DEVELOPING A CHEMICAL EVOLUTIONARY SEQUENCE FOR LOW-MASS STARLESS CORES

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Abstract. I review the basic processes that may be used to develop a chemical evolutionary sequence for low-mass starless cores. I highlight observational results from the Arizona Radio Observatory-Green Bank Survey. Observations were performed with the SMT 10-m, ARO 12-m, and GBT 100-m toward a sample of 25 nearby ($D < 400$ pc) low-mass starless cores which have radiative transfer models of the 850 μm emission and observed SED ($160 - 1300$ μm). The cores were observed in the lines of NH_3 (1,1) and (2,2), o-NH_2D $1_{11} - 1_{01}$, C_2S $1_2 - 2_1$, C_3S $4 - 3$, HCN $1 - 0$, HC_5N $9 - 8$, HC_7N $21 - 20$, $C^{18}O$ and $C^{17}O$ $2 - 1$, and p-H_2CO $1_{01} - 0_{00}$.

1 Introduction

Low-mass starless cores are the earliest observed phase of isolated low-mass star formation. They are identified via submm dust continuum and dense gas molecular lines, they typically contain a few solar masses, they have sizes of approximately 0.1 pc, and they may form one or a few low-mass (M $\sim$ 1 $M_\odot$) stars. Several hundred starless cores have been observed in the nearest star-forming molecular clouds and isolated Bok globules. Recent large scale surveys of nearby molecular clouds have established a remarkable connection between the Core Mass Function and the Initial Mass Function of stars (e.g., Motte et al. 1998, Johnstone et al. 2000), indicating the importance of constraining the evolution of starless cores in order to understand the initial conditions of disk and protostar formation. Theoretically, the basic core formation and evolution process is still debated between a turbulent-dominated (Mac Low & Klessen 2004) or ambi-polar diffusion-dominated model (Shu et al. 1987). Observationally, a fundamental challenge is to determine the evolutionary state of a starless core. Given a set of observations, can we determine how close a starless core is to forming a protostar?

One step toward understanding the evolutionary state of a starless core is to determine its physical structure ($n(r)$ cm^{-3} and $T(r)$ K). Radiative transfer modeling of submillimeter dust continuum emission have successfully fit the density structure with hydrostatic configurations (Bonnor-Ebert Spheres, BESs), while the calculated temperature structure decreases toward the center of the core due to attenuation of the ISRF (Evans et al. 2001). Since BESs may be parameterized in terms of their

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central density, n_c cm^{-3}, it is natural to think that this may be the main evolutionary variable for starless cores. However, detailed molecular line observations have revealed that the chemical structure $(X(r))$ can strongly vary among cores with similar central densities. Figure 1 shows the example of L1498 and L1521E, two starless cores in Taurus which have comparable n_c (Tafalla et al. 2006), but very different chemical structures. L1521E is centrally peaked in C$_3$S with weak NH$_3$ emission while L1498 is centrally peaked in NH$_3$ and heavily depleted in C$_3$S. These observations can be explained if the cores are evolving at different rates. **In order to determine the evolutionary state of a starless core, it is necessary to map the chemical structure of the core**.
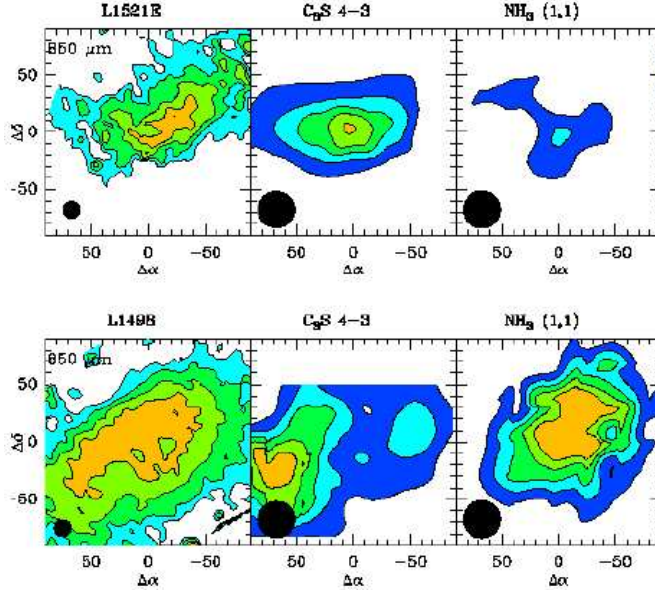

Fig. 1. Observations of L1521E (top) and L1498 (bottom) in 850 μm, C$_3$S, and NH$_3$ showing chemical differentiation. Data are from the ARO-GBT survey and Shirley et al. (2005)

2   Chemical Processes in Starless Cores

The rate at which molecules are created and destroyed differ for each species; therefore, the relative abundance of molecular species may be used as a chemical clock. A prediction that appears to be ubiquitous among starless core chemodynamical models is that there exists a class of molecules, named "early-time" molecules, which form rapidly in the cold, moderate density environments typical of nascent starless cores (e.g., CO, C$_2$S, C$_3$S, SO). The early-time molecule abundance peaks typically within a few 10^5 years and then decreases due to various destruction mechanisms (see below). Another class of molecules, named "late-time" molecules, build up in abundance slower and remain in the gas phase longer at low temperatures and high densities (e.g., N$_2$H$^+$, NH$_3$, H$_2$D$^+$). It has been proposed that observations of the abundance ratio of species such as [C$_2$S]/[NH$_3$] may date the chemical maturity of a core (Suzuki et

al. 1992). Figure 1 shows an example of two cores with very different chemical states in early-time and late-time molecules despite having comparable central densities.

The environments of starless cores are cold ($T < 15$ K) and dense ($n_c > 10^4$ cm^{-3}), thus many gas phase species adsorb onto dust grains. The best example is the second most abundant molecular species, CO, which freezes out of the gas at a rate of $(dn_{\mathrm{CO}}/dt) \propto n_g T^{1/2} S n_{\mathrm{CO}}$, where n_g is the dust grain density and S is the sticking coefficient (Rawlings et al. 1992). Since the timescale for freezeout depends on the density and temperature of the core, the amount of CO depletion encodes the history of the physical structure of the core. For instance, a core that evolves slowly (quasi-statically) will have less CO depletion compared to a core that evolves quickly to the same n_c. Complicating factors to the simple adsorption model include competing desorption processes due to direct cosmic ray heating, cosmic ray photodesorption, and H$_2$ formation on grains, all of which may be important in starless cores (Roberts et al. 2007). CO is a destruction agent of many gas phase ions (e.g. N$_2$H$^+$ and H$_2$D$^+$), therefore the abundance history of these species are directly related to the amount of CO freezout (see Figure 2). The resulting chemical networks in heavily depleted environments are very different (see Vastel et al. 2006). Mapping of starless cores have revealed a plethora of depleted species toward the dust column density peaks (Tafalla et al. 2006).

Deuterium fractionation is an important chemical diagnostic in low-mass cores. At low temperatures, many chemical reactions involving HD favor the formation of deuterated molecules due to the lower zero-point vibrational energy of deuterated species compared to the hydrogenated species. The classic deuteration reaction operating in the environments of starless cores is H$_3^+$ + HD $\rightarrow$ H$_2$D$^+$ + H$_2$ + 230 K, where the backreaction is inefficent at low temperatures (Vastel et al. 2006). As the density increases, the temperature decreases, and species such as CO freeze-out, the deuteration of hydrogenated species may increases up to four orders of magnitude over the cosmic [D]/[H] $\sim 10^{-5}$ (Roberts et al. 2004). Figure 2b illustrates the observed degrees of deuteration of N$_2$H$^+$ increases with the amount of CO depletion in the core (Crapsi et al. 2005). Similarly, since a deuterated species, such as NH$_2$D, may be viewed as an extreme late-time molecule, a comparison between deuterated and early-time molecules from the ARO-GBT survey indicate increasing late-time vs. early-time molecules with increasing central density is the core (Figure 2a).

The chemical structure of the core is also important for determining which species are good probes of the kinematical structure of the core. Several species (CS, H$_2$CO, HCO$^+$, HCN) have been identified as infall tracers, molecules that are moderately optically thick and display asymmetric, self-aborbed line profiles. Recent surveys have attempted to search for evidence of large scale infall (e.g. Sohn et al. 2007). Furthermore, the linewidths of heavy species that lack hyperfine structure, such as C$_3$S (68 amu), are dominated by non-thermal motions and can trace turbulent motions or large-scale kinematical motions along different lines-of-sight in the core.

A more thorough review of the chemical processes in starless cores may be found in Di Francesco et al. (2005 and references therein). The comparison of early-time vs. late-time species, the amount of depletion, the amount of deuteration, and the identification of large scale kinematical motions should be used together to elucidate the evolutionary state of a starless core. Other indicators, such as the ortho-to-para evolution of symmetric molecules with non-zero spins and variations in the structure of ionization fraction should also be explored.
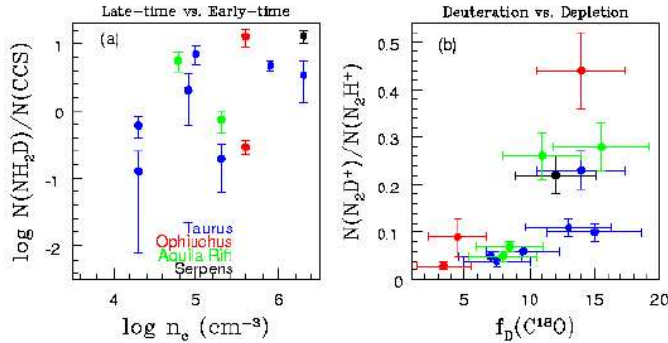
Fig. 2. Left: The ratio of the "late-time" species NH_2D to the "early-time" species C_2S vs. n_c toward cores where both lines were detected in the ARO-GBT survey. Right: The deuterium fraction of N_2H^+ vs. the CO depletion factor reported by Crapsi et al. (2005).

3   Developing an Evolutionary Sequence

Ultimately, to determine the evolutionary state of a starless core, we should model the molecular line radiaitve transfer of each transition along multiple lines-of-sight and compare to a grid of chemodynamical models (e.g. Lee et al. 2004). This processes is computationally intensive and the current generation of chemodynamical models have not fully explored the parameter space of possible conditions in nearby starless cores. An alternative first step is to develop a Boolean evolutionary comparison. A flag of 1 (more evolved) or 0 (less evolved) is given to a particular observed property of the core if the chemical criterion is met, and the sum of flags represents the observed chemical maturity of the core. This strategy was implemented by Crapsi et al. (2005) for a sample of 12 starless cores and is being extended to the sample of 25 cores with a larger set of chemical criteria in the ARO-GBT survey (Shirley et al. 2008, in prep.).

While there is still much work to develop a detailed understanding of the chemical processes within low-mass starless cores, it is now possible and necessary to synthesize the chemical evolutionary indicators.

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