The Composition at the Outer Edge of the Galaxy

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ABSTRACT

We present observations of a 10-Gyr-old molecular cloud at the outer edge of the Galactic disk (28 kpc). We detected CO, ^{13}CO, ^{18}CO, CS, CN, SO, HCN, HNC, HCO^+, CH_3OH, HCS^+, H_2CO, C_2H, C_3H_2, and NH_3 but we did not detect CO^+, N_2H^+, DCN, HC_3N, ^{34}CS, SiO, SiS, ^{17}CO, or SO_2. The NH_3, H_2CO, and CS abundances indicate that T = 20 K and n = 5x10^3 cm^{-3}. The N-containing molecules were weak and we did not detect the usually strong N_2H^+ or HC_3N lines. Using our 5300 chemical reaction model we calculate that the N is depleted in this cloud by about 24*x* and this cloud has a 5*x* lower metallicity (similar to dwarf irregular galaxies or damped Lyman alpha systems) and a lower cosmic-ray ionization rate possibly resulting from 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 10 Gyr old gas gas from the early halo and is a window to the early Galaxy providing a new way to understand the origin of the Galactic disk.

INTRODUCTION

Large 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, 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; Digel et al.,1994, located 28 kpc from the Galactic Center. The purpose of this research is to determine the 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 outer edge of the Galaxy. We observed a large set of molecules because some molecules are tracers of physical properties such at temperature, density or ionization while other species trace the chemical abundances. Our observations are a window to the early Galaxy and provide a new way to understand the origin of the Galaxy.

OBSERVATIONS and RESULTS

We have completed over 300 hours of observations using the U. of Arizona 12m radio telescope on Kitt Peak and the 100m Effelsberg telescope. We observed H_2CO, NH_3, and SO with the Effelsberg telescope. All the other molecules were observed with the 12m telescope. The observations were done in position switching mode. Because this edge cloud is so far away most of the spectral lines are so weak that we required 1-10 hours per molecule per transition. We detected CO, ^{13}CO, ^{18}CO, CS, CN, SO, HCN, HNC, HCO^+, CH_3OH, HCS^+, H_2CO, C_2H, C_3H2, and NH_3. We did not detect DCO^+, N_2H^+, DCN, HC_3N, $C^{34}S$, SiO, SiS, ^{17}CO, or SO_2. The spectra are shown in figures 1 – 6. Figures 1, 2, and 6 of NH_3, SO, and H_2CO, respectively, were taken with the 100 m telescope with mJy on the y-axis. Figures 3, 4, and 5 were taken with the 12m telescope and show the combined spectra for the molecular lines given in table 1. The 12m telescope scale is in T_r* (the equivalent brightness temperature lossless telescope with unity efficiency outside the atmosphere) and the 100m scale in flux density where S = 1.02 T_r*. The y-axis for figures 4 and 5 is shown in increments of 0.020 K while for the stronger lines of ^{13}CO, CS, and HCO^+ in figure 6 the y-axis is shown in increments of 0.100 K Most of our observations of EC2 were done at the position Edge 2A [_ = 02:44:52.6; _ = 58:16:00 (1950)]. We also made observations at two additional positions, Edge 2B and Edge 2C, shown in figure 2. Our results are presented in Table 1., where we list the molecule, transition, intensity, and rms.

Table 1. Molecules observed

Line	Freq. (GHz)	Intensity (K)	rms (K)
$H_2CO\ 2_{11}-1_{10}$	150.49839	0.037	0.005
CS 3-2	146.96905	0.043	0.008
$C^{34}S$ 3-2	144.61715		0.01
$H_2CO\ 2_{12}-1_{11}$	140.83952	0.051	0.013
$CN\ 1_{3/2,5/2}-0_{1/2.3/2}$	113.49098	0.021	0.004
$1_{3/2,3/2}-0_{1/2.1/2}$	113.49098	0.016	0.004
$C^{17}O$ 1-0	112.35899		0.007
^{13}CO 1-0	110.20135	0.718	0.065
$C^{18}O$ 1-0	109.78216	0.057	0.014
SO 3-2	99.29988	0.057	0.007
CS 2-1	97.98097	0.125	0.024
$CH_3OH\ 2_0-1_0$ A+	96.741420	0.019	0.005
$2_{-1}-1_{-1}$ E	96.73939	0.025	0.005
N_2H^+ 1-0	93.1735		0.007
HNC 1-0	90.6635	0.032	0.007
HCO^+ 1-0	89.18852	0.132	0.014
HCN 1-0	88.6318	0.036	0.013
	88.6339	0.051	0.013
C_2H 1-0	87.3169	0.073	0.007
	87.3286	0.028	0.007
$H^{13}CN$ 1-0	86.34018		0.006
HCS^+ 2-1	85.3479	0.032	0.009
$C_3H_2\ 2_{12}-1_{01}$	85.3382		0.016
HC_3N 9-8	81.88147		0.007
DCO^+ 1-0	72.03933		0.005
$SO\ 1_0-0_1$	30.002	0.073	0.018
NH_3 2-2	23.723	0.0146	0.005
1-1	23.694	0.040	0.006
$H_2CO\ 2_{11}-2_{12}$	14.488	-0.0125	0.006
$1_{11}-1_{12}$	4.830	-0.0355	0.006

Figure 1.

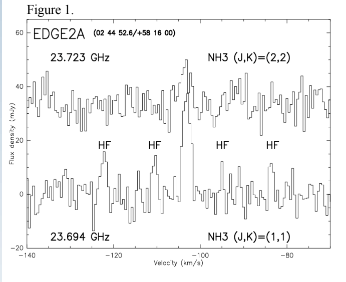

Figure 2.

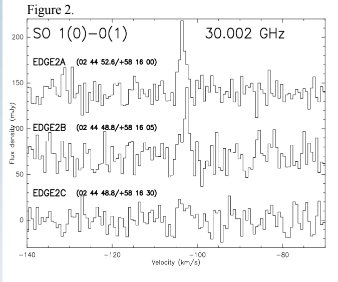

Figure 3.

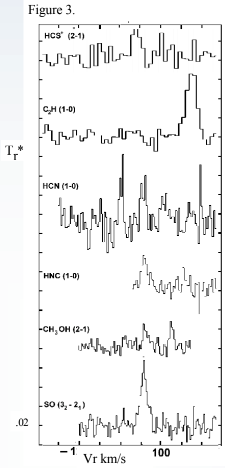

Figure 4.

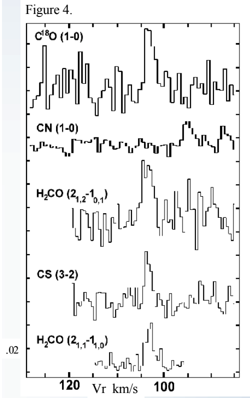

Figure 5.

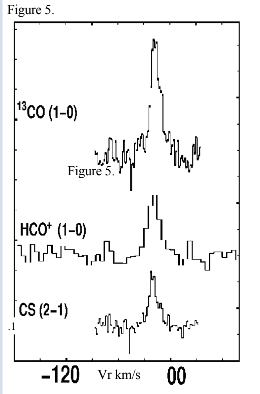

Figure 6.

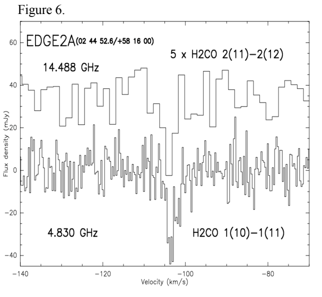

Table 2. Molecular Abundance Ratios

X/HCO^+	Edge cloud	Low N (3*x*) model	L 134N
CS	.692	.168	.124
SO	1.04	.065	.719
NH_3	3.01	3.13	7.63
NH_2^+	< .024	.034	.077
CN	.600	2.08	.061
HCN	.506	.274	.925
HNC	.212	.327	3.25
HC_3N	< .029	.010	.054
CH_3OH	.309	.0016	.641
C_2H	14.9		.288

DISCUSSION and CONCLUSIONS

Using our molecular transition model we determined that the gas temperature is T_k = 20K (from 12 hyperfine lines of NH_3) and the density is 5x10^3 cm^{-3} (from four lines of H_2CO). In order to analyze the composition of this cloud we have calculated the abundance ratios for the molecules X/HCO^+ for the edge cloud. In table 2 we compare the X/HCO^+ ratios in the edge cloud and in L134N (a dark starless cloud above the Galactic plane) to our low metallicity-low N model based on our 5300 chemical reaction astrochemistry code (Roberts and Millar, 2000, A&A, 361, 388). We calculated the molecular abundances from the analysis gradient (Rolleston, Smartt, Dufton, and Ryans; 2000, A&A, 363, 537) extended to 28 kpc with 5*x* lower abundances of C, O, Fe, and Si; and an 8*x* lower N abundance. We then reduced the N abundance by an additional 3*x* resulting in a 24*x* decrease in N and increased the D abundance by 3*x*. Our results are consistent with current models of Galactic chemical evolution that predict that the abundances of C, N, O, ^{13}C, and ^{15}N will be the lower at the edge than in any other interstellar cloud (Maciel and Quireza., 1999, A&A, 345, 629) because the infall of gas occurs at a faster rate in the innermost regions than in the outermost ones (Matteucci & Chiappini, 1999, Astroph. and Sp. Sci., 265, 425). Combing our observations and chemical model we estimated that this cloud is depleted in N so that we are observing gas from an early burst of massive star formation in the Galactic halo. 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. Thus the edge cloud probably results from infalling 10 Gyr old gas gas from the early halo giving us an opportunity to study the formation of the Galactic disk. Our observations are a window to the early Galaxy and provide a new way to understand the origin of the Galactic disk. The edge cloud has an unusual composition that may be unique in the Galaxy and similar to dwarf irregular galaxies

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