Models of molecular clouds

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Chapter II

CARBON DEPLETION IN TURBULENT MOLECULAR CLOUD CORES

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Acccepted for publication in The Astrophysical Journal
Received, November 15, 1981; accepted, April 1, 1982

SUMMARY

Observations of dense molecular cloud cores indicate that about 10% of the carbon is still in the gas phase (depletion factor ~0.1) in spite of the fact that the depletion time, the time needed for heavy elements to freeze out on dust grains, is several orders of magnitude smaller than the cloud lifetime. To resolve this problem we suggest that the material in molecular cloud cores is circulated by turbulence and that every time a parcel of gas and dust reaches the outer layers of the core, dust mantles that have formed by accretion in the center are evaporated and/or photodesorbed. The observed mild degree of depletion results because the circulation time and the depletion time are of the same order of magnitude. Since the time to reach molecular equilibrium in the outer layers of a cloud core is short compared to t_{circ} the dust plays no role in the chemistry. In the center of a cloud core the time to convert C to CO is of order t_{circ} so that an appreciable fraction of the gaseous carbon remains in atomic form. From a brief discussion of the energetics we conclude that the turbulence observed in molecular cloud cores can be maintained during the lifetime of the cloud if the envelope collapses onto the core at a rate of about 10^{-6} $M_{\odot}$ yr^{-1}.

Subject headings: Interstellar: molecules -- turbulence.

1. INTRODUCTION

Ever since the interaction of interstellar gas with dust grains was first studied in the 1940's it has been assumed that all atoms and molecules heavier than helium will stick upon collision with dust grains at the low dust temperatures that prevail in interstellar space (van de Hulst, 1949; Hollenbach and Salpeter, 1970). If indeed all heavy elements stick upon collision with dust grains the depletion timescale, the time required for heavy atoms and molecules to condense out on grains, is of order several times 10^5 yr at gas densities of about 10^4 cm^{-3} typical for the cores of molecular clouds. On the other hand the lifetimes of molecular clouds are of order 10^7 yr or larger (Bash, Green and Peters, 1977; Cohen et al., 1980) so that it is difficult to understand the relatively mild degree of carbon depletion of about 0.1 (the fraction still remaining in the gas phase) that has been derived for several molecular cloud cores from the observation of DCO^+/HCO^+ ratios (§2).

From a review of the physical processes that could return molecules from dust grains to the gas phase (§3) we find that in the outer layers of a cloud evaporation and photodesorption of grain mantles are sufficiently efficient to return most heavy elements to the gas phase. In the cores of molecular clouds, however, none of the processes discussed can prevent virtually all heavy elements from condensing out on grains.

To resolve the depletion dilemma we propose in this Letter that matter in the molecular cloud core is circulated by turbulent motions such that the core is continuously replenished with undepleted matter from the surface layers (§4). This circulation is an effective way of limiting the depletion because the circulation time scale is of the same order of magnitude as the depletion time scale in the cloud core.

2. MOLECULAR CLOUD CORE PARAMETERS

In Table 1 we summarize physical parameters of the gas in the quiescent cores of several well-studied molecular clouds. For our calculations to be presented in §3 we use the parameters listed under "standard cloud core". Models of hydrostatic cloud cores supported by turbulent pressure have recently been constructed to explain the observations of L134 by de Jong, Dalgarno and Boland, (1980).

Table 1: Parameters for several molecular cores

Cloud	Distance (pc)	Core size (pc)	v_t[a] km s^{-1}	T K	$n(H_2)$ cm^{-3}	$\frac{DCO^+}{HCO^+}$	δ_C	Ref.
L 134	100	0.3×0.5	0.3	10	9×10^3	0.12	0.07	1-5
L 183	100	0.06×0.17	0.14	9	3×10^4	0.11	0.08	6,7
						0.20	0.04	8
TMC 1	100	0.06×0.25	0.4	10	3×10^4	0.05	0.17	7,9
TMC 2	100	0.09	0.3	10	1×10^4			10,11
Standard cloud core		0.2	0.3	10	2×10^4		0.09	

[a]Turbulent velocity defined as $v_t = \Delta v(FWHM)/(\pi \ln 2)^{1/2}$.

References:

1. Mattila et al. (1979)
2. Downes et al. (1976)
3. Dickman et al. (1980)
4. Wootten et al. (1980)
5. Watson et al. (1978)
6. Ungerechts et al. (1980)
7. Langer et al. (1978)
8. Snell (1979)
9. Churchwell et al. (1979)
10. Walmsley et al. (1980)
11. Ho et al. (1977)

On the assumption that virtually all gas phase carbon is in CO an upper limit to the carbon depletion factor δ_C, the ratio of the gas phase abundance to the cosmic abundance of carbon, can be derived from observations of the $DCO^+/H^{13}CO^+$ line ratio. This derivation is based on chemical fractionation schemes reviewed by Watson (1977). Recent laboratory measurements by Adams and Smith (1981) of the crucial reaction

$$H_3^+ + HD \rightleftarrows H_2D^+ + H_2 \qquad (1)$$

suggest that the forward rate-coefficient of this reaction, and consequently of the DCO^+ formation rate, is enhanced by a factor of six compared to previous estimates (Watson, Snyder and Hollis 1978; Langer et al. 1978). The carbon depletion factors of $\delta_C \approx 0.1$ listed in Table 1 are calculated using the new rate of reaction (1). Similar depletion factors have recently been derived by Frerking, Langer and Wilson (1981) for several dense cores in the molecular cloud complexes near ρ Ophiuchi and in Taurus using a different method based on $^{12}C^{18}O$ observations.

3. MOLECULE EJECTION FROM DUST GRAINS

Before reviewing several physical processes that could return molecules adsorbed onto grains to the gas phase we first derive an expression for the depletion factor δ. Let R_{ej} be the ejection rate of molecules from grains per individual adsorbed molecule and let N be the number of molecules available for ejection per dust grain. Then the depletion factor δ can be calculated from the steady-state equation

$$\frac{\delta\, x_{mol} n_H}{t_{depl}} = n_d N R_{ej} \qquad (2)$$

where x_{mol} is the molecular abundance with respect to hydrogen, n_H is the hydrogen nuclei density, n_d is the dust grain density, and t_{depl} is the time it takes for molecules moving at thermal velocities to collide with a dust grain.

To numerically evaluate Eq.(2) we adopt $x_{mol} = 6\times10^{-4}$ and $m_{mol} = 28\ m_H$ equivalent to assuming that all heavy elements (CNO) are in molecules and that on the average each molecule contains two heavy atoms. For the dust we adopt the following parameters: a dust-to-gas mass ratio of 0.01, a grain radius of 2×10^{-5} cm and a specific density of dust grain material of 1 gr cm^{-3}, equivalent to assuming a dust-to-gas number density ratio of 5×10^{-13} and a mean projected surface area of dust grains per hydrogen nucleus of 6×10^{-22} cm^2 (cf. Spitzer, 1978). We note that these dust parameters imply that in the general interstellar medium about half of all heavy atoms are locked up in dust grains in good agreement with C, N and O abundances observed in diffuse interstellar clouds (Morton, 1974; Lugger et al., 1979; de Boer, 1979).

Inserting the gas and dust parameters discussed above and assuming that all molecules stick upon collision with a dust grain we obtain

$$t_{depl} = 2\times10^{10}\ n_H^{-1}\ T^{-1/2} \quad \text{yr} \qquad (3)$$

and

$$\delta = 5\times10^{8}\ NR_{ej}\ n_H^{-1}\ T^{-1/2} \qquad (4)$$

where NR_{ej} is in s^{-1}, n_H in cm^{-3} and T in Kelvin. In the derivation of Eqs.(2-4) we have neglected the fact that owing to the depletion the dust grain surface area increases (by a factor less than $2^{2/3}$).

Throughout the remainder of this Letter we shall use this theoretical average CNO depletion factor for comparison with the observed carbon depletion factor.

a) Thermal evaporation

According to Watson and Salpeter (1972) the rate of thermal evaporation of molecules from dust grains may be written

$$R_{ev} \approx 1 \times 10^{12} \exp\left[\frac{-D}{T_d}\right] \quad \text{molecule}^{-1}\ s^{-1} \qquad (5)$$

where D is the adsorption energy in Kelvin of a molecule on the grain surface and T_d is the temperature of the dust grains. Vapor pressure data (cf. Weast 1976) indicate a sublimation heat of D $\approx$ 1000 K for CO, O_2 and N_2 and larger values for other molecules. Then we find from Eq.(2) that for $N = 3\times10^6$ molecules in the surface layer of a dust grain a dust temperature $T_d \gtrsim 20$ K is required to prevent the depletion factor from decreasing below 0.1 at typical molecular cloud core densities. To maintain $T_d \geq 20$ K in molecular clouds an embedded energy source or a dust heating mechanism other than radiative heating is required.

Draine and Salpeter(1979b) have recently discussed the evaporation of dust grains due to heating by optical light flashes of supernovae. Neglecting interstellar extinction but including the effect of extinction A_V into the cloud we find from their analysis that grain mantles will completely evaporate out to a distance $d = 930\ (1000\ K/D)^{3.3} \exp(-0.5\ A_V)$ pc from the supernova. Assuming that supernovae occur once per 25 yrs in the galactic disk (radius 15 kpc) we then derive an ejection rate $R_{SN} = 1.5\times10^{-4}\ (1000\ K/D)^{6.6} \exp(-A_V)\ yr^{-1}$ per adsorbed molecule for the case that d exceeds the half thickness of the gaseous disk. Then for $N = 3\times10^8$ molecules in a grain mantle we find from equation (4) a depletion factor

$$\delta_{SN} = 6 \left(\frac{2\times10^4\ cm^{-3}}{n(H_2)}\right) \left(\frac{1000\ K}{D}\right)^{6.6} \left(\frac{10\ K}{T}\right)^{1/2} \exp[-A_V] \ . \qquad (6)$$

In the outer layers of a cloud core where $n(H_2) \approx 10^3\ cm^{-3}$ and $T \approx 25$ K (de Jong, Dalgarno and Boland, 1980), grain mantle sublimation by supernova flashes keeps the heavy elements from depleting below $\delta \approx 0.1$ if $A_V < 6$. The extinction toward the center of a cloud core typically amounts to about 8 visual magnitudes (cf. Table 1).

The rate of grain mantle evaporation may be enhanced by the grain explosion process proposed by Greenberg (1976). Dust grains exposed to ultraviolet radiation require less heat to evaporate because of the chemical energy stored in the grain mantle during photoprocessing by ultraviolet photons.

b) Photodesorption

Ultraviolet photons are able to desorb molecules from the surface of a dust grain. The efficiency of this process, however, is quite uncertain (Watson and Salpeter, 1972; Barlow, 1978b; Draine and Salpeter, 1979b). The rate of desorption per individual adsorbed molecule is given by

$$R_{des} = 2\times10^{-10}\ \epsilon\chi\ \exp[-1.8\ A_V]\ \text{molecule}^{-1}\ s^{-1} \tag{7}$$

where ϵ is the photodesorption yield, the probability that photoexcitation of the adsorbed molecule will be followed by desorption, χ is an intensity scale factor multiplying the interstellar radiation field of Habing(1968) and A_V is the visual extinction into the cloud. The exponential factor in Eq.(7) is consistent with a photon energy range of 6 to 13.6 eV for photodesorption if we use the grain scattering model of Black and Dalgarno(1977).

Substituting Eq.(7) in Eq.(4) we find a depletion factor

$$\delta_{des} = 0.01\left(\frac{\epsilon}{0.005}\right)\left(\frac{\chi}{1.0}\right)\left(\frac{2\times10^4\ \text{cm}^{-3}}{n(H_2)}\right)\left(\frac{10\ K}{T}\right)^{1/2} \exp[-1.8\ A_V] \tag{8}$$

where we have assumed that photodesorption only operates in the outermost surface layer of the grain mantle containing $N \approx 3\times10^6$ molecules. For $n(H_2) = 10^3\ \text{cm}^{-3}$ and $T = 25$ K in the outer layers of a cloud core photodesorption prevents the depletion from falling below $\delta \approx 0.1$ for $A_V \lesssim 1$.

c) Cosmic rays

Let y be the cosmic ray yield, the number of molecules ejected per low-energy cosmic ray collision with a dust grain. Then from Eq.(4) we derive a depletion factor

$$\delta_{CR} = 3\times10^{-5} y \left(\frac{\zeta}{5\times10^{-18}\ s^{-1}}\right) \left(\frac{2\times10^4\ \text{cm}^{-3}}{n(H_2)}\right) \left(\frac{10\ K}{T}\right)^{1/2} . \tag{9}$$

The numerical factor in Eq.(9) was calculated by converting the cosmic ray ionization rate ζ of H_2 to a proton flux using the ionization cross section of 7.2×10^{-19} cm^2 given by Cravens and Dalgarno(1978) for 100 MeV protons. Estimates of the yield of cosmic rays colliding with dust grains, whether due to sputtering or to evaporation from hot spots, suggests that y is at most equal to one and most probably of order 10^{-4} (de Jong and Kamijo, 1973; Barlow, 1978a; Draine and Salpeter, 1979a). Thus it is clear from Eq.(9) that cosmic rays are unable to prevent heavy elements from becoming almost completely depleted in the cloud core.

d) Grain-grain collisions

The rate at which molecules are returned to the gas by evaporation of dust grains when they collide with each other depends critically on the relative grain velocities. Dirty-ice mantle material which has a sublimation heat of about 10^{10} ergs cm^{-3} evaporates when dust grains collide with relative velocities exceeding 1 km s^{-1}. An upper limit to the evaporation rate of molecules by grain-grain collisions can be derived if we assume that all kinetic energy of the collision is available for evaporation even for relative velocities smaller than 1 km s^{-1}. We then have

$$NR_{gg} < \frac{n_d \sigma_d m_d}{kD} v^3 \qquad (10)$$

where σ_d is the geometrical cross section and m_d is the mass of a dust grain, v is the relative velocity of dust grains and all other symbols have the same meaning as before. Inserting this expression into Eq.(4) and assuming that the gas and dust move together so that dust grains collide with the same relative velocities as observed for the gas ($v = v_t$, the turbulent velocity of the gas, see Table 1) we find an upper limit to the depletion factor

$$\delta_{gg} < 0.6 \left(\frac{v_t}{0.3 \text{ km s}^{-1}}\right)^3 \left(\frac{1000 \text{ K}}{D}\right) \left(\frac{10 \text{ K}}{T}\right)^{1/2} \quad . \qquad (11)$$

However at the gas densities prevalent in molecular cloud cores most grains are slowed down by collisions with the gas before they collide with each other so that the actual value of v will be one to two orders of magnitude smaller than v_t (Völk et al., 1980). Thus molecules are not returned at a high enough rate by grain-grain collisions to explain the observed depletion factor.

We conclude that none of the processes that we have discussed in this section can prevent the gas in the cores of molecular clouds (where $A_V \gtrsim 4$) from becoming much more strongly depleted of heavy elements than is indicated by the observations.

4. DEPLETION IN A TURBULENT CLOUD MODEL

To explain the observed mild degree of depletion in the cores of molecular clouds we present in this section a simple cloud model in which clumps of gas and dust are moving back and forth with the observed turbulent velocities. Each time a clump reaches the surface layers of the cloud the dust mantles which have been growing by accretion in the core are evaporated by SN flashes or photodesorbed by ultraviolet photons of the general interstellar radiation field. Evidence supporting the presence of turbulent motions in molecular clouds has recently been summarized by Evans (1980). At the end of this section we briefly discuss the energetics of turbulent clouds.

Let us consider a cloud core with radius R_c and turbulent velocity v_t so that matter in the surface layers reaches the core on a circulation timescale $t_{circ} = R_c/v_t$. For our standard core parameters we find $t_{circ} \approx 3\times10^5$ yr. A necessary condition for our model to work is that grain mantles in the surface layers of a cloud core completely evaporate or photodesorb on a timescale smaller than t_{circ}. From §3a we find that the outer layers of a cloud ($A_V \lesssim 1$) are illuminated by supernova flashes sufficiently often to evaporate the grain mantle within t_{circ} for $D \lesssim 1500$ K, a typical value for volatile mantle material. According to Eq.(7) the time for one monolayer to photodesorb in the unattenuated interstellar radiation field ($\chi = 1$, $A_V = 0$) equals $160/\varepsilon$ yr so that it takes about $10^4/\varepsilon$ yr to photodesorb the whole mantle. Thus for photodesorption to be sufficiently efficient we require a yield $\varepsilon \gtrsim 0.05$, about one order of magnitude larger than the value estimated by Draine and Salpeter (1978b). The uncertainties in this estimate amount to several orders of magnitude.

When we assume that all collisions of molecules with grains lead to accretion and that depletion only occurs over t_{circ} the average depletion factor in the core of a molecular cloud becomes (cf. de Jong, Dalgarno and Boland, 1980)

$$\delta_{core} = \delta_0 \exp(-t_{circ}/t_{depl}) \quad . \tag{12}$$

Putting $\delta_0 = 0.5$ (cf. §3) and inserting our standard cloud core parameters in Eq.(3) we find $\delta_{core} = 0.07$ in excellent agreement with the observed carbon depletion factors listed in Table 1.

Substituting the explicit expressions for t_{circ} and t_{depl} in Eq.(12) one finds that the depletion factor depends exponentially on the quantity $n_H R_c/\delta V_D$. Therefore in molecular clouds with larger column densities ($A_V \simeq 100$) and larger turbulent motions ($\delta V_D \simeq 2$ km s^{-1}) we still expect depletion factors of order 0.1 on the basis of our model.

The timescale to convert atomic carbon into CO is of order t_{circ} (Prasad and Huntress, 1980) so that we predict C/CO ratios of order unity in molecular cloud cores. Such C/CO ratios have been recently inferred from CI observations of molecular clouds by Phillips et al.(1980).

It is of interest to note that the time to reach chemical equilibrium in the outer layers of a cloud core is short compared to t_{circ} (photoreactions dominant, see de Jong, Dalgarno and Boland, 1980). This implies that molecules coming off dust grains do not affect the molecular equilibrium so that the dust just acts as a sink and as a source of heavy elements.

Because dissipation by shock waves is so efficient it is difficult to understand how turbulence in interstellar clouds can be maintained. According to Fleck (1980) the velocity shear resulting from differential galactic rotation supplies enough energy to maintain the turbulence in giant molecular clouds. However, this mechanism is ineffective for the small molecular cloud cores discussed in this Letter because $v_t/R_c \simeq 3$ km s^{-1} pc^{-1} is much larger than the velocity shear in the solar neighborhood, A-B = 0.03 km s^{-1} pc^{-1} (A and B are the Oort constants of galactic rotation).

Fully developed turbulence on a size scale ℓ has an energy dissipation rate $dE/dt = v_t^3/2\ell$ per unit mass (Batchelor, 1967). From the equation of energy balance we find that in a cloud core of mass M_c and radius R_c the turbulence can be maintained by the release of gravitational energy due to contraction of the core during a time $t_{grav} \simeq 2\ GM_c\ell/R_c v_t^3$. Assuming that the core contracts until $\ell \simeq R_c$ and inserting typical cloud core parameters (see Table 1) we find $t_{grav} \simeq 3\times10^6$ yr, too short to maintain the observed turbulence during the cloud lifetime.

In the core-envelope cloud model suggested by Evans(1980) the envelope of the cloud collapses onto the turbulent hydrostatic core. For this case we derive in the same way as above that an accretion rate of $\dot{M} = v_t^3 R_c/2G\ell$ is sufficient to maintain the turbulence. Inserting our standard cloud core parameters and putting $\ell \approx R_c$ as suggested by the high spatial resolution observations of the TMC 1 core by Churchwell, Winnewisser and Walmsley (1978), we obtain $\dot{M} \approx 10^{-6}\ M_{\odot}\ yr^{-1}$. For the dust cloud L134 Mattila, Winnberg and Grasshoff (1979) estimated a cloud mass $M \gtrsim 50\ M_{\odot}$. Hence the mass of a typical cloud of the kind that we are considering here is large enough to power the turbulence in the core by the collapse of the envelope during its lifetime.

In some molecular cloud cores the turbulence could perhaps be powered by stellar winds from T Tau stars as suggested by Norman and Silk (1980). They consider fairly large and massive molecular clouds containing about 10 T Tau stars per pc^3 (Jones and Herbig, 1979). Due to the presence of T Tau stars the ultraviolet radiation field in the cloud may be somewhat enhanced but not enough to affect the heavy element depletion in the core.

We would like to thank Dr. B. T. Draine for critically reading an earlier version of this paper and Dr. A. Dalgarno for a very useful suggestion. This research was supported in part by the Netherlands Foundation for Astronomical Research (ASTRON) with financial aid from the Netherlands Organization for the Advancement of Pure Research (Z.W.O.).

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