English summary

Multiple stars, that is two or more stars composing a gravitationally bound system, are common in the universe. Characteristics such as their varying brightness have lead to these stellar systems being given cultural importance in ancient cultures. They have also been of the subject of academic study, and with the advent of the telescope, our knowledge of these systems grew. With the expansion of our capacity to observe the universe, multiple stars have been found to be the cause of many interesting phenomena, from supernovae and planetary nebulae, to binary black hole mergers. Multiple stars have fueled our imagination, both in written and visual fiction, wondering what planets around these stellar systems would be like, and how multiple sunrises might appear. Recent observations of missions like Kepler have shown that planets can exist around multiple stars. The question of how these systems are formed rises from our curiosity and interest in figuring out what would lead to stable multiple stellar systems. Early theories proposed that one star would pull another star into its orbit, thus forming a binary stellar system. However, this idea had serious problems, such as the need for close proximity of a large number of stars, and the involvement of a third star. Understanding how stars form and evolve can help solve the question of the formation of multiple stars.

Based on observations and models, the process of star formation can be briefly sketched as follows. Rotating clouds of dense dust and gas can, under the right conditions, collapse to form protostars embedded deep within the core of the clouds. These embedded protostars drive strong narrow outflows, a signature of ongoing star formation. Rotation and the infall of material toward the star eventually lead to the formation of a flattened (rotating) structure, a disk, which is expected to form at some point in the early stages of star formation. The disk will be the eventual site of planet and comet formation. As the protostar evolves and grows, the material in the cloud core decreases both from accretion onto the protostar and the clearing effect of the outflow. When most of the surrounding material has been cleared, a single young star and planets, if any formed, remain. Observations of protostars, from the earliest embedded stages to the resulting young stars, show that multiple stars are common. This points to the fact that most stars are born as multiple stellar systems, and that our picture of star formation needs to be revised.

The fact that multiple stars are born has brought a myriad of questions regarding these systems. This thesis addresses several open questions relating to the formation and evolution of multiple protostellar systems, namely

1. When do disks form and what is their impact on the protostellar systems?
2. Do all stars in a multiple stellar system form at the same time?

3. What factors enhance or hinder the formation of multiple protostellar systems?
4. How do single and multiple stars compare in structure, both physically and chemically?

The first question is interesting since disks are not only the eventual site of planet and comet formation, but can also play a role in forming multiple stars in the early stages of the star formation process. The next two questions deal with the way multiple star form. Fragmentation, the process of material break-up in the star forming cloud core, is widely considered as the main formation mechanism of multiple stars. But it is not yet clear when and what factors lead to fragmentation and the eventual formation of a multiple protostellar system, and how it could affect their evolution. The fourth question aims to understand whether single and multiple stars have differences in their structure, and if they are product of multiplicity or some other process.

With the objective to address these questions, observations of molecules and dust emission are combined with physical and chemical models to describe the structure of the observed protostars. Dust emission traces the location of the protostar, and can help determine the stage of formation of the protostar. Molecules are important since they can trace the kinematics, function as temperature and density meters, and reveal the chemical structure of the observed protostars. Chemistry can be a powerful tool to understand the processes in the universe.

This thesis

Chapter 1 of this thesis gives a detailed introduction to our current understanding of star formation, both of single and multiple stars. The observations presented in this work span from millimeter to near-infrared wavelengths, and were obtained with ground and space-based telescopes. The Atacama Large Millimeter/submillimeter Array, also known as ALMA, is a radio interferometer located in the Chajnantor plateau, Atacama desert, Chile, and was used to observe the chemical and physical structure of multiple protostars at scales of 100 astronomical units (1 astronomical unit is the distance from the Earth to the Sun). The Atacama Pathfinder EXperiment (APEX), located near ALMA, is a single-dish radio telescope and was used to probe protostars at scales of the cloud cores (1000 astronomical units). Archival photometric maps from the Herschel Space Observatory and the Spitzer Space Telescope were used in this work as well.

Chapter 2 addresses the question of when disks form. For this purpose, a very young embedded protostellar system, VLA 1623-2417, is studied. VLA 1623-2417 is a triple protostellar system located in the heart of ρ Ophiuchus (distance = 391 light-years). The three components show different characteristics, most likely product of being at different evolutionary stages. One of the components, VLA 1623-2417 A, presents a flattened disk-like structure both in dust and molecular line emission. Studying the kinematics traced by the molecule $C^{18}O$ with a simple model indicates that the emission is indeed tracing a rotating disk, with a radius of about 150 astronomical units, five times the radius of Neptune's orbit. Given that VLA 1623-2417 A is a very young, deeply embedded, protostar, finding a rotating disk around this source evidences that these structures can form very early in the star formation process.

Rotating disks can form in the early stages of star formation, as described in Chapter 2, thus their presence must impact the evolution of the protostar in some manner. This question is addressed in Chapter 3, by studying the material surrounding the rotating disk of VLA 1623-2417 A. For this purpose, molecules typically associated with the cold material in the cloud core of protostars are studied. The molecule DCO^+ is used to trace the cold material of VLA 1623-2417 A, since this molecule is mainly formed at temperatures of 20 K or below. Combining the observations with a simple chemical model can help to analyze the DCO^+ emission. The position of the observed DCO^+ emission is found to be closer to the source than expected from a spherically symmetric density and temperature structure, that is if the protostar were heating up the surrounding material equally in all directions. Instead, the DCO^+ emission is observed to be closer to the protostar along the rotating disk, but not along the direction of the outflow. The reason for this is that the disk causes a drop in temperature at its edge because it is shadowing the material from heating by the protostar. This indicates that the presence of a disk has a significant impact on the surrounding material, by altering both its temperature and chemical structure.

The physico-chemical structure of embedded protostars is further studied in Chapter 4, using molecules that trace the cold and warm gas of protostellar cloud cores. Two multiple protostellar systems, IRAS 16293-2422 and VLA 1623-2422, are studied. Both protostellar systems are located in ρ Ophiuchus and are deeply embedded in their natal cloud core. IRAS 16293-2422 is a very bright protostellar binary, while VLA 1623-2417 is a dimmer triple protostellar system studied in Chapters 2 and 3. VLA 1623-2417 A has been found to have a rotating disk (Chapter 2), while IRAS 16293-2422 A presents a large, flattened disk-like structure with a radius of about 200 astronomical units. The other sources in each system have no confirmed disk(-like) structure. The cold gas is traced by the molecules DCO^+, N_2H^+ and N_2D^+, which form at temperatures below 20 K and thus characterize cold regions. For warm environments with temperature of 50 to 100 K or UV-irradiated by the central protostar, the molecules $c{-}C_3H_2$ and C_2H are good tracers. The cold molecules are found to be located closer to the source in both systems due to the presence of the disk(-like) structure, but not along any other direction. For VLA 1623-2417, N_2H^+ or N_2D^+ are not observed, most likely due to the low brightness of the protostar, and the very low temperatures (below 10 K) caused by the disk which shadows the material. This agrees with the results of Chapter 3. The warm molecule $c{-}C_3H_2$ traces the outflow cavity in both systems, consistent with the presence of this molecule in warm and UV-irradiated environments. The molecules $c{-}C_3H_2$ and C_2H tend to trace the same region. This is true for VLA 1623-2417, but not for IRAS 16293-2422. It is interesting to note that the multiplicity of these systems does not seem to have a significant impact in the chemical structure, however this needs to be explored further.

Chapter 5 examines the question if all stars in a multiple stellar system form at the same time. In order to answer this question, embedded protostars are studied, rather than protostars in later stages of the star formation process. This is because embedded protostars have the conditions of formation almost intact, while protostars in the later stages have undergone considerable evolution. However, this also poses a problem. The ages of embedded protostars are almost impossible to determine with certainty. On the other hand, the evolutionary stage of a protostar, its “age" in a way, is determined by the distribution of their brightness with respect to wavelength, also termed a spectral energy distribution (SED). During the embedded stage, the brightness of a protostar is mostly concentrated at long wavelengths due to the dust cocoon in which the protostar is formed. As the protostar evolves, the cloud core disperses and the brightness of the protostar progressively shifts to shorter wavelengths, and as it becomes a hydrogen-burning star its brightness peaks in the visible regime. Thus, the evolutionary stage of a protostar relative to its siblings in a multiple protostellar system is used to determine whether all the protostars in the system formed at the same time or at different moments. The SEDs for all the identified protostellar systems in the Perseus molecular cloud (distance = 750 light-years) are constructed using data from literature and archival photometric maps from the Herschel Space Observatory. For multiple protostellar systems, the SEDs of the individaul components can only be disentangled for separations between the protostars of 1600 astronomical units, due to the resolution of the Herschel Space Observatory observations. The orientation of the protostar with respect to the line of sight can impact the constructed SED, since a protostar viewed along its outflow will appear older than it may actually be, since no envelope would be detected. Thus to determine whether the protostars within multiple systems are formed simultaneously or not, the orientation of the protostar, its physical structure and the SED are taken into consideration. The results of this study find that one-third of the time, the components of multiple protostellar systems are not formed at the same time. In other words, some cloud cores continue forming protostars even after one or two have formed, while others do not. This provides important information for theory and models of multiple star formation, and at the same time, leads to the question of what factors cause some multiple protostellar systems to continue forming protostars.

Chapter 6 examines one of the possible factors that can influence multiple star formation: temperature. Models that include the heating of the gas and dust by the central protostar suggest that once a protostar is formed, the heated gas and dust does not generally fragment further. However, the results from Chapter 5 suggest that there are other factors that influence fragmentation and the formation of multiple stars. To address whether there is a temperature-fragmentation relation or not, the gas and dust at scales of 1000 astronomical units is investigated. Single-dish observations with APEX are used to observe molecules that are good thermometers, such as DCO^+ and H_2CO, as well as molecules that trace regions irradiated by the protostar, such as $c-C_3H_2$ and C_2H. These molecules are observed toward a selected sample of protostellar systems in the Perseus molecular cloud which includes single and multiple systems. Including both types of systems allows the comparison of conditions in single and multiple stars, which can help determine whether temperature is a key element in multiple star formation. The observations, and derived temperature measurements from the observed molecules, show that there is no clear relation between temperature and multiple or single stars. In fact, the only observed difference is that multiple stellar systems have large cold gas reservoirs compared to single protostars. These findings suggest that mass and density, rather than temperature, play a role in fragmentation, and consequently, the formation of multiple protostellar systems.

Conclusions

The results from this thesis contribute useful pieces to the puzzle of multiple star formation, and are briefly summarized here. Large disks can form in the early stages of star formation, and they can impact the physicochemical structure of protostars. This is important for star formation in general, since it changes our view of the process of protostellar evolution. But in addition, both of these factors, disks and the physicochemical structure, can influence the formation of multiple protostellar systems, since they provide ingredients for fragmentation. Not all protostars in a multiple protostellar system form at the same time. This indicates that in some cases, the conditions in the cloud core are appropriate for further fragmentation. These conditions, however, are not associated with temperature and instead could be related to mass and density.

The results of this thesis provide a step forward in understanding the formation of multiple protostars, but additional research is needed. For example, it would be interesting to find out if the results found for the Perseus molecular cloud also apply to other star forming regions. Our understanding of the process of star formation needs to be revised to include the formation of multiple stars, since they are the most common outcome of star formation. Models and theory should be revised with the results of observations, and the predictions that come out of these models can then provide direction for our observations.