THE CHEMISTRY OF DARK CLOUDS: NEW ASTROCHEMICAL TOOLS FOR STAR FORMATION STUDIES

Edwin A. Bergin

Harvard Smithsonian Center for Astrophysics, 60 Garden St., Cambridge MA 02138

Abstract

The past decade has led to significant improvements in our understanding of the physical structure of the molecular cores of cold dark clouds. Observational efforts, in combination with improved knowledge of cloud structure, now provide clear evidence that the chemistry of dark clouds is dominated by the depletion of gaseous species onto grain surfaces. We outline the basis of these observational efforts and show how the abundance determinations have moved beyond single point analyses to the derivation of abundance profiles. We discuss the basic physics of the interaction between molecules and grain surfaces and show that when physics is coupled into a chemical model there is excellent agreement, for a limited set of species, between theory and observations. We discuss our improved understanding of cloud chemistry can be used as a new tool for studies of the formation of stars and planetary systems.

Key words: astrochemistry – ISM: molecules – ISM: globules – ISM: clouds – stars: formation

1. Introduction

The formation of dense molecular condensations, and eventually stars, involves large changes in the physical properties of the atomic and molecular gas. These changes also have very specific consequences on the chemical interactions of the gas and dust inside the forming cores/stars. In particular as the density increases molecules in the gas phase collide with dust grains with greater frequency and, if the molecules stick with any reasonable efficiency, they will deplete from the gas phase. Thus, the density gradient that results from core condensation is accompanied by chemical gradients, with the inner parts of the core representing high density chemistry (with freeze-out onto grains), and the outer parts representing the original low density molecular composition. Indeed, these molecular depletions have been suggested as the primary chemical indicator of the earliest stages of the star formation process (Mundy & McMullin 1997; Bergin & Langer 1997). Such chemical structure should be particularly evident in dark clouds because the low temperatures ($\leq 10$ K) preclude thermal evaporation of the molecules frozen in the mantle.

The process of star formation is by nature a dynamic one and molecular emission is the primary method for obtaining information on kinematic motions inside molecular clouds. Extensive efforts have been placed towards using molecular tracers, typically CS and HCO$^+$, to search for the presence of star-forming infall due to gravitational collapse (see Evans 1999; Myers, Evans, & Ohashi 2000 and references therein). The freeze-out of molecules onto grain surfaces significantly reduces the effectiveness of using molecular emission as a tracer of motions. Indeed the inside-out collapse models of Shu (1977) predict that the highest infall speeds are found in the exact regions where molecules are expected to freeze-out.

Despite these arguments it is only recently that detections of gas phase freeze-out have become commonplace. Until recently inherent difficulties in extracting molecular abundances from gas phase emission prevented definitive detections of gas-phase freeze-out. Previous studies assumed local thermodynamic equilibrium (LTE) to estimate total column densities. However, molecular emission from tracers with high dipole moments is far from LTE. In addition, secondary tracers such as CO and its isotopic variants were previously used to estimate the total H$_2$ column density, since it cannot be observed directly. It is now known that depletion of CO in cold regions seriously hampers its utility as an estimator of the total hydrogen column density.

The recent advent of sensitive continuum and heterodyne arrays probing millimeter/sub-millimeter wavelengths, along with wide-field infrared imaging devices, has led to an explosion of clear detections of gas phase depletion/freeze-out (Bacmann et al. 2002; Bergin et al. 2002, Tafalla et al. 2002, Hotzel et al. 2002, Caselli et
al. 2002, Jessop & Ward-Thompson 2001, Kramer et al. 1999, Alves et al. 1999). At this conference alone there are 8 contributions discussing gas-phase depletions (Carey et al., Di Francesco et al., Feldman et al., Savva et al., Kontinen et al., Lai et al., Lee et al., and Peng et al., this volume). Observations of dust in emission or absorption provide direct knowledge of the dust distribution. In addition, since the dust column density and mass is correlated with the H$_2$ column density and mass (Hildebrand 1983; Gordon 1995), these observations provide the clearest information to date on the spatial distribution of H$_2$ molecules. Furthermore, with some geometrical assumptions, the radial profiles of core density can be constructed; these methods have greatly increased our knowledge of the physical conditions throughout the star formation process (Andr´e et al. 2000, Alves, Lada, & Lada 2001). Knowledge of the density and column density distribution of H$_2$ also significantly aids the molecular observations in two ways. (1) By indirectly confirming the location of the H$_2$ density and column density peak and, (2) by providing the density profile which helps to unravel the similar effects of density and abundance on excitation. These advances have moved chemical analyses beyond surveys of objects that show evidence for complicated chemistry (e.g. TMC-1, L134N) towards studies of more centrally concentrated objects that are closer to collapse and star formation.

In this concise review we outline how combined studies of dust emission/absorption with molecular emission have improved our ability to estimate molecular abundances and, in consequence, how our picture of dark cloud chemistry has been changed to one dominated by the effects of freeze-out. In the following (§§2 & 3) we briefly outline our current theoretical understanding of gas-grain interactions. Furthermore we discuss key observational efforts that demonstrate the systematic nature of gas-phase freeze-out in condensed cores and how these observations can be qualitatively understood by a coupling of gas-grain chemical models to sophisticated radiative transfer models. In §4 we discuss how our improved understanding opens the door towards using astrochemistry as a new and potent tool to study the process of star formation.

2. Gas-Phase Freeze-Out: Theory

The rate of deposition of a molecule in the gas phase onto a grain surface is

\[ k_{\text{freeze-out}} = \pi a^2 \tau S n_{gr} \]  

where $a$ is the grain radius, $\tau$ is the mean thermal velocity, $S$ is the sticking coefficient, and $n_{gr}$ the space density of grains. If we use “classical” grains with $a = 1000$ Å and $n_{gr} = 1.3 \times 10^{-12} n(H_2) \text{ cm}^{-3}$ (Spitzer 1978), then the timescale for a molecule to freeze-out onto a grain surface is:

\[ \tau_{\text{freeze-out}} \approx \frac{2 \times 10^9 \text{ yr}}{S m n(H_2)} \]  

where $m$ is the molecular weight and $S$ is the sticking coefficient. CO is a typical tracer of molecular cores which have typical densities of $n(H_2) \sim 10^{5} \text{ cm}^{-3}$ (Evans 1999). For a sticking coefficient of unity the freeze-out timescale is $< 10^4$ year, well above the estimated time for thermal evaporation ($\gg 10^8$ yr), but below estimated ages of $\sim 1 - 10 \text{ Myr}$ (Palla and Stahler 2000; Hartmann 2001; Lee and Myers 1999). Thus it is surprising that a gas-phase is observed at all, instead the near total freeze-out of the gas phase would be expected (e.g. Iglesias 1977). This points to the existence of some non-thermal mechanism to desorb or remove molecules from the grains and allow for the observed active gas phase chemistry.

Various mechanisms have been identified, including spot heating due to cosmic-ray or X-ray impacts, chemical desorption, and others. The reader is referred to Williams (1993) for more detailed discussion. The strength of the molecule bond to the grain surface is a key parameter that determines the efficiency of evaporation. Because low temperatures preclude the breaking of chemical bonds, molecules are not expected to be chemically bound to grain surfaces. Instead the approaching molecule has an induced dipole interaction with the grain surface and mante and is bound through weaker Van der Waals-London interactions called physical adsorption (Kittel 1996). Van der Waals interactions are proportional to the product of the polarizabilities of the molecule and the nearby surface species ($E_b \propto \alpha_{\text{mol}} \alpha_{\text{surface}}$). Because of this property some species are more tightly bound to the grain surface than others. For example CS is expected to be more tightly bound to the grain surface than CO or N$_2$. In addition, theoretical analysis has suggested that N$_2$ has a weaker bond to a water ice surface than CO (Sadlej et al. 1995).

Models which have achieved the best success in reproducing observations are those that incorporate these assumptions regarding bond strengths, resulting in a desorption process that preferentially removes more weakly bound species (Bergin & Langer 1997; Charnley 1997; Nejad & Wagenblast 1999; Aikawa et al. 2001; Li et al. 2002). As a sample in Figure 1 we provide chemical abundances as a function of time for a cloud with a centrally concentrated density profile. This result uses the model for B68
discussed by Bergin et al. (2002) where the density profile is that for a Bonnor-Ebert sphere near-equilibrium that is kept constant with time as the chemistry evolves. This is a simplification as more realistic models couple the physical and chemical evolution (Bergin & Langer 1997). One byproduct of CO depletion is an increase in the DCO$^+$/$\text{HCO}^+$ ratio (see Aikawa et al. 2001; Caselli et al 2002; Caselli 2002 for further discussion). In the following section we show that the pattern of differential depletions – early CS depletion, followed by CO, and finally $\text{N}_2$ – is observed in numerous sources. Similar effects would be observed in any model that incorporates these particular assumptions with regards to the gas-grain physics and evolves to a centrally concentrated state.

3. Gas-Phase Freeze-Out: Observations

Combined gas/dust investigations have resulted in the development of a new method to derive molecular abundances. This method derives abundance profiles as a function of radius, as opposed to a line of sight average. More specifically, the observed core density profile from the dust observations is used as an input to one-dimensional (1D) radiative transfer codes (Monte-Carlo is generally used; e.g. Bernes 1979; Hogerheijde and van der Tak 2000). The temperature profile is another parameter that is constrained by dust thermal emission or by multi-transitional studies of molecular emission. Variables are the abundance profile and velocity structure (both bulk and turbulent). With these constraints, and iterating over the variables, the radiative transfer model predicts the radial profile of emission which can then be compared in detail to the observations. This technique has been outlined by van Dishoeck and Hogerheijde (1999) and applications can be found in van der Tak et al. (2000), Tafalla et al. (2002), Bergin et al. (2002), and Lee et al. (2002).

Below we discuss some recent investigations that highlight: (1) the observed depletions are differential in nature and are systemic in the dense ISM (Tafalla et al. 2002) and (2) current gas-grain chemical models are capable of qualitatively matching observations of a limited set of key species (Bergin et al. 2002).

3.1. Tafalla et al. 2002

In the top panels of Figure 2 we show integrated molecular emission maps of the centrally concentrated molecular core L1517B for sample species with a map of the 1.2 mm continuum emission (Tafalla et al. 2002). The notable feature in this figure is the lack of correlation between the 1.2 mm continuum – a tracer of $\text{H}_2$ – with $\text{C}^{18}\text{O}$ and CS emission; where the continuum peaks the molecular emission exhibit local minima. In contrast, the $\text{N}_2\text{H}^+$ emission peak is coincident with the continuum emission maximum. An analysis of these data using the physical description of the source given by the dust continuum emission is shown in the lower panels (Tafalla et al. 2002). Here the radial profiles of emission (solid

Figure 1. Left panels: Chemical abundances of select tracers as a function of cloud depth ($A_V = 1$ to 17 mag) from a t-dependent model sampled at $t = 2 \times 10^4$ yr. Right panels: same except for $t = 7 \times 10^4$ yr. The top axis on left and right sides show the density that corresponds to extinction on the lower x-axis. The model shown is representative for the evolution of the chemistry in an object that is centrally concentrated such that the highest densities are present at the greatest extinctions. This gives rise to the observed chemical structure as the depletion rate increases with density.
Figure 2. Top panels: Maps of 1.2mm continuum, C$^{18}$O(1-0), C$^{17}$O(1-0), N$_2$H$^+$(1-0), and CS(2-1) emission in L1517B. Bottom panels: Radial profiles of continuum and integrated emissions. Observations are indicated by solid squares while the lines are results from models of the radiative transfer for two abundance profiles. The solid red lines are constant abundance models while the blue lines represent models with a rapid decrease in the central abundance. Taken from Tafalla et al. (2002).

squares) are compared to model predictions. Models that assume constant abundance are shown as solid red lines; these models predict excess emission at the core center for the CO isotopes and CS. To reach agreement with observations the abundances of these species must be sharply reduced in the densest regions of the core (models shown as solid blue lines) – presumably through freeze-out. Constant abundance models provide a reasonable match for N$_2$H$^+$, while NH$_3$ requires a slight abundance increase towards the center.

Tafalla et al. also compare the observations directly to the chemical models of Bergin & Langer (1997), finding good agreement to models of fast-collapse. Most significantly similar results are found for all 5 cores examined in this work, as well as in sources observed by other studies (Kuiper, Langer, & Velusamy 1996; Ohashi et al. 1999; Lee et al. 2002; Bergin et al. 2002). This demonstrates the systematic nature of depletions – they are observed in nearly all centrally concentrated low mass cores. Thus differential depletions in cold dark clouds must be a chemical signature of the earliest stages of star formation.

3.2. BERGIN ET AL. 2002: B68

The dark cloud B68 is another example of a centrally concentrated object that exhibits emission features which are attributed to gas phase freeze-out. In this core the H$_2$ distribution is traced through a map of dust visual extinction (A$_V$) derived via near-infrared extinction mapping techniques (e.g. Alves, Lada, and Lada 2001). In Figure 3 we present the B68 A$_V$ map along with a series of molecular emission maps. In this core we see that the N$_2$H$^+$ emission peaks in a shell partially surrounding the peak of dust extinction. Moreover, the N$_2$H$^+$ peaks inside the much larger C$^{18}$O emission hole, which itself lies inside the CS emission depression. Analysis of these data differed from Tafalla et al. (2002) in that a gas-grain chemical model is directly linked to a radiative transfer model predicting the profile of integration emission. This allows for chemical considerations to determine how the abundance is structured with depth. For example, photodissociation limits the abundance at cloud edges and the competition between depletion and desorption determines how the abundance declines with density.
Figure 3. The observed emission distribution of visual extinction or total column density (color/gray scale) in the B68 dark cloud. Contours are integrated emission maps of $^{18}$CO (left-hand panel), N$_2$H$^+$ (middle), and CS (right-hand panel). These observed emission distributions show a sequence of increasing molecular depletion from CS, to $^{18}$CO, and even N$_2$H$^+$ (Bergin et al. 2002; Lada et al. 2002).

Figure 4 presents an analysis of the N$_2$H$^+$ and $^{18}$CO emission; in this case the open squares show the integrated emission as function of visual extinction. This particular representation of the data is independent of cloud geometry, depending only on physical variables. Furthermore, if the emission is in LTE and optically thin the integrated emission from a source with constant abundance would appear as a straight line in this diagram (e.g. Frerking et al. 1982; Lada et al. 1994). Clearly the $^{18}$CO-A$_V$ relation deviates from a straight line at high extinctions. Such structure in this relation could be due to freeze-out or high opacities. To discriminate between these possibilities, observations of a lesser abundant isotope are typically needed (and in this case confirm freeze-out). The dashed line is the “best fit” radial abundance profile predicted in the chemical model and the solid line is the resulting emission profile. For $^{18}$O the observations require significant freeze-out and also an abundance reduction at low extinction due to photodissociation. In the case of N$_2$H$^+$ an abundance reduction at low extinction is required, but only a small decrease in abundance at high A$_V$ is needed to match observations.

In Figure 5 we present a more qualitative comparison of the structure predicted by the chemical models to the B68 data. Here the left-hand panel represents the peak contours predicted by a spherical radiative transfer model combined with the chemistry for transitions of CS, $^{18}$CO and N$_2$H$^+$. The right-hand panel shows an identical representation of the observed emission in B68. Although clear divergences from spherical symmetry are evident there exists striking agreement between model and observation. The results presented here and elsewhere suggests that we are making progress in our understanding of the chemistry in these cold regions (e.g. Tafalla et al. 2002; Alkawa et al. 2001; Li et al. 2002; Lee et al. 2002). The decrease in the N$_2$H$^+$ abundance is also significant as this suggests that its parent molecule (N$_2$) is freezing onto grain surfaces. If this result is observed beyond B68 it could have important implications for our ability to use molecules as the tracers of star formation dynamics.

3.3. Summary of Trends

The above results are excellent examples of the trends that are becoming apparent in chemical studies of low mass dark clouds. These trends have suggested changes in the way molecular emission is used to probe star forming cores.

1. The use of $^{18}$O as a probe of the H$_2$ column density in regions below the sublimation temperature of CO ($\sim 20$ K) is no longer appropriate. Whether this extends to warmer cores in giant molecular clouds re-
Figure 4.  Point by point comparison of C^{18}O $J=1-0$ and N$_2$H$^+$ integrated intensity with visual extinction for the entire B68 dark cloud. In all plots the data are presented as open squares with error bars while solid curves represent the emission predicted by a model combining chemistry with a Monte-Carlo radiative transfer code. The dashed lines are the best fit molecular abundance profiles with the axis labeled to the right (abundance of N$_2$H$^+$ is multiplied by 100). In a symmetric model the abundance profiles represent the radial chemical structure within a pencil beam towards the extinction peak and thus are shown only for one-half of the total maximum extinction. Adapted from Bergin et al. (2002).

Figure 5.  Comparison of model emission predictions with observational data. Left: Color scale map of CS ($J=3-2$) emission predicted from the B68 chemical model. Also shown are the peak contours of C^{18}O $J=1-0$ (blue) and N$_2$H$^+$ $J=1-0$ (yellow). Right: Similar plot of the observed emission in B68. Although the core clearly shows deviations from spherical symmetry there is a close correspondence between model predictions and observations.
mains an open issue (see Mauersberger et al. 1992; Chandler & Carlstrom 1996; Gibb & Little 1998; Savva et al., this volume)

2. Due to freeze-out the CS abundance can be sharply reduced when n > 10^4 cm^-3 and is no longer a reliable tracer of motions in high density gas. However, this molecule is still a good probe of low density molecular gas prior to condensation and after star formation.

3. The emission from N_2H^+ and NH_3 most closely resembles the maps of dust emission/extinction. N_2D^+, DCO^+, and NH_2D are also found to be well correlated with the dust (Caselli et al. 2002; Shah and Wooten 2001). These tracers are emerging as the best probes of the innermost regions of dense cores prior to the formation of a star.

4. Once a star has been born the heating of the inner envelope returns some tracers to the gas phase. This has not specifically been addressed in this paper but the reader is referred to recent work in this area including: Hogerheijde et al. (1999), Maret et al. (2002), Jørgensen et al. (2002), and references therein.

4. The Future of Dark Cloud Astrochemistry

For a few key species we are now finding a convergence between observation and theory. This opens the door towards using chemistry as a new tool to study the process of star formation. Below we discuss how this can be accomplished through both observational and theoretical efforts.

4.1. Observations

One new tool is the isolation of specific tracers that either do not freeze-out or freeze onto grain surfaces at late stages. Observations of these tracers (e.g. N_2H^+) over small or large scales can provide complementary kinematical information to continuum observations. For instance, in regions that are currently forming stellar clusters, we can investigated the core-core velocity dispersion and dense core gas motions relative to the overall structure (see Walsh; Hogerheijde, this volume). On similar scales combined studies of an “early” depleter (e.g. CS) and a high density tracer (e.g. N_2H^+) can also take advantage of the chemical evolution to detect cores prior to condensation (CS), during condensed stages (N_2H^+) and after star formation (see Lee et al. 2002; Lee, this volume).

The presence of differential depletions can certainly reduce the effectiveness of using molecular emission as a tracer of star formation kinematics. However, with careful choice of tracers one can use our expanded chemical knowledge to reconstruct the radial profile of kinematical motions. Indeed it is likely that the key to fully unraveling star formation dynamics lies in our improved understanding of the chemistry. One example is in B68 where the emission lines of C^{18}O and N_2H^+ are characterized by a systematic and well defined velocity gradient across the face of the cloud. However, the magnitude and direction of the velocity gradient is different between the two tracers. The chemical analysis presented in Figure 4 shows that N_2H^+ emission traces the innermost regions of the B68 core, while emission from C^{18}O predominantly traces the outer layers. Thus, if the gradient is due to rotation, then the combined chemical/dynamical analysis suggests that the core is differentially rotating (Lada et al. 2002).

Another example of the importance of chemistry to dynamics is shown in Figure 8. The left-hand panel shows spectra of 3 molecules taken towards the same position in the L183 molecular core. The double peaked structure observed in the optically thick CS and HCO^+ emission is now commonly used as a tracer of motions along the line of sight (e.g. Evans 1999). However, in L183 the CS profile is consistent with infalling motions, while HCO^+ is consistent with outflow. Since both of these transitions sample the same level of excitation this set of conflicting data must be due to chemistry. In particular, the answer must lie in the differences in the abundance structure of each molecule, and changes in the velocity field, as a function of depth.

A qualitative example of how these tracers could sample different motions along the line of sight is shown in the right-hand panel of Figure 8. This example uses the combined chemical/radiative transfer model constructed for B68. In the plot the x-axis is the radial position inside the cloud with a radius of 0.065 pc, and the y-axis shows the time evolution. The lines delineate the τ = 1 surface of the line core emission. All positions to the left of a given line for a particular transition have higher opacities. For example, for t < 8 × 10^4 yr emission from N_3H^+ is optically thin and traces the entire line of sight through the cloud. At later times the abundance rises and the emission becomes thick and only probes a surface that is successively further from the core center.

When optically thick molecular transitions are used to probe motion via asymmetric self-reversals the emission preferentially probes the τ = 1 surface and hence the magnitude and direction of motions at that depth. This plot clearly demonstrates that as the chemistry evolves
Figure 6. Left: Comparison of CS (2-1), HCO\(^+\) (1-0), and N\(_2\)H\(^+\) (1-0) spectra taken towards the same position in the dark cloud L183. The vertical line shows the systemic velocity of the cloud as determined by the optically thin N\(_2\)H\(^+\) emission. The CS and HCO\(^+\) optically thick spectra show evidence for motions along the line of sight. However, for CS the spectra is consistent with infall, while HCO\(^+\) appears to be consistent with outflowing motions (Lee & Myers 2002, in preparation). Right: Plot showing the emission surface for selected molecular transitions from a combined chemical and radiative transfer model of B68. The x-axis is the radius position in the core and the y-axis shows the chemical evolution. The lines delineate the \(\tau = 1\) surface for the core of the spectral line of selected molecular transitions. All positions to the left of a given line trace greater opacities and are not probed by observations. When optically thick molecular line is used to trace motions via asymmetries in the profile the emission preferentially probes the \(\tau = 1\) surface and hence the motions at that depth. This plot demonstrates that as the chemistry evolves each molecule is sensitive to motions at different regions along the line of sight.

the various tracers are sensitive to different layers within the cloud. For instance in this model CS (J=2-1) and HCO\(^+\) (J=1-0) initially both probe the outer layers. As the cloud evolves, CS differentially depletes and the \(\tau = 1\) surface retreats deeper into the cloud. Eventually, (for \(t > 3 \times 10^4\) yr) HCO\(^+\) emission traces outer layers, while CS probes the inner layers. This plot is not supplied as a template for the actual evolution of any particular core, rather it is shown as an example of how evolutionary changes in the chemical composition can affect observed emission, and more importantly the interpretation. Therefore, with observation of several species, and knowledge of the chemical abundance and physical profiles, another powerful new tool is the ability to search for structure in the radial velocity field, a key to understanding star formation.

5. Theory

Our understanding of chemical theory in dark clouds also must evolve. Areas that clearly need further investigation include comparison of models to observations of similar cores (L1544, L1517B, B68) in species beyond the typical suite of tracers (e.g. CO, CS, N\(_2\)H\(^+\)). For example Lee et al. (2002) find that the abundance of CCS is depleted in the the L1512 and L1544 cores, but find evidence for a small abundance rise in the center. This would be in agreement with the models of Ruffle et al. (1997) that suggest a rebound in the abundances of complex molecules due to CO freeze-out. Do other complex molecules provide similar results and can we further refine our understanding of gas phase pathways? This moves the testing of chemical models beyond comparison to abundances derived in template sources, such as TMC-1 and L134N, to observational comparisons with more centrally condensed objects that have well defined physical properties. Abundances derived in these sources still have uncertainties
due to calibration, collision rates, and geometrical assumptions, but can generally be considered more reliable than simple line of sight averages. Finally one challenge for future theory is to place the above observations in context of the non-detections of water vapor and molecular oxygen in cold cores (Snell et al. 2000; Bergin & Snell 2002). Some efforts have begun to examine this question (Viti et al. 2001; Charnley et al. 2001; Roberts & Herbst 2002).

Models that combine chemistry with dynamics have become increasingly more sophisticated. The ultimate goal of these efforts is to use chemical observations to refine our understanding of star formation theory. This goal is noteworthy and it remains to be seen whether the chemical unknowns regarding gas-grain interactions dominate (e.g. sticking coefficients, binding energies, grain sub-structure, surface chemistry, exact desorption process). Combined models have recently begun to attempt to reproduce not only the pattern of depletions, but also the column densities observed in L1544, a new template source (Aikawa et al. 2001; Li et al. 2002). This commendable step is needed to move theory beyond qualitative towards quantitative comparisons with observations. However, in §3.2 we demonstrated that we now have the capability to place model predictions into radiative transfer models and predict direct observables. This is important because column density estimates depend on assumptions regarding excitation that may not be reproduced in the model at the given time where model column densities best match observational estimates. Hence one could reproduce the column density and not the observed emission because of differences in the radial profile of physical conditions. This task is time consuming, but sophisticated radiative transfer codes are now readily available (see Hogerheijde & van der Tak 2002). The combination of chemical/dynamical models with radiative transfer truly offers the best opportunity to take chemical models and astrochemistry to the next level and potentially begin to test star formation theory.

6. Summary

The chemical processes that result in the formation of molecules play an important role in star and planetary formation through molecular contributions to the stability of the cloud against gravitational forces. Given the widespread nature of gas-phase freeze-out it is becoming increasingly evident that knowledge of the chemistry is also required in order to fully characterize the star formation process. The future of dark cloud chemical studies is promising as more complex and predictive models will be developed that can be compared to observations with increasing resolution and sensitivity. This will lead to crucial tests of chemical theory but also presents a completely new approach to star formation studies, bringing astrochemistry into a wider realm as a potent tool.

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