for the ionized gas as the heating is dominated by photo-ionization from the star, the gas accelerates away from the IF depending on the degree of divergence of the ionized flow. The acceleration will eventually decrease and the flow will reach a terminal velocity v_{t}, which occurs when the expansion and heating timescales of the gas become comparable and the isothermal approximation breaks down (Henney 2007). Thus, in short, the shape of the IF (convex, flat, or concave) and the incident ionizing photon flux (regulating the velocity of the IF into the cloud and the density of the ionized flow) uniquely determine the structure of the resulting photo-evaporation flow. In particular, the velocity v and density n regulate the structure of the flow as a function of distance x from the IF (Fig. 1.5), which we will refer to as the *flow parameters* of the ionized gas (Sec. 1.2.3).

Studying the structure of ionized gas flows is crucial to our understanding of the formation and evolution of H II regions. For example, the photo-evaporation of globules or the disruption of molecular clouds through champagne flows may contribute to the mass-loading of the hot interior of a stellar wind-blown-bubble or a superbubble (Sec. 1.2.2). Furthermore, the escape of material from the H II region interior will lead to depressurization, stalling the expansion of the volume, while the expelled gas will input kinetic energy and drive turbulent motions into the surrounding medium. Finally, photo-evaporation flows entrain dust particles, acting as a (significant) source of dust input into the bubble interior (Sec. 1.2.3).

1.2.2 OB associations, supernovae, and superbubbles

Early studies of space distributions of stars by Kapteyn (1914) and Pannekoek (1929) revealed that many stars appeared clustered on the sky. Today, it is known that massive stars tend to form in multiple systems or clusters (Zinnecker & Yorke 2007), bound together in large groups known as OB associations (e.g., de Zeeuw et al. 1999a). Studies of OB associations focus on characterizing the membership, structure, and kinematics of the stellar content of the association. The age distribution in many evolved OB associations imply that stars do not necessarily form coevally. For example, the Orion OB association (Orion OB1) reveals several subgroups that are distributed in a layered structure at different locations with respect to the Orion Molecular clouds (OMCs; Blaauw 1964; Brown et al. 1994). Star formation thus appears to have propagated through the molecular clouds episodically, where feedback from the older subgroups may have formed shock waves that compressed material from nearby regions, triggering the formation of a next generation

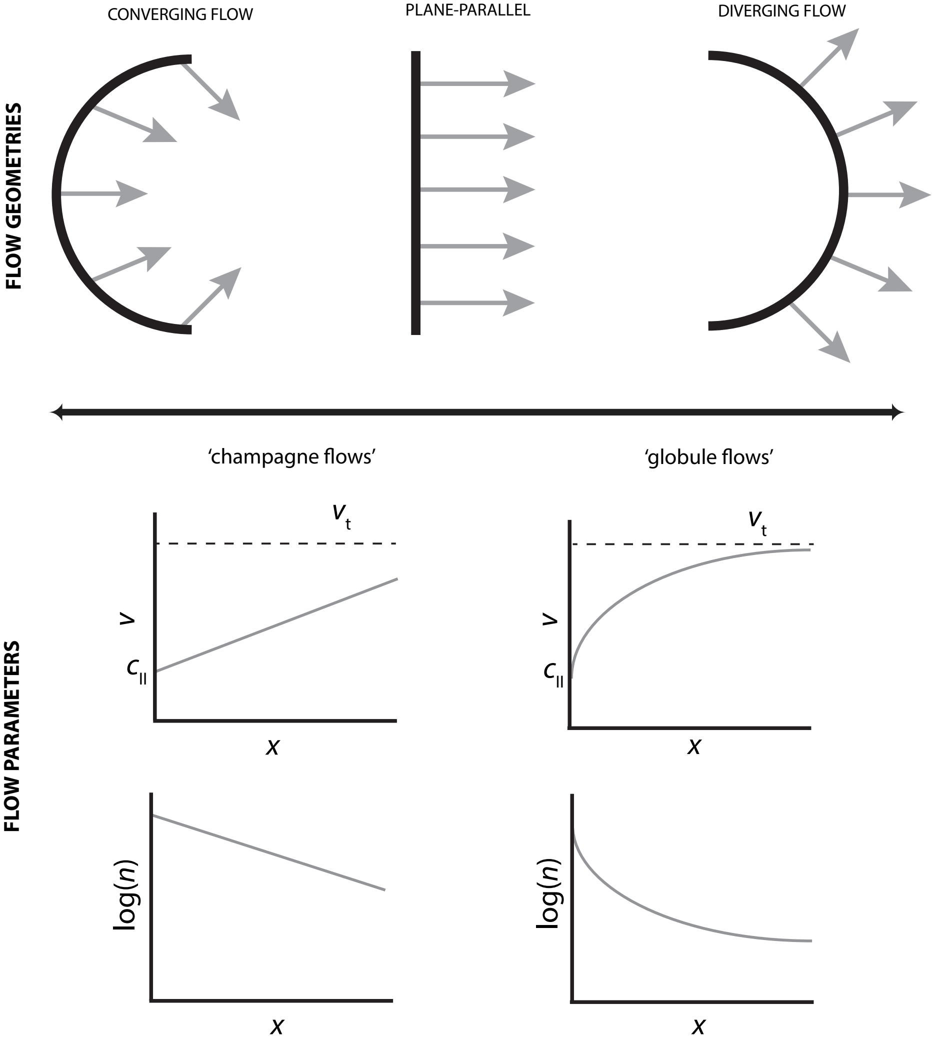

Figure 1.5: Photo-evaporation flows (grey arrows) from ionization fronts (black lines). The shape of the ionization front (concave, flat, convex) determines the structure of the photo-evaporation flow from the surface (Henney et al. 2005), in particular the *flow parameters* of the ionized gas. Concave ionization fronts lead to accelerating flows that resemble classical 'champagne flows', while convex ionization fronts will lead to 'globule flows'.

of stars (Elmegreen & Lada 1977).

The tendency of massive stars to concentrate in OB associations has implications for the formation of H II regions and bubbles that surround the associations, and need to be contrasted with the theory of isolated bubbles around single stars described in Sec. 1.2.1. In an OB association, stars will form close to one another, such that their radiative and mechanical energy input will merge, and their combined efforts will lead to the formation of large ($\sim10^2$ pc), dynamic structures in the ISM that are often termed as superbubbles (e.g., McCray & Kafatos 1987).

Theoretically, the initial stage of the formation of a superbubble will be dominated by either the stellar winds or radiation pressure from the central OB association. At a certain time, the most massive component within the OB association will detonate as a SN within a pre-existing cavity. The SN ejecta will be launched at great velocity and introduce a large amount of mechanical energy into the surroundings. After a fast initial phase, where the SN ejecta expand freely until an amount of ISM material similar to its own mass is encountered, a reverse shock will heat the ejecta and its kinetic energy will be thermalized, from which point it will expand adiabatically because of the overpressure compared to the surrounding gas. When the temperature of the hot gas drops below $\sim10^6$ K, radiative cooling will become important and the newly shocked material will cool and collapse into a thin shell to form a supernova remnant: a shell of compressed material will then move out from the OB association. Once the blast wave becomes subsonic, the energy of the remnant will thermalize and it will disperse its energy as a sound wave that pressurizes the interior medium of the superbubble. In case of repeated supernovae, interior blast waves can remain supersonic and reach the cooled outer shell of the superbubble, in which case the energy is radiated away, or the blast wave bounces and eventually thermalizes inside the interior (Mac Low & McCray 1988).

Observationally, the basic structure of superbubbles is expected to be similar to that created by the interaction of a stellar wind with the ISM: a dense, swept-up shell encapsulates a hot, tenuous interior. The dense supershells are easily discernible in maps of neutral (Heiles 1979) or ionized (Reynolds & Ogden 1979) hydrogen. The interiors of superbubbles can be traced in X-rays (Chu & Mac Low 1990a; Snowden et al. 1995), even though the measured X-ray luminosities do not always agree with the standard model (Weaver et al. 1977), a problem that is also encountered with observations of isolated bubbles (see Chu 2008, and references therein). Some superbubbles appear too bright at X-ray wavelengths, notably in the Large Magellanic Cloud (Chu & Mac Low 1990a). Several mechanisms have been proposed to explain the X-ray overluminosity, such as heating by shocks from off-center supernovae within the superbubble cavity (Chu & Mac Low 1990a) or enhanced metal abundances because of SN enrichment (Silich et al. 2001). Other superbubbles appear to be too dim in X-rays, possibly as a result of mass-loading (Sec. 1.2.1) that cools the interior of the superbubble, lowering the expected X-ray luminosity. Finally, X-ray emission has been observed beyond the outer dense shell of several superbubbles (Dunne et al. 2001), indicative of 'blow outs' of the superbubbles similar to the emergence of H II regions such as the blister H II region of the Orion Nebula, where ionized (Fig. 1.4) and hot gas (Güdel et al. 2008) are observed to leak out of the region.

Superbubbles expanding in the disk of a galaxy may eventually blow out of the plane when the size of the bubble reaches one or two gas layer scale heights of the neutral disk (Mac Low & McCray 1988). The opening angle of the blowout is inversely related to the Mach number of the shock at the blow-out region, forming either wide-angle jets or narrow chimneys that sets up an interaction between the disk and the extended halo (Norman & Ikeuchi 1989). The dense gas from the superbubble shell will be susceptible to Rayleigh-Taylor fragmentation instabilities, ultimately forming dense clumps that fall back to the disk (Mac Low et al. 1989). However, the hot gas will penetrate deep into the halo, where it settles on a much higher scale height ($\sim$1 kpc; Tielens 2005). Over-all, the blow-out of superbubbles will initiate a large energy circulation that attributes to the metal enrichment of the halo or, in case the gas will be able to escape the potential well of the disk, the IGM. While only a small part of the mass of the superbubble is hurled into the halo, superbubble blowouts may still dominate the mass budget of the extended, low-density halo. Furthermore, the holes that are carved by the blowouts may offer channels through which radiation from the stars can ionize the halo and may even drive gas-dynamics (Silich & Tenorio-Tagle 2013) or momentum-driven galactic winds (Murray et al. 2005). In addition, the disk-halo connection will add to the mixing of (enriched) gas in the plane as matter rains back from the halo onto the galactic disk.

1.2.3 Dust as a tracer and intermediary of radiative feedback

While the ‘explosive’ feedback (Krumholz et al. 2014) from massive stars in the form of UV radiation (Dale et al. 2005; Walch et al. 2012), stellar winds (Toalá & Arthur 2011; Rogers & Pittard 2013), and from SN (Hill et al. 2012; Gatto et al. 2015) have traditionally gained much attention in explaining the origin of large expanding shells (Heiles 1984; Churchwell et al. 2006) and the evolution of the ISM into its filamentary, multiscale appearance seen to date (Fig. 1.2), only recently the role of ‘momentum feedback’ has been assessed, in particular in the form of radiation pressure on dust (Krumholz & Matzner 2009; Draine 2011a; Silich & Tenorio-Tagle 2013). Radiation pressure provides yet another way of imparting kinetic energy to the gas and setting it in motion. As the radiative energy of a star over its lifetime ($\sim 10^{53}$ erg; Tielens 2005) greatly exceeds that of a stellar wind ($\epsilon E \sim 10^{49}$ erg; with ϵ the efficiency at which the mechanical luminosity of the star couples to the ISM as kinetic energy) or supernova ($\epsilon E \sim 10^{50}$ - 10^{51} erg; Veilleux et al. 2005), it constitutes a major potential source of energy. Most of the radiative energy of a star is used up to ionize and heat the gas and will be lost through radiative cooling. However, if only a small fraction of this energy couples as momentum to the gas through radiation pressure upon dust, this mechanism may play a crucial role in shaping the ISM around massive stars (Krumholz & Matzner 2009; Lopez et al. 2011) or launching galaxy-sized winds (Murray et al. 2005; Hopkins et al. 2011).

Because of its large cross-section compared to (ionized) gas, dust is the main absorbent of radiation pressure. The change in momentum can indirectly be transferred to the gas through gas-grain collisions. It has been proposed that radiation pressure acting on dust produces density stratifications inside H II regions as the gas and grains move outwards coherently (Draine 2011a). Furthermore, radiation pressure may be the dominant source in driving the dynamics of giant H II regions (Krumholz & Matzner 2009) such as the 30 Doradus region (Lopez et al. 2011), but its importance relative to gas pressure becomes smaller when going to star clusters of lower ionizing luminosity, i.e., containing a single or a handful of OB stars, which is the typical cluster size in the near few kiloparsec of the solar neighborhood (Mathews 1969; Arthur et al. 2004). On the other hand, by including the central clusters mechanical luminosity and evolution of its radiative luminosity, Silich & Tenorio-Tagle (2013) showed that radiation pressure only dominates at the very early stages of H II region formation, irrespective of its mass and ionizing luminosity. The above described controversial results underline our poor understanding of the importance of radiation pressure as a mechanism of stellar feedback to the ISM. Moreover, theoretical work often relies on assumptions that simplify the analytical or numerical analyses, but do not necessarily provide an accurate description of the exact radiative interaction of a massive star with its surroundings.

Much work on addressing radiation pressure feedback of massive stars has been performed theoretically (Yorke & Sonnhalter 2002; Krumholz & Matzner 2009; Hopkins et al. 2011). Observational work has been hampered by the fact that it is difficult to separate pressure contributions from the warm 10^4 K (Hα emitting) gas, the hot 10^6 - 10^7 K (X-ray emitting gas), direct absorption of starlight, and dust-processed stellar radiation (re-emitted in the IR). Comparison of all these pressures has been limited to a few special cases, notably the 30 Doradus region in the Large Magellanic cloud, a study performed by Lopez et al. (2011) and Pellegrini et al. (2011). Still, these authors reach opposite conclusions regarding the importance of radiation pressure compared to the other forms of feedback, largely following from different assumptions that characterize the gas phases within the 30 Doradus region (for a review on the discrepancies, see Krumholz et al. 2014).

It seems advantageous to study the various forms of stellar feedback in regions well away from the complex geometries of star forming regions, or confusion caused by structures along the line-of-sight. While most massive stars are formed in OB star clusters, many are eventually ejected from their parent association: up to 25% of massive stars (Zinnecker & Yorke 2007) end up as OB-runaways with space velocities in excess of 30 km s^{-1} (Blaauw 1961). These stars can therefore travel notable distances away from their birth place. During their lifetime, massive stars in the field will interact with the ISM either through a stellar wind, or through radiation pressure. If a star moves supersonically with respect to its environment, a stellar wind will create a *bow shock* at the stand-off distance from the moving star, where the ram pressure and momentum flux of the stellar wind and the interstellar medium balance (van Buren & McCray 1988; Mac Low et al. 1991; Kaper et al. 1997). The swept-up material in the bow shock is heated by radiation of the OB star, making the dusty component of the shells visible in the infrared, while the gas component will be observable depending on the local density, the compression ratio of the pre- and post shock gas, and the contrast with the material of the ISM along the line of sight. Many of the arc-shaped infrared features surrounding OB stars detected by *IRAS* and, more recently, *WISE* have been associated with stellar-wind bow shocks, even though detection of their gaseous counterparts is limited to a few incidental cases. Using radio continuum data, Peri et al. (2015) found a total of 8 sources (out of 73 total) that - possibly - show gas emission coincident with the infrared arcs.

Radiation pressure from a moving OB star is expected to create a similar structure compared to the arc-shaped bow shocks. However, a fundamental difference between radiation pressure and a stellar wind is that the first predominantly acts upon the dust component of the ISM, and gas will follow this motion only if the coupling between both components is sufficient for the gas to be dynamically perturbed (see below), while the second acts on the gas component (pressure) of the ambient medium. Furthermore, in case of radiation pressure, the OB star does not need to move supersonically with respect to the ISM for the interstellar matter to be swept up in a shell. Thus, in principle, radiation-pressure-driven *bow waves* (van Buren & McCray 1988) may lead to IR arcs surrounding OB stars *without* any gaseous counterparts. However, no such structure has ever been detected in the ISM.

Forces governing dust dynamics

The movement of dust through the ISM is governed by a balance between the gravitation pull from massive bodies, radiation pressure from stars, and collisions or friction with gas particles. Gas drag either occurs through direct collisions, determined by the gas density and the grain geometrical cross-section, or through long-range Coulomb interactions. The theory is based on that developed by Chandrasekhar (1943) for dynamical friction within star clusters, but was reformulated for a test particle confined in a plasma by Spitzer (1962) and Draine & Salpeter (1979). The charge state of the grains is an important parameter in determining the magnitude of Coulomb coupling between gas and dust, and theories of spherical grains interacting with ions that exhibit a Maxwellian velocity distribution (Draine & Salpeter 1979; Tielens 2005) are often employed in the calculation of dust charge. Still, the derived charge states are heavily dependent on the assumed photo-ionization yields that remain poorly constrained by laboratory work (Willis et al. 1973; Abbas et al. 2006).

Ionization fronts offer a unique opportunity to study dust dynamics. The velocity and density jump across an IF, and the subsequent acceleration of the gas away from the front (Fig. 1.5) will lead to a significant change in momentum transfer between gas and dust. If the momentum transfer towards the grains is sufficient, dust will be *entrained* in the photo-evaporation flow and travel along with the gas. The entrainment process is dependent on several factors. On the one hand, it will depend on the *flow parameters* of the ionized gas (density and velocity of the ionized flow; Sec. 1.2.1). On the other hand, it will depend on the way the grains couple to the gas, a process that is intimately linked to dust grain characteristics such as mass, geometry, and charge state, all of which remain subject to debate (Sec. 1.1.2).

1.2.4 Summary: the energy balance of the ISM

From stars to the ISM: Over its lifetime, a massive stars radiates some 10^{53} erg that mainly serves to photo-ionize and heat surrounding gas and will eventually be radiated away. While the energy is not conserved, momentum can not be radiated away, and part of the radiative energy may couple to the ISM as kinetic energy, mainly through radiation pressure acting upon dust. The acquired momentum can then indirectly be transferred towards the gas through gas-grain collisions. The efficiency of this mechanism is dependent on various parameters and has never been tested observationally, such that its importance to the dynamics of the ISM remains unclear. Stellar winds shock heat gas, creating hot plasmas that expand and do work on their surroundings, delivering some $\sim 10^{49}$ erg (Tielens 2005) of kinetic energy, while the rest of the mechanical luminosity of the star will be stored as thermal energy of the hot gas. Similarly, the explosive power of SNe will transfer a fraction of its energy towards kinetic energy of the surrounding gas (10^{50} - 10^{51} erg; Veilleux et al. 2005).

The aforementioned feedback mechanisms of massive stars to the ISM manifests themselves as bubble HII regions (~few 10 pc), supernova remnants ($\sim 10^2$ pc), but as most of massive stars form in clusters, they tend to form superbubbles (~few 10^2 pc). Massive stars in the field may form stellar-wind-driven bow shocks or radiation-pressure-driven bow waves with radiation pressure, before ending their life as a SN.

From the ISM to stars: Massive stars will constantly stir the surrounding medium and mainly push the gas and dust outwards from the location of star formation, limiting the gas supply and, ultimately, star formation efficiency. Thus, on the one hand, the energy input of massive stars tends to provide a negative feedback for continuing star formation, especially when considered that, in reality, all feedback mechanisms will act simultaneously. The shockwaves associated with the injected mechanical energy and the transfer of momentum will collect gas and dust in giant shells or filaments. Gas and dust interchange momentum and may move coherently when the coupling between both components is sufficient. On the other hand, compression of the interstellar material in the shells or filaments can lead to the condensation of atomic and molecular clouds that may form a new generation of stars.

1.3 Orion as a benchmark study

This introduction started off with a short description of the Orion region that immediately stressed its importance to studies of star formation and the ISM. While not specifically addressed in the contents of this thesis, it must be noted that studies of Orion has influenced many areas in astronomy. Multiple interstellar molecules have been discovered in Orion, such as CO (Wilson et al. 1970). The Hubble Space Telescope provided *direct* detection of dozens of evaporating protoplanetary disks (‘proplyds’; O’Dell et al. 1993) surrounding young stellar objects that appear to be severely affected by the intense radiation field exerted by the main powerhouse of the Orion nebula, θ^1 Ori C, which provided insights and constraints on both star- and planet formation scenarios. Orion harbors such great detail that complete books have been written and filled on the characteristics of the region. Still, recent results indicate that some of the previous results regarding Orion need to be revised, while hidden treasures have yet to be uncovered. In the following paragraphs, we briefly discuss specific regions and characteristics of the Orion region that directly relate to the remaining content of this thesis.

The stars

In the past 15 Myr, the Orion region has given birth to $\sim 10^4$ stars across the mass spectrum (Bally 2008). The Orion OB association, Orion OB1, is divided in several subgroups and clusters that differ in age and location, partially being superimposed along the line of sight (Blaauw 1964; Brown et al. 1994). The stratification of the different subgroups and their relative position with respect to the OMCs indicate that star formation propagated through the pre-existing molecular clouds episodically, which connects well with the ‘sequential star formation’ scenario described by Elmegreen & Lada (1977). The members of the oldest subgroup, Orion OB1a (~8 - 12 Myr; Bally 2008), may have triggered the formation of the Orion OB1b subgroup (3 - 6 Myr) towards the south in Orion’s Belt, from which star formation seemed to have propagated further south in the Orion OB1c region (2 - 6 Myr), and perhaps the λ Ori region in the north (< 5 Myr). The youngest massive subgroup is the Orion OB1d subgroup (> 2 Myr), which includes the Orion Nebula cluster (ONC) located at the northern tip of the Orion Molecular A cloud. The ONC is the best studied star forming region in the sky. The most comprehensive studies have been performed by Hillenbrand (1997) and Megeath et al. (2012) that revealed thousands of (young) stellar objects, where the most massive stars are located in the cluster center.

Noteworthy here is the Trapezium system in the heart of the Orion Nebula (Fig. 1.1d), which appears to be a mass-segregated sub-cluster within the region. Smaller star forming clusters are spread in cores throughout the OMCs (Gibb 2008; Allen & Davis 2008). In addition, detections of numerous cometary clouds with heads pointing towards the Orion OB1 association are scattered throughout the Orion region and show signs of sequential star formation (e.g., Stanke et al. 2002; Lee et al. 2005; Bally et al. 2009).

Each 'bursts' of star formation has left its mark on the Orion region. The Orion OB1a group has injected energy and momentum and has, by now, completely emerged from the parent molecular cloud. The Orion OB1b group, some 50 pc to the east, still resides close to the molecular cloud and might have formed the protrusion out of OMC B apparent as the GS206+17-13 H I shell (Ehlerová & Palouš 2005). The supergiant status of the Belt stars indicate that a SN may already have gone off within this subgroup. The λ Ori group has formed the awe-inspiring, 10° sized spherical H II region (Reich 1978) encapsulated by a molecular ring or bubble (Maddalena & Morris 1987). The Orion OB1c and OB1d are still (partly) embedded (Hillenbrand 1997; Megeath et al. 2012). Despite their youth, they have already started to begin sculpting the OMCs and the ISM in their vicinity in the form of, e.g., the Orion nebula.

The sword

Already addressed in Sec. 1.2.1, the blister-like appearance of the Orion nebula is caused by a champagne flow of ionized gas streaming of the Orion Molecular Cloud (OMC) that is initiated by ionizing radiation of the main ionizing star, θ^1 Ori C. The large-scale gas flow contains only several solar masses of ionized gas, indicating that the champagne phase has only recently commenced, perhaps just some 1.5×10^4 yr ago (O'Dell et al. 2009). X-rays have been detected in the Extended Orion Nebula (Güdel et al. 2008) that reveals the leakage of the hot shocked wind gas from θ^1 Ori C into the surrounding medium.

The superbubble

Assuming a standard initial mass function, Bally (2008) inferred that about 30 - 100 stars more massive than 8 $M_\odot$ have formed in Orion OB1, and argued that over the last 12 Myr, about 10 - 20 SNe have exploded in the region. The combined efforts of UV radiation, stellar winds, and SNe from Orion OB1 have continuously disrupted the star forming clouds and created a large X-ray emitting superbubble ($> 10^2$ pc) that spans over ~40 degrees or ~300 pc on the sky towards the Eridanus constellation (at a distance of 400 pc, here the assumed distance towards the Orion region; Menten et al. 2007), and may be evolving towards blowout of the Galactic plane (Mac Low & McCray 1988). Because of its proximity and evolutionary state, the Orion-Eridanus superbubble acts as a benchmark to the study of other superbubbles that lack the spatial information of the Orion region. The structure and evolution of the Orion-Eridanus superbubble will be thoroughly discussed in Chapter 5.

Stellar motions

The *Hipparcos* satellite has observed all nearby OB associations with the aim to obtain a detailed knowledge of the stellar content and dynamics of nearby OB associations, which in its turn has allowed to address many fundamental questions on star formation, such as the dependence of star formation with respect to the location within giant molecular clouds, the conditions that set the initial mass function of stars, the importance of binaries and clusters, and the study of OB runaway stars (Brown et al. 1999). Indeed, some of the brightest stars of the Orion constellation (such as α Ori, β Ori, and κ Ori) may be OB runaways (Bally 2008). While *Hipparcos* proper motions provide clues to their past trajectories, the origin of these stars remain unclear. The interaction of α Ori with the surrounding medium becomes clear from the arc-shaped bow shock that envelops the star in its direction of movement (e.g., Decin et al. 2012), permitting to constrain mass-loss events from the central star and the characterization of the ambient ISM. Figure 1.1b, 1.1c, and 1.1d show similar arc structures on all observable scales that exemplify the interaction of the mechanical or radiative luminosity of the stars with the surrounding ISM.

1.4 This thesis

In this introductory chapter, I reviewed our current understanding of the interplay between stars and the ISM, and argued that Orion offers a unique opportunity to address many of the open questions presented in beginning of this chapter. Perhaps after this might one start to fully appreciate the significance of Fig. 1.1 and the level of detail that it harbors. In the next chapters of this thesis, some of the important and puzzling details that stand out in this picture will be addressed. For one, the ubiquity of mid-IR arcs that surround the main ionizing stars in Orion provide important clues to the dynamics of the ISM and the interaction between the stars with their surroundings, and the mediating role of dust therein. We will combine the dynamics of the gas, the dust, and the stars within Orion to quantify these interactions and to derive a novel method to study the properties and evolution of interstellar dust (Ch. 2 & 3), to explain the presence of dust in these harsh regions of space (Ch. 4), and to constrain the importance of dust as an intermediary of radiative feedback to the ISM (Ch. 4). The result have implications for many regions of massive star formation within our Galaxy and these will be discussed (Ch. 4). On larger scales, it is evident that the powerful processes accompanying (massive) star formation have turned the Orion region into its current complexity (Fig. 1.1). The image represents a snapshot in time, and the final chapter of this thesis will combine the previous derived knowledge on specific regions within Orion that forces us to revise our thinking on the history and evolution of the *entire* Orion-Eridanus region (Ch. 5). In detail, the next chapters will address the following:

Chapter 2 describes the interaction of radiation pressure of the σ Ori AB system with dust carried along by the IC 434 photo-evaporative flow of ionized gas from the dark cloud L1630/OMC B. We build a quantitative dynamical model for the radiative interaction of a dusty ionized flow with nearby (massive) stars, which is then employed to extract properties of the dust entrained within the ionized gas, such as the size distribution and charge state of the grains. We argue that this is the first example of a ‘dust wave’ created by radiation pressure of a massive star moving through the interstellar medium, discuss how our findings impact the importance of stellar winds, and reveal that dust waves should be common around stars showing the ‘weak wind phenomenon’.

Chapter 3 extends the results from chapter 2 by combining our dynamical model with numerical simulations of photo-evaporation flows, and the history and large-scale evolution of the Orion Belt region. We extend our analysis of the σ Ori dust wave over a much broader wavelength range, improve our dynamical model to constrain dust quantities such as geometry (porosity / fluffiness), as well as the efficiency of absorbing radiation pressure by the grains. We argue that the dust in the ionized gas of the IC 434 region cannot be explained by current dust models, as it is markedly different from that observed in the diffuse ISM, and place our findings in the context of recent studies on dust evolution.

Chapter 4 exploits Spitzer- and Herschel surveys of the Galactic plane to search for the signatures of dust waves, and reveals that dust waves are ubiquitous within the Galactic plane. We perform hydrodynamical simulations of expanding H II regions to investigate the conditions needed for the development of dust waves, and discuss that evolved H II regions are ideal candidates for observing dust waves and for studying the properties of dust in ionized regions of space. Dust waves within Galactic bubbles offer a solution regarding the presence and morphology of dust inside H II regions, and imply that winds are of limited importance in such systems, which may in its turn connect to observed weak-wind strengths and the difficulty in detecting diffuse X-rays around main-sequence stars. In addition, dust waves provide direct evidence that bubbles are relieving their pressure into the ISM through a champagne flow that inject turbulence into the ISM, while acting as a probe of the radiative interaction of a massive star with its surroundings.

Chapter 5 combines recent observational data with the results drawn from the previous chapters to arrive at new and more complete picture of the Orion-Eridanus superbubble. The superbubble is larger and more complex than previously thought, and displays an active interplay between star formation, stellar feedback, and ISM evolution. During the lifetime of the superbubble, H II region champagne flows and thermal evaporation of embedded clouds continuously mass-load the superbubble interior, while winds or supernovae from massive stars in Orion rejuvenate the superbubble by sweeping up the material from the interior cavities in an episodic fashion, possibly triggering the formation of new stars that form shells of their own. The cycle of mass-loading, interior cleansing, and star formation repeats until the molecular reservoir is depleted or the clouds have been disrupted, from which the superbubble will disappear and merge with the ISM.