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Organic chemistry around young high-mass stars

Allen, Veronica Amber

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Chapter 6

Conclusions and Outlook

6.1 Summary and conclusions

Throughout this thesis we have focused on understanding the chemistry surrounding young high-mass stars. Using sub-millimeter observations and chemical modeling we related the chemical composition of several young stars to their evolutionary states and investigated the formation of high-mass stars through disks. We also worked to understand the formation of the prebiotic molecule formamide (NH_2CHO) and the importance of grain-surface and gas-phase processes using observational tests.

In **Chapter 2**, we study the hot cores in the two high-mass star-forming regions G35.20-0.74N (G35.20) and G35.03+0.35 (G35.03). It has previously been established that these sources contain candidates for high-mass Keplerian disks (Sánchez-Monge et al. 2013a). Through chemical and spectral analysis, we found chemical differentiation within the disk candidate G35.20 B where the continuum peak associated with the southeastern side (B3) shows enhanced complex cyanide abundances compared to the northwestern side (B2). This chemical difference implies that there are multiple sources within G35.20 B and that this sort of circum-multiple disk will be a complex structure under higher resolution observations. Additionally, we observe that, although the chemical composition of the hot cores in G35.20 and G35.03 are very similar, we do not detect deuterated species in G35.03 A whereas there are deuterium fractions of 5-20% in G35.20 A and B. We conclude that G35.03 A is likely to be an older source as a high deuterium fraction is a sign of relative youth.

In **Chapter 3**, we seek to understand the chemical differences seen in G35.20 B (described in **Chapter 2**). We test various parameters of a time-dependent chemical model in an attempt to replicate the observed abundances of the different continuum peaks. After determining that the main constraint on fitting the abundances of B3 was the model abundance of vinyl and ethyl cyanide (CH_2CHCN and C_2H_5CN, respectively), we found that we could not increase the abundances of these species through changes in density, initial temperature, longer periods at a high temperature, or initial ice composition. The only parameter that significantly changed the abundances of the complex cyanides was the cosmic-ray ionization rate. By increasing the value to resemble the average observed value (Indriolo et. al 2015) we can reproduce the abundances observed across G35.20 B and the ages obtained in that model show that the age difference between the sources within G35.20 B is only $\sim$2000 years.

In **Chapter 4**, we study the outflows associated with G35.20 and G35.03 in order to test the hypothesis of the presence of a Keplerian disk and constrain the number of sources withing G35.20 B. If outflows are observed to be approximately perpendicular to the rotation of the disk, this is strong evidence for a disk-outflow system that is expected at this stage of star formation. We observe millimeter-wave transitions of SiO, HCO^+, and $H^{13}CO^+$, commonly used tracers of outflow activity and shocks, and determine the basic mechanical parameters of the outflow emission. The observations indicate that there could be two components to the outflow detected using HCO^+ in G35.20 one of which is perpendicular to the observed rotation in G35.20 B. These appear to be associated with the two radio continuum sources within the proposed disk implying that this is a multiple system with a large (>2000 AU) disk surrounding it where at least two sources are driving outflows. The emission associated with G35.03 is less clearly associated with the hot core but there appear to be multiple outflows with an unclear orientation.

In **Chapter 5**, we investigate the much-debated formation mechanism of interstellar formamide through observations of several young O-type stars. These very high-mass (>20 $M_\odot$) sources strongly effect their surroundings with high-energy photons, high temperatures, and strong stellar winds making a unique laboratory for studying whether grain-surface or gas-phase processes are more important in forming this species. We analyzed high-resolution spectral line images of formamide and its two potential precursors (HNCO and H_2CO) and found that for most of our sources the emission of neither precursor was consistently more similar to that of formamide. For two of the six sub-sources, the emission peak position, velocity structure, and velocity dispersion maps of HNCO were closer to formamide than those of H_2CO. This implies that the conditions in these two sources support the formation of formamide on the grain-surface over the formation in the gas.

In the greater context of high-mass star formation, G35.20 B continues to be a strong candidate for a high-mass Keplerian disk surrounding a young multiple system. Despite the chemical difference within the system (**Chapter 2**), the detection of a two-component outflow (**Chapter 4**) and the small age difference between the sub-sources (**Chapter 3**) is strong evidence for the disk. Based on the age of this system from our chemical models (**Chapter 3**), this is still a very young system ($\sim$20,000 years since the beginning of the warm up phase) where the stars are not likely to have reached the main sequence. The G35.03 system is harder to understand, but there are many signs that it is a later stage than G35.20. While it still shows hot core chemistry, the lack of deuterated species and the uncollimated outflows show that this source is approaching the end of the hot core stage.

6.2 Future Outlook

For G35.20 B, higher spatial resolution observations would solidly confirm the presence of a Keplerian disk or show multiple fragments which appear to be coherently rotating at a lower resolution. Observations of the cosmic-ray ionization rate in G35.20 would constrain that parameter in chemical models and show whether this is the right approach to reproducing the abundances observed in this source.

With regards to chemical modeling, a full 2D model of G35.20 B and a full map spectral analysis to complement it would help in understanding how a multiple system affects the chemistry of its surroundings. Further laboratory experiments need to be done to fill out the gas-phase formation network of ethyl cyanide, as the chemical networks are currently incomplete.

To further our studies of the formation of formamide, a dedicated survey of different types of environment observing several transitions of each species needs to be performed in order to determine whether the dominant formation route is environment dependent. It is possible that each pathway is more dominant in different environments. Observing isotopologues wherever possible will help with any optical depth issues that may arise in these regions.

In the future, it would be beneficial to analyze other chemically rich young stars in a similar manner to our analysis of G35.20. By finding multiple disk/outflow systems, we gather evidence about whether high-mass stars form in a way similar to low-mass stars. By determining the chemical composition of young high-mass stars and comparing this to models we can approximate ages for them and determine how their physical characteristics change over time.