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The Chemical Composition of a Molecular Cloud at the Outer Edge of the Galaxy

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Abstract

Centimeter and millimeter-wave observations of a molecular cloud at the extreme outer edge of the Galactic disk (kinematic galactocentric distance: ~28 kpc) are presented. We detected CO, ^{13}CO, ^{18}CO, CS, CN, SO, HCN, HNC, C_2H, HCO^+, $H^{13}CO^+$, HCS^+, NH_3, H_2CO, C_3H_2 and CH_3OH, while ^{17}CO, ^{34}CS, SiO, SiS, N_2H^+, DCN, DNC, DCO^+, SO_2 and HC_3N remained undetected. From the NH_3 and H_2CO data, a kinetic temperature of $T_{\rm kin} \sim 20$ K and a density of $n(H_2) \sim 5\times10^3$ cm^{-3} are derived. Nitrogen bearing molecules show, when detected, only weak lines. Commonly strong line emitters such as N_2H^+ and HC_3N were not seen. Using a numerical network including 5300 chemical reactions we determined that N is depleted by approximately 24 times, and the metallicity is reduced by a factor of five (similar to dwarf irregular galaxies or damped Lyman alpha systems) relative to the solar neighborhood. These unusual abundances are probably the result of the infall of halo gas enriched in O, C, and S from a burst of massive star formation in the Galactic halo shortly after the Milky Way was formed. This activity would have produced both O and S, which are produced by massive stars; C, which is produced by massive and intermediate mass stars; but less N abundance because the secondary element N is produced primarily from low mass stars. Thus the edge cloud probably results from infalling halo gas from the early Galaxy that was not significantly processed during the last 10 Gyr and provides a new way to understand the origin of the Galactic disk. Our observations of the early Galactic disk abundances will constrain models of nucleosynthesis, Galactic chemical evolution, and astrochemistry.

1.1 Introduction

Extended molecular clouds at the outer edge of the Galaxy have been detected whose kinematic distances from the Galactic Center are 22 kpc and 28 kpc, respectively, suggesting that they are located beyond the optical disk (Digel, de Geus, and Thaddeus, 1994, ApJ, 422, 92). These clouds have not been studied in any detail as only CO and ^{13}CO were previously detected. We present extensive observations of the farthest known molecular cloud, Edge Cloud 2, hereafter EC2, in Digel, de Geus, and Thaddeus, 1994 (SIMBAD designation [DDT94] cloud 2), located 28 kpc from the Galactic Center). The purpose of this research is to determine chemical composition, physical properties (kinetic temperature, electron density, and ionization rate), and isotopic ratios $^{12}C/^{13}C$, $^{14}N/^{15}N$, and $^{17}O/^{18}O$) in EC2 at the extreme outer edge of the Galaxy. We observed a large set of molecules because some molecules trace physical properties such as temperature, density or ionization while other molecules trace chemical abundances. Since the Galactic disk formed from infalling halo gas material, the composition of the outermost edge of the Galaxy gives us an opportunity to study the formation of the Galactic disk.

1.2 Observations and Results

We have completed over 300 hours of observations, using the U. of Arizona 12-m telescope on Kitt Peak and, for H_2CO, NH_3 and SO, the MPIfR 100-m telescope at Effelsberg. The observations were done in position switching mode. Because the edge cloud is so far away, most of the spectral lines are weak and required 1 to 10 hours per transition. We detected CO, ^{13}CO, ^{18}CO, CS, CN, SO, HCN, HNC, C_2H, HCO^+, $H^{13}CO^+$, HCS^+, NH_3, H_2CO, C_3H_2 and CH_3OH. We did not detect ^{17}CO, ^{34}CS, SiO, SiS, N_2H^+, DCN, DCO^+, DNC, SO_2, or HC_3N. Most of our observations of EC2 were done at position Edge 2A, $\alpha_{1950} = 02^h\,44^m\,52.6^s$, $\delta_{1950} = 58^\circ\,16'\,00''$. We also made observations towards two nearby additional positions, Edge 2B ($\alpha_{1950} = 02^h\,44^m\,48.86^s$, $\delta_{1950} = 58^\circ\,16'\,05''$) and Edge 2C ($\alpha_{1950} = 02^h\,44^m\,48.8^s$, $\delta_{1950} = 58^\circ\,16'\,30''$). Our results are summarized in Table 1 (position Edge 2A) and Table 2 (position Edge 2B and Edge 2C) where we list the molecular species, transitions, intensities, line widths and rms noise levels. The spectra are shown in Figures 1 to 4. Figures 1, 2, and 4 used the data taken with the 12-m telescope and show the combined spectra for the molecular lines given in Tables 1 and 2. The y-axis for the stronger lines of ^{13}CO, CS, and HCO^+ in Figure 1 is shown in increments of 0.10 K while the y-axes in Figs. 2 and 4 are shown in increments of 0.020 K and 0.05 K respectively. Figure 3 used the data taken with the 100-m telescope and shows the spectra of SO, NH_3, and H_2CO with the y-axis given in mJy. The 12-m telescope scale is in T_R^* (the equivalent brightness temperature of a lossless telescope with unity efficiency outside the atmosphere) and the 100-m scale in flux density where the flux S_ν 1 mJy$\sim$ 1 K on a T_R^* scale. Figure 4 shows the lines taken at positions Edge 2B and Edge 2C.

1.3 Galactic Chemical Evolution Models

Current models include time and spatial variations in the infall and star formation rate whereby the Galactic halo and bulge quickly formed first (within 0.8 Gyr) separately from the thin disk in two infall episodes. Chemical abundances of the interstellar medium and their radial variation across galactic disks provide a fundamental set of constraints for theories of disk formation and evolution. The most accepted mechanism to explain the existence of abundance gradients in disk galaxies is the so called "biased-infall" (Matteucci & Chiappini, 1999, Astrophysics and Space Science, 265, 425), where infall of gas occurs at a faster rate in the innermost regions than in the outermost ones ("inside-out" disk formation). Models of Galactic chemical evolution predict that the abundances of C, N, O, ^{13}C, and ^{15}N will be the lower at the outer edge than in any other interstellar cloud (Maciel & Quireza, 1999, A&A, 345, 629) because of the slower infall rate in the outermost region. Growing observational evidence for slow formation of disks in spiral galaxies associated with continuing infall of primordial (or low metallicity) gas over the lifetime of the disk (e.g. Braun & Burton 1999, A&A, 341, .437) seems to give support to the above scenario. Lubowich et al. (2000, Nature, 405, 1025) demonstrated that continuous infall of low-metallicity gas is occurring in the Galactic Center.

Since the Galactic disk formed from infalling halo gas material, the composition of the outermost edge of the Galaxy formed about 10 Gyr ago gives us an opportunity to study the formation of the Galactic disk. Of particular relevance to test these models are the abundances in the very outer galactic disk. Recent chemical evolution models for abundance gradients and the formation of the Milky Way (Chiappini, Matteucci, and Romano, 2001, ApJ, 554, 1044) show that the steepness of the outer gradients are particularly sensitive to thresholds in star formation, to the halo-thick disk enrichment history, and to the radial variation of the disk formation timescales. They concluded that some abundance ratios increase substantially toward the outermost disk regions but that "more observations at large Galactocentric distances are needed to test these predictions." The fact that N is almost constant with the galactocentric distance up to 18 kpc (Chiappini, Romano, and Matteucci, 2003, MNRAS, 339, 63) reflects the high N production in AGB stars. The primary N contribution from AGB stars is however very uncertain. At such large galactocentric distances a N production threshold may be operating. We will test these models by comparing our observed molecular abundances to calculations done for a low metallicity gas.

1.4 Discussion and Conclusion

The NH_3 data, i.e. the spectra of the two lowest metastable ($J=K$) inversion lines, gives a kinetic temperature of $T_{\rm kin} \sim 20$ K which is consistent with the warm phase of molecular gas at large galactocentric distances detected in spiral galaxies (Papadopoulos, Thi, and Viti, 2002, ApJ, 579, 270). The H_2CO data yields a density of $n(H_2) \sim 5\times10^3$ cm^{-3}. In order to analyze the composition of this cloud we have calculated the abundance ratios, X/HCO$^+$, for the molecules in EC2. We calculated the molecular abundances for a cloud with fivetimes lower abundances of C, O, Fe, and Si; and an eight times lower N abundance based on the abundance gradient of B stars extended to 28 kpc (Rolleston, Smartt, Dufton, and Ryans, 2000, A&A, 363, 537). We further increased the D abundance by an additional three times consistent with the D/H ratio of 3.9×10^{-5} in the Galactic anticenter (Chengalur, Braun, and Burton, 1997, A&A, 318, L35).

Table 3 compares the X/HCO$^+$ ratios measured in EC2 to the abundance ratios in L134N (a starless dark cloud well above the Galactic plane; Dickens et al., 2000, ApJ, 542, 870) and the abundance ratios calculated for our low metallicity-low N model based on our 5300 chemical reaction astrochemistry code (Roberts and Millar, 2000, A&A, 361, 388). We obtained a better agreement between our data and the chemical model calculations when we decreased the N abundance by an additional three times resulting in a 24 times decrease in the N abundance. Our abundance ratios are not in agreement with the abundance ratios in the recently formed nearby molecular cloud L134N which has not had significant star formation or stellar processing. Combining our observations with our chemical model we estimate that EC2 is reduced in metallictiy by five times and depleted in N by approximately 24 times compared to our local ISM.

The most likely explanation for our result is that we are observing gas from a burst of massive star formation. This activity would have produced S and O, which are produced from massive stars, C, which is produced by massive and intermediate mass stars, but less N, which is produced primarily from low mass stars. Although there is some star formation triggered by a nearby B star in EC2 based the discovery of young stellar objects from near-

IR observations, the extremely low molecular gas density in the outer Galactic disk implies that this region is not very evolved and is similar to the environment in the early stage of the formation of the Galactic disk and dwarf irregular galaxies (Kobayashi and Tokunaga 2002, ApJ, 532, 423). Because our data shows a significant gradient in the N abundance beyond 18 kpc, we believe that this cloud has not had significant AGB or massive star formation. Thus EC2 has not had significant stellar processing during the past 10 Gyr and may be a remnant of the gas that formed the Galactic disk.

Until we are able to more accurately measure the metallicity in EC2 (planned in future observations), we are unable to determine if the gas in EC2 came from the material that initially formed the Galactic halo; a burst of massive star formation early in the Galaxy; or from material ejected from massive supernovae in globular clusters. Our results are in agreement with current models of Galactic chemical evolution that predict that the abundances of C, N, and O will be the lower at the edge than in any other interstellar cloud. The edge cloud, EC2, is significantly depleted in N by 24 times and may be a remnant of the gas that formed the Galactic disk. Thus the composition of this molecular cloud at the outermost edge of the Galactic disk (28 kpc) may be unique in the Galaxy and provides a new way to understand the origin of the Galactic disk.

Table 1.1. *Molecules observed in Edge Cloud 2 at position A.*

Molecule	line	frequency (GHz)	T_r^* (K)	ΔV (km/s)	rms (K)
H_2CO	$2_{1,1}$-$1_{1,0}$	150.49839	0.037	1.77	0.005
CS	3-2	146.96905	0.043	2.18	0.008
$C^{34}S$	3-2	144.61715	-	-	0.01
H_2CO	$2_{1,2}$-$1_{1,1}$	140.83952	0.051	2.51	0.013
CN	$1_{3/2,5/2}$-$0_{1/2,3/2}$	113.49098	0.021	2.22	0.004
	$1_{3/2,3/2}$-$0_{1/2,1/2}$	113.49098	0.016	1.71	0.004
$C^{17}O$	1-0	112.35899	-	-	0.007
^{13}CO	1-0	110.20135	0.718	2.23	0.065
$C^{18}O$	1-0	109.78216	0.057	2.05	0.014
SO	3-2	99.29988	0.057	1.93	0.007
CS	2-1	97.98097	0.125	2.18	0.024
CH_3OH	$2_{0,2}$-$1_{0,1}$ A^+	96.741420	0.019	1.37	0.005
	$2_{-1,2}$-$1_{-1,1}$E	96.73939	0.025	0.97	0.005
N_2H^+	1-0	93.1735	-	-	0.007
HNC	1-0	90.6635	0.032	1.40	0.007
HCO^+	1-0	89.18852	0.132	2.73	0.014
HCN	1-0	88.6318	0.036	1.51	0.013
	1-0	88.6339	0.051	1.03	0.013
C_2H	1-0	87.3169	0.073	2.87	0.007
	1-0	87.3286	0.028	1.77	0.007
$H^{13}CN$	1-0	86.34018	-	-	0.006
HCS^+	2-1	85.3479	0.032	2.14	0.009
C_3H_2	$2_{1,2}$ -$1_{0,1}$	85.3382	0.030	2.03	0.010
HC_3N	9-8	81.88147	-	-	0.007
DCO^+	1-0	72.03933	-	-	0.005
SO	1_0-0_1	30.002	0.073	1.5	0.018
NH_3	2-2	23.723	0.0146	2.6	0.005
NH_3	1-1	23.694	0.040	2.0	0.006
H_2CO	$2_{1,1}$-$2_{1,2}$	14.488	-0.0125	1.2	0.006
	$1_{1,1}$-$1_{1,2}$	4.830	-0.0355	2.9	0.006

Table 1.2. *Molecules observed in Edge Cloud 2 at positions B and C.*

Molecule	line	frequency (GHz)	T_r^* (K)	ΔV (km/s)	rms (K)	position
^{13}CO	1-0	110.20135	0.5963	2.53	0.039	C
$C^{18}O$	1-0	109.78216	0.039	2.59	0.012	B
SO	3-2	99.29988	-	-	0.007	C
CS	2-1	97.98097	0.120	2.55	0.008	B
	2-1	97.98097	0.118	1.72	0.023	C
N_2H^+	1-0	93.1735	-	-	0.009	B
HC_3N	10-9	90.97023	-	-	0.008	C
HCO^+	1-0	89.18852	0.114	2.19	0.011	B
	1-0	89.18852	0.076	2.20	0.011	C
$H^{13}CO^+$	1-0	86.754429	0.026	1.90	0.006	B
SiO	2-1 v=0	86.84701	-	-	0.007	B
	2-1 v=1	86.243422	-	-	0.024	C
C_3H_2	$2_{1,2}$-$1_{0,1}$	85.3382	0.25	2.97	0.016	C
HC_3N	9-8	81.88147	-	-	0.015	C
DNC	1-0	76.30573	-	-	0.005	B
DCO^+	1-0	72.03933	-	-	0.007	B
SO	1_0-0_1	30.002	0.075	1.1	0.026	B
	1_0-0_1	30.002	-	-	0.032	C

Table 1.3. *Abundance ratios relative to HCO^+.*

X/HCO^+	Edge cloud 2	low N model	L134N
CS	0.692	0.168	0.124
SO	1.04	0.065	0.719
NH_3	3.01	3.13	7.63
N_2H^+	$< .024$	0.034	0.077
CN	0.600	2.08	0.061
HCN	0.506	0.274	0.925
HNC	0.212	0.327	3.25
HC_3N	< 0.029	0.010	0.054
CH_3OH	0.309	0.0016	0.641
C_2H	14.9		0.288

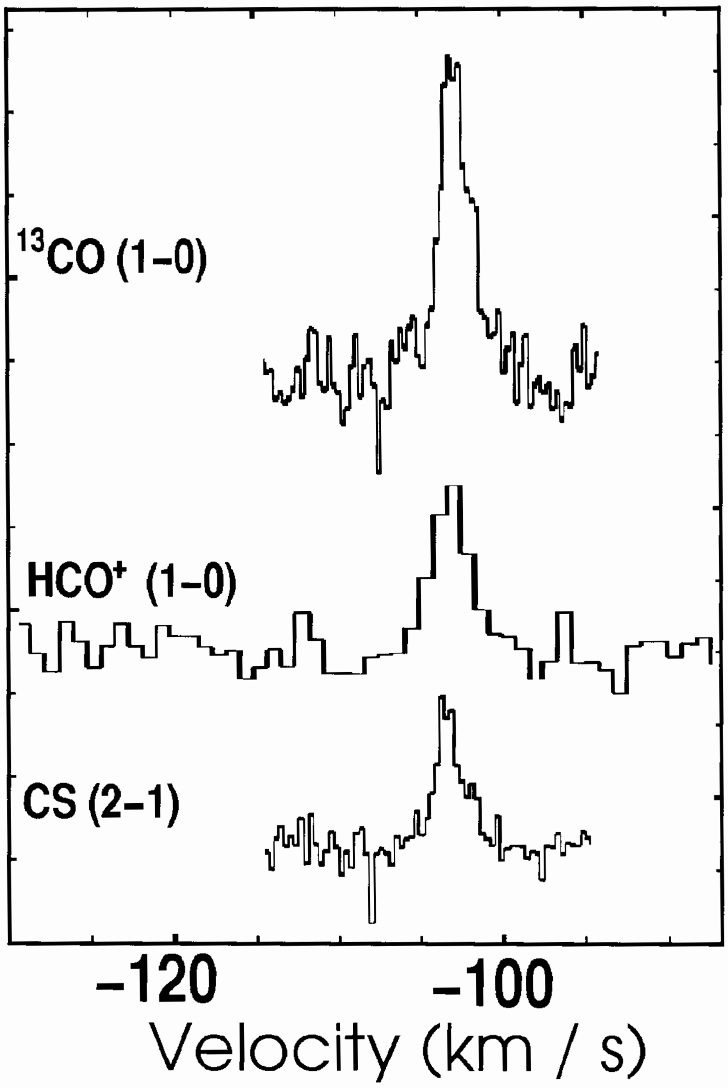

Fig. 1.1. Molecular lines of ^{13}CO, CS, and HCO$^+$ observed in Edge Cloud 2 at position A with a y-axis of T_r^* in increments of 0.10 K.

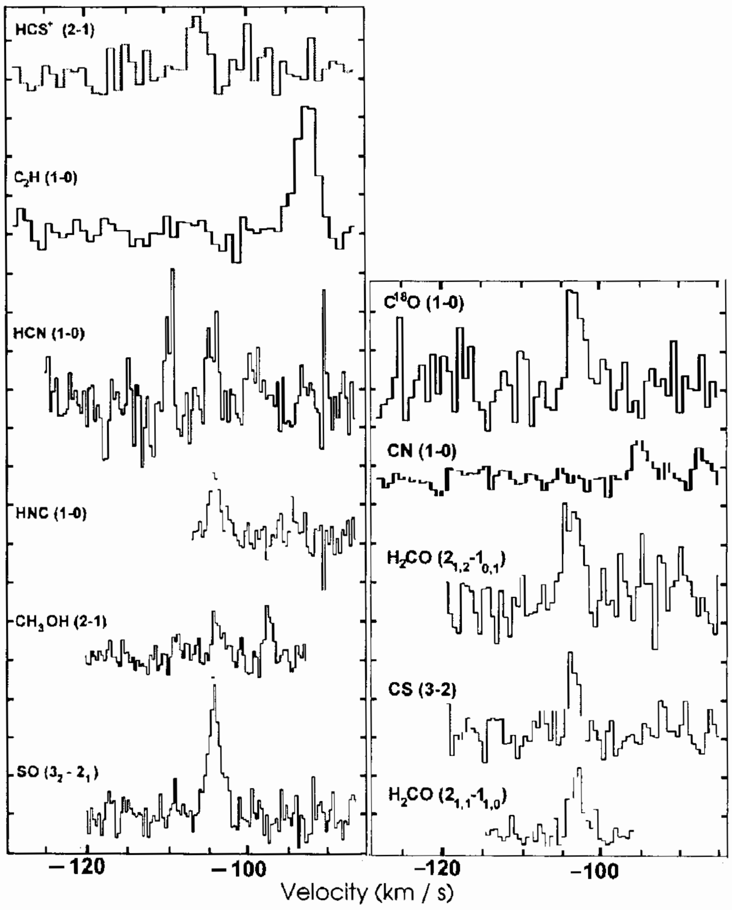

Fig. 1.2. Molecular lines observed in Edge Cloud 2 at position A with a y-axis of T_r^* in increments of 0.020 K.

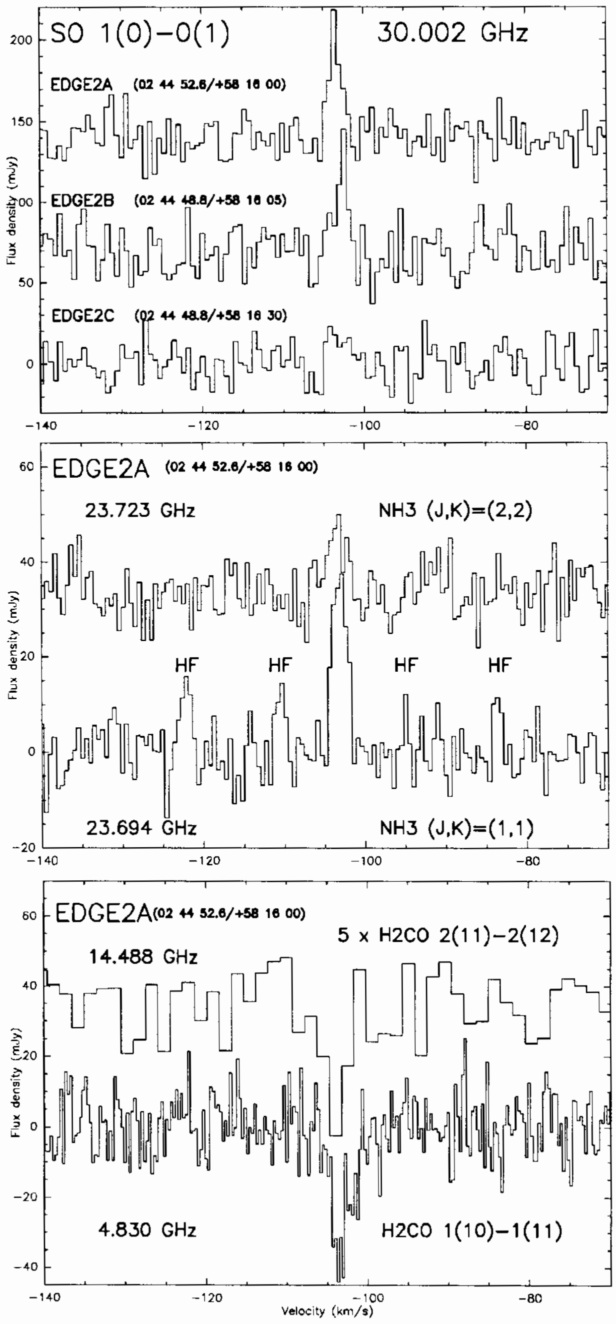

Fig. 1.3. Molecular lines of SO, NH_3, and H_2CO observed in Edge Cloud 2 position A.

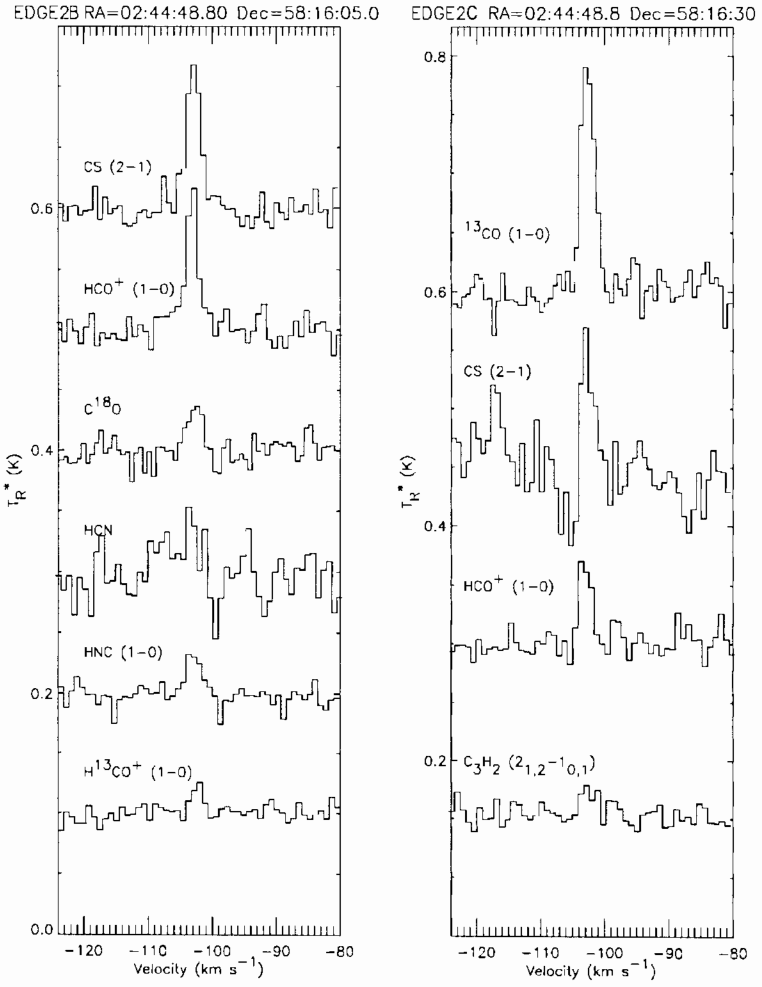

Fig. 1.4. Molecular lines observed in Edge Cloud 2 at positions B and C.with a y-axis of T_r^* in increments of 0.05 K.