Far and mid-infrared studies of star forming regions

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Summary

This thesis focuses on understanding the physical and chemical processes that take place in regions forming both low and high mass stars, in particular the early evolutionary stages of star formation. The physical and chemical processes during star formation influence the thermal balance and the chemical composition of the interstellar medium and its evolution. Star forming regions are among the most chemically rich and complex regions of the Universe and they are located in dense parts of the interstellar medium. The study of their molecular content is one of the major goals of astrochemistry in general and this thesis in particular. But why are we so interested in the chemical composition of these regions?

We know that several processes during star formation influence the chemical composition, complexity and evolution of the interstellar medium. Vice versa, the chemical composition and evolution of the interstellar medium have their own influence on the evolution and possibly the mass of a newly born star. The dynamical processes that lead to the collapse of an interstellar cloud and thus the creation of a protostar are highly connected with the chemical composition of the gas. The thermal pressure of the gas and the magnetic fields resist the gravitational forces and thus the collapse, and both are connected with the chemical composition of the medium. Namely, the thermal balance **(Chapter 2, 3)** can only be understood if we know: what kind of molecules can be formed, when and where do they form and how much do they contribute to the cooling of the gas via line emission? What are the main heating mechanisms during star formation? The magnetic fields on the other hand, are coupled with the medium through ions. Knowing the ionization structure and the abundance of ions is mandatory to understand the overall star formation processes.

Another topic of interest is understanding the evolutionary stages of very young objects **(Chapter 4)**. The processes that turn a prestellar core to a protostar and the several evolutionary stages can be probed by molecular and dust emission. Molecular emission is a powerful tool in probing the several mechanisms that take place during star formation since different chemical species probe different regions and conditions (i.e. temperature, density, velocity distribution). A question of practical importance is: what are the main observational signatures that one can use in order to distinguish the different evolutionary stages?

Last, but not least, understanding the formation/destruction of molecules in star formation **(Chapter 5)** is directly connected with understanding the chemical history of

stars and planetary systems. Complex organic molecules, which are the building blocks of life, have been observed towards young protostars. How, where and in which form do they form? Studying and understanding the chemical reactions and evolution in star forming regions could eventually lead to understanding their distribution in protoplanetary systems and to get closer to maybe understand how prebiotic molecules form and the origin of life on Earth.

The specific questions that we are addressing in this thesis are:

- What is the thermal balance, the chemical and dynamical structure in PDRs and what is the impact of UV radiation and clumpiness in such environments ? (Chapter 2, 3)
- How can we constrain the evolutionary state of dense cores? (Chapter 4)
- What is the physical and chemical structure of low mass protostellar envelopes? How does their chemical structure compare to the high mass case? (Chapter 5)
- How do outflows influence the chemistry of the protostellar surroundings? (Chapter 5)

To answer these questions, I have used molecular line and continuum data at millimeter/submillimeter wavelengths, using a variety of instruments, from single dish ground-based observatories (i.e. JCMT, IRAM) to interferometer (CARMA) and up to stratosphere (SOFIA) and space (Herschel). To interpret the observations, I used a variety of radiative transfer models (i.e. RADEX, RATRAN).

This thesis focuses on two targets, the S140 photon-dominated region (PDR), which is connected with high mass star formation and NGC1333 IRAS4, where a cluster of low mass protostars is forming. The specific scientific questions, the methodology and the main results of this thesis are described below.

• The thermal balance of dust and gas in photon-dominated regions

The S 140 region is a great environment to study the thermal balance in PDRs. In order to study the thermal coupling between dust and gas (**Chapter 2**) and the thermal balance in this region I used a dataset that traces both continuum dust emission (PACS, SOFIA/FORCAST, SOFIA/GREAT,SCUBA) and molecular lines (IRAM-30m, HIFI). I modeled the CO molecular emission using the radiative transfer codes RADEX (van der Tak et al. 2007a) and RATRAN (Hogerheijde & van der Tak 2000) in order to constrain the gas kinetic temperature, volume density and CO column density across the region. In addition, deriving the energy input is important for studying the thermal balance (**Chapter 3**). We put together the results of the gas and dust emission (DUSTY; Ivezic et al. 1997) and the results regarding the cooling budget (fine-structure lines of [OI]-63μm and [CII]-158μm) and the PDR modeling (Kaufman et al. 1999).

Our main results in S140 are a) the gas is systematically warmer than the dust by at least 5-15 K despite the high gas density (**Chapter 2**), and we conclude that this is a result of a deep UV penetration from the embedded sources in a clumpy medium and/or oblique shocks and b) the line-to-continuum ratios of far-IR CII and OI lines which trace the cooling budget, are lower than in any other Galactic source ($< 10^{-4}$), and are actually matching the far-IR line deficit seen in Ultraluminous Infrared Galaxies (ULIRGs; Malhotra et al. 1997; Muñoz & Oh 2015). Striking is also the fact that the main emission of fine-structure lines in S 140 is spatially offset from the main heating source which is currently a puzzle (**Chapter 3**).

The possible difference between gas and dust temperature at high densities should be considered when analyzing continuum and molecular line observations using advanced radiative transfer models. In addition, given the fact that the observed far-IR line deficit in ULIRGs is not fully understood, S 140 appears to be a useful template that may lead to a future model and thus better understanding.

• **The earliest phases of low mass star formation**

Protostellar evolution, following the formation of a protostar is becoming reasonably well characterized, but the evolution from a prestellar core to a protostar is not well known, although the first hydrostatic core (FHSC) has been suggested be a pivotal step (Larson 1969). One of the sources of my thesis, the NGC1333 IRAS4 region, is a low mass star forming region which contains three young stellar objects, IRAS 4A, IRAS 4B and IRAS 4C. IRAS 4C is a potentially very young object, that we can directly compare with the nearby Class 0 objects IRAS 4A and IRAS 4B. In order to investigate the evolutionary status of these objects (**Chapter 4**), I used molecular line survey (JCMT 330-373 GHz -maps) and continuum observations (CARMA). I used a set of observational constraints others than the bolometric temperature which is widely used and I modeled the emission using RADEX.

I found differences among the three sources in four aspects: a) the kinetic temperature as probed using the H_2CO lines is much lower towards IRAS 4C than the other two sources, b) the line profiles of the detected species show strong outflow activity towards IRAS 4A and IRAS 4B but not towards IRAS 4C, c) the HCN/HNC abundance ratio is lower than 1 towards IRAS 4C, which confirms the cold nature of the source, d) the degree of CO depletion and the deuteration are the lowest towards the warmest of the sources, IRAS 4B.

Based on these findings, IRAS 4C seems to be in a different evolutionary state than the IRAS 4A and IRAS 4B sources, but our results are not fully consistent with a younger or an older object. The major issues are the absence of outflow activity and the cold nature of IRAS 4C which could point towards a first hydrostatic core (FHSC). A more detailed physical model of IRAS 4C is one of my future plans. This method can be extended to a bigger sample of FHSC candidates (Enoch et al. 2010; Chen et al. 2010; Pineda et al. 2011; Pezzuto et al. 2012; Schnee et al. 2012) and I am particularly interested in comparing the results of such sample with a sample of very low luminosity objects ($<$

0.1 $L_\odot$; VeLLOs). Such a study may lead to the understanding of the link between a prestellar core and a protostar which is predicted by theory to be the first hydrostatic core.

The number of the observed FHSC candidates in Perseus (six) is an order of magnitude higher than predicted. This can imply a lower accretion rate ($< 4\times10^{-5}$ $M_\odot$/yr) than what models predict (Evans et al. 2009).

Chapter 5 focuses on the chemistry of young embedded protostars. Classical hot cores, associated with high–mass star formation, are characterized by high temperatures and high densities and are of interest because of the complex organic molecules that they host. Similarly, a complex organic chemistry has been reported in the inner envelopes of low–mass young protostars, the so–called hot corinos (e.g. Ceccarelli 2008). But is the underlying chemistry actually the same?

In order to study the chemical structure of low-mass protostellar envelopes, compare it to the high–mass case and investigate the influence of the outflows such environments I use JCMT and HIFI spectral surveys and compare the observed abundances with time dependent chemical models (ALCHEMIC; Semenov et al. 2010). The chemical models used include both gas phase, gas-grain, and surface reactions. The models predict the abundance profiles over the radius adopted from the physical models ($\sim$5000 AU) for timescales between 10^3–10^6 yrs from the species of interest (e.g. CO, HCO^+, CH_3OH), which one can directly compare with the empirical abundances obtained using RATRAN having adopted the same physical model. We find that the empirical abundance profiles for most species appear to match the modeled chemical abundances in the outer envelope and that they are systematically 1 to 2 orders of magnitude lower than in a prototypical high mass protostellar envelope (AFGL 2591; Kaźmierczak-Barthel et al. 2015). We attribute the observed differences to the higher temperatures around the hot cores and to the absence of the freeze-out zone as compared to the low mass protostars.

For some species the observed abundances deviate from the modeled abundances. The observed drop in the snowline of CO is only $\sim$2 orders of magnitude, compared to $\sim$6 orders of magnitude that the chemical models predict. The strong outflow activity and the winds that YSOs produce, result in a high velocity gas, but also the evacuation of regions near the protostar. These cavities that are associated with outflows, have been seen previously (e.g. near NGC 1333 IRAS4 and SVS13; Lefloch et al. 1998) and the UV radiation is expected to play a crucial role in such environments since it can penetrate to longer distances. We have simulated an outflow cavity by increasing the UV radiation that the observed species are exposed to. The observed CO abundance profile appears to be reproduced by UV= 10$\times$ISRF and A_V= 1 mag. This might be crucial in understanding the constant CO empirical abundance resulted in RATRAN even at temperatures as low as 10 K where CO is expected to be frozen out on grains and thus be less abundant. We find that this approach improves the fit among the theoretical abundance profiles and the observed ones. A more detailed 2D/3D chemical modeling that takes into account disk structure and outflow cavities is expected to be more accurate and it is in my future plans. Lastly, I used time dependent chemical models in order to constrain the age of NGC 1333 IRAS 4A ($>4\times>10^4$ yrs).

• **Future outlook**

For this thesis I worked on a variety of projects as described above, and contributed to providing answers to scientific questions in the field. During this process, not only some questions did not get answers but also new questions were raised.

An example of such a striking new question is: why do we observe such a large far-IR line deficit towards S 140 and could this source be a suitable template to understand the observed deficit in ULIRGs? Among my future scientific interests is modeling of S 140 using advanced PDR codes (e.g. KOSMA-tau) and obtaining (sub)-mm mapping observations covering all three infrared sources and the ionization front, in order to study the spatial distribution of more species. An example of such observations is the high–J transitions of CO using SOFIA. In addition, HCN maps of multiple transitions towards S 140 could help constraining the volume density n_{H_2} of the region. The long term goal of this project is to constrain a model that can have an application to the far-IR line deficit observed in ULIRGs.

Another scientific direction of interest, is to observationally constrain the missing link between prestellar cores and protostars, the so called first hydrostatic core (FHSC). A future project could be focused on a bigger sample of FHSC candidates from the literature and observe these at high angular resolution with interferometers (e.g. ALMA). The main questions to still be answered are: Is there a link between very low luminosity objects ($<$ 0.1 $L_\odot$; VeLLOs) and FHSCs? What is the deuteration and the outflow activity (if any) towards FHSC candidates? The predicted number of FHSCs in Perseus is one order of magnitude lower than the observed number. Could we exclude some of them as being misidentified, or does the theory needs to be improved regarding the accretion rate in the early phases of star formation? In addition I aim to constrain the physical structure of IRAS 4C using continuum observations and radiative transfer codes such as DUSTY.

Lastly, the development of 2D/3D chemical models which include a disk structure and outflow cavities from low and high mass protostellar objects is crucial to better constrain the abundance profiles observed in several sources (e.g. NGC 1333 IRAS 4A).