Molecular Abundance Variations Among and Within Cold, Dark Molecular Clouds

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Abstract. The latest table of molecular abundances in the cold, dark clouds TMC-1 and L134N is presented. Molecular abundance variations between TMC-1 and L134N, those within TMC-1 and L134N, and those among 49 dark cloud cores surveyed by Suzuki *et al.* (1991) are interpreted as an effect of chemical evolution.

Key words: Interstellar Molecules - Molecular Abundance - Chemical Evolution

1. Interstellar Molecules in Cold, Dark Clouds

The cold, dark molecular clouds are formation sites for low-mass stars. These clouds often contain several dense cores with $T_K \sim 10$ K, $n(H_2) \sim 10^4 - 10^5$ cm^{-3}, and the mass of one to a few $M_\odot$. Such physical conditions together with lack of embedded high-luminosity sources make the cold, dark molecular clouds ideal testing sites for models of gas-phase ion-molecule chemistry.

The recent development of large millimeter-wave telescopes like the 45-m telescope at Nobeyama and the 30-m dish of IRAM, and highly sensitive submillimeter-wave telescopes have resulted in detections of many new interstellar molecules. Some 90 interstellar molecules so far detected are summarized by Irvine, Ohishi and Kaifu (1991) (very recently CCO and SiN have been detected, and H_3O^+ has been confirmed.). They also list molecules detected in cold, dark clouds. As is well known, many radicals and molecular ions which have very short lifetimes under terrestrial conditions are often found in cold, dark clouds. Most of the molecules listed in Table II of Irvine, Ohishi and Kaifu were detected at the cyanopolyyne peak of TMC-1 (Taurus Molecular Cloud 1) that is located about 140 pc from the Sun. Characteristic molecules in TMC-1 are the carbon-chain molecules (C_nX ; X=H, N, O and S) and their derivatives. Several chemical models, e.g. Herbst & Leung (1989), show that these molecules' abundances peak in the "early time" ($\sim 3 \times 10^5$ years) and decrease rapidly as clouds reach the steady state.

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Such molecules are not abundant in all cold, dark clouds which we can observe at present. One good example is provided by a comparison of molecular abundances between TMC-1 and L134N. Both clouds have very similar physical environments. But the molecular abundances have great differences, as are summarized in Table I. Carbon-chain molecules are much more abundant in TMC-1 (abundance ratios are greater than 2), while NH_3, SO, SO_2, CH_3OH, and NO are more abundant in L134N. Some molecules such as CO, CS, HCO^+ and H_2CO do not show any significant differences between the two clouds. The carbon-chain molecules and their derivatives are, as we have stated before, abundant in the "early time" of cloud evolution. NH_3, SO, SO_2, CH_3OH, and NO show a common characteristic in their formation chemistries : they include endothermic reactions or neutral-neutral ones. CO, CS, HCO^+ and H_2CO are widespread and usually very abundant in most or all molecular clouds.

There are a few published ideas to explain such abundance differences. One is that TMC-1 is carbon-rich while L134N is oxygen-rich. Another one is that TMC-1 is in the early stage of its chemical evolution and L134N is more evolved. Considerable effort to explain the abundance differences with these ideas has been made. But no one has found a clear answer for this basic question.

2. Abundance Variations within TMC-1 and L134N

One important approach for the above mentioned question would be to investigate abundance variation within a cloud. It is very natural for the chemistry to be strongly affected by the physical conditions (kinetic temperature, density, elemental abundance, radiation field, etc.) of the cloud.

Hirahara *et al.* (1991) have compared molecular distributions of several carbon-chain molecules (CS, C_2S, C_3S, HC_3N, HC_5N, and C_4H) with other ones (NH_3, HCS^+, SO and N_2H^+) in TMC-1, and found that carbon-chain molecules peak at the cyanopolyyne peak while NH_3, SO and N_2H^+ peak around the ammonia peak. The difference is prominent and, surprisingly, it is similar to that found in Table I between the two clouds TMC-1 and L134N ! They analyzed the data for C_2S and derived that the number density of molecular hydrgen at the cyanopolyyne peak is about 10^4 cm^{-3} and that for the ammonia peak is about 10^5 cm^{-3}. There is no clear evidence for current star-formation in the vicinity of TMC-1. These facts together with small core sizes ($\sim$ 0.02 pc) suggest that the cores may be younger than the time when the cloud would reach the steady state of its chemical evolution. Therefore Hirahara *et al.* favored the conclusion that the cyanopolyyne peak is chemically younger than the ammonia peak.

Swade (1989) made extensive mapping observations for L134N with $C^{18}O$, CS, C_3H_2, SO, $H^{13}CO^+$, NH_3, and so on. Although physical conditions do

TABLE I

Measured Molecular Abundances in Dark Clouds

Species	N(Species)/N(H_2) × 10^8		TMC-1/L134N	Note
	TMC-1	L134N		
CO	8000	8000	1	
C_2O	0.06			
C_3O	0.01	< 0.005	> 2	
C_2	5			a
OH	30	7.5	4	b
CH	2	1	2	b
C_2H	5-10	< 5	> 1	
C_3H	0.05			
C_4H	2	0.1	20	
C_5H	0.03			
C_6H	0.01			
CH_3CCH	0.6	< 0.12	> 5	
CH_3C_4H	0.02			
CN	3	< 0.3	> 10	
C_3N	0.1	< 0.02	> 5	
CH_3CN	0.1	< 0.1	> 1	
CH_3C_3N	0.05			
HCN	2	0.4	5	
HNC	2	0.6	3.3	
$HCNH^+$	0.19	< 0.31	> 0.6	
HC_3N	0.6	0.018	30	
HC_5N	0.3	0.01	30	
HC_7N	0.1	< 0.002	> 50	
HC_9N	0.03			
$HC_{11}N$	0.01			
CH_2CHCN	0.02	< 0.01	> 2	
CS	1	0.1	10	
HCS^+	0.06	0.006	10	
C_2S	0.8	0.06	13.3	
C_3S	0.1	< 0.02	> 5	
CH_2C_2	0.03			
CH_2C_3	0.08			
HNCO	0.02			
N_2H^+	0.05	0.05	1	
NH_3	2	20	0.1	
HCO^+	0.8	0.8	1	
H_2CO	2	2	1	
H_2CCO	0.1	< 0.07	> 1.4	
OCS	0.2	0.2	1	
SO	0.5	2	0.25	
SO_2	< 0.1	0.4	< 0.25	
CH_3CHO	0.06	0.06	1	
C_3H_2	1	0.2	5	
$c-C_3H$	0.06	0.03	2	
CH_3OH	0.2	0.3	0.66	
HC_2CHO	0.02			
CH_2CN	0.5	< 0.1	> 5	
H_2S	< 0.05	0.08	< 0.6	c
H_2CS	0.3	0.06	5	
NO	< 3.0	6.0	< 0.5	d
HCOOH	< 0.02	0.03	< 0.66	

Notes. Values assume column densities N(H_2) = 1×10^{22} cm^{-2} in both clouds. Positions are :

$$\mathrm{TMC}-1 : \alpha(1950) = 4^h38^m38.6^s,\ \delta(1950) = 25°35'45'' ;$$
$$\mathrm{L134N} : \alpha(1950) = 15^h51^m30.0^s,\ \delta(1950) = 2°43'31'' .$$

a : 20 arcmin from std. position. b : beam size ≫ that for heavier species. c : TMC-1 (detected at the ammonia peak (-4',+6')); L134N (3 × stronger at 1' west). d : Values refer to position in note a.

not seem to vary greatly, these molecules show very different distributions : for example, NH_3 shows two peak positions while $H^{13}CO^+$ has a single maximum between these two positions of NH_3, and furthermore SO shows several peaks away from the peaks of NH_3 and/or $H^{13}CO^+$. Thus it is clear that the molecular abundances listed in Table I are not entirely representative for both clouds. Swade concluded that the distributions reflect variation of the carbon to oxygen ratio within L134N. But his argument is based on the steady state chemistry. Many chemical model calculations show that it takes about 10^7 years to reach the steady state, which is usually longer than the clouds' lifetime. This means that the chemistry is not in the steady state, and therefore an argument based on the steady state chemistry may not be valid.

3. Variations among Cloud Cores and their Chemical Evolution

Another approach to study the abundance variation is to survey many dark cloud cores with some selected key molecules. Suzuki *et al.* (1991) have surveyed 49 dark cloud cores in the Taurus and in the Ophiuchus regions with C_2S, C_3S, NH_3 and related molecules. Although their purpose by comparing chemical network calculations and observational facts was to investigate the formation mechanism of the C_2S radical, they found that the abundance of the C_2S radical has a strong correlation with the chemical evolution of the cloud.

They also suggest that the abundance ratio of C_2S to that of NH_3 will be a good indicator of the chemical evolution as well as the physical evolution. Fig. 1 plots fractional abundances of C_2S of the cores surveyed by Suzuki *et al.* as a function of the column density ratio of C_2S to NH_3. These plots are classified into two categories : cores without IRAS point sources and those with IRAS. Because IRAS point sources are regarded as candidates for proto-stars, the cores with IRAS sources would be physically more evolved than those without IRAS sources.

As we can see from Fig. 1, the cores without IRAS sources tend to be distributed in the upper-left region of the diagram, while those with IRAS sources tend to stay in the oppsite side. When we overlay an "evolutionary track" of the chemical evolution of the core (Suzuki *et al.* 1991), the upper-left portion of the figure corresponds to a cloud age of 4 – 10 $\times 10^5$ years and the lower-right part corresponds to 10 – 20 $\times 10^5$ years (in the case of $n(H_2) = 10^4$ cm^{-3}, $T_K = 10$ K). The cyanopolyyne peak of TMC-1 is located in the upper-left region, the amminia peak is in the central area, and L134N locates at the furthest right side among the three cores. This clearly means that the cyanopolyyne peak of TMC-1 is the chemically youngest core, the ammonia peak of TMC-1 is chemically older than the cyanopolyyne peak, and L134N is the most evolved. Although the absolute

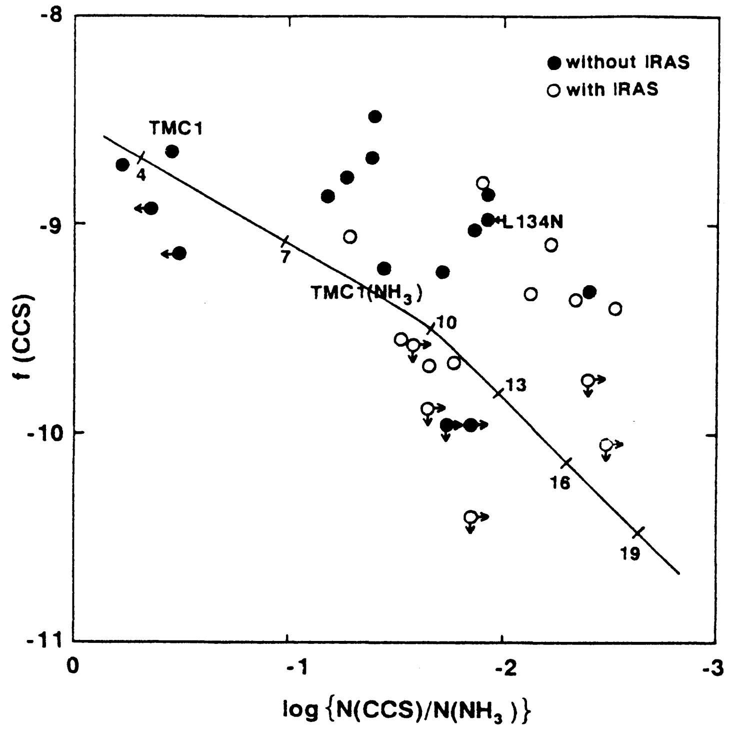

Fig. 1. Variation of the fractional abundance of C_2S to H_2 as a function of the abundance ratio of C_2S to NH_3. Filled circles represent dark cloud cores without IRAS point sources, and open circles are cores with IRAS sources. Arrows indicate limits. Solid line is the "evolutionary track" in the case of $n(H_2) = 10^4$ $cm^{-3}, T_K = 10$ K. Numbers along the line represent "chemical age" of the cloud in unit of 10^5 years.

values of the "chemical age" are not reliable, this diagram clearly shows a correlation of the chemical evolution and the physical evolution of the dark cloud cores. Finally we note that the simulation did not assume any elemental abundance variation, and we believe it will be possible to explain most of the abundance variations of molecular clouds by this idea of "chemical evolution".

4. Summary

Recent extensive millimeter-wave and centimeter-wave observations have revealed that the molecular abundances of cold, dark cloud cores vary not only from cloud to cloud but also from core to core inside a single cloud. Several ideas have been proposed to explain such variations. We propose that the variations can be reconciled considering the chemical evolution of the cloud core. More active research including the survey observations of dark cloud cores and reaction network calculations, are neccesary to understand the relation between the chemistry and the physics of dark cloud cores.

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QUESTIONS AND ANSWERS

Qin Zeng: You did very good job to measure the column densities, but how to obtain the abundances from the column densities?

M.Ohishi: Fractional abundances of molecules are defined by $f(mol.) \equiv N(mol.)/N(H_2)$, where $N(mol.)$ and $N(H_2)$ represent the column densities of the molecule and of H_2, respectively.