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

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Summary & outlook

In this thesis, I have addressed many aspects of the interaction between stars and the matter residing in the ISM. Much of this work has relied on observations of recent infrared space observatories. However, with the end of the *Spitzer*, *Herschel*, *Planck*, and WISE missions, the influx of (far-)IR to submillimeter observations will slow considerably. Nonetheless, the archives still provide a wealth of information, while SOFIA, together with ground-based facilities, such as the recently commissioned *Atacama Large Millimeter Array* (ALMA), will continue to define the research questions that will be addressed with the next generation of (space) telescopes. Looking beyond the era of the *Hubble Space Telescope* (HST), *Hipparcos*, and the IR space missions from the last decade, we will have the *James Webb Space Telescope* (JWST), *Gaia*, while future IR missions are already on the drawing board, such as the *Space Infrared Telescope for Cosmology and Astrophysics* (SPICA). This chapter is devoted to summarize the main results from the first four years of my academic career, to specify and formulate the questions that have remained and have arisen during this course, and to highlight some of the promising opportunities in the field that shimmer on the horizon.

Chapters 2 & 3: Dust waves & dust characterization in H II regions

- **Results:** we have developed a new method to study the properties of interstellar dust. Observations of gas and dust at the interface between molecular clouds and H II regions were exploited, and we developed a model that describes the interaction of a dusty ionized flow of gas with nearby (massive) stars, where radiation pressure stalls dust and force it to flow around the star to form a dust wave. In this way, we were able to constrain important parameters of the dust grains within ionized regions. Some of the results are puzzling, and seem to contrast with other studies of interstellar dust.
- **Open questions:** The dust grain size distribution from the IC 434 region is bimodal, consisting of large micron-sized fluffy/porous grains and small compact particles. We have hypothesized in Ch. 3 that grain properties may reflect their previous environment, linking the presence of large grains in the IC 434 H II region to the molecular clouds from which they are ‘freshly’ evaporated. The dust population that is introduced into the H II region will be processed as it is suddenly exposed to the harsh conditions in the ISM, such as gas-grain friction, (thermal) sputtering, and interstellar shocks. Perhaps, dust in the diffuse ISM, far away from dense molecular clouds, represents an ‘equilibrium state’ after the grains are fully processed by the ISM. The models from, e.g., Draine & Li (2007) do seem to reproduce and dominate dust emission properties of diffuse clouds and complete galaxies (e.g., Smith

et al. 2007). However, it is very important to note that observations performed with beams that integrate a large part or even a complete galaxy will not detect the (micro-)processes that may occur between the dense and diffuse phases of the ISM at $\sim$ pc scales. Yet, it is these regions that could be physically interesting and where important physical parameters of the grains may be probed, as is illustrated by the results from Ch. 2 and 3. Does interstellar dust in the diffuse ISM represent a steady state configuration, or do the grains undergo a steady evolution? Perhaps the relevant question is: what are the processing timescales of interstellar dust when transitioning between different phases of the ISM?

Specifically, Coulomb interactions between gas and dust may be less efficient in the IC 434 region than predicted by theory. In the RCW 120 and RCW 82 H II regions, the location of the dust waves are compatible with this finding (Ch. 4). Is it the physical conditions of the region, the intrinsic grain properties, or the charging mechanism of the grains that we do not fully understand? In case of the latter, how does this impact the photo-electric heating efficiency from (small) grains?

- **The way forward:** the results from Ch. 2 and 3 stress that we need to stay critical as we advance our knowledge concerning interstellar dust. At the distance of Orion, *Spitzer* and *Herschel* offered the necessary angular resolution (< 1 pc) to separate the dust emission coming from the H II region from that located in the bright PDRs. In addition, and as will be discussed below, we were also able to recognize the existence of dust waves inside interstellar bubbles throughout the Galactic plane, the exploitation of which may provide valuable information on dust in H II regions and the evolution of the grains between different phases of the ISM. However, *Herschel* lacks the sensitivity to detect the faint, diffuse emission from dust in a large sample of H II regions, especially at $70\ \mu\text{m}$, a crucial regime to distinguish between warm and cold components of dust within H II regions (Ch. 3). The diffuse dust from the IC 434 region could not be detected at $70\ \mu\text{m}$ by *Herschel*, but was recovered using IRAS observations. The photometric sensitivity of *Herschel* is limited by thermal noise emission (mostly from the telescope itself) and the noise of the readout electronics. SPICA (Swinyard et al. 2009) appears to be the next space-based satellite that will peer into the far-IR. SPICA will provide a telescope similar to *Herschel*, but will be cooled to $\lesssim 6$ K, thus removing its self-emission and reaching a sensitivity of up to two orders of magnitude greater as compared to *Herschel*, and will be equipped with photometric, spectroscopic, and coronagraphic capabilities. With SPICA, we will be able to improve the dust observations in the IC 434 region and extend similar studies of dust in H II regions to much greater distances, and hence probe a large sample of H II regions that vary in density, physical size, environment, and source luminosity.

Galactic studies of H II regions are often complicated by confusion that will affect the process of separating contributions from dust emission related to structures along the line of sight, dust that is located in the PDRs of H II regions, and grains that are mixed inside the ionized gas. In this regard, the large Magellanic cloud offers a unique opportunity to study dust evolution, given the location offset from the Galactic plane, its face-on appearance, and its relative proximity. JWST will be crucial here, because at the distance of the Large Magellanic cloud (50 kpc; Walker

2012), its large mirror (6.5 m) will offer the angular resolution ($\sim 0.25''$ or 1 pc at 10 μm) that will allow to resolve dust populations from individual H II regions, such as the 30 Doradus region, and perhaps dust waves surrounding individual stars. Indeed, studies of OB stars in the LMC and SMC have revealed a population of ‘dusty OB stars’ with dramatic mid-IR excesses (Bonanos et al. 2010; Sheets et al. 2013), well explained by the dust wave scenario. The study of dusty OB stars and dust evolution between different phases of the ISM could provide quantitative information on dust properties across the large Magellanic cloud and the cycling of matter on a galaxy-wide scale.

Lastly, while advances in observational facilities are clearly desirable to develop our understanding of interstellar dust and its relation to the structure and evolution of the ISM, it must be noted that laboratory work also provides a promising avenue for future research on interstellar dust. Recent measurements on laboratory analogues of interstellar silicate materials provide clues to the optical properties of interstellar silicates, but the analysis of this data is challenging (see Jones 2014, and references therein). In addition, photo-electric yields for carbonaceous and silicate materials as measured by Willis et al. (1973) and Abbas et al. (2006) differ by up to an order of magnitude. The results reveal a clear size dependence on photo-electric emission and a significant difference in yields measured from bulk materials compared to those measures on individual dust grains. More laboratory work is needed to better constrain fundamental properties of interstellar dust, such as their intrinsic composition and photo-electric yields.

Chapter 4: Interstellar bubbles & stellar feedback mechanisms

- **Results:** we studied the expansion of Galactic H II regions and the formation of dust waves therein. The bubbles seen in *Spitzer* and *Herschel* surveys of the Galactic plane offer a unique opportunity to study the formation of dust waves and stellar feedback mechanisms in relative young regions of simple geometry. At the same time, dust waves offer a natural explanation for the presence and morphology of dust in H II regions, and provide direct evidence for bubble flows that may be a key source of turbulence controlling the structure of the ISM on small scales.
- **Open questions:** The existence of radiation-pressure-driven dust waves in interstellar bubbles questions the importance of stellar winds during the formation of H II regions. Do main sequence stars really have weak winds? How does this translate to the relative contributions to the dynamics of H II regions from stellar winds (Weaver et al. 1977), overpressure of ionized gas (Spitzer 1978), or radiation pressure on dust grains (Krumholz & Matzner 2009)? We have shown that the importance of dust as an intermediary of radiative feedback depends heavily on the assumed gas and grain properties. If the right conditions are met, radiation pressure may be an important mechanism of stellar feedback to H II region dynamics, or even galactic outflows.
- **The way forward:** The results from Ch. 4 illustrate that we still do not fully understand the main sources of energy that drive the complex and chaotic appearance of the ISM seen to date (Ch. 1). In order to advance our knowledge on

the processes that govern the interactions between gas, dust, and stars, we must first understand the individual components. The characterization of interstellar dust has been discussed above. The IR surveys of the Galactic plane and nearby galaxies have opened up the IR sky as never before, offering important information about the structure and dynamics of the dusty ISM. However, complementary high-resolution, high-sensitivity radio spectroscopic surveys are needed to resolve the distribution of the gas component and its dynamics. Indeed, radio recombination line (RRL) measurements trace many physical properties of ionized gas, such as temperature, density, metallicity, and perhaps most importantly, its kinematics (see Thompson et al. 2015, and references therein). Current spectroscopic surveys are limited, as there is a tradeoff between sensitivity and angular resolution. On the one hand, single-dish surveys like SIGGMA (Liu et al. 2013) on Arecibo offer the sensitivity to trace interstellar plasmas down to electron densities of $n_e \sim 10 \text{ cm}^{-3}$, but only at several arcminutes of resolution. On the other hand, interferometric surveys such as THOR (Bihr et al. 2015) offer better angular resolution ($\sim 10''$), but its sensitivity only allows to trace high-density plasmas at $n_e \gtrsim 1000 \text{ cm}^{-3}$.

The future *Square Kilometer Array* (Dewdney et al. 2009), with its bandwidth, survey speed, and unprecedented sensitivity, will provide a unique opportunity to perform deep spectroscopic surveys of ionized gas down to densities below 50 cm^{-3} for the entire Galactic Plane at a $\sim 2''$ resolution, offering a synergy with ALMA studies of higher-frequency recombination lines. Moreover, its coverage includes multiple transitions of light radicals and molecules (Thompson et al. 2015). Thus, the SKA will revolutionize our understanding of the kinematic structure of the ionized (and molecular) component of the ISM at a resolution comparable to those of the IR surveys of the Galactic plane, allowing to directly quantify the coupling between gas and dust, and the importance of the various feedback mechanisms to the structure and evolution of the ISM.

Chapter 5: Evolution of superbubbles & the connection to star formation and molecular clouds lifetimes

- **Results:** we have performed an observational analysis of the Orion-Eridanus superbubble using the tools developed in the previous chapters. The synergy of different datasets resulted in an updated picture of the morphological and dynamical structure of the superbubble. Furthermore, we proposed a scenario for its future evolution. The Orion molecular clouds gradually evaporate and mass-load the interior of the superbubble through destructive champagne flows and thermal evaporation of clouds embedded in the hot gas. Explosive feedback mechanisms accelerate, sweep-up, and compress these ‘poisoned’ plasmas in an episodic fashion to form nested shells within the Orion-Eridanus superbubble that may cool, collapse, and fragment, to form stars of their own. The shells rejuvenate the superbubble by cleansing the interior and by plastering the mass and add momentum to the outer wall, driving the further expansion of the superbubble.
- **Open questions:** the results from this chapter revealed that the structure and evolution of the Orion-Eridanus superbubble is more complex than previously thought,

exhibiting an active interplay between stellar feedback, ISM evolution, and star formation. However, one can question whether the Orion-Eridanus superbubble can be viewed as a prototypical example for superbubbles in general. Is ‘rejuvenation’ of a superbubble a common phenomenon? How does this affect the lifecycle of molecular clouds and their integrated star formation efficiency? Is there a connection between the nested shells and the existence of separate subgroups in the Orion OB association? Is triggered star formation at play in the Orion region? Does the superbubble eventually blow out of the plane and ‘feed’ the Galactic halo?

- **The way forward:** The all-sky surveys from WISE and *Planck* have mapped the extremely large region on the sky covered by the Orion-Eridanus superbubble (45×45 degrees), while the position of the superbubble outside of the galactic plane allowed for the detection of the ionized gas component and its kinematics at optical wavelengths. Acquiring similar datasets of Galactic superbubbles, as well as those within nearby galaxies, will be limited by either confusion, extinction, sensitivity, or spatial resolution. An exception to this rule are the superbubbles located in the Magellanic clouds (Lopez et al. 2011; Pellegrini et al. 2011; Lopez et al. 2014). JWST will play a crucial role here by obtaining high-resolution and sensitive images of the dust structure of bubbles and superbubbles throughout the Magellanic clouds. The detection of $24\ \mu\text{m}$ emission from dust waves within superbubble structures will provide information on the dynamics of interior flows and the evaporation of molecular clouds that fuels the expansion of superbubbles (Ch. 5).

The disk-halo connection of galaxies and the importance of superbubble blowouts remains poorly understood, in part because the emission from the gas and dust of extended haloes is very faint and hard to detect. Highly ionized gas species can be traced with absorption lines studies, but the studied amount of sightlines are sparse and left at the mercy of available background sources. JWST, equipped with an integral-field-unit and an unprecedented sensitivity, may be able to trace the emission structure and dynamics of galactic winds of many nearby galaxies, such as that observed in M82 (e.g., Engelbracht et al. 2006). Together with our work on the various forms of stellar feedback in Ch. 4 and the evolution of superbubbles in Ch. 5, we may be able to further develop our understanding to the origin of these galactic winds and establish the disk-halo connection within galaxies.

Even within nearby star forming regions, proper motions and the three-dimensional distribution of stars are poorly constrained by photometric indicators or the astrometric accuracy offered by *Hipparcos* (van Leeuwen 2007), such that questions whether or not star formation is triggered in Orion OB1 remain open and controversial. *Gaia* (de Bruijne 2012) will measure parallaxes and proper motions at an accuracy two orders of magnitude higher than *Hipparcos*, delivering astrometric, photometric, and spectroscopic data of over a billion stellar objects, thus providing the necessary measurements to determine positions, distances, motions, and luminosities of nearby stars. In this way, we will obtain the three-dimensional distribution of nearby stars that is essential to address the importance of, e.g., triggered star formation (Elmegreen & Lada 1977) in Orion (Ch. 5), for which one needs *precise* measurements of proper motion, radial velocities, and ages. In this way, the circle of interactions between gas, dust, and stars in the ISM of Orion will be completed.

Summary

In conclusion, exciting times lie ahead, as considerable potential lies within the exploitation of future facilities that will provide us with the right tools to advance our knowledge of the interplay of gas, dust, and stars in the ISM. Concretely, and in direct relation to the contents of this thesis, JWST will allow us to probe the origin and evolution of interstellar dust over a much larger distance, and we will be able to compare the results from Ch. 2 and 3 from this thesis to that of more distant regions than Orion, out to the Magellanic clouds. Future radio telescopes, like the SKA, will allow us to address the importance of stellar feedback mechanisms after charting the gaseous structure of the Milky Way by peering through the Galactic plane with unbiased surveys (Ch. 4). *Gaia* will provide the definite location of stellar populations within Orion to assess the connection between the stars and the nested shells of the Orion-Eridanus superbubble (Ch. 5).

Final remarks

This outlook has mainly focussed on observational prospects, as observations lie at the root of many of the questions addressed in this thesis and, more importantly, reflects my personal interests. However, it is my belief that breakthroughs and revolutions in astronomy will only be possible through the combined efforts of theorists, modelers, experimentalists, and observers from the physical, chemical, and biological sciences, while future generations of talented scientists need to keep inspired with images and mind-bending questions that come along while investigating the vast richness of the Universe.

The golden era of (far-)IR space observatories has, at the moment, temporarily slowed its pace. Still, a vast wealth of observational data remains unexplored, perhaps exemplified through the contents of this thesis, where I have formulated and addressed some of the puzzling questions that have arisen while looking at Orion, classically one of the best studied regions of the sky. Only when we fully grasp the complex processes that govern galactic ecologies in the local Universe, will we be able to relate this to observations of the early Universe at high-redshifts, and fully appreciate the capabilities that will be offered by future facilities.