HYDROSTATIC MODELS OF MOLECULAR CLOUDS

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1. INTRODUCTION AND SUMMARY

It is customary to convert observed brightness temperatures of molecular lines to molecular column densities by assuming some excitation temperature to describe the population of the energy levels of the molecule. Observers often speak about "abundances" after dividing these column densities by the dimension of the cloud that is being studied. This procedure can be misleading because the level populations are usually not well characterized by one single excitation temperature and because clouds are probably quite centrally condensed. Some molecules are formed preferentially at high densities in the opaque cores of clouds, others reach their maximum abundance in the moderately shielded much less dense outer regions of clouds.

We have constructed a plane-parallel model of the well-studied molecular cloud L134 assuming that it is in hydrostatic equilibrium supported by turbulent pressure. This cloud model is quite centrally condensed. Molecular abundances are calculated by solving the coupled set of equations of chemical equilibrium and thermal balance as a function of depth in the cloud. Depletion of atoms and molecules onto dust grains is taken into account. Column densities of several molecules are predicted and compared with the observations.

2. INGREDIENTS OF THE MODEL

We consider a self-gravitating plane-parallel cloud layer that is in hydrostatic equilibrium supported by turbulent pressure. The turbulence is assumed to be Gaussian and is characterized by the Doppler width δV_D. The chemistry consists of about 150 reactions between about 40 species of the Carbon-Oxygen family (Herbst and Klemperer 1973; Black and Dalgarno 1977). The gas is heated by photoelectrons from dust grains

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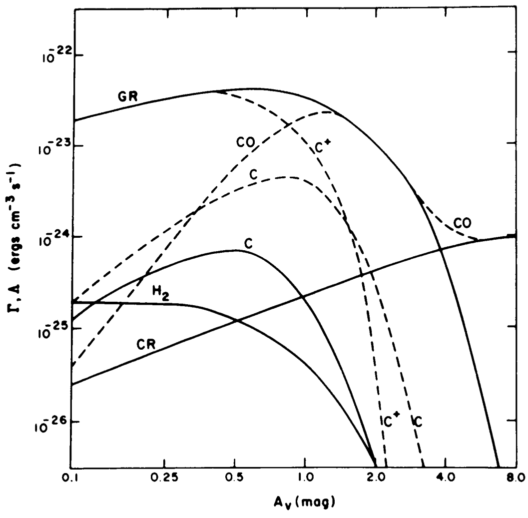

Figure 1. Heating (——) and cooling (- -) rates in the cloud model of L134.

and by cosmic ray (CR) ionizations. It is cooled by collisional excitation of C^+ions, C^oatoms and CO molecules followed by radiative decay. Radiation trapping of the cooling photons is very important (in the core of the cloud). The escape probability of the cooling radiation is calculated assuming the same turbulent velocity field characterized by the parameter δV_D. The depletion of Carbon and Oxygen by collisions with and sticking onto dust grains is approximately included in the calculations by assuming that depletion occurs through CO collisions. The depletion depends on the temperature and the density of the gas. The amount of depletion increases with depth and depends on the age of the cloud. For more details the reader is referred to de Jong, Dalgarno and Boland (1979).

TABLE 1. Parameters characterizing the cloud model of L134

A_V	$n_H(cm^{-3})$	T(K)	δ
0	35	68	0.250
0.1	840	33	0.209
0.25	2040	27	0.168
0.5	4000	24	0.120
1	7710	21	0.068
2	14400	13.3	0.036
4	24700	6.7	0.023
8	32800	7.0	0.010

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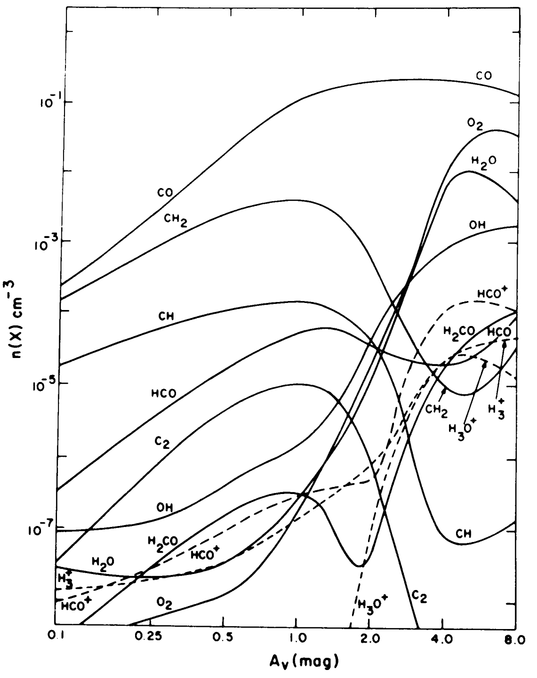

Figure 2. Molecular abundances in the cloud model of L134.

3. A MODEL OF L134

The dark cloud L134 is about 1pc in diameter and has a visual extinction in the centre larger than 7 magnitudes. Molecular line observations of L134 have recently been summarized by Mattila, Winnberg and Grasshoff (1979). The temperature in the core of the cloud is about 10K (from CO) and the molecular Hydrogen density in the core exceeds 10^4cm^{-3}(from H_2CO). The full width at half maximum of the molecular lines is in the range 0.3 -1 km s^{-1}. In the core of the cloud Carbon and Oxygen are strongly depleted and the degree of ionization is quite low (Watson, Snyder and Hollis 1978). The "observed" column densities of several molecules are given in Table 2.

Our model of L134 consists of a symmetrical plane-parallel cloud layer with a visual extinction of 8 magnitudes to the centre. The ambient gas pressure is 3×10^3K cm^{-3} and the ambient radiation field is interstellar. The turbulence parameter δV_D equals 1 km s^{-1} and we have assumed a CR ionization rate of 2×10^{-18} s^{-1}. The resulting density and temperature distribution is given in Table 1. The thickness of the cloud layer is 0.9pc. The depletion factor δ decreases strongly towards the centre. The temperature distribution is hardly affected by the depletion because the cooling lines are thermalized (cooling independent of abundance cf. de Jong, Chu and Dalgarno 1975).

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TABLE 2. Observed and predicted column densities (cm^{-2}) in L134.

Species	N(H)/T*	CH	OH	CO	HCO^+	H_2CO
observed	1×10^{18}	1×10^{14}	5×10^{14}	4×10^{17}	4×10^{13}	1×10^{14}
predicted	1.3×10^{18}	9.7×10^{13}	7.2×10^{14}	2.0×10^{17}	6.7×10^{13}	3.0×10^{13}

Species	CH_2	H_2O	H_3O^+	HCO	C_2	O_2
predicted	2.4×10^{15}	3.2×10^{15}	1.1×10^{13}	6.0×10^{13}	4.7×10^{12}	1.1×10^{16}

*quantity proportional to 21 cm optical depth (units $cm^{-2}\ K^{-1}$)

In figure 1 we show the heating and cooling rates as a function of depth in the cloud. In the outer parts the gas is heated by photoelectrons from dust grains and cooled by C^+ fine structure transitions. In the core CR heating and CO rotational line cooling dominate.

In figure 2 we show the variation with depth of the abundances of several molecular species. There are clearly two regimes. In the outer parts molecules are formed by diffuse cloud chemistry (CH, CH_2, C_2 and HCO) and in the core dark cloud chemistry dominates (OH, H_2O, HCO^+, H_2CO and O_2). All Carbon is in CO over most of the cloud. The use of more up-to-date chemical schemes (cf. Huntress 1979) changes some of these features but the general pattern persists (de Jong et al. 1979). The predicted column densities in Table 2 are in fair agreement with those derived from the observations.

The degree of ionization in the cloud core is very low ($\sim 10^{-8}$). The main ion is HCO^+. This low degree of ionization is of importance for the dynamical evolution because the ambipolar diffusion time of the cloud becomes of the same order of magnitude as the cooling time, the chemical equilibrium time and the free-fall time (all of order few times 10^5yrs). Since these time scales are smaller than the age of the cloud (few times 10^6yrs derived from the amount of depletion) nothing, apart possibly from rotation, seems to prevent fragmentation and star formation in the core of L134.

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DISCUSSION FOLLOWING DE JONG

Kutner: You compare certain abundances predicted by the model with observed abundances, but the observed abundances are really derived quantities dependent on some cloud model. Would it not be a more meaningful test of any cloud model to synthesize line profiles for various species at various positions, and compare them with the observations?

de Jong: Yes, I think so. We are planning to calculate the brightness temperatures of several molecular lines in L134 to carry out such a comparison. The only observed line whose brightness temperature is calculated in our model is the $J=1 \rightarrow 0$ line of CO at 2.6 mm, because it is one of the cooling lines. Its predicted brightness temperature is about 12K, in excellent agreement with the observations.

Churchwell: L134 and TMC1 are two cloudlets where the line widths are roughly equivalent to the expected thermal width. There is also an indication of a significant rotation rate. Therefore one must depend on other mechanisms to support the clouds. How fast must the core rotate to support itself against gravitational collapse? Is it slow enough that the rotation could have been missed? Or are these clouds perhaps being supported in some other way (e.g. magnetic field)?

Clark: Published data establish reasonably unambiguously that L134 is rotating (Brooks et al.) and has an equatorial bulge. It would seem that your model may be inappropriate.

de Jong: These questions have crossed our minds. We have also constructed models that are supported purely by thermal pressure. These models are even more strongly centrally condensed. However the observations indicate that, though the core of these clouds may be supported by thermal pressure alone, in the outer parts the line widths are superthermal. As far as rotation is concerned, of course rotation affects the density stratification of the cloud. Thermal pressure and rotation could in principle be incorporated in our models. The present approach has been chosen because it is simple and easy.

Mouschovias: How did you obtain your estimate of the time scale for ambipolar diffusion? Are you aware of a recent result that this time scale varies by many orders of magnitude from point to point within a dense cloud (Ap. J. 228, 475, 1979)?

de Jong: I am arguing that the ambipolar diffusion time varies strongly with position in the cloud because it is proportional to the degree of ionization. Only in the core of the cloud does the degree of ionization become sufficiently small that the magnetic field cannot prevent collapse.

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