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PHYSICAL AND CHEMICAL FRACTIONATION OF DEUTERIUM IN THE INTERSTELLAR MEDIUM

PAUL BRUSTON,[1] JEAN AUDOUZE,[2] ALFRED VIDAL-MADJAR,[1] AND CLAUDINE LAURENT[1]

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ABSTRACT

Two mechanisms able to induce variations in the interstellar D/H ratio are analyzed:

i) In diffuse or low density media the radiation pressure mechanism induced by UV stellar fluxes shifts the deuterium population with respect to the hydrogen one. This mechanism appears to be very sensitive to temperature gradients and to ionization effects.

ii) In dense media, the deuterium abundance can be enhanced because of the large photodissociation rate of HD by UV fluxes compared to that of H_2 (shielding of H_2).

A comparison between the probabilities to observe a given D/H ratio on a given line of sight shows that the unperturbed D/H ratio should be 2 to 2.5×10^{-5} in the nearby interstellar medium and not 1.5×10^{-5} as commonly thought before.

Finally we note that it is not surprising to observe significant variations of the D/H ratio in the immediate vicinity of the Sun if the hypothesis of the presence of a dense core near the solar system is adopted.

Subject headings: deuterium — interstellar: abundances — interstellar: matter — interstellar: molecules

I. INTRODUCTION

In a previous article (Vidal-Madjar *et al.* 1978), we discussed the possible existence of a nearby interstellar cloud approaching the solar system from the Scorpius-Ophiuchus direction. Such a scenario was designed to account for the important variation of the deuterium to hydrogen ratio between different lines of sight in the vicinity of the solar system. In particular, Dupree, Baliunas, and Shipman (1977) have determined a higher D/H ratio (D/H $\sim 4 \times 10^{-5}$) on the line of sight of α Aur than that of α Cen A where D/H $\sim 3 \times 10^{-6}$. More recently, Laurent, Vidal-Madjar, and York (1979) determined similar although less pronounced differences in front of several O and B stars of the Orion complex.

These observations suggest that the observed D abundance can be significantly affected by physical and/or chemical processes. In our previous contribution the assumption was made that this variation is due to a selective radiation pressure effect acting on D and not on H which would displace one population of atoms with respect to the other.

The purpose of this paper is to reinvestigate some processes which should affect significantly the observed D atomic abundance. In particular, we have used recent theoretical models describing the thermodynamics of the interstellar medium such as the one developed by McKee and Ostriker (1977). From their model, one has a representation of the temperature-density pattern of the interstellar medium which reproduces the current observations, taking into account the supernova explosions. Large temperature gradients should take place in the interstellar medium, and these should affect the radiation pressure mechanisms discussed previously. Moreover, the atomic D abundance is significantly affected in regions where molecules such as HD or H_2 do exist.

After a discussion of some consequences of the most recent observations of the D abundance presented in § II, we analyze the dependence with temperature of the diffusion and ionization processes affecting this abundance in § III. An estimate of the enhancement or depletion effects on D is then proposed in § IV. Some remarks concerning the chemical fractionation due to molecular formation on the vicinity of dense clouds are made in § V. From this observational and theoretical analysis, a few comments concerning the nearby interstellar medium are presented in § VI.

II. THE INHOMOGENEITY OF THE INTERSTELLAR D/H

The first observational evidence has been given by Dupree, Baliunas, and Shipman (1977) who determined quite discrepant interstellar D/H ratios in front of two very near stars α Cen A and α Aur (D/H $\sim 3 \times 10^{-6}$ in front of α Cen A and D/H $\sim 4 \times 10^{-5}$ in front of α Aur). This result has been challenged by McClintock *et al.* (1978), who argued that the above observations are still compatible with a uniform D/H ratio $\sim 1.8 \times 10^{-5}$. But to reach such a conclusion, McClintock *et al.* were forced to use extreme solutions for their fits, especially to decrease the high D/H ratio in front of α Aur, or to increase the low D/H value toward α Cen A by suggesting a very complex structure for the very short α Cen A line of sight.

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[1] Laboratoire de Physique Stellaire et Planétaire, Verrières-le-Buisson.

[2] Institut d'Astrophysique de Paris.

TABLE 1A

D/H TOWARD NEARBY STARS

Name	Spectral type	l^{II}	b^{II}	d(pc)	n(H I) (cm^{-3})	D/H	References
α Cen A	G2.0 V	316	1	1.33	0.2 ± 0.05	$2.4(+1.2, -0.7) \times 10^{-6}$	Dupree *et al.* 1977
					0.06 – 0.30	$0.9\text{–}2 \times 10^{-5}$	McClintock *et al.* 1978
ϵ Eri	K2.0 V	196	48	3.3	0.08 ± 0.04 or 0.005 ± 0.04	$1.1\text{–}2.9 \times 10^{-5}$	McClintock *et al.* 1978
ϵ Ind	K5.0 V	336	−48	3.5	~0.1	$\sim 1.8 \times 10^{-5}$	McClintock *et al.* 1978
α CMi	F5.0 IV–V	214	13	3.5	0.11 ± 0.02	$1.3 \pm 0.6 \times 10^{-5}$	Anderson *et al.* 1978
α Aur	G5.0 III	163	5	13.7	0.03 ± 0.01	$3.9(+5.7, -1.7) \times 10^{-5}$	Dupree *et al.* 1977
					0.04–0.05	$1.8\text{–}4 \times 10^{-5}$	McClintock *et al.* 1978
λ And	G8.0 III–IV	110	−15	26	0.03–0.08	$1.3\text{–}5 \times 10^{-6}$	Baliunas and Dupree 1979
HR 1099............	G5–KO IV +G5 V	185	−41	33	0.005 ± 0.002	$1.2\text{–}4.5 \times 10^{-5}$	Anderson and Weiler 1978

TABLE 1B

D/H TOWARD MORE DISTANT EARLY TYPE STARS

Name	Spectral type	l^{II}	b^{II}	d(pc)	n(H I) (cm^{-2})	D/H	References
β Cen..................	BI III	312	1	84	3.3×10^{19}	$1.25(+1.25, -0.45) \times 10^{-5}$	Rogerson and York 1973
μ Col	O9.5 V	237	−27	701	7.0×10^{19}	$6.3(+1.0, -2.3) \times 10^{-6}$	York and Rogerson 1976
γ^2 Vel.................	O9 I + WC8	263	−8	377	6.0×10^{19}	$2(+1.2, -0.75) \times 10^{-5}$	York and Rogerson 1976
α Cru	B0.5 IV	300	0.4	114	4.0×10^{19}	$2.5(+0.7, -0.9) \times 10^{-5}$	York and Rogerson 1976
α Vir	B1 IV	316	51	86	1.0×10^{19}	$1.6(+1.2, -0.6) \times 10^{-5}$	York and Rogerson 1976
γ Cas..................	B0.5 IVpc	124	−2	194	1.0×10^{20}	$(1.5 \pm 0.5) \times 10^{-5}$	Vidal-Madjar *et al.* 1977
					1.1×10^{20}	$(1.3 \pm 0.25) \times 10^{-5}$	Ferlet *et al.* 1980
ζ Pup	O4 Inf	256	−2	668	0.97×10^{20}	$2.3(+0.7, -0.3) \times 10^{-5}$	Vidal-Madjar *et al.* 1977
δ Ori..................	O9.5 II	204	−18	384	1.7×10^{20}	$(7 \pm 2) \times 10^{-6}$	Laurent *et al.* 1979
ε Ori	B0 Ia	205	−17	409	2.8×10^{20}	$(6.5 \pm 3) \times 10^{-6}$	Laurent *et al.* 1979
ι Ori	O9 III	210	−20	429	1.4×10^{20}	$1.4(+0.5, -1) \times 10^{-5}$	Laurent *et al.* 1979

More recently determinations of the interstellar D/H ratio have been performed (see Table 1) which show that the nearby interstellar medium should be quite inhomogeneous. In particular, the D/H value toward λ And ($0.13\text{–}0.5 \times 10^{-5}$) is quite different from that found in front of α Aur which is greater than 1.8×10^{-5} according to all determinations.

The D/H ratio can be determined more precisely in front of early type stars. Laurent, Vidal-Madjar, and York (1979) have shown that D/H could vary over longer distances (100–1000 pc) and that this value can be lower than 9×10^{-6} in front of two Orion stars. This last value is clearly different from the lowest possible values found in front of other early type stars. Figure 1 shows the histogram of these available D/H ratios. Although the sample of stars is small, this histogram indicates a spread much larger than the average uncertainties on the determinations. Therefore, the interstellar D/H ratio is not uniform even in the solar neighborhood.

III. THE RADIATION PRESSURE MECHANISM

A deuterium atom of the interstellar medium is subjected to two effects:

(i) *The collisions with hydrogen atoms.*—In first approximation, one can assume a mean interval of time between two collisions: $t = \lambda/\bar{v}$, where λ is the collision mean free path and $\bar{v}$ the thermal velocity of the deuterium atoms.

(ii) *The radiation pressure induced by a stellar flux* Φ.—This induces on a D atom (see Vidal-Madjar *et al.* 1978) an acceleration

$$\gamma = \frac{F}{m_{\mathrm{D}}} = \frac{\pi e^2}{m_e c^2} f \frac{\Phi}{m_{\mathrm{D}}},$$

where f is the oscillator strength of the transition, m_e and e the mass and charge of the electron, c the speed of light, and m_{D} the mass of the D atom.

During the mean collision time t, the path induced by the radiation effect is $l = \frac{1}{2}\gamma t^2$; thus the diffusion velocity of D inside the interstellar gas is:

$$v_{\mathrm{D}} = l/t = \tfrac{1}{2}\gamma(\lambda/\bar{v}),$$

where $\bar{v} = (2kT/m_{\mathrm{D}})^{1/2}$, T being the temperature of the medium, and λ is the mean free path $= 1/(\pi n \sigma^2)$ ($\pi\sigma^2$ is the collision cross section between D and H, and n is the hydrogen volume density).

The diffusion velocity v_D can then be written as:

$$v_D = \frac{1}{2\pi n \sigma^2} F \left(\frac{1}{2 m_{\mathrm{D}} k T}\right)^{1/2} = A \frac{F}{n T^{1/2}}.$$

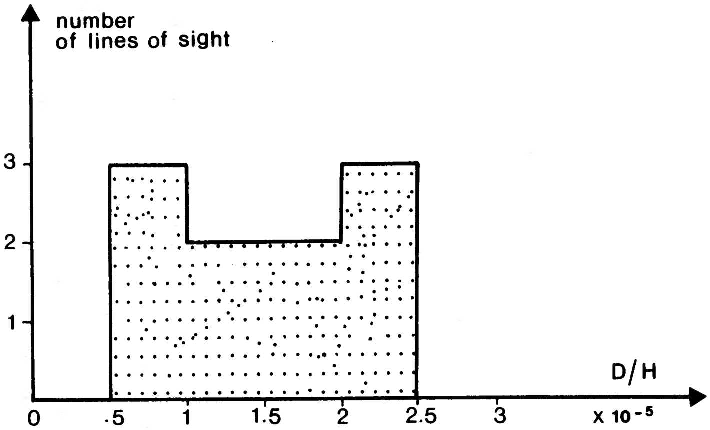

FIG. 1.—Histogram of the present available observations of the D/H ratio in the interstellar medium deduced through more than one line of the Lyman series. The lines of sight are counted as one observation even if several absorbing clouds were detected.

This approximation is in agreement with the diffusion equation defined by Chapman and Cowling (1970)

$$v_D = D_i F/kT\,,$$

where the diffusion coefficient D_i is proportional to $T^{1/2}n^{-1}$.

Let us assume now a shift of the deuterium population due to the radiation pressure effect between a region a and a region b of temperatures T^a and T^b. For this population, we should have $n_D v_D = \text{const}$. Therefore the D/H ratios in regions a and b are related by:

$$X_1 = \left(\frac{\mathrm{D}}{\mathrm{H}}\right)^b = \frac{n_{\mathrm{D}}{}^b}{n_{\mathrm{H}}{}^b} = \frac{n_{\mathrm{D}}{}^a v_D{}^a}{n_{\mathrm{H}}{}^b v_D{}^b} = \frac{n_{\mathrm{D}}{}^a n^b}{n_{\mathrm{H}}{}^b n^a}\left(\frac{T^b}{T^a}\right)^{1/2}.$$

Assuming first that $n = n_{\mathrm{H}}$, we find

$$X_1 = \frac{n_{\mathrm{D}}{}^a}{n_{\mathrm{H}}{}^a}\left(\frac{T^b}{T^a}\right)^{1/2} = \left(\frac{\mathrm{D}}{\mathrm{H}}\right)^a\left(\frac{T^b}{T^a}\right)^{1/2} = X_0\left(\frac{T^b}{T^a}\right)^{1/2}. \qquad (1)$$

In these equations, n_{D} and n_{H} are the deuterium and hydrogen volume densities, and X_0 is the initial D/H density ratio before the beginning of the process: X_0 is assumed to be the same in the different regions.

The variation of the D/H ratio due to radiation pressure effect is then proportional to the square root of the temperature ratio between the two regions.

Since the radiation pressure mechanism affects only the atoms and not the ions, the actual value of the D enrichment (or depletion) depends on the ionization effects.

If x^a and x^b are the hydrogen or deuterium ionization rates in regions a and b, equation (1) transforms into

$$\begin{aligned} X_2 = \frac{n_{\mathrm{D}}{}^b}{n_{\mathrm{H}}{}^b} &= \frac{n_{\mathrm{D}}{}^a}{n_{\mathrm{H}}{}^a}\left(\frac{T^b}{T^a}\right)^{1/2}\left(\frac{1-x^a}{1-x^b}\right) \\ &= X_0\left(\frac{T^b}{T^a}\right)^{1/2}\left(\frac{1-x^a}{1-x^b}\right). \qquad (2)\end{aligned}$$

In this approximation, the ionization strengthens the enhancement of D in high T regions since x is an increasing function of T.

Equation (2) does not take into account the recombination effects. One should write that the recombination conserves the total number of deuterium (neutral and ionized):

$$n_{\mathrm{D}T} = n_{\mathrm{D}} + n_{\mathrm{D}^+}\,.$$

Since

$$n_{\mathrm{D}^+} = X_0 n_{\mathrm{H}^+} = \frac{x^b}{1-x^b} X_0 n_{\mathrm{H}}{}^b$$

and

$$n_{\mathrm{D}} = X_2 n_{\mathrm{H}}{}^b\,,$$

from this relation one deduces that

$$\begin{aligned} \frac{n_{\mathrm{D}}{}^b}{n_{\mathrm{H}}{}^b} &= (1-x^b)\frac{n_{\mathrm{D}T}}{n_{\mathrm{H}}{}^b} \\ &= X_0\left[\frac{x^b}{1-x^b} + \left(\frac{T^b}{T^a}\right)^{1/2}\frac{1-x^a}{1-x^b}\right](1-x^b)\,.\end{aligned}$$

Therefore,

$$\begin{aligned} X_3 = \left(\frac{\mathrm{D}}{\mathrm{H}}\right)^b &= \frac{n_{\mathrm{D}}{}^b}{n_{\mathrm{H}}{}^b} \\ &= X_0\left[\left(\frac{T^b}{T^a}\right)^{1/2} + x^b - x^a\left(\frac{T^b}{T^a}\right)^{1/2}\right]. \qquad (3)\end{aligned}$$

If one compares equations (1) and (3) one notices that the ionization effects do not change drastically the enhancement of D since $T^b > T^a$ implies $x^b > x^a$. On the other hand, if $T^b < T^a$ and $x^a \approx 1$, then $n_{\mathrm{D}}{}^b/n_{\mathrm{H}}{}^b \approx x^b(n_{\mathrm{D}}{}^a/n_{\mathrm{H}}{}^a)$, which evidence the fact that no neutral deuterium could be shifted from a fully ionized region. In this case the depletion value depends more on the ionization rate than on the temperature ratio.

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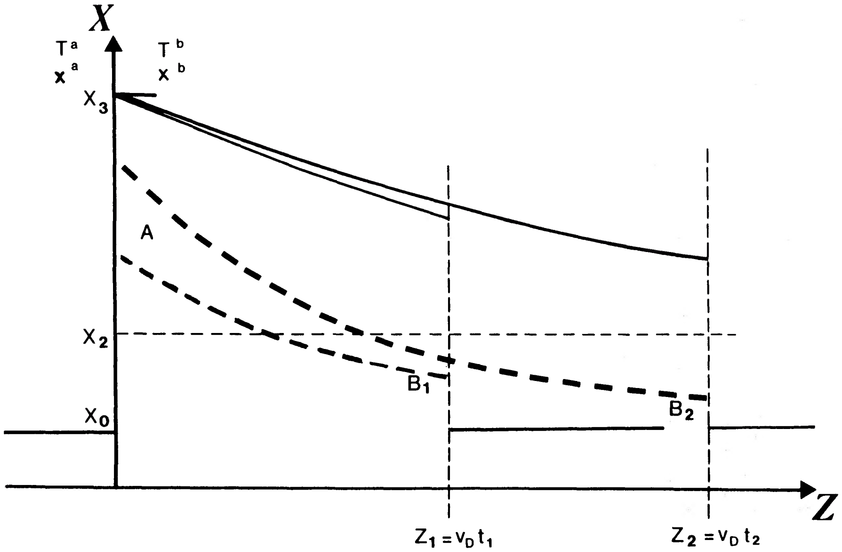

FIG. 2.—The distribution of D/H ratio through the perturbed region is presented for two values t_1 and t_2 of the time after the beginning of the radiation pressure mechanism, and for two hypotheses on the recombination effect velocities as compared to the diffusion velocity. In *solid lines*, the ionization equilibrium is not reached behind the discontinuity layer because of the slow recombination velocity. In *dashed lines*, the ionization equilibrium is reached in any place and time. In region A, behind the discontinuity, the ratio D/H evolves from X_3 to X_2. In region B, near the diffusion front the ratio D/H evolves from X_3 to the primordial value X_0.

Let us analyze now the evolution with time of the D/H distribution in the region between the temperature discontinuity and the diffusion front. Figure 2 presents such distributions for two values t_1 and t_2 of the time after the beginning of the radiation pressure mechanism. There are two cases:

i) If the time needed to reach ionization equilibrium is long compared to the diffusion time scale, the abundance of neutral D is given by X_2 and evolves toward X_3 at large diffusion distances (Fig. 2, *solid lines*). The mean value across the perturbed region (which is the one to compare with observations) which is equal to X_2 at the beginning will also evolve with time toward X_3.

ii) If the time needed to reach ionization equilibrium is short, then two different situations arise which are represented by the dashed lines in Figure 2: (*a*) In the location just behind the temperature discontinuity (A) the density of D ions tend to equilibrate with the population of D atoms diffused through the temperature discontinuity then n_D/n_H evolves from X_3 toward X_2. (*b*) By contrast, near the diffusion front (region B_1 at time t_1, B_2 at time t_2), the population of D atoms tends to equilibrate with a constant D ion density, and n_D/n_H evolves from X_3 to the original value X_0.

One can demonstrate that the average D/H ratio remains roughly constant with time and is given by equation (3) (a discussion of this point can be found in Appendix A).

Finally, equation (3) provides reasonable estimates of the enhancements or depletions due to diffusion and ionization effects. This shows the crucial role played by the temperature of the different phases of the interstellar medium in the segregation processes suffered by deuterium.

IV. GEOMETRY OF A "PERTURBED" REGION IN THE INTERSTELLAR MEDIUM

From McKee and Ostriker (1977), two temperature discontinuities should be considered (Fig. 3) inside an interstellar cloud (where the observations are possible) with respect to the direction of the UV flux: (i) the first discontinuity between the hot interstellar medium ($T \sim 4.5 \times 10^5$ K) and the warm ionized medium ($T \sim 8 \times 10^3$ K), and (ii) the second between the dense cold neutral medium ($T \approx 80$ K) and the warm neutral medium ($T \approx 8 \times 10^3$ K).

Around the first discontinuity (region 1) $(\mathrm{D/H})^b \approx 0.5(\mathrm{D/H})^a$ (i.e., the value of x^b in eq. [3] since $x^a = 1$). D/H is then on average lower in this region, while behind the dense core (region 2) one can infer from equation (3) an enrichment in D/H of about 10 times the original D/H ratio.

Region 1, which is certainly quite extended, is located on one side of the cloud and therefore is probably not much affected by turbulence effects inside the cloud. Turbulent motions are expected to act only on very short scales compared to that of region 1 (a rough discussion of the effect of turbulent motions on the radiative pressure mechanism can be found in Appendix B). By contrast, the enriched region should be small compared to the whole warm region and can be strongly affected by turbulent motions. Therefore, on average a line of sight has more chance to show a depletion than an enrichment into D. Furthermore, as can be seen on Figure 3, enrichment on a given line of sight will not be observable since this line of sight has also to cross unperturbed or depleted regions.

To understand the present distribution of the D/H measurements, we consider the simple picture of spherical clouds with a depleted region in the direction of the

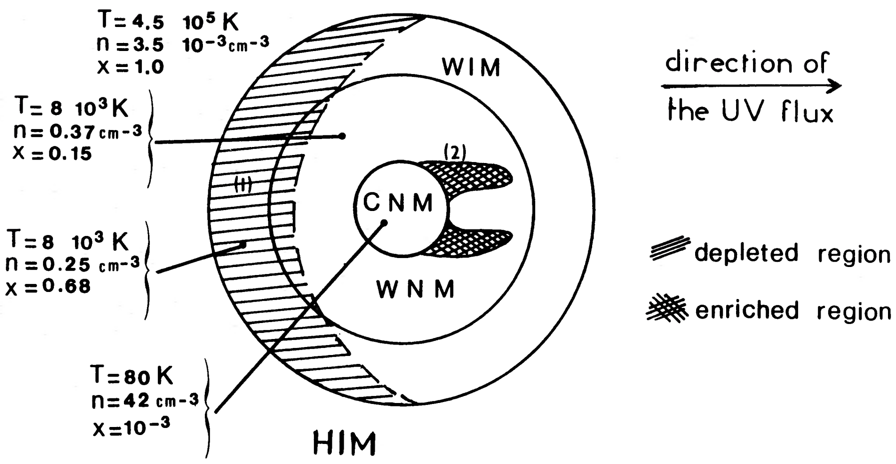

FIG. 3.—A standard cloud from the McKee and Ostriker (1977) model. Assuming that the stellar UV flux is coming from the left (*arrow*), two regions are represented where the D/H ratio should be perturbed: (i) region 1 at the limit of the hot and warm medium where depletion of deuterium is expected, and (ii) region 2, behind the cold core where strong enrichment in deuterium is predicted. Notice the probable shape of region 2 due to UV shielding by the dense core itself, stopping on its axis the radiation pressure mechanism.

UV flux (Fig. 4). For this analysis, we assume also that the cloud is near a OB star association. At a distance of, say, 50 pc (i.e., at the edge of the H II region surrounding the association), the UV flux released by 10 stars is $\Phi \approx 10^{-6}$ photons cm^{-2} s^{-1} Hz^{-1}. Furthermore, under these conditions, all the Lyman lines contribute to the mechanism, since the hydrogen Lα absorption line saturated at the center of the line is not broad enough to be saturated at the deuterium Lα wavelength. The total oscillator strength is then $f \approx 0.5$, and thus the diffusion velocity is $v_D \approx 10^5$ cm s^{-1}. Since the geometrical configuration should be roughly stable within, say, 20 pc (which corresponds for an average velocity of a cloud to a transit time of $\sim 10^6$ years), the depleted region should extend over 1 pc. Therefore, on average, half of the cloud should be depleted by about a factor 2 in D/H while the other half should have the original D/H ratio.

With this crude D/H pattern in interstellar clouds, the distribution of the D/H value (X) can be estimated over different lines of sight.

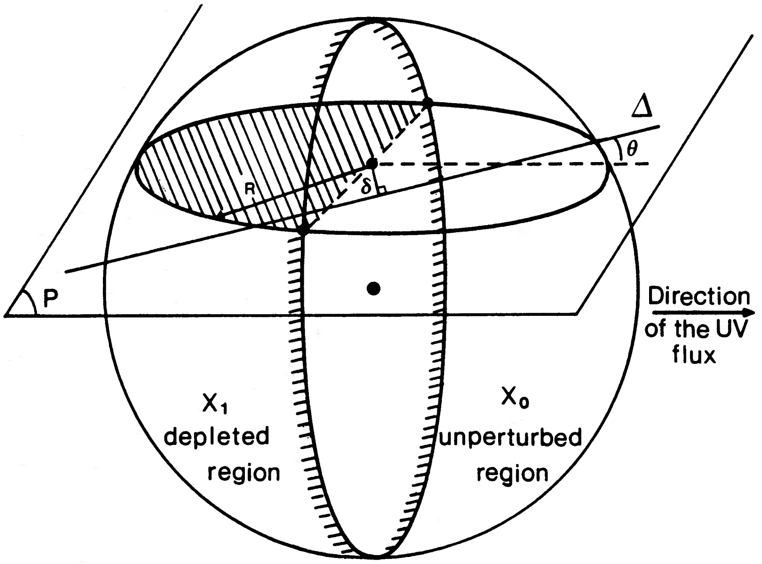

FIG. 4.—An average situation is presented for an interstellar cloud: about half of the warm region is depleted in deuterium while the other half is unperturbed (see text). The small enriched region 2 of Fig. 3 is ignored here because a line of sight crossing it has to also cross the unperturbed or depleted regions over longer path lengths inducing probably unobservable effects. Δ is a given line of sight, P is the plane containing Δ and parallel to the direction of the UV flux. For the definition of the parameters θ, R, and δ, see Appendix C.

If the original D/H value is X_0, the depleted one X_1, with $X_m = (X_1 + X_0)/2$ and $\Delta X = X_0 - X_1$, let us note

$$\omega = 2\frac{X_m - X}{\Delta X} .$$

The probabilities $\mathscr{P}$ to measure a D/H value smaller than a given X value are (see Appendix C):

$$\begin{aligned} \mathscr{P}\left(\frac{\mathrm{D}}{\mathrm{H}} \le X\right) &= 0 \quad \text{for } X < X_1 \\ &= 1 \quad \text{for } X \ge X_0 \\ &= \frac{1}{2} - \frac{1}{\pi}\int_0^{\pi/2} \frac{\omega}{(\tan^2\theta + \omega^2)^{1/2}}\, d\theta \\ &\qquad\qquad \text{for } X_1 \le X < X_0 . \end{aligned}$$

Figure 5*a* displays this probability $\mathscr{P}$ with respect to X while Figure 5*b* shows the expected distribution of observed values. It is interesting to note the similarity between this theoretical distribution and the histogram of the present observations. Because of the poor statistics, the similarity in shape can be fortuitous. Anyhow, if this analysis is correct, it suggests that the unperturbed D/H ratio within 1000 pc of the Sun is close to the highest observed value, i.e., D/H ≈ 2–2.5×10^{-5}, and not to the average value, i.e., D/H $\approx 1.5 \times 10^{-5}$ as is currently thought.

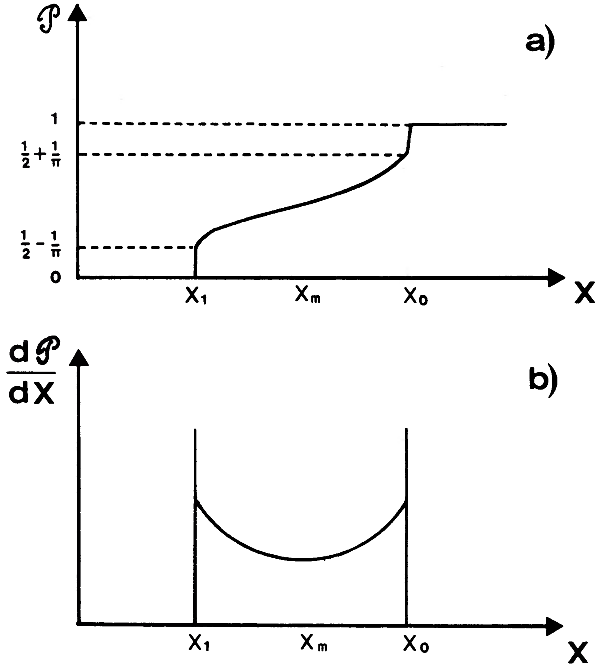

FIG. 5.—(*a*) The probability distribution of observing a D/H ratio smaller than a given value X for random lines of sight passing through an average cloud as described on Fig. 4. The limits X_1 and X_0 represent the value of the D/H ratio in the depleted and unperturbed region respectively. (*b*) The histogram related to the probability distribution presented on Fig. 5*a*. This histogram, when compared to the observed one presented on Fig. 1, may indicate that the unperturbed D/H ratio in the interstellar medium should be in the range 2–2.5 × 10^{-5} rather than near the average value of 1.5 × 10^{-5} as commonly thought.

V. MOLECULAR FRACTIONATION EFFECTS

The formation of molecules takes place in the denser regions of interstellar clouds. This process leads to significant D/H fractionation effects. It is well known now (see, e.g., Watson 1974) that the most abundant molecules H_2 are formed at the surface of interstellar dust grains. By contrast, the HD molecule is formed in the gaseous phase through the charge exchange reaction $\mathrm{D}^+ + \mathrm{H}_2 \rightarrow \mathrm{HD} + \mathrm{H}^+$.

A quite small abundance of HD is observed (e.g., Spitzer and Morton 1976), $\mathrm{HD/H_2} \approx 10^{-6}$, because H_2 shields itself from the photodissociation effect induced by the stellar UV flux.

One can evaluate the atomic D/H ratio in regions where molecules are abundant: From Watson (1974):

$$\frac{n(\mathrm{D})}{n(\mathrm{H})} \sim \frac{n(\mathrm{HD})}{n(\mathrm{H_2})}\frac{\Gamma_{\mathrm{HD}}}{\Gamma_{\mathrm{H_2}}} ,$$

where $\Gamma_{\mathrm{H_2}}$ and Γ_{HD} are the photodissociation rates of H_2 and HD due to the UV radiation:

$$\frac{\Gamma_{\mathrm{HD}}}{\Gamma_{\mathrm{H_2}}} \sim \frac{J_{\mathrm{HD}}}{J_{\mathrm{H_2}}} ,$$

where the parameters J have been computed by Hollenbach, Werner, and Salpeter (1971) for different physical conditions of the absorbing medium. In the denser parts of the clouds, they showed that $J \approx \tau_0^{-1/2}$, where τ_0 is the total optical depth of the center of the line. On the other hand, at the edge of a cloud, they showed that $J \approx 1$.

There is a fairly large region in the cloud where the absorption could be strong for H_2 and weak for HD. Under these conditions,

$$\frac{n(\mathrm{D})}{n(\mathrm{H})} \sim \frac{n(\mathrm{HD})}{n(\mathrm{H_2})}\frac{J_{\mathrm{HD}}}{J_{\mathrm{H_2}}} \sim 10^{-6}[\tau_0(\mathrm{H_2})]^{1/2} .$$

In regions where $\tau_0(\mathrm{H_2}) < 10^6$, the observed atomic D/H ratio can thus increase to values as large as 10^{-3}. The observation of such a spectacular increase is, however, quite unlikely because the lines of sight cross not only such atomic D-rich regions but also low-density envelopes where D/H $\sim 10^{-5}$. Furthermore, the amount of D atoms in the enriched region is very small compared to the total amount of D on this line of sight. However, enrichments might be observed on lines of sight where H_2 is as abundant as H I, i.e., for lines of sight where $E_{B-V} > 0.1$.

Let us note finally that the observations presented on the histogram of Figure 1 are not affected by these molecular fractionations since the H_2 column densities are small on the corresponding lines of sight. This implies that the higher D/H values reported on this figure cannot be explained by this effect.

VI. THE NEARBY SOLAR NEIGHBORHOOD

Let us discuss now the nearby interstellar medium in this general framework. From various observations, it seems now that the solar system is embedded in an interstellar cloud: first, soft X-ray observations (e.g., Burstein *et al.* 1977; Apparao, Hayakawa, and Hearn 1979) suggest that the solar system is surrounded by a rather extended ($\sim$ 100 pc diameter) and hot ($T \sim 5 \times 10^5$ K) region while UV observations inside the solar system (e.g., Cazes and Emerich 1977) or toward nearby stars (e.g. Dupree, Baliunas, and Shipman 1977) indicate that the temperature of the medium is less than 10,000 K; second, hydrogen density determinations seem to drop off at a few parsecs from the Sun (Table 1 and McClintock *et al.* 1978). Therefore, within the model of McKee and Ostriker (1977), the solar system seems to be embedded in the warm region of an interstellar cloud (see Fig. 3).

Following the previous discussion, it is not surprising to observe in the immediate vicinity of the Sun variations of the D/H ratio since this cloud is furthermore observed in a unique mode, that is to say from its interior. It is then possible not only to observe depleted values but also to detect toward close stars even the enriched region (see discussion in § IV and Fig. 3). More observations will certainly clarify this picture of the environment of the solar system; in particular, a confirmation of high D/H values (Dupree, Baliunas, and Shipman 1977) may indicate the presence of a cold core in the solar system neighborhood.

VII. SUMMARY AND CONCLUSION

From the above study, it appears that the nearby interstellar medium should be very complex and that at least two different processes can affect the observed atomic D abundance: (i) the previously suggested radiation pressure mechanism, and (ii) the chemical fractionation.

We have noticed that temperature gradients in the interstellar medium affect very significantly mechanism (i) while mechanism (ii) is effective at the edge of a dense molecular core.

A rough comparison between the histogram of the D observations and the probabilities that a line of sight crosses a D depleted or a D enriched region suggests that the unperturbed D abundance should be D/H $\approx 2.25 \times 10^{-5}$. This strenghtens the common opinion according to which the present D observations are in favor of an open universe.

The D segregation related to the chemical fractionation mechanism seems to be up to now unobserved but may affect evaluation made along slightly reddened lines of sight.

Finally, the reanalysis of the immediate vicinity of the solar system would suggest that it is embedded in an interstellar cloud; and if observations of high D/H ratio are confirmed, this would indicate the presence of a cold core in the immediate solar neighborhood.

The present study convinces us that the deuterium observations in the interstellar medium are not only a cosmological tool but also an exciting way to unravel the thermodynamics of the observed regions.

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APPENDIX A

COMPUTATION OF THE AVERAGE D/H RATIO IN THE PERTURBED REGION

At $t = 0$, when the process starts, the extension of the perturbed region is $z = 0$. At time t, the extension of this region is $z = v_D t$.

From time $t = 0$ to time t the total deuterium input in the perturbed region is:

From region a, a number of neutral atoms due to the diffusion process through the temperature discontinuity and given from equation (2):

$$N_D = X_0 \left(\frac{T^b}{T^a}\right)^{1/2} \frac{1 - x^a}{1 - x^b} n_H{}^b v_D t \qquad \left[X_0 = \left(\frac{n_D}{n_H}\right)^a\right] .$$

At the diffusion front a number of ions due to the displacement of the front:

$$N_{D^+} = X_0 \frac{x^b}{1 - x^b} v_D t n_H{}^b .$$

So

$$N_{D\,\mathrm{total}} = \frac{X_0 v_D t n_H{}^b}{1 - x^b} \left[\left(\frac{T^b}{T^a}\right)^{1/2} (1 - x^a) + x^b\right] .$$

Assuming that there is an ionization equilibrium at each point, the number of neutral deuterium atoms is

$$N_D = (1 - x^b) N_{D\,\mathrm{total}} .$$

Since the corresponding number of hydrogen atoms is

$$\bar{N}_H = v_D t n_H{}^b ,$$

the average value of the neutral deuterium to hydrogen density ratio across the perturbed region is

$$X_0[(T^b/T^a)^{1/2}(1 - x^a) + x^b] = X_3 .$$

APPENDIX B

THE EFFECT OF TURBULENT MOTIONS ON THE RADIATIVE PRESSURE MECHANISM

It is difficult to evaluate by what factor the turbulent motions act against the radiation pressure mechanism. However, several observations suggest that mixing mechanisms occurring inside interstellar clouds are rather unimportant: some observations of the starlight polarization through dense clouds performed by Carrasco, Strom, and Strom (1973) indicate that different types of grains can be separated inside such clouds; moreover significant gradient in the $^{12}C/^{13}C$ ratios by factors 6 to 10 from the center to the edge have been found in dense molecular clouds by Goldsmith and Langer (1978) and Encrenaz, Falgarone, and Lucas (1975).

In fact, the media considered in the present study are less dense and more ionized. These regions might indeed be less submitted to turbulent mixing because of the presence of galactic magnetic fields frozen in such regions.

Therefore, turbulent mixing effects have been neglected in the present study, although this question is still debatable.

APPENDIX C

CALCULATION OF THE PROBABILITY FUNCTION $\mathscr{P}(X)$

We consider a spherical cloud where half of the warm region is depleted in deuterium (D/H = X_1) while the other half is unperturbed (D/H = X_0). The cold core, if present, is neglected.

A line of sight Δ crossing this cloud is characterized as follows (Fig. 4): P is the plane parallel to the UV flux which contains Δ; θ is the angle between Δ and the UV flux direction $(0 \leq \theta \leq \pi/2)$; $x = \delta/R$, where R is the radius of the circle representing the intersection of P and the cloud boundary and δ is the distance of Δ from the center of this circle $(-1 \leq x < 1)$.

The observed D/H value X on a line of sight defined by θ and x is clearly independent of the two parameters defining P due to the simple geometry used here.

Let us define $X_m = (X_1 + X_0)/2$ and $\Delta X = X_0 - X_1$. Then we obtain:

$$X = X_1 \quad \text{for } -1 < x \leq -\cos\theta\,,$$

$$X = X_m + \frac{\Delta X}{2}\frac{x\tan\theta}{(1-x^2)^{1/2}} \quad \text{for } -\cos\theta < x < \cos\theta\,,$$

$$X = X_0 \quad \text{for } \cos\theta \leq x < 1\,.$$

For a given X value, this gives x as a function of θ by:

$$\text{if} \quad X = X_1\colon -1 < x \leq -\cos\theta\,,$$

$$\text{if} \quad X_1 < X < X_0\colon x = \frac{\omega}{(\tan^2\theta + \omega^2)^{1/2}} \quad \text{with } \omega = \frac{2(X - X_m)}{\Delta X}\,,$$

$$\text{if} \quad X = X_0\colon \cos\theta \leq x < 1\,.$$

The area defined on the (x, θ)-diagram for these parameters is equal to π, and thus the probability for measuring, on a given line of sight, a D/H value ξ such as $\xi \leq X$ is:

$$\text{for} \quad X < X_1\colon \mathscr{P}(X) = 0\,;$$

$$\text{for} \quad X_1 \leq X < X_0\colon \mathscr{P}(X) = \frac{1}{2} + \frac{1}{\pi}\int_0^{\pi/2}\frac{\omega}{(\tan^2\theta + \omega^2)^{1/2}}\,d\theta \quad \text{with } \omega = \frac{2(X - X_m)}{\Delta X}\,;$$

$$\text{for} \quad X \geq X_0\colon \mathscr{P}(X) = 1\,.$$

Note that the function $\mathscr{P}(X)$ presents two discontinuities, the probability for having the strict equality $\xi = X_1$ or $\xi = X_0$ being

$$\frac{1}{2} - \frac{1}{\pi}\int_0^{\pi/2}\frac{1}{(\tan^2\theta + 1)^{1/2}}\,d\theta = \frac{1}{2} - \frac{1}{\pi} \qquad (\omega = 1)\,.$$

The function $\mathscr{P}(X)$ is presented on Figure 5*a*. Figure 5*b* shows the derivative function of $\mathscr{P}(X)$ which is to be compared in shape with the observational histogram presented on Figure 1.

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JEAN AUDOUZE: Institut d'Astrophysique de Paris, 98 bis, Boulevard Arago, 75014 Paris, France

PAUL BRUSTON, CLAUDINE LAURENT, and ALFRED VIDAL-MADJAR: Laboratoire de Physique Stellaire et Planétaire, B. P. n° 10, 91370 Verrières-le-Buisson, France