Orion's Dragon and other stories: Feedback by massive stars

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1

Introduction

1.1 Feedback and the evolution of galaxies

Since we know that the universe has its origins in the Big Bang, understanding stellar feedback has been one of the key ingredients to understanding the evolution of the universe. Stellar feedback comes in the form of energy input by supernova explosions, stellar radiation, and winds. The exact amount of stellar feedback is crucial for the formation of large-scale structure and galaxies. Computational models describing the evolution of large-scale structure and galaxies, such as EAGLE (Evolution and Assembly of Galaxies and their Environments; Schaye et al. 2015), lean heavily on subgrid physics to be incorporated. These subgrid physics, often parametrized as the star-formation rate (SFR), can be explored in local star-forming regions. However, the star-formation rate is presumed to vary during cosmic lifetime, due to the complex interplay of gravity and stellar feedback with additionally varying elemental abundances, and it is important to understand different physical process involved in the feedback of massive stars on the ISM that control this relationship. While star-formation processes predominantly produce low-mass stars, it is the most massive stars that dominate feedback processes by their strong ultraviolet radiation field, mass-loss winds, and, not least, by their death throes when they go supernova.

Stellar feedback comes in two flavors. Massive stars can disrupt their nascent clouds and thereby prevent further star formation (negative feedback). On the other hand, the compression of clouds under the influence of shock waves induced by stellar winds and radiation can lead to enhanced star formation (positive feedback). The efficiency of both processes is controversial. Some studies imply that the efficiency with which clouds are disrupted is small and that the initial conditions, under which the massive stars formed, are decisive (Dale et al. 2014; Watkins et al. 2019). The model for triggered star-formation (Elmegreen & Lada 1977) was challenged by new models that incorporate a wider range of physical processes (Walch et al. 2015). Also the dominant source of feedback is still heavily debated. While many bubbles surrounding massive stars radiate significant in X-ray emission (Townsley et al. 2014), the tell-tale signature of stellar winds, models imply that stellar radiation, ionizing the gas that expands due to overpressure, is more efficient in driving the expansion of these bubbles (Haid et al. 2018; Geen et al. 2020). This thesis focuses on the region of massive star formation in the Orion molecular cloud as a template for the study of feedback from massive stars on nearby molecular clouds either through radiation creating photoionization and photodissociation flows or through the mechanical energy input by stellar winds.

1.2 Ionized gas, PDR structures, and forbidden lines

It has proven difficult to quantify stellar feedback. Despite the detection of X-rays from the cavities of supernovae remnants and wind-blown bubbles, the mass motions the hot gas induces in the interstellar medium could not be efficiently traced. Velocity-

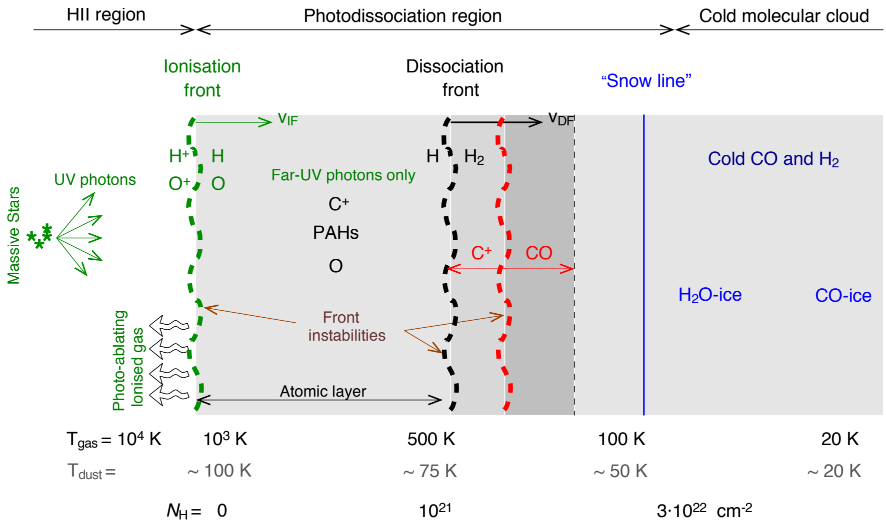

Figure 1.1: Schematic drawing of a photodissociation region (PDR) adjacent to an H II region created by massive stars (Goicoechea et al. 2016).

resolved observations of optical lines from the ionized gas advanced our knowledge of the energy input from massive stars a step further. However, most of the mass in motion is contained in the dense shells of neutral gas that are swept up by the expanding hot and ionized gas (Weaver et al. 1977; Spitzer 1978). Those neutral shells emit strongly at infrared wavelengths, both in continuum emission from UV-heated dust grains, but also in forbidden far-infrared (FIR) lines. Line radiation has the advantage that the dynamics can be traced through the Doppler effect if high-spectral resolution spectrometers are available.

Among the forbidden far-infrared lines is the fine-structure line of ionized carbon, the [C II] $^2P_{3/2}$-$^2P_{1/2}$ line at 158 μm. Together with the [O I] $^3P_1$-$^3P_2$ fine-structure line of atomic oxygen at 63 μm, it is the dominant coolant of neutral gas: The interstellar gas is heated by the photoelectric effect of far-ultraviolet (FUV) photons ($E \simeq$ 6-13.6 eV) on small dust grains and large molecules (polycyclic aromatic hydrocarbons, PAHs) and cools through fine-structure lines of trace elements (Hollenbach & Tielens 1999; Wolfire et al. 1995; Bakes & Tielens 1994). While the ionized gas is heated by photoionization from EUV photons ($E > 13.6$ eV), EUV photons are usually used up in the H II region adjacent to the neutral shells and the neutral gas has the structure of a photodissociation region (PDR). PDRs will be created on the surface of a molecular cloud, where FUV photons impinge on the surface. The schematic structure of such a PDR is shown in Fig. 1.1. The FUV photons are absorbed in the atomic surface layers, where they ionize carbon with an ionization potential of 11.2 eV. Hydrogen atoms combine to hydrogen molecules on dust grains surfaces at the dissociation front. In the deeper layers of a PDR (visual extinction $A_V \gtrsim$ 1-2), carbon will become neutral and eventually form molecules such as CO, the most abundant one after molecular hydrogen. At very low temperatures inside a molecular cloud, molecules freeze out on cold dust grains.

The [C II] line will be the brightest far-infrared line emitted by swept-up shells around massive stars, with moderate gas densities ($n \sim 10^3$-10^4 cm^{-3}) and moderate temperatures ($T \sim$ 100-300 K). As emission lines have a well-defined frequency, it

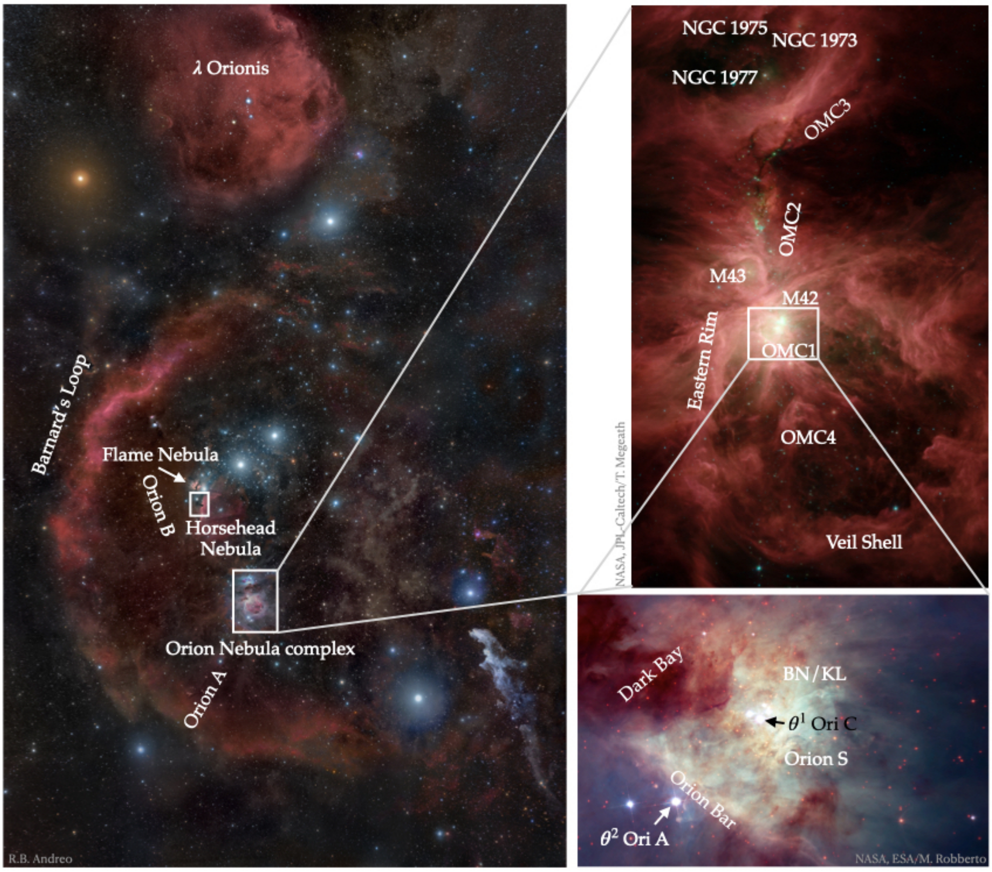

Figure 1.2: Zoom into the constellation of Orion. *Left:* Photograph of the constellation of Orion (image credit: R.B. Andreo). The Horsehead Nebula in the Orion B molecular cloud and the Orion Nebula in the Orion A molecular cloud are visible in this long-time exposure (white rectangles). *Upper right:* *Spitzer*/IRAC multi-color image of the Orion Nebula complex (image credit: NASA, JPL-Caltech/T. Megeath). Mid-infrared wavelengths reveal dust and large molecules irradiated by star light. *Lower right:* The inner Orion Nebula, with the massive Trapezium stars, as seen by the *Hubble Space Telescope* (image credit: NASA, ESA/M. Robberto). The ionized gas in this regions emits in UV and optical lines. The background PDR and the Orion Bar are mainly visible at infrared and (sub-)millimeter wavelenghts.

is possible to determine gas motions with high accuracy due to the Doppler shift. With the upGREAT instrument onboard SOFIA this has become possible for far-infrared lines such as the [C II] line with sub-km s^{-1} velocity resolution and high spatial resolution (15.9$''$ at the frequency of the [C II] line). Large-scale mapping of nearby star-forming regions allows to study stellar feedback in more detail than previously possible. In particular, it makes it possible to detect large-scale motion of the gas affected by stellar feedback.

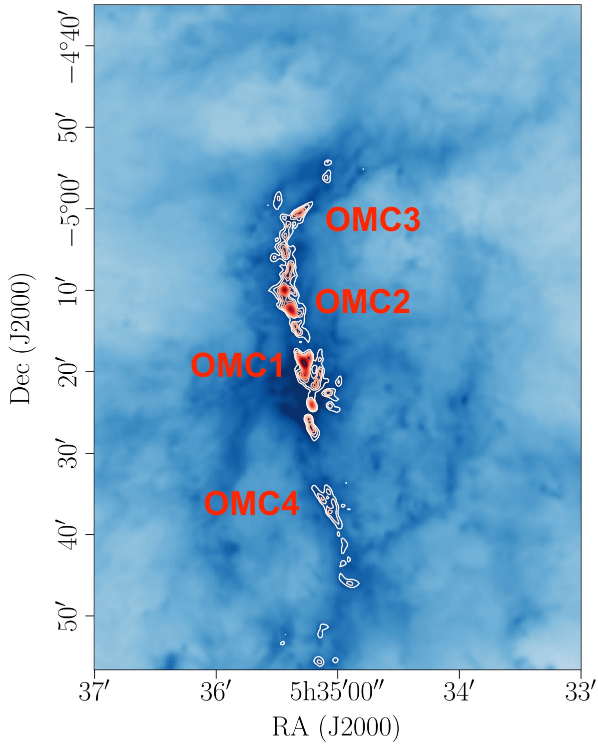

Figure 1.3: *Herschel*/SPIRE 500 μm (blue color scale) and IRAM 30m N_2H^+ (J=1-0) (red contours) emission from the Integral-Shaped Filament. Sub-millimeter emission arises from the cold dust in the extended filament. N_2H^+ emission stems from high-density concentrations along the filament. The positions of the molecular cores OMC1 to 4 are indicated.

1.3 The Orion molecular cloud

The Orion molecular cloud in the constellation of Orion is the nearest site of active massive star formation, with a distance of $\sim$ 400 pc from earth (Menten et al. 2007; Großschedl et al. 2018). The Orion molecular cloud consists of two parts, the Orion A and the Orion B molecular cloud. Figure 1.2 shows an overview of the constellation of Orion, zooming in into the prominent Orion Nebula in Orion A. The Orion Nebula is shaped by the massive stars hosted in its inner regions, the Trapezium stars. Among the Trapezium stars, the O7V star θ^1 Ori C is the most massive with a mass of about 33 solar masses. While originally the denotation Orion Nebula or M42 referred only to the inner bright Huygens Region, an H II region, we know now that the entire shell structure visible at infrared wavelengths is created by feedback from the θ^1 Ori C, whose wind has created a bubble filled with hot, X-rays emitting plasma (Güdel et al. 2008), the Extended Orion Nebula (EON). We subsume the entire structure, including the outward areas of hot and ionized gas, that is affected by feedback from the most massive central stars under the name Orion Nebula. To the north of the Orion Nebula, we find the H II regions of M43, with central B0.5V star NU Ori, and NGC 1973,1975, and 1977. The latter group of reflection nebulae possess as dominant source of radiation the B1V star 42 Orionis in NGC 1977.

The Orion Nebula, M43, and NGC 1977, together the Orion Nebula complex, are connected by the molecular spine of the Integral-Shaped Filament (ISF), that is readily observed as cold dust at sub-millimeter wavelengths (Johnstone & Bally 1999) and tracers of cold, dense molecular gas such as CO or N_2H^+ rotational lines (Hacar et al. 2017), as shown in Figure 1.3. Along the ISF, we find several star-forming cores, the Orion Molecular Cores (OMC) 1 to 4. The massive Trapezium stars have formed at the surface of the most massive core, OMC1. They are shielded towards the observer by a translucent layer of largely neutral gas, the so-called Orion's Veil (van der Werf & Goss 1989; O'Dell & Yusef-Zadeh 2000; Abel et al. 2004). At the surface of OMC1, the radiation from the Trapezium stars have created an ionized gas region, the Huygens Region. A heavily irradiated PDR (e.g., Goicoechea et al. 2019) separates the ionized gas from the molecular cloud in the background. The Orion Bar is a part of this dense PDR that is curving towards the observer and, hence, is viewed nearly edge-on (e.g., Tielens et al. 1993). Due to its geometry and brightness, it is the most extensively studied PDRs to date. Encircling the constellation of Orion is Barnard's Loop, an expanding shell structure that may have been created by a supernova (Ochsendorf et al. 2015) and is photoionized by massive stars in the Orion OB association (O'Dell et al. 2011). At even larger scales, Barnard's Loop is nested into the Orion-Eridanus superbubble, that is filled with and rejuvenated by dilute gas from stellar feedback events (Ochsendorf et al. 2015).

Another iconic structure in the constellation of Orion is the Horsehead Nebula. Situated at the edge of the L1630 molecular cloud in Orion B, it is illuminated by the O9.5V star σ Ori, that is approaching the cloud and photoevaporating it (Ochsendorf et al. 2014). The Horsehead Nebula and the neighboring edge of L1630 exhibit the layered emission structure of prototypical PDR. As opposed to the Orion A molecular cloud, the star-formation efficiency in Orion B is low (Megeath et al. 2016). Orion B hosts two sites of massive star formation, that have been studied in [C II] emission previously, the Flame Nebula (NGC 2024; Graf et al. 2012) and NGC 2023 (Sandell et al. 2015) close to the Horsehead Nebula. The Horsehead Nebula itself shows weak star-forming potential in its filaments, where only a few young stellar objects (YSOs) can be identified.

1.4 SOFIA/upGREAT

In this thesis, we make use of velocity-resolved [C II] observations to trace stellar feedback in the Horsehead Nebula and the Orion Nebula complex. The observations were obtained with the Stratospheric Observatory for Infrared Astronomy (SOFIA). SOFIA is a heavily modified Boeing 747-SP with a 2.5-meter mirror mounted at the rear (see Fig. 1.4). Flying out of Palmdale, California, or on Southern Deployment out of Christchurch, New Zealand, it is possible to reach altitudes where atmospheric water vapor does not block out infrared radiation completely and it is possible to observe wavelengths from the mid-infrared to the far-infrared (λ = 3-609 μm) with different instruments, that can be exchanged. The heterodyne receiver upGREAT (the upgraded German Receiver for Astronomy at Terahertz Frequencies; Fig. 1.5) allows for observations at far-infrared wavelengths. Heterodyne receivers rely on a signal provided by a local oscillator that is mixed with the telescope signal. The mixed signal can be processed electronically. The Low-Frequency Array (LFA) of upGREAT is tuneable to the frequency of the [C II] line (1.900537 THz) and consists of 2×7 independent pixels in two polarizations. With this, mapping speed is increased by a factor of ~ 20 compared to the single-pixel Heterodyne Instrument for the Far-

Figure 1.4: The Stratospheric Observatory for Infrared Astronomy (SOFIA) in flight (image credit: NASA/Jim Ross).

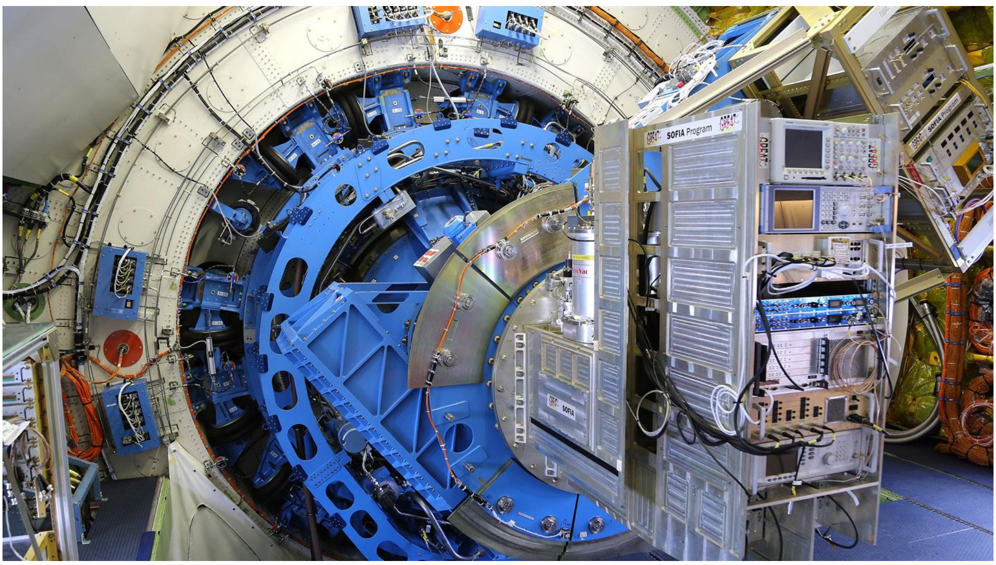

Figure 1.5: The GREAT instrument mounted to SOFIA's mirror backend (image credit: DLR).

Infrared (HIFI) onboard the *Herschel* Space Observatory and large-scale mapping has become feasible.

[C II] observations of the Horsehead Nebula and the adjacent L1630 molecular cloud over an area of $12' \times 17'$ have been obtained in 2015 with SOFIA/ upGREAT

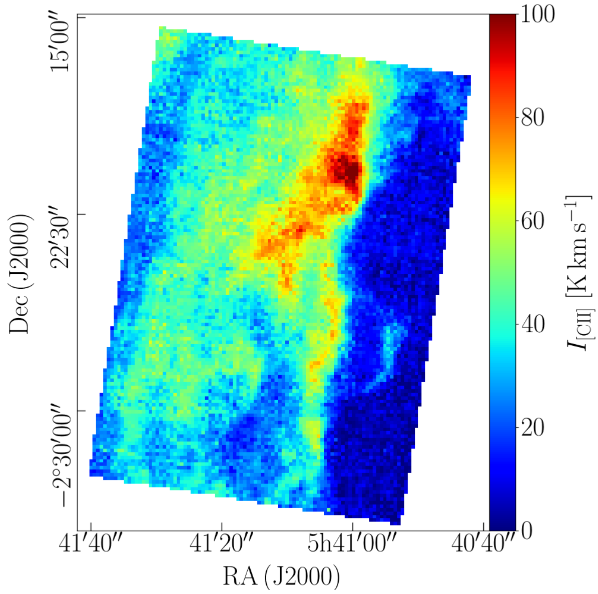

Figure 1.6: [C II] line-integrated emission from L1630 with the Horsehead Nebula in the Orion B molecular cloud.

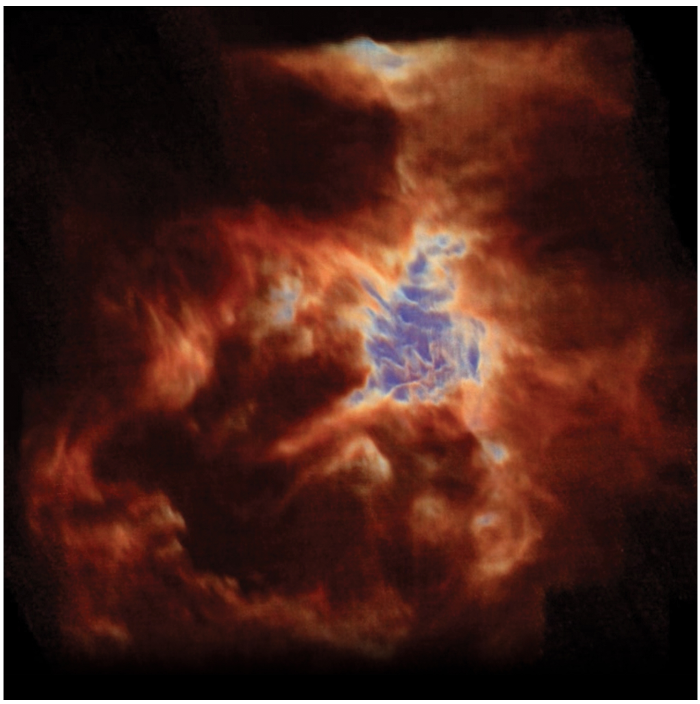

Figure 1.7: A screenshot from the rotating [C II] data cube that is Orion's Dragon, observed by SOFIA/upGREAT (image credit: NASA/SOFIA).

in order to prove the feasibility of large-scale mapping. Figure 1.6 shows the [C II] line-integrated intensity from L1630. The Orion A C^+ Square-Degree survey towards Orion A, carried out in November 2016 and February 2017, proved that even larger areas can be mapped efficiently with SOFIA/upGREAT and lead to the discovery of Orion's Dragon, the nickname of the cropped rotated [C II] data cube of the Orion Nebula complex that is shown in Figure 1.7.

1.5 Thesis outline

Feedback by massive stars is key to understanding the evolution of the interstellar medium of galaxies. In this thesis, I have studied the mechanical and radiative response of molecular clouds on stellar energy input in the Orion molecular cloud, the closest region of massive star formation in our Galaxy.

In Chapter 2 of this thesis, we analyze the velocity-resolved [C II] emission from L1630, comprising the Horsehead Nebula, in the Orion B molecular cloud. We study the characteristics of the PDR gas created by the FUV radiation from the approaching illuminating O9.5V star σ Ori on the surface of this cloud. We compare the SOFIA/upGREAT [C II] emission to *Spitzer*/IRAC 8 μm emission of FUV-irradiated polycyclic aromatic hydrocarbons (PAHs), *Herschel*/PACS and SPIRE FIR continuum emission of warm dust, and IRAM 30m CO(1-0) emission of the molecular gas to determine the origin of [C II] emission.

In Chapter 3, we study the [C II] emission, observed with SOFIA/upGREAT, from the M42 and EON region and demonstrate that the mechanical energy input by the stellar wind from θ^1 Ori C has created a 4 pc diameter bubble that is expanding rapidly with a velocity of 13 km s^{-1}.

In Chapter 4, we study the expanding shells of M43 and NGC 1977 created by the respective ionizing stars. The expansion velocity of these bubble is much less than for M42. This reflects the weak stellar winds from these somewhat less massive stars and, in contrast to M42, expansion here is driven by the thermal pressure of the ionized gas.

In Chapter 5 and 6, we analyze the relation between the [C II] emission and other tracers of the radiative interaction of massive stars with their environment. The emphasis is on deriving quantitative relations that can be used to predict the expected [C II] emission from observations of other tracers, and to assess the use of [C II] emission as a SFR indicator. Chapter 5, in particular, discusses the utility of spatially resolved [C II] observations towards the Orion molecular cloud as a template for extragalactic [C II] studies and the so-called [C II] deficit, that is observed towards extragalactic regions of very high FIR luminosity. Chapter 6 explores the detailed spatial relations between tracers of radiative feedback in M42, M43, and NGC 1977 and links this to PDR physics. This in particular makes use of IRAM 30m CO(2-1) line observations, that are part of the Large Program "Dynamic and Radiative Feedback of Massive Stars" (Goicoechea et al. 2020). Furthermore, we investigate the photoelectric heating efficiency as measured by the [C II] cooling efficiency in relation with properties of PAHs.

1.6 Outlook

In this thesis, I have studied the interaction of a single O7V star with its environment, the structure and characteristics of the neutral shell surrounding the bubble it created. This was complemented by a study of an O9.5V star passing by a molecular cloud and a study of the bubbles surrounding two B1/1.5V stars. We expect that feedback processes will be different in regions that differ in the concentration of massive stars and formation history.

Velocity-resolved [C II] mapping of the starburst region 30 Doradus (the Tarantula Nebula) in the Large Magellanic Cloud (LMC), hosting a cluster of massive stars, will shed light on the processes of stellar feedback in a super-starcluster with ~ 1000 OB stars. Large-scale velocity-resolved [C II] mapping of other star-forming regions, such as the sample of the SOFIA C+ Legacy Program FEEDBACK will allow for a more comprehensive study of the forms and effects of stellar feedback in local sources. The FEEDBACK survey observes 11 galactic high-mass star-forming regions in the [C II] $158\,\mu$m and the [O I] $63\,\mu$m lines. In total, an area of $6700\,\mathrm{arcmin}^2$ will be covered at an angular resolution of $15.9''$ in the [C II] line and $6.3''$ in the [O I] line. The 11 observed regions differ in their geometry (ridges, filaments, shells, fragmented or not) and their stellar content (ranging from a single late O star to clusters of a few early O stars with several late O stars, with additional B and Wolf-Rayet stars). The survey aims at investigating the morphology and dynamics of the neutral gas, triggered star formation, the energy input into the ISM by massive stars, PDR physics and chemistry assisted by detailed PDR modelling (complemented by other PDR line observations such as the [C I] $609\,\mu$m line and mid- and high-J CO lines, observable with the SOFIA and APEX telescopes), and the formation of filaments, pillars, and globules in the vicinity of massive stars (Schneider et al. 2020).

In addition, the [C II] observations will be complemented by observations of low-J CO rotational lines to study transmission of feedback into the molecular counterpart. While the molecular gas in the Orion Nebula is certainly affected by stellar feedback, as evident for instance by the discovery of hydrodynamic instabilities in the CO(2-1)-emitting gas, this has been difficult to quantify on large scales due to the overwhelming amount of data. More comprehensive techniques need to be applied in order to quantify feedback on the molecular gas and its connection to the neutral gas emitting in [C II]. Such techniques have been developed recently, for instance the histrograms of oriented gradients (HOG) (Soler et al. 2019) and the analysis of turbulent modes (Orkisz et al. 2017). Particularly the transmittance of turbulence, into molecular clouds and into the diffuse interstellar medium, is of importance to the understanding of the evolution of the ISM (Federrath & Klessen 2012; Kim et al. 2013). In the context of the Orion Nebula, the hot gas within the cavity will eventually be vented into the surrounding diffuse medium of the Orion-Eridanus superbubble, thus renewing the turbulence of the dilute gas and mass loading the superbubble's interior.

As we have noted earlier, [O I] $63\,\mu$m cooling is important to consider in the Orion Nebula complex. Further studies could endeavor to get a better handle on the physical conditions in the shells by observing the [O I] $63\,\mu$m and $145\,\mu$m cooling lines. The [O I] $63\,\mu$m line is optically thick in most contexts, but the [O I] $145\,\mu$m can be employed to trace the column of the emitting gas. Besides for the derivation of physical conditions, the [O I] $63\,\mu$m intensity is needed to construct a more reliable semi-empirical relation of the gas heating efficiency depending on the physical conditions. As we have seen, [C II] line profiles in the Orion Nebula complex are rich in components, thus high-

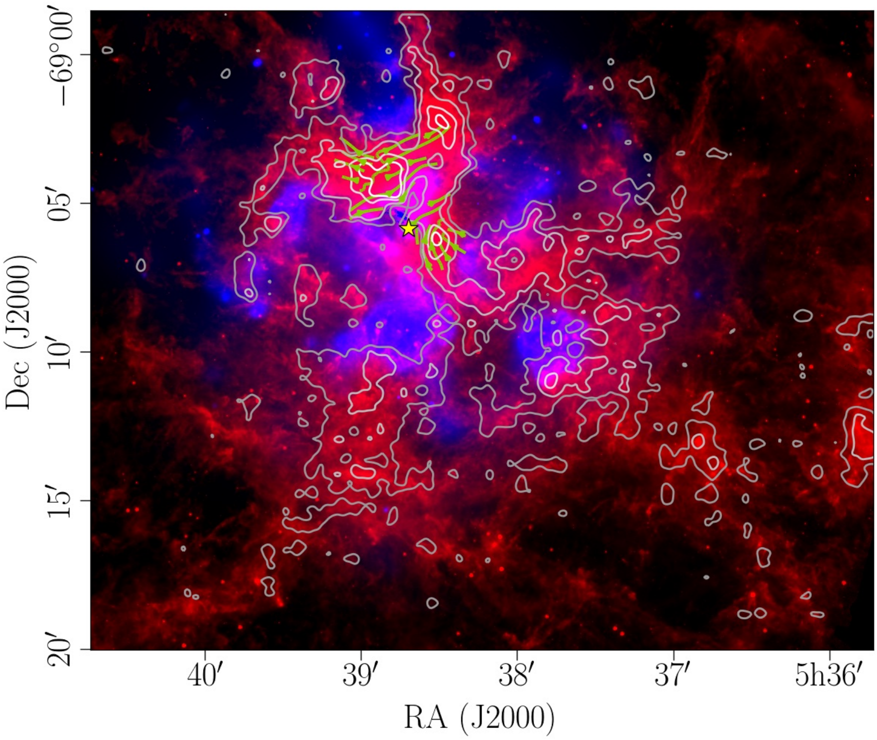

Figure 1.8: [C II] line-integrated intensity towards the starburst region 30 Doradus in the Large Magellanic Cloud (contours, from grey to white: 30, 50, 100, 150 $\mathrm{K\,km\,s^{-1}}$) on *Spitzer*/IRAC 8 μm intensity (red) and Chandra X-ray emission (blue). Green streamlines indicate the orientation of the magnetic field lines as measured by SOFIA/HAWC+. The yellow star marks the position of the star cluster R136.

spectral-resolution observations of the [O I] 63 μm and 145 μm lines, as possible with SOFIA/upGREAT, would be required. Also the physical properties and motions of the ionized gas in and adjacent to the shells could be determined using observations of the [NII] FIR lines, for instance the [N II] 205 μm line with SOFIA/4GREAT. Both FIR [O I] line and [N II] line observations could be compared with *Hubble* Space Telescope (HST) optical [O I] 630 nm and [N II] 658 nm observations towards the Orion Nebula to determine the properties of the gas, and hence the amount of stellar feedback and its effect on the geometry of the region, with higher accuracy. The ionized gas could also be traced by hydrogen radio recombination lines (RRLs). Like the [N II] FIR lines, those will be faint towards the cavity of the EON and would require long integration times when observed. Those observations would be possible with the IRAM 30m telescope at Pico Veleta, Spain. The IRAM 30m telescope would be the facility of choice to study molecular line emission from the Orion Nebula in greater detail. While the dense ISF has been studied extensively, the wider molecular background that is affected by the stellar feedback from the massive stars has been less studied. Those studies could reveal important details about the impact of stellar feedback on the natal molecular clouds of massive stars.

One of the least understood aspects of stellar feedback is the role magnetic fields play. Observations of the magnetic field lines, by means of dust polarization measure-

Figure 1.9: Me in front of SOFIA in Palmdale, CA (February 17, 2017).

ments, have become feasible recently with the HAWC+ instrument onboard SOFIA. Magnetic fields build up in compressed gas shells due to flux freezing. The magnetic pressure in the gas counteracts the radiation and gas pressure from the inside of the shell. As such, magnetic fields can inhibit the expansion of shells and thus regulate stellar feedback. SOFIA/HAWC+ observations have been obtained towards the bright filaments close to the stellar cluster R136 in 30 Doradus. In combination with magnetohydrodynamic simulations, combining [C II] line and dust polarization observations will shed light on the magnetic field strength and orientation encountered in such expanding shells. The Davis-Fermi-Chandrasekhar method for determining magnetic field strengths in interstellar gas can then be evaluated numerically. Figure 1.8 shows the [C II] line-integrated intensity towards 30 Doradus and the magnetic field lines from dust polarization on top of the IRAC 8 μm emission and Chandra X-ray emission. The [C II] position-velocity diagrams reveal several expanding bubbles that encircle the hot, X-ray emitting plasma heated by stellar winds and supernovae. Relating the kinetic energies of the shells to the stellar content and the magnetic fields will improve our understanding of the regulation of stellar feedback in a variety of contexts.

1.7 Epilogue

I consider it a great privilege that I was enabled to join not only the flight campaign on observing the [C II] square-degree map, the largest-ever map obtained in [C II] emission, of the Orion Nebula complex, but also the flight series observing the star-forming region 30 Doradus in the Large Magellanic Cloud (LMC). Among my most vivid memories is that of the two faint specks of diffuse starlight that are the Large and the Small Magellanic Cloud, next to the bright band of stars in the Milky Way, seen from the cockpit of SOFIA. But also flying in the crisp morning light above the Sierra Nevada back to Palmdale made an impression. It was amazing, also, what a sleep-deprived brain is still able to achieve. In summary, I learned a lot, not only about the passion and dedication of those who keep SOFIA running, but of course also a lot about the technical details that are necessary to conduct the precise measurements of far-infrared radiation. And once, when humanity will have been long extinct, and all our knowledge of star-forming processes will be long forgotten, the interstellar horses, dragons, and tarantulas will still shine in all their glory.