The infrared spectrum of massive protostars: circumstellar disks and high mass star formation

Barr, A.G.

English Summary

Stars are born in dense clouds of gas and dust in the interstellar medium. With the formation of stars, comes also the formation of planetary systems. Out of the thousands of planets already discovered, the Earth appears to be unique. It is a planet that possesses the ideal conditions for the sustainment of life. To understand whether the Earth is truly unique, or just very rare, a proper understanding of the star formation process is necessary.

The star formation process occurs over timescales of millions of years. Thus, over the course of a single human lifetime, we will only observe forming stars as snapshots in their evolution. By comparing many different objects, and assuming that all stars form the same way, we can piece together an evolutionary sequence. The clouds which stars are born in are so dense that they are invisible to optical light (the wavelengths visible to the human eye). Therefore to look into them we must switch to longer wavelength light, in particular infrared and sub-millimetre (sub-mm). Hence the use of telescope facilities such as the Stratospheric Observatory for Infrared Astronomy (SOFIA) and the Atacama Large Millimetre Array (ALMA), which allow us to look through the dust extinction of dense clouds. The difference between optical and infrared images is illustrated in Figure 5.27.

One particular tool in the astronomer's toolbox is the emission and absorption of light by molecules. A certain molecule will emit or absorb light at a unique combination of discreet frequencies, called lines. In this way, a molecule owns its own molecular fingerprint (see Figure 1.6 of this thesis). Using high enough spectral resolution, we can separate all of these emission and absorption features, and derive information such as temperatures, velocities and chemical abundances. The chemical abundance allows us to determine how much of a molecule is present with respect to another. Thus we can extract information about the chemical process which led to the observed abundances. Most of the molecules in star forming regions consist of hydrogen, carbon, oxygen and nitrogen, and the relevant molecules to this thesis are carbon monoxide (CO), carbon monosulfide (CS), water (H_2O), hydrogen cyanide (HCN), acetylene (C_2H_2) and ammomia (NH_3).

Stars can be split into two groups, based on their mass: low mass stars (stars with mass less than 8 $M_\odot$) and high mass stars (stars with mass greater than 8 $M_\odot$). These two groups have similar formation routes, but there are important differences. For one, massive stars have not been observed to have planets around them, likely reflecting the extreme environment of these stars. Massive stars are arguably more important than low mass stars on cosmic scales. They influence the heating and

Figure 5.27: The Taurus Molecular cloud observed at two different wavelengths. The image on the left is taken in the visible part of the spectrum, and the image on the right is what the same cloud looks like at a wavelength of one millimetre. The cloud looks dark to us, however at longer wavelengths, we see that there is much more going on. Forming stars can be seen as bright dots in the right hand panel. Credit: ESO/APEX (MPIfR/ESO/OSO)/A. Hacar et al./Digitized Sky Survey 2. Acknowledgment: Davide De Martin.

cooling of galaxies, stimulate the production of new stars, and are the main producers of many of the elements heavier than carbon.

An important stage in the low mass star formation process is the disk phase. Here material can accrete onto the protostar via a disk which surrounds the star, thus it increases in mass and continues to grow. The disk is a consequence of the conservation of angular momentum, as rotating, infalling material spreads out in a flattened structure around the star, such as that shown in Figure 5.28. Large outflows and winds perpendicular to the disk also form as material is ejected from the star-disk system. Thus the cloud surrounding the star begins to be dispersed. It is still highly contested if disks are as important in the formation of high mass stars as they are for low mass stars. Theory predicts the need for disks in making massive stars, as some mechanism is required for material to overcome the large outward pressure so the star can continue to grow. A disk is the natural solution, however detections of disks around high mass stars are very rare, especially for the more massive stars.

This Thesis

Using unique observations, this thesis has discussed the formation of massive stars, focusing on the details at small scales. The results of the first spectral survey of the 3-13 μm region of two massive protostars, AFGL 2591 and AFGL 2136, was presented. These data were obtained from the Stratospheric Observatory for Infrared Astronomy (SOFIA) observations as well as the Infrared Telescope Facility (IRTF) and Gemini

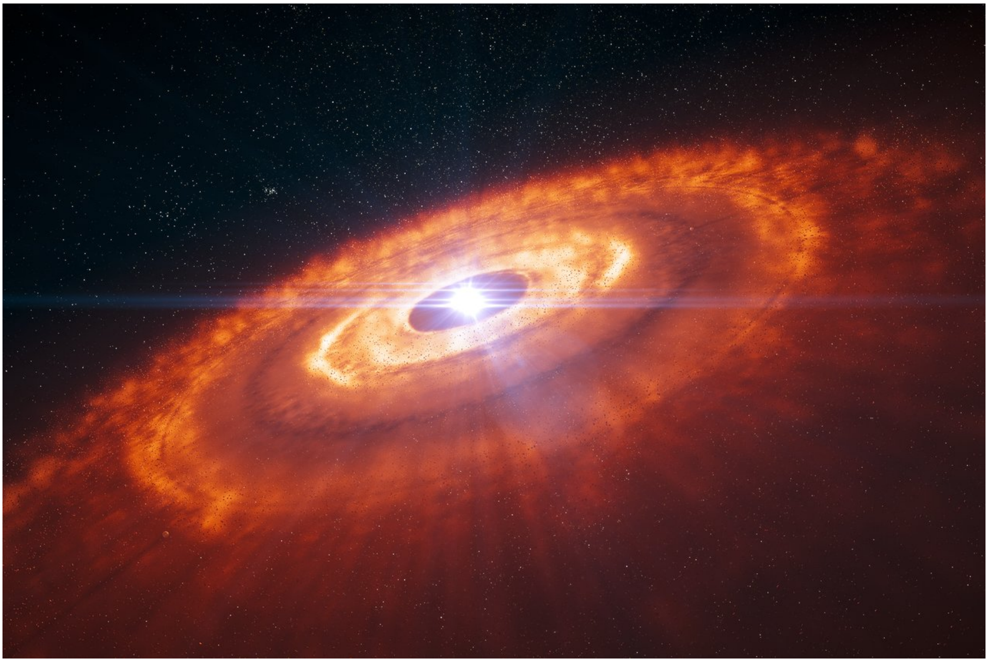

Figure 5.28: Artist's impression of a circumstellar disk around a forming star. Credit: ESO/L. Calcada

telescopes. Our results address the production of important organic molecules in the disks of massive stars, as well as the temperature structure of the disk.

Chapter 2 revealed the difference in physical conditions between large and small scales in the sites of star formation, with observations of the CS molecule in AFGL 2591. Pre-ALMA observations at sub-mm wavelengths were unable to distinguish the disk region of massive protostars from the cloud region. However absorption studies at infrared wavelengths naturally probe very small scales. Thus much hotter and denser gas is observed at infrared wavelengths compared to previous sub-mm studies. The amount of sulphur-bearing molecules observed in dense regions of the galaxy are lower than what is expected. Our detected abundance of CS was very high, suggesting that a large reservoir of warm sulphur-bearing molecules is present very close to the star, and previously unobserved. Hot gas of 700 K is observed in CS, indicating that this gas is likely produced via the high temperature chemistry in a disk atmosphere.

In chapters 3 and 4, we dug deeper into the more important questions with regards to massive star formation. Here we presented a model to explain the observation of absorption lines in a circumstellar disk. This model can account for a range of observational constraints derived from several molecules in AFGL 2591 and AFGL 2136: HCN, C_2H_2, CS, CO, NH_3 and H_2O. Such line formation requires a temperature gradient which increases towards the mid-plane of the disk. Subsequently, such a temperature gradient requires that the heating of the disk is dominated by viscous process in the mid-plane, rather than heating from stellar radiation. These processes lead to accretion of material onto the star, and allow for the star to grow larger. Several observational constraints are worth mentioning, as they raise important points of attention in the model. The abundance of HCN and C_2H_2 vary with wavelength, implying that these species are concentrated towards the inner 200 AU of the disk. Vibrationally excited bands of CO and C_2H_2 give results that require densities $> 10^{10}$ cm^{-3}. The abundances of all molecules are consistent with what is expected from chemical models of disks. Finally, the H_2O absorption lines are saturated, but do not go to zero flux, as normally occurs. This behaviour is a direct prediction of our disk model.

Chapter 5 addressed the 3 μm spectrum for a range of massive protostars. We found that at this wavelength, MonR2 IRS 3 showed HCN lines in emission. The gas was hot with a temperature of 500 K. This emission was consistent either with an expanding shell of gas, or the atmosphere of a circumstellar disk. HCN and C_2H_2 lines were detected towards AFGL 2136 in absorption. The results for these molecules, combined with chapters 3 and 4, were strongly supportive of the disk model. An alternative to the disk model is that the gas lies close to the star but not in a disk. In order for this model to work, H_2O gas must be more extended than HCN and C_2H_2 gas. This appeared very unlikely however, as H_2O is more easily produced. The disk model was the preferred model as it more realistically fits in with all of the observed observational constraints.

Future Outlook

The detection of hundreds of lines in the infrared has great potential for identifying and studying disks in massive protostars. Extending these kinds of studies to more objects will be fundamental for opening this field further. New larger and better telescopes that will soon be available for this are the James Webb Space Telescope (JWST) and Extremely Large Telescope (ELT). This thesis will be vital to guiding studies with JWST which will not be able to take high spectral resolution observations. JWST will allow the opportunity to study low mass objects at infrared wavelengths due to the high power. Therefore we will be able to determine if absorption lines are common in low mass protostars in the earliest stages of formation.

Also of great importance is the development of theoretical models. Currently models do not exist which treat a circumstellar disk heated from the inside. These are vital for a deeper understanding, and more realistic picture, of the disks discussed in this thesis. Such models would also have to include chemistry, as different physical processes may be required to initiate the formation of molecules.