Metal-poor Molecular Gas in Edge Cloud 2

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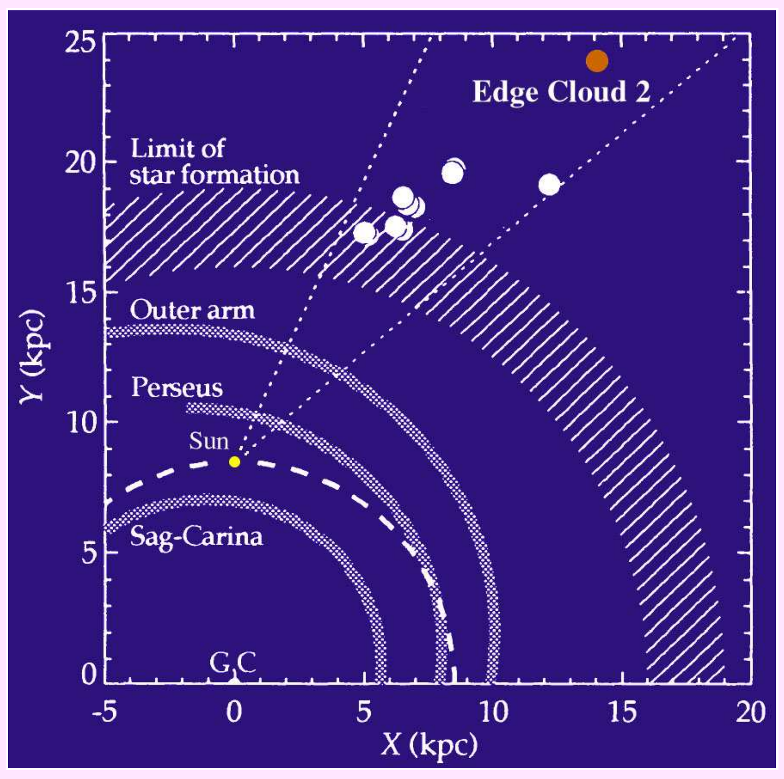

Figure 1: Distant molecular clouds on the Galactic plane (Digel et al. 1994).

Edge Cloud 2 (EC2) is a molecular cloud at a kinematic galactocentric distance of 28 kpc, some 6 kpc further away than the next most distant molecular cloud, and much further than the extent of the optical disk of the Milky Way, $\sim$ 19 kpc, and almost as far as the most distant H I detected, at $\sim$ 30 kpc. EC2 was found to have an associated H II region excited by an early B star MR1 (de Geus et al. 1993), and Snell et al. (2002) argue that it is the most distant star-forming cloud in the Milky Way, with evidence for massive star formation. Rolleston et al. (2000) have calculated metal depletion for C, N, O $\sim$ 5, and EC2 is the only edge cloud detected in the high-density tracer CS (Digel et al. 1996). We are carrying out an observational study of EC2 to determine physical parameters, chemical abundances and isotopic ratios by developing a chemical kinetic model of metal-poor gas. This will afford us a window to the early Galaxy and to molecular evolution in low metallicity Galactic clouds and extragalactic sources.

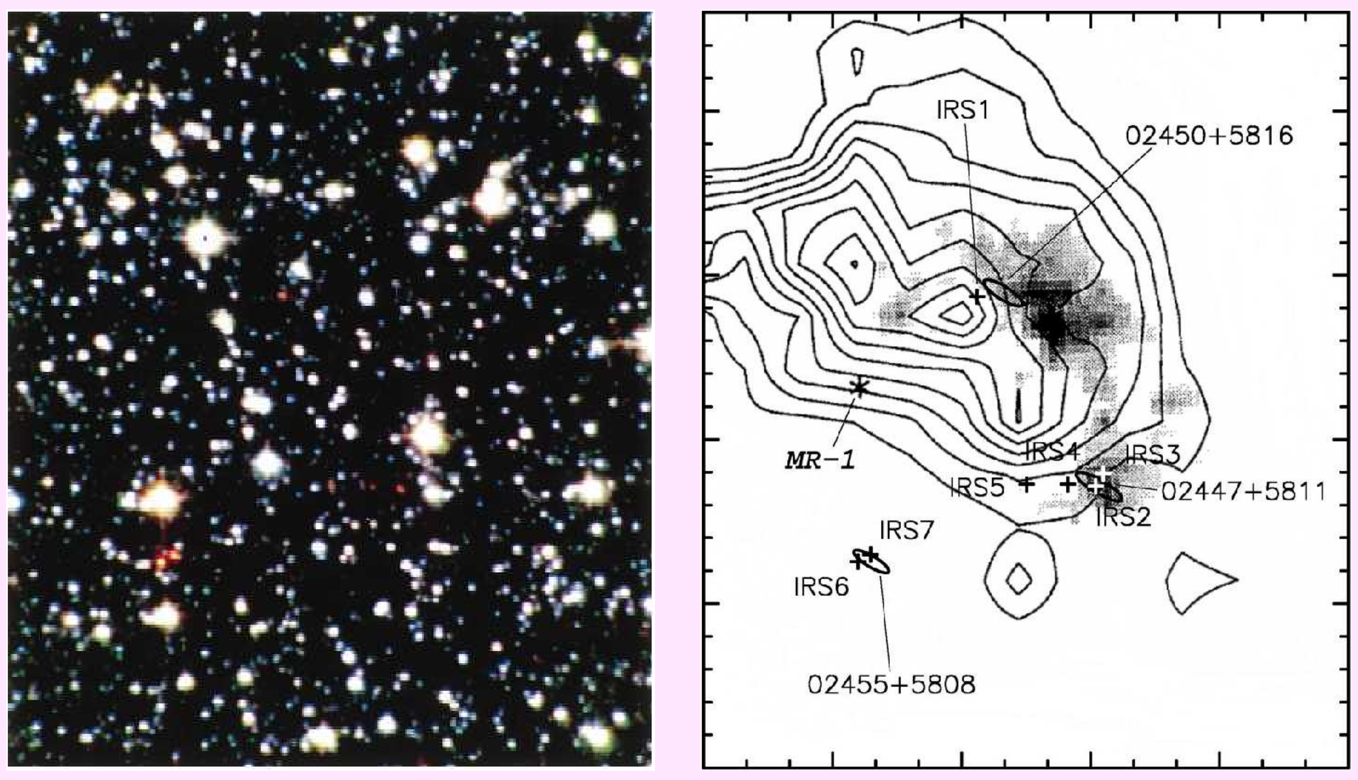

Figure 2: Seven red NIR (near infrared) sources associated with EC2 (Kobayashi & Tokunaga 2000; de Geus et al. 1993). Image and map size 23.0' (NS) $\times$ 19.6' (EW).

Observations

We have observed EC2 in a number of molecular lines using the University of Arizona 12m telescope at 3 and 2mm, and the Effelsberg 100m dish at 1.2, 2 and 6cm. Fig. 4 shows a sample spectrum of HCO^+ 1–0 and Table 2 summarises our UoA 12m detections (and non-detections) to date.

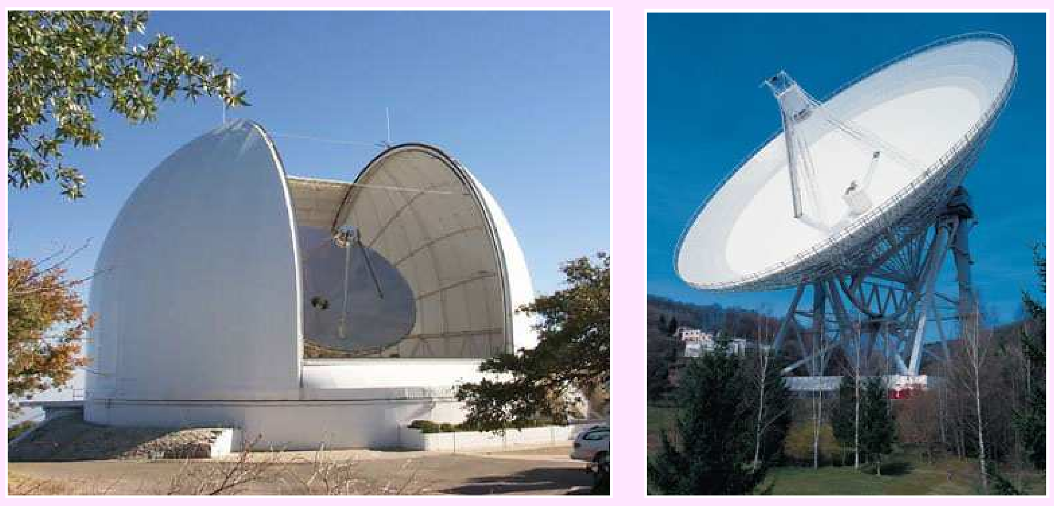

Figure 3: University of Arizona 12m telescope and Effelsberg 100m dish.

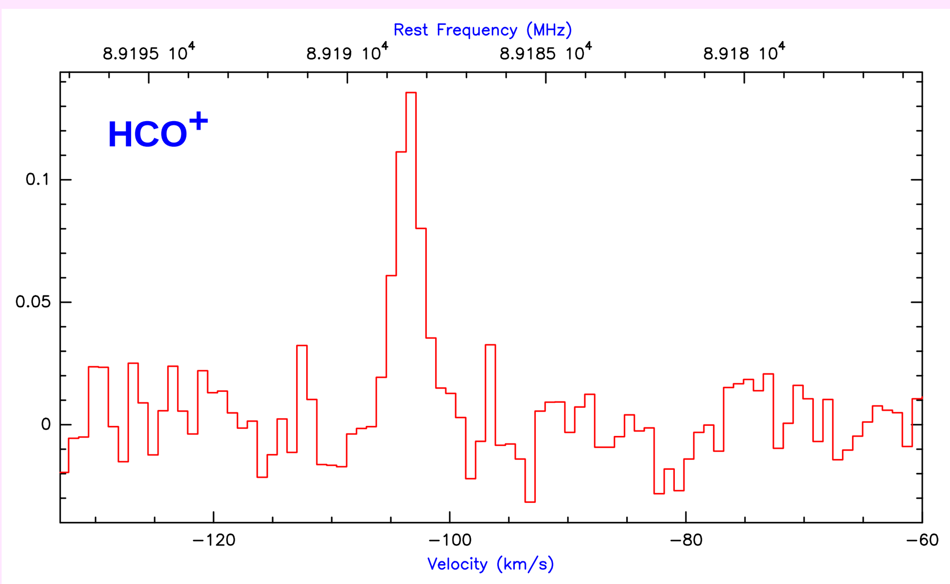

Figure 4: Spectrum of HCO^+ (Formyl) 1–0 observed in EC2. HCO^+ is the next best tracer of H_2 after CO.

Fig. 5 shows Effelsberg spectra of NH_3 and H_2CO from which we derive that the gas temperature is T_k = 20 K (from 12 hyperfine lines of NH_3) and the density is $5 \times 10^3 \mathrm{cm}^{-3}$ (from four lines of H_2CO).

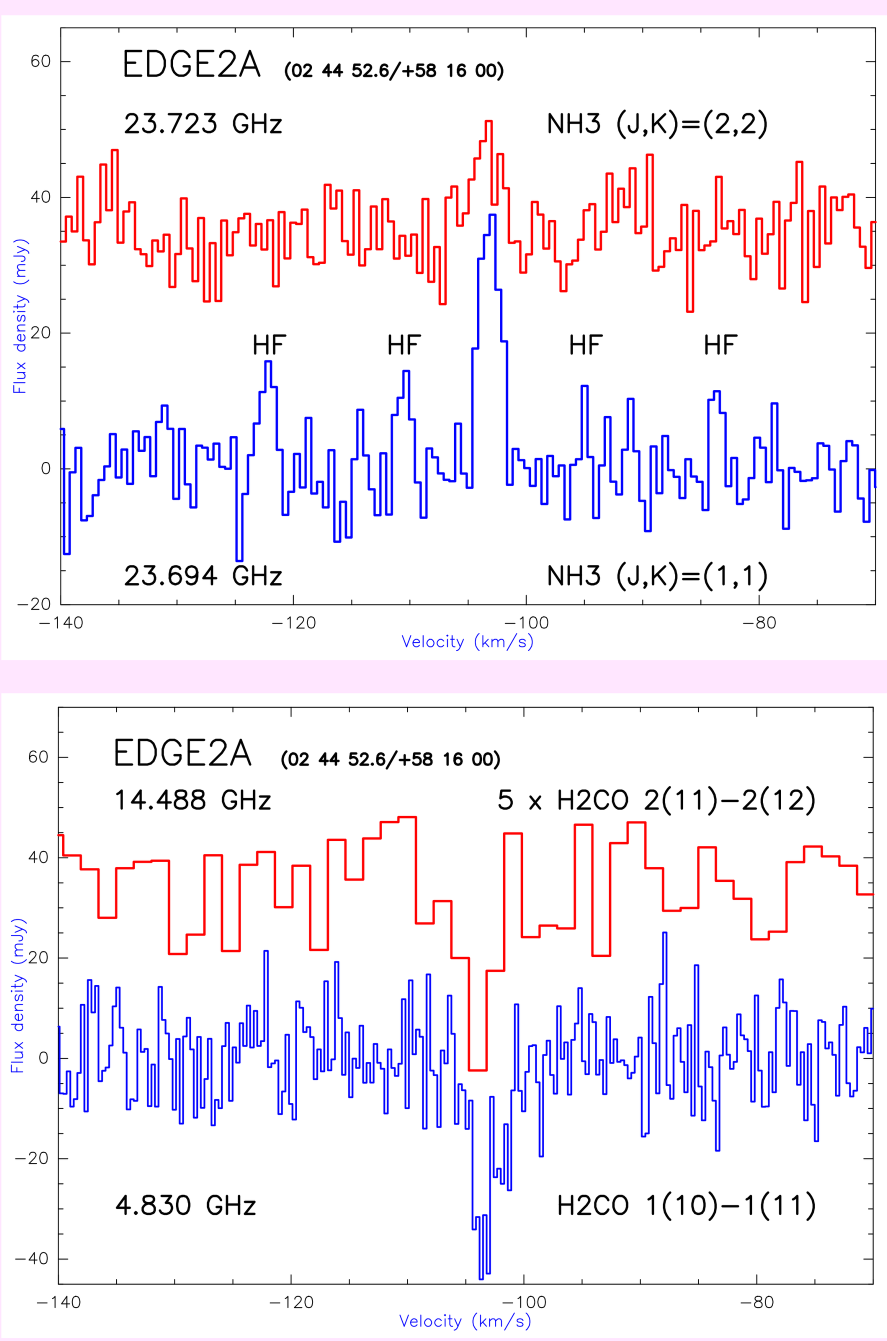

Figure 5: Spectra of (a) NH_3 (Ammonia) (J,K)=(2,2) & (J,K)=(1,1), (HF = group of satellite hyperfine components) and (b) H_2CO (Formaldehyde) 2(11)–2(12) & 1(10)–1(11) observed in EC2.

Analysis

Table 1 shows derived molecular abundances relative to HCO^+ in EC2, and for comparison those in a local dark cloud L134N (Dickens et al. 2000). In total, our observations reinforce the uniqueness of EC2: it has extremely low gas pressure; very small spiral arm perturbation; low metallicity; and similarities to molecular gas in irregular dwarf galaxies such as the Magellanic Clouds. Comparing observed nitrogen bearing molecules in EC2 with L134N, we find N underabundant in EC2.

X/HCO^+	EC2	Low metallicity	L134N
CS	0.692	0.392	0.124
SO	1.040	0.594	0.719
CH_3OH	0.309	0.002	0.641
C_2H	14.900	0.318	0.288
CN	0.600	2.225	0.061
HCN	0.506	0.715	0.925
HNC	0.212	0.873	3.250
HC_3N	< 0.029	0.026	0.054
N_2H^+	< 0.024	0.035	0.077
NH_3	3.010	6.789	7.630

Table 1: Steady-state molecular abundance ratios for a low metallicity model compared to EC2 and L134N (Dickens et al. 2000). Model parameters: $T_k = 10$ K; $n(H_2) = 10^4 \mathrm{cm}^{-3}$; CRI $= 1.3 \times 10^{-17} \mathrm{s}^{-1}$; initial abundances as listed in Table 3.

Modelling

In parallel with our observations we are developing chemical kinetic models for EC2, including the effects of low metallicity and the inclusion of deuterium chemistry. A comparison between observations and a low metallicity model is given in Table 1, with initial fractional abundances listed in Table 3. Comparing observed nitrogen bearing molecules in EC2 with our model, we find that there needs to be an additional decrease of N in the model by a factor of $\sim$ 2 to obtain a clear agreement with observations (except for CN). Compared to 'local' clouds such as L134N, N in EC2 is thus underabundant by a factor of $\sim$ 10. Fig. 6 shows a plot of fractional abundances of some species versus time using different parameters to those of the low metallicity model in Table 1, but the same elemental abundances as listed in Table 3. Since this shows that DCN/HCN and HCN, etc. vary with time, we also need to investigate the 'early time' behaviour of our models to determine the age of EC2.

Line	Trans.	Intensity (K)	rms (K)
^{13}CO	1–0	0.718	0.065
$C^{18}O$	1–0	0.057	0.014
$C^{17}O$	1–0	—	0.007
CS	2–1	0.125	0.024
CS	3–2	0.043	0.008
$C^{34}S$	3–2	—	0.01
CH_3OH	2_0–1_0 A^+	0.019	0.005
	2_{-1}–1_{-1} E	0.025	″
H_2CO	$2_{1,1}$–$1_{1,0}$	0.037	0.005
$H^{13}CO^+$	1–0	—	0.009
DCO^+	1–0	—	0.005
$H^{13}CN$	1–0	—	0.006
HC_3N	9–8	—	0.007
N_2H^+	1–0	—	0.007
HCO^+	1–0	0.132	0.014
SO	3_2–2_1	0.057	0.007
HCS^+	2–1	0.032	0.009
C_3H_2	$2_{1,2}$–$1_{0,1}$	—	0.016
C_2H	1–0	0.073	0.007
		0.028	″
HCN	1–0	0.036	0.013
		0.051	″
HNC	1–0	0.032	0.007
H_2CO	$2_{1,2}$–$1_{1,1}$	0.051	0.013
CN	$1,\frac{3}{2},\frac{5}{2}$–$0,\frac{1}{2},\frac{3}{2}$	0.021	0.004
	$1,\frac{3}{2},\frac{3}{2}$–$0,\frac{1}{2},\frac{1}{2}$	0.016	″

Table 2: Detections in EC2 (2:44:52.6+58:16:0.0 $_{1950}$).

Future Work

The ability to constrain chemical models of EC2 depends on observing tracers which are sensitive to the physical and chemical parameters. We have been awarded time on the JCMT at Mauna Kea Observatory in June 2004 to extend our observations to additional transitions at higher frequency, to better trace the dense gas associated with star formation, and to constrain molecular and elemental abundances, density, temperature, and column densities. In this context, observations of the C I line at 492 GHz will be very valuable in constraining, with CO, the total elemental abundance of carbon, and therefore give additional information on how good the CO/H_2 ratio can trace mass at low metallicities (Walter et al. 2003). Fig. 6 shows that C I is more abundant than CO up to 10^5 years in the model. Likewise, better constraints on the HCO^+ abundance can be linked to the cosmic ray ionisation (CRI) rate and electron fractionation. We shall also be able to compare our results (both elemental and molecular abundances) with those in other dwarf galaxies, particularly the Magellanic Clouds (Chin et al. 1996, 1997, 1998). In connection with the discovery of young stellar objects associated with EC2 (Kobayashi & Tokunaga 2000), we are also planning observations with the Effelsberg 100m dish to look for methanol (CH_3OH) and water (H_2O) masers. Assuming that EC2 is comparable to the MCs, its closer proximity, by a factor of 2-3, offers an ideal opportunity to study star formation in metal-poor molecular gas in greater detail.

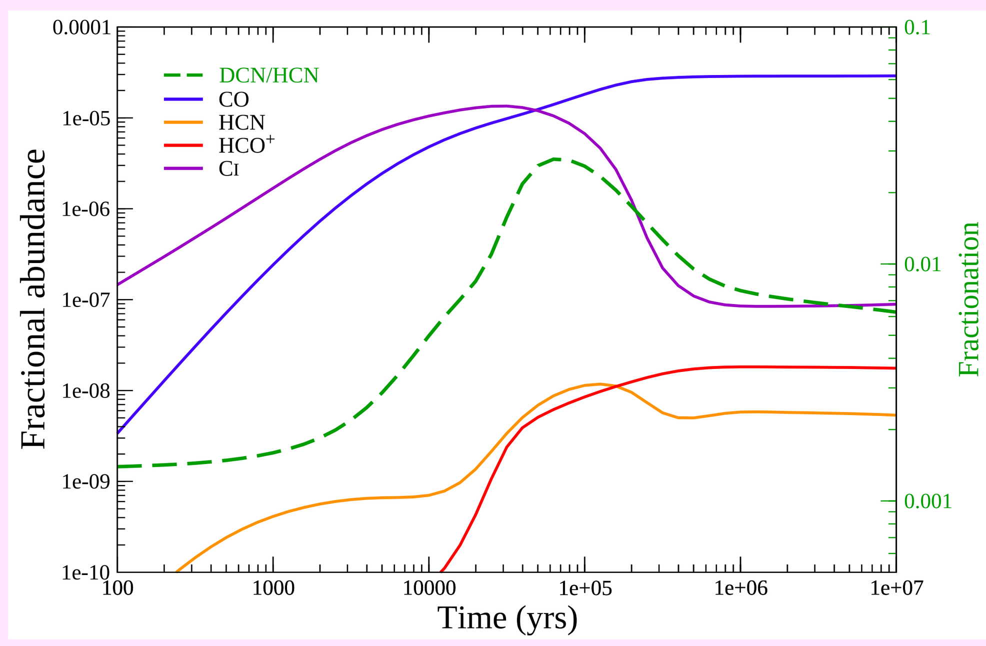

Figure 6: Fractional abundance model for CO, HCN, HCO^+ and C I compared to DCN/HCN with $T_k = 20$ K; $n(H_2) = 5 \times 10^3 \mathrm{cm}^{-3}$; CRI rate $= 1.3 \times 10^{-17} \mathrm{s}^{-1}$; D/H $= 4 \times 10^{-5}$; initial elemental abundances as listed in Table 3.

Species	Abundances	Species	Abundances
H_2	5.00×10^{-1}	Si^+	3.99×10^{-9}
He	1.40×10^{-1}	Fe^+	1.99×10^{-9}
C^+	1.46×10^{-5}	S^+	2.00×10^{-8}
N	2.69×10^{-6}	HD	1.60×10^{-5}
O	3.51×10^{-5}		

Table 3: Initial fractional abundances, relative to total hydrogen density, used in low metallicity model (Table 1) and fractional abundance model (Fig. 6).

References

Chin, Y.-N., Henkel, C., Millar, T. J., Whiteoak, J. B., & Marx-Zimmer, M. 1998, A&A, 330, 901

Chin, Y.-N., Henkel, C., Millar, T. J., Whiteoak, J. B., & Mauersberger, R. 1996, A&A, 312, L33

Chin, Y.-N., Henkel, C., Whiteoak, J. B., et al. 1997, A&A, 317, 548

de Geus, E. J., Vogel, S. N., Digel, S. W., & Gruendl, R. A. 1993, ApJL, 413, L97

Dickens, J. E., Irvine, W. M., Snell, R. L., et al. 2000, ApJ, 542, 870

Digel, S., de Geus, E., & Thaddeus, P. 1994, ApJ, 422, 92

Digel, S. W., Lyder, D. A., Philbrick, A. J., Puche, D., & Thaddeus, P. 1996, ApJ, 458, 561

Kobayashi, N. & Tokunaga, A. T. 2000, ApJ, 532, 423

Rolleston, W. R. J., Smartt, S. J., Dufton, P. L., & Ryans, R. S. I. 2000, A&A, 363, 537

Snell, R. L., Carpenter, J. M., & Heyer, M. H. 2002, ApJ, 578, 229

Walter, F., Bertoldi, F., Carilli, C., et al. 2003, Nature, 424, 406

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