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IS THE SOLAR SYSTEM ENTERING A NEARBY INTERSTELLAR CLOUD?

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ABSTRACT

A model, based on different observations of the local interstellar medium, indicates the presence of a very close interstellar cloud in front of the Scorpius-Ophiuchus association (almost in the direction of the galactic center) approaching the solar system from a distance of about 0.03 pc at a velocity of about 15–20 km s^{-1}. These observations are as follows:

1. The strong gradient of the hydrogen density in the interstellar medium deduced from current observations of this gas inside the solar system ($n_H \sim 0.1$ cm^{-3}) and in front of many nearby stars in the anticenter direction ($n_H \sim 0.01$ cm^{-3}).
2. The anisotropy of the UV flux (around 950 Å) from the brightest and closest O and B stars.
3. The important variation of the deuterium to hydrogen ratio, which ranges from 2×10^{-6} in the α Cen A direction to 4×10^{-5} in the α Aur direction.

A mechanism based on a selective radiation pressure effect that acts on deuterium atoms and not on hydrogen atoms explains satisfactorily the large spread in the deuterium abundance in the local interstellar medium. The operation of this mechanism requires that the geometrical configuration remain stable for approximately 10^7 years. This requirement implies the existence of a nearby interstellar cloud.

Possible candidates do exist in the proper sky direction. One candidate, extensively discussed, presents a persistent interstellar absorption pattern over an angle of 40° related to a high column density of hydrogen ($N_H \sim 10^{21}$ cm^{-2}). Another with a $N_H \sim 10^{20}$ cm^{-2} column density, although covering only a few degrees in the sky, would lead to the same consequence. The presence of such candidates is not at all contradicted by the interstellar reddening and absorption line observations.

Other implications of the presence of such a close cloud are presented.

Subject headings: deuterium — interstellar: matter — solar system: general

> I find that if the results that have been presented to us this afternoon are correct, I say if they are correct, then a hitherto unknown body must exist in the vicinity of the solar system.
>
> Fred Hoyle, *The Black Cloud*

I. INTRODUCTION

Material in the interstellar medium is distributed inhomogeneously, consisting of cold and dense clouds ($T \sim 50$ K, $n_H \gtrsim 10$ cm^{-3}) with radii of a few parsecs immersed in a hot ($T > 10^4$ K), but dilute ($n_H \sim 0.1$ cm^{-3}), intercloud medium. The average separation between two clouds can be a few hundred parsecs, and cloud velocity can be within a range of 20–30 km s^{-1}. Increasing evidence of strong interactions between this nearby interstellar medium and the interplanetary medium has been presented, for instance, by the direct observation of the local interstellar medium (reviewed in the next section). Possible implications of encounters between dense interstellar clouds and the solar system have been explored previously. Such encounters are not rare: Talbot and Newman (1977) have estimated that the solar system could have encountered ~130–140 clouds with $n_H > 10^2$ cm^{-3} and ~15 clouds with $n_H > 10^3$ cm^{-3} during its lifetime.

The model presented here suggests the presence in the close neighborhood of the solar system (e.g., at a distance of a few hundredths of a parsec) of a cloud in the Sco-Oph direction that will encounter the solar system in approximately 10^4 years. Section II of this paper presents three important areas of observations in the vicinity of the solar system: (1) a H density gradient, (2) the anisotropy of the far-UV flux (around 950 Å), and (3) a large variation of the D/H ratio in two different lines of sight. Possible mechanisms that may strongly affect the observed D/H ratio on a very small scale are discussed in § III. The correlation of these observational data constitutes a single argument that favors the segregation of deuterium by anisotropic UV radiation pressure. For this mechanism to be effective, a stable density gradient would be necessary over a period of about 10^7 years. This time scale is a strong indication of the presence of a nearby interstellar cloud for which observational arguments are presented and discussed in § IV. Finally some implications of the presence of such a cloud are presented in § V.

II. THE OBSERVATIONS

a) A Hydrogen Density Gradient in the Vicinity of the Solar System

Three kinds of observations indicate the existence of such a gradient:

i) By observing the emissions related to the interstellar H and He atoms entering the solar system, the physical parameters of the interstellar medium at the edge of the solar system are found to be: density $n_H \sim 0.1\ cm^{-3}$; temperature $(12 \pm 1) \times 10^3$ K; velocity, ranging from -20 to $-10\ km\ s^{-1}$ and approaching from $\alpha = 16^h48^m$, $\delta = -15°$ (Thomas and Krassa 1971; Bertaux and Blamont 1971; Weller and Meier 1974; Bertaux *et al.* 1976; Freeman *et al.* 1976; Adams and Frisch 1977; Cazes and Emerich 1977).

ii) Along the line of sight toward β CMa and ϵ CMa (at a distance from the solar system of 70 and 200 pc, i.e., in front of and out of the Gum nebula) the average H density is less than $0.01\ cm^{-3}$ (Bohlin 1975). Furthermore, in the direction of many very close stars (Table 1) $n_H \approx 0.02\ cm^{-3}$. Therefore, the local intercloud density should be $0.01\ H\ cm^{-3}$ rather than $0.1\ H\ cm^{-3}$.

iii) Figure 1 displays the projection on the galactic plane around the solar system of all the lines of sight corresponding to the stars listed in Table 1. This figure shows that the galactic longitudes of these directions are within 45° of the anticenter direction; the exceptions are the α Boo and α Eri directions, for which the galactic latitude is higher than 60°, and α Cen A, in front of which the average hydrogen density seems to be a factor of 10 higher than in the other directions. Thus, the interstellar density on *one side* of the solar system seems to be closer to $0.02\ cm^{-3}$ than to $0.1\ cm^{-3}$, and a few measurements on the other side (particularly α Cen A) favor a density somewhat higher than $0.1\ cm^{-3}$.

Therefore, the existence of a density gradient in the nearby interstellar medium indicates that in the opposite direction from which almost all the nearby stars are observed the H density should be greater than $0.1\ cm^{-3}$.

b) The Anisotropy of the Stellar Flux at 950 Å near the Sun

Henry (1977) has shown that the contribution to the flux at 975 Å comes only from stars earlier than B4,

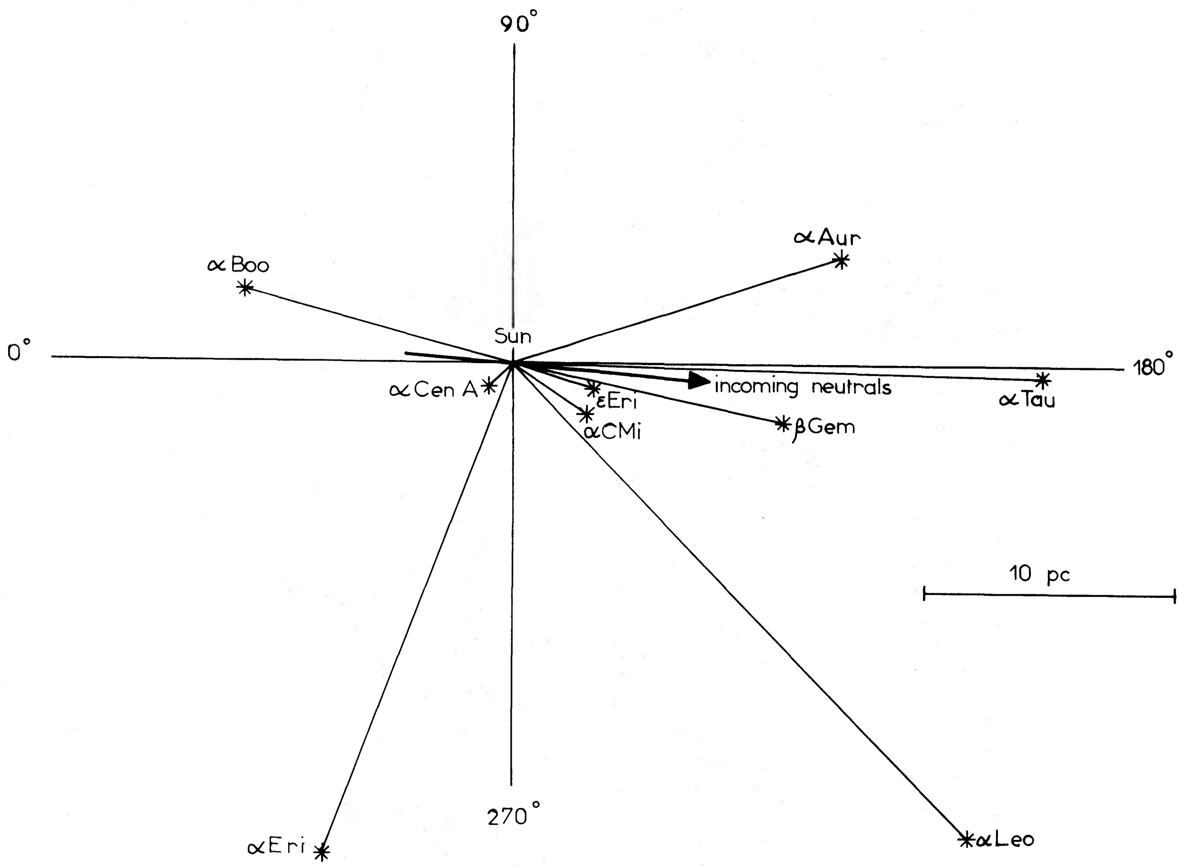

FIG. 1.—Projections in the galactic plane of all nearby stars for which the hydrogen column densities have been evaluated along their lines of sight by the *Copernicus* satellite. On this figure, the projection of the direction of the vector velocity of the interstellar neutral atoms measured inside the solar system is also displayed.

TABLE 1

Interstellar Atomic Hydrogen toward Nearby Stars

Name	l^{II}	b^{II}	d (pc)	n_{H} (cm^{-3})	Reference
ϵ Eri	195°51′	−48°02′	3.3	0.08 ± 0.04, 0.05* ± 0.04	McClintock *et al.* 1975*b*, 1976
α Eri	290°51′	−58°48′	21	0.07	Rogerson and York 1973
α Boo	15°08′	69°07′	11	0.02–0.1 (difficult to determine)	Moos *et al.* 1974; McClintock *et al.* 1975*a, b*
α Leo	226°26′	48°56′	26	0.02	Rogerson and York 1973
α Tau	180°58′	−20°15′	21	0.02–0.2	McClintock *et al.* 1975*a, b*
β Gem	192°14′	23°25′	11	0.02–0.15	McClintock *et al.* 1975*a, b*
α CMi	213°42′	13°02′	3.5	0.015–0.03	Evans *et al.* 1975
α Aur	162°35′	4°34′	13.7	0.03 ± 0.01	Dupree *et al.* 1977
α Cen A	315°46′	0°43′	1.33	0.20 ± 0.05	Dupree *et al.* 1977

* This value is determined from calculations with T = 10,000 K, and the previous one corresponds to T = 5,000 K.

which are located near the galactic plane. The distribution of hot star associations in this plane shows that the far-UV flux is certainly not isotropic (see Fig. 2). According to calculations by Henry (1977), nearly all the contribution to the flux appears to come from the Sco-Cen and the Orion associations. In order to evaluate quantitatively the resulting far-UV flux, the vector sum of fluxes was computed at 950 Å from about 750 of the brightest O and B stars in the sky with a dust attenuation of about $11E(B-V)$ mag (see Fig. 3, courtesy of the referee). The net calculated flux (1.5×10^{-8} photons cm^{-2} s^{-1} Hz^{-1}) is directed toward $l^{\text{II}} = 90°$, $b^{\text{II}} = +6°$, a direction halfway between the Sco-Cen and the Orion associations. Therefore these two systems seem to contribute equally to the far-UV flux, which is unambiguous evidence that the far-UV flux in the solar neighborhood is indeed anisotropic.

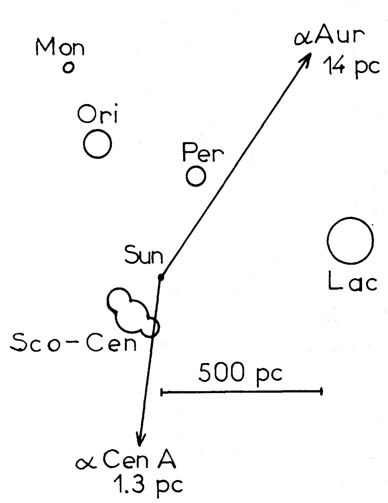

Fig. 2.—Positions projected on the galactic plane of the main associations and clusters with earliest type O–B2 stars (according to Blaauw 1964). The diameters of the circles represent the largest projected diameters of the associations. The two lines of sight of α Aur (13.7 pc distant) and α Cen A (1.3 pc distant) are also displayed on the figure.

c) Variation of the D/H *Ratio in the Solar Neighborhood*

Recent investigations have dealt with the *Copernicus* observations of the Lyman series absorption UV lines due to deuterium and hydrogen in the nearby interstellar medium in front of various stars (Rogerson and York 1973; York and Rogerson 1976; Vidal-Madjar *et al.* 1977; Dupree, Baliunas, and Shipman 1977; Laurent, Vidal-Madjar, and York 1978). The first determinations of Rogerson and York (1973) yielded an interstellar D/H $\sim (1.4 \pm 0.02) \times 10^{-5}$ that is consistent with the values derived from the solar wind ^{3}He/^{4}He ratio by Geiss and Reeves (1972) and with the molecular measurements on Jupiter (Combes, Encrenaz, and Owen 1978). However, more recent studies exhibit a much larger spread of the D/H ratios determined in different directions of the nearby interstellar medium; in particular, Dupree, Baliunas, and Shipman (1977) report that D/H = $(3.9\ [+5.7, -1.7]) \times 10^{-5}$ in the line of sight of α Aur (l^{II} = 162°35, b^{II} = 4°34) and D/H = $(2.4 \times [+1.2, -0.7]) \times 10^{-6}$ in that of α Cen A (l^{II} = 315°46, b^{II} = 0°43).

III. MECHANISMS CAUSING A D/H VARIATION

Several mechanisms might account for a variation of the local D/H ratio.

1) Deuterium is destroyed inside the stars at comparatively low temperatures ($T > 10^5$ K).

i) Solar and stellar winds could be deuterium-depleted. Assuming that the solar wind could accumulate inside the limits of the solar system, one may explain the low D/H value toward α Cen A. However, this phenomenon would not account for the anisotropy of the D/H ratio. If stellar winds were able to accumulate enough hydrogen (which has yet to be demonstrated) to account for such a low D/H value (note that α Cen is a triple star system), they still could not account for the high D/H ratio in front of α Aur and for the local hydrogen density gradient.

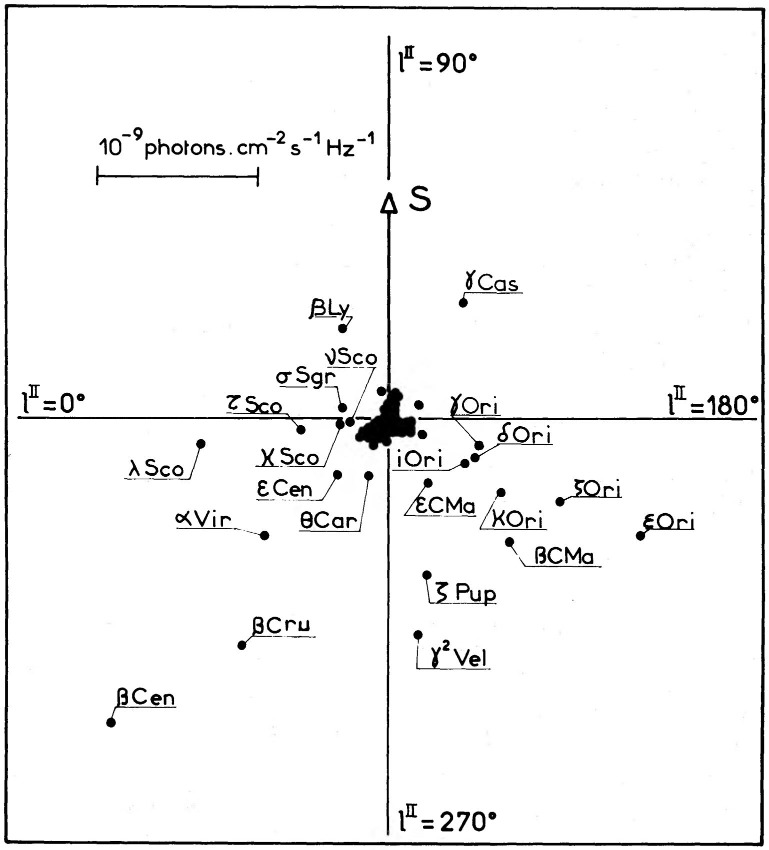

FIG. 3.—A scalar proportional to the far-UV flux coming from some of the 750 brightest O and B stars in the sky were computed. These scalars are displayed here in polar coordinates where the azimuth of each point corresponds to the star galactic longitude and the distance from the origin is proportional to the star UV flux (taking into account a dust attenuation of $\sim 11\ E(B-V)$ magnitude). The direction of the net flux corresponding to the 750 stars is represented by the vector S.

ii) Deuterium depletion would also result if deuterium-free material were ejected by a pre–white dwarf during its planetary nebula phase. Measurements of CO (Mufson, Lyon, and Marionni 1975) for different planetaries have shown that these objects could eject 1–2 $M_\odot$ with a velocity of ~ 20 km s^{-1}. Any white dwarf within 5 pc of the Sun could have filled the α Cen A line of sight with hydrogen-rich, deuterium-poor material. For this mechanism to explain both the hydrogen density gradient and the low deuterium abundance, the direction of the planetary nebula expansion should be similar to that of hydrogen atoms inside the solar system. This requirement rules out Sirius B, Procyon B, van Maanen's star, and 40 Eri B. The only possible remaining candidates are either Wolf 489, which is distant (~ 7 pc) but in the favorable direction, or L145–141, which is closer (~ 5 pc) but in a less favorable direction. This explanation for the D/H variation implies that the interstellar D/H ratio should be low inside the solar system. In any case, this mechanism does not explain in a simple fashion the large deuterium abundance in the direction of α Aur.

2) The relative increase in deuterium in the direction of α Aur might be explained in terms of spallation reactions induced in this region either by flare particles produced by this star or by some huge cosmic ray fluxes confined to this region. In either case, a significant deuterium enhancement would entail a very large Li-Be-B production (Li/H as great as 10^{-7} for D/H $\sim 10^{-5}$). Such production rates should result in inhomogeneity by a factor greater than 100 in the interstellar Li-Be-B composition. Therefore, this explanation will be eliminated until such inhomogeneities in interstellar Li-Be-B are observed.

3) Fractionation effects due to the formation of molecules could, in some cases, explain the variation of the observed deuterium abundances in *molecules*. This argument does not apply to the atomic deuterium abundance since there are not enough molecules in the local interstellar medium to explain such a large variation.

4) A selective radiative ionization process would preferentially ionize more hydrogen than deuterium since the deuterium Lyman continuum has a shorter wavelength. However, this process is only relevant in H II regions contained in Strömgren ionizing spheres; this is not the case for the nearby interstellar medium.

5) The final candidate mechanism we shall consider

here is resonance radiation pressure which acts selectively on deuterium atoms. Resonance radiation pressure (Milne 1927; Michaud 1970; Lucy and Solomon 1970; Blum and Fahr 1970; Scargle 1973) may act selectively on isotopes, as described by Zare (1977), and particularly on deuterium atoms and not on hydrogen atoms because the corresponding interstellar Lyman lines are saturated and very broad. Therefore, stellar flux cannot reach the hydrogen atoms but easily affects the deuterium atoms.

This radiation pressure mechanism can operate only if the following geometrical conditions are fulfilled: (1) the stellar flux is anisotropic, and (2) there is a density gradient in the interstellar medium. These two conditions, which are mandatory for the deuterium separation mechanism to function, are satisfied in the solar vicinity (§ II). The radiation pressure effect can be evaluated as follows. The radiation pressure on deuterium atoms is due only to Lyman radiation with wavelengths shorter than or equal to Lyman δ (950 Å). The stellar flux corresponding to the first three members of the Lyman series is suppressed both by the very large absorption due to H atoms and by the H_2 absorption lines observed through dense clouds. Thus, the oscillator strength corresponding to the sum of the higher terms of the series is $f \approx 0.03$.

For each photon absorption event, there is a momentum transfer from the photon to the atom; the resonance radiation pressure acts on an absorbing deuterium atom as a force F_r:

$$F_r = \frac{\pi e^2}{m_e c} f \frac{F_s}{c} = m_D \gamma \,, \qquad (1)$$

where f is the oscillator strength of the transition, F_s is the stellar flux on the atom (ergs cm^{-2} s^{-1} Hz^{-1}), e and m_e are the charge and the mass of an electron, respectively, c is the light velocity, and γ is the acceleration which is induced on the deuterium atoms of mass m_D.

Under such a force F_r, the deuterium atoms will be displaced over a distance L_D with respect to those of hydrogen. The radiation pressure will therefore modify the D/H ratio in regions where there is a density gradient. The density gradient can be approximated by an exponential relation:

$$n = n_0 \exp\left[-(r - r_0)/L\right] , \qquad (2)$$

where n_0 is the density at a distance r_0 from the center of the cloud, and L is the scale height of this gradient. With this crude relation, the integrated density N over a line of sight is

$$N = n_0 L \,. \qquad (3)$$

Since Dupree, Baliunas, and Shipman (1977) have observed a factor of 10 difference for the D/H ratio between two lines of sight, the deuterium should be displaced $L_D \sim L$ to account for such a large variation. In this estimate we have tacitly assumed that the lower deuterium abundance corresponds to a depleted value and the higher to an enriched value. The "normal" local D/H abundance in the interstellar medium is, consequently, assumed to be the average between these two extremes.

The displacement, L_D, of deuterium atoms in a hydrogen gas by a radiative force, F_r, can be determined by solving the general diffusion equation for a binary mixture as defined by Chapman and Cowling (1970) (see also Montmerle and Michaud 1976). The diffusion velocity of the deuterium atoms, v_D, may be defined as

$$v_D = D_i F_r / kT \,, \qquad (4)$$

where D_i is the diffusion coefficient, k is the Boltzmann constant, and T is the local interstellar medium temperature.

From a simple approximation in the rigid colliding sphere model one can estimate that $D_i \sim 3 \times 10^{22}$ cm^2 s^{-1} in the local interstellar medium where $n_H \sim 0.1$ cm^{-3} and $T \sim 10^4$ K.

An estimate of the mean free path under the same conditions yields $\delta r \sim 10^{17}$ cm, i.e., 0.03 pc. With the computed UV flux near the Sun of 1.5×10^{-8} photons cm^{-2} s^{-1} Hz^{-1} around 950 Å (see § II), the corresponding acceleration is:

$$\gamma \approx 2.5\ 10^{-9}\ \mathrm{cm\ s^{-2}} ,$$

and the deuterium diffusion velocity is:

$$v_D \sim 2.10^2\ \mathrm{cm\ s^{-1}} .$$

These estimates show that (since $L_D = v_D t$) even in regions where a very sharp H density gradient (with a scale height of, e.g., 0.001 pc) is present, the time scale for an efficient separation mechanism is $t > 10^6$ years. Therefore, the density gradient pattern and the UV flux geometry should remain stable, at least during such a period. The UV flux geometry has been shown to be stable over this period of time; the early-type star associations are of age 10^6–10^7 years (Blaauw 1964), and their geometry is significantly modified by relative motions only over about 10^7 years.

On the other hand, according to the classical two-phase model of Field, Goldsmith, and Habing (1969), the density gradient of the interstellar medium can remain stable only if it borders an interstellar cloud. Furthermore, as shown by Mészáros (1972), the lifetime of an interstellar cloud is essentially controlled by the depletion of heavy elements on grains. He estimated that the depletion time t_D is proportional to $n^{-1}T^{-1/2}$ (where n and T are the cloud density and temperature) and of the order of 3×10^7 years for an average interstellar cloud. This shows that any cloud above the instability limit for the cloud phase will be acceptable for our proposed mechanism.

In conclusion, the mechanism based on selective radiation pressure may explain most simply the *two* extreme values of the D/H ratio observed near the Sun (note that the local geometric configurations favor this mechanism); the only requirement to fulfill

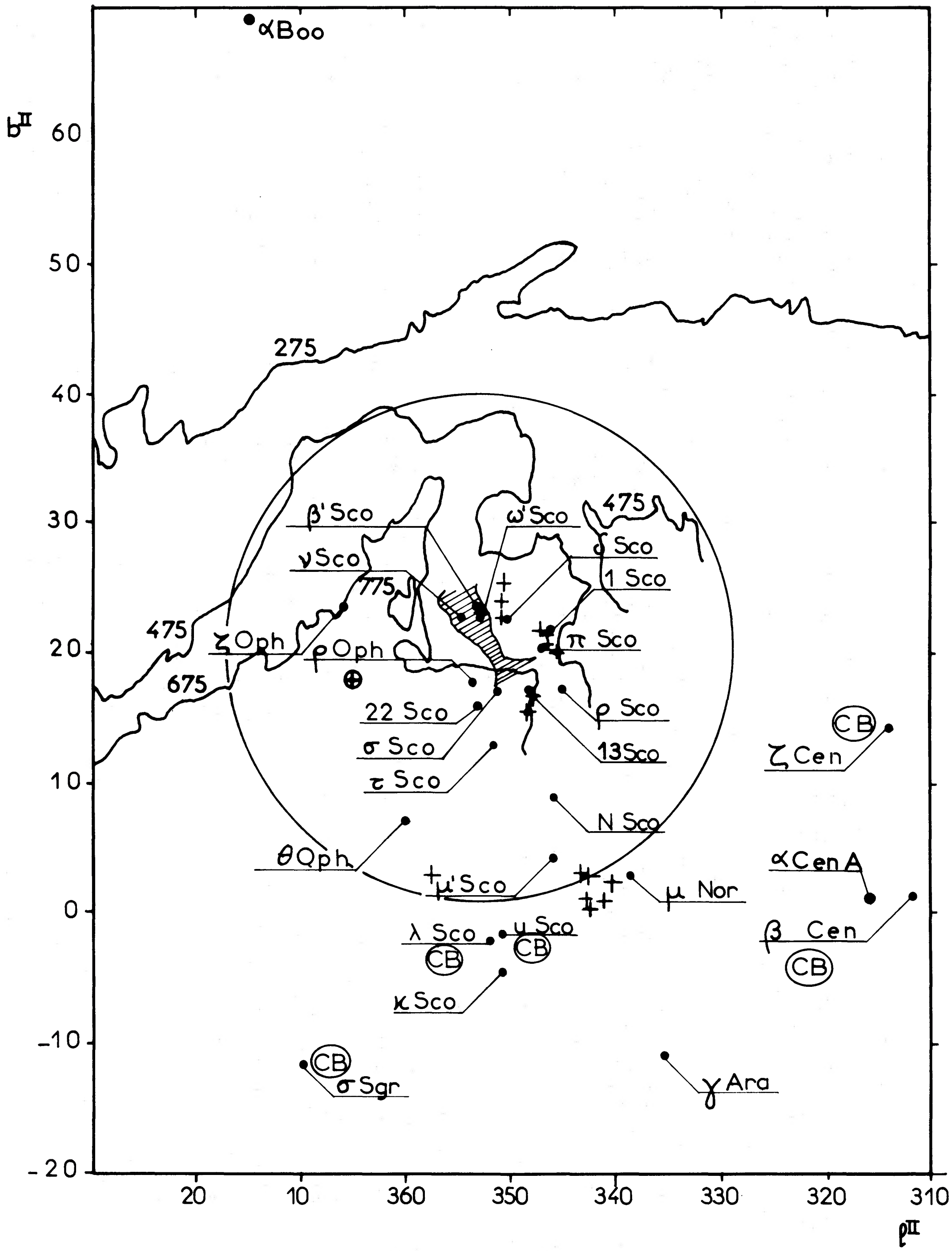

FIG. 4.—Region of the sky (in galactic coordinates), approximately between the α Cen A and α Boo directions, where the candidate clouds can be located. The rough boundary of the first candidate is represented by the large circle of ~40° diameter. This boundary fits roughly the upper part of the 21 cm contour map of Heiles (1975). Most of the stars inside this limit exhibit a large hydrogen column density ($\sim 10^{21}$ H atoms cm^{-2}) while, for those outside, $N_H < 10^{20}$ cm^{-2} as in almost all the other regions of the sky (if one excludes the two very long lines of sight of μ Nor and γ Ara). The close stars used by Bohlin (1975) are referred to as CB. The plus signs represent close stars ($d <$ 250 pc) used in the reddening study taken from Deutschman *et al.* (1976). It is possible to locate them through their HD numbers by using Table 3 and Fig. 5. In the hatched area, the second candidate, a weak cloud observed in 21 cm at -20 km s^{-1} heliocentric velocity by Sancisi and Van Woerden (1970), is also presented. Finally, the circled cross indicates the direction in the sky from which the neutral atoms are entering the solar system.

the condition of stability is the presence of an interstellar cloud near the Sun with an average density greater than 3.5 cm^{-3} (Mészáros 1972).

IV. DISCUSSION CONCERNING THE PRESENCE OF A NEARBY INTERSTELLAR CLOUD

a) *Location of the Candidate Cloud*

A more precise location of the candidate cloud can be determined by using the information in Table 1 and Figure 1. Accordingly, the cloud should be between the α Cen A and the α Boo lines of sight (closer to the α Cen A line of sight). This area (in the Sco-Oph region) is represented in Figure 4.

The observations of Herbig (1968) and, especially, those of Hobbs (1969*a*, *b*), who studied the interstellar Na lines in the direction of about 10 stars belonging to the Sco-Oph complex, suggest that there exists in this direction a regionally persistent absorption pattern around -10 to -15 km s^{-1}. Moreover, several rocket experiments (reviewed by Jenkins 1970) and the Orbiting Astronomical Observatory (*OAO 2*) (Savage and Jenkins 1972; Jenkins and Savage 1974) have observed Lα interstellar absorption in the direction of early-type stars. These data indicate an average interstellar density much larger toward Scorpius than in other directions of the sky. More recently, Bohlin (1975) confirmed these results using the *Copernicus* observations. His work also indicates the presence of a dense, thin sheet of gas extending over a large area of the sky (estimated at a distance of $\sim$160 pc) in front of some of his star sample (Table 2) in the direction of the galactic center. According to all these observations the angular area of the sky in which the candidate could be located is $\sim$40°, approximated by the circle in Figure 4.

b) *Distance Range and Reddening*

Previous analyses have correlated reddening and distance and found no evidence for the existence of a cloud near the Sun. For instance, FitzGerald (1968) observed very little reddening in any direction of the sky, within 50 pc from the Sun. However, he averaged measurements over volumes of 20 pc $\times$ 20 pc $\times$ 80 pc which is not a suitable method for precise analysis of the nearby interstellar medium (d < 50 pc). Therefore, we have analyzed the reddening only in the direction of the candidate cloud. The intrinsic $B - V$ values of Deutschman, Davis, and Schild (1976) were used to determine reddening. Figure 5 details the results obtained for a given sample of nearby stars (within 250 pc from the Sun) as a function of their distance.

For the very close stars displayed on Figure 1, reddening is high for α Cen A, α Boo, and α Eri. For the other six stars, reddening seems to increase slightly with distance. For all nine stars, the reddening determinations confirm the hydrogen density distribution near the Sun as described in § II.

The remaining stars in Figure 5 are those seen in the Sco-Oph direction. One can distinguish two kinds of stars: (*a*) those (6) that are out of but near the angular location of the candidate cloud; (*b*) the remaining stars (as shown in Fig. 4), listed in Table 2 as the stars with available N(H) measurements or in Table 3 as stars taken from Deutschman, Davis, and Schild (1976) with available $E(B - V)$ values (0° < b^{II} < 40°; 20° > l^{II} > 330° represent the limits for the

TABLE 2

HYDROGEN COLUMN DENSITIES OBSERVED TOWARD STARS NEAR THE DIRECTION OF THE CANDIDATE CLOUD

Star	d (pc)	N (H) (10^{20} atoms cm^{-2})	Remarks
ζ Oph........	200	5.0	Bohlin 1975
θ Oph........	200	3.0	
ρ Oph........	211	...	
β^1 Sco........	174	13	
δ Sco.........	154	14	Bohlin 1975
κ Sco.........	161	1.5	
λ Sco.........	103	< 0.24	Bohlin 1975
μ^1 Sco........	190	3.5	
ν Sco.........	174	15	
π Sco.........	200	5.2	Bohlin 1975
ρ Sco.........	210	5	
σ Sco.........	138	20	
τ Sco.........	236	3.1	Bohlin 1975
υ Sco.........	134	< 0.18	Bohlin 1975
ω^1 Sco........	225	12	
1 Sco.........	232	10	
13 Sco.........	230	7	
22 Sco........	216	10	
N Sco........	330	7.0	
β Cen.........	81	0.33	Bohlin 1975
ζ Cen.........	86	1.05	Bohlin 1975
σ Sgr.........	57	< 0.3	Bohlin 1975
μ Nor........	1004	10	Bohlin 1975
γ Ara.........	718	4.8	Bohlin 1975

TABLE 3

REDDENING OBSERVED TOWARD STARS IN THE DIRECTION OF THE CANDIDATE CLOUD (from Deutschman *et al.* (1976)

HD Number	l^{II}	b^{II}	d (pc)	$E(B-V)$
142096........	350.73	25.38	165	0.20
142114........	346.87	21.61	130	0.13
142250........	345.57	20.01	204	0.09
142301*.......	347.12	21.51	251	0.14
142445........	346.52	20.64	70	0.10
142883........	350.88	24.09	196	0.21
143567........	350.87	22.68	146	0.15
144470........	352.75	22.77	253	0.24
145483........	347.74	16.50	105	0.11
146624........	348.55	15.41	53	0.02
149711†.......	340.39	2.36	262	0.21
150591........	342.77	3.12	243	0.12
150742†.......	343.08	3.18	227	0.11
151473........	341.29	0.49	163	0.25
152491........	342.47	0.04	131	-0.02
152742‡.......	342.90	0.06	22	0.18
157955........	357.22	2.88	103	0.02

* Photometry and spectral type disagree.

† Photometry and luminosity disagree.

‡ Photometry disagrees with both spectral type and luminosity.

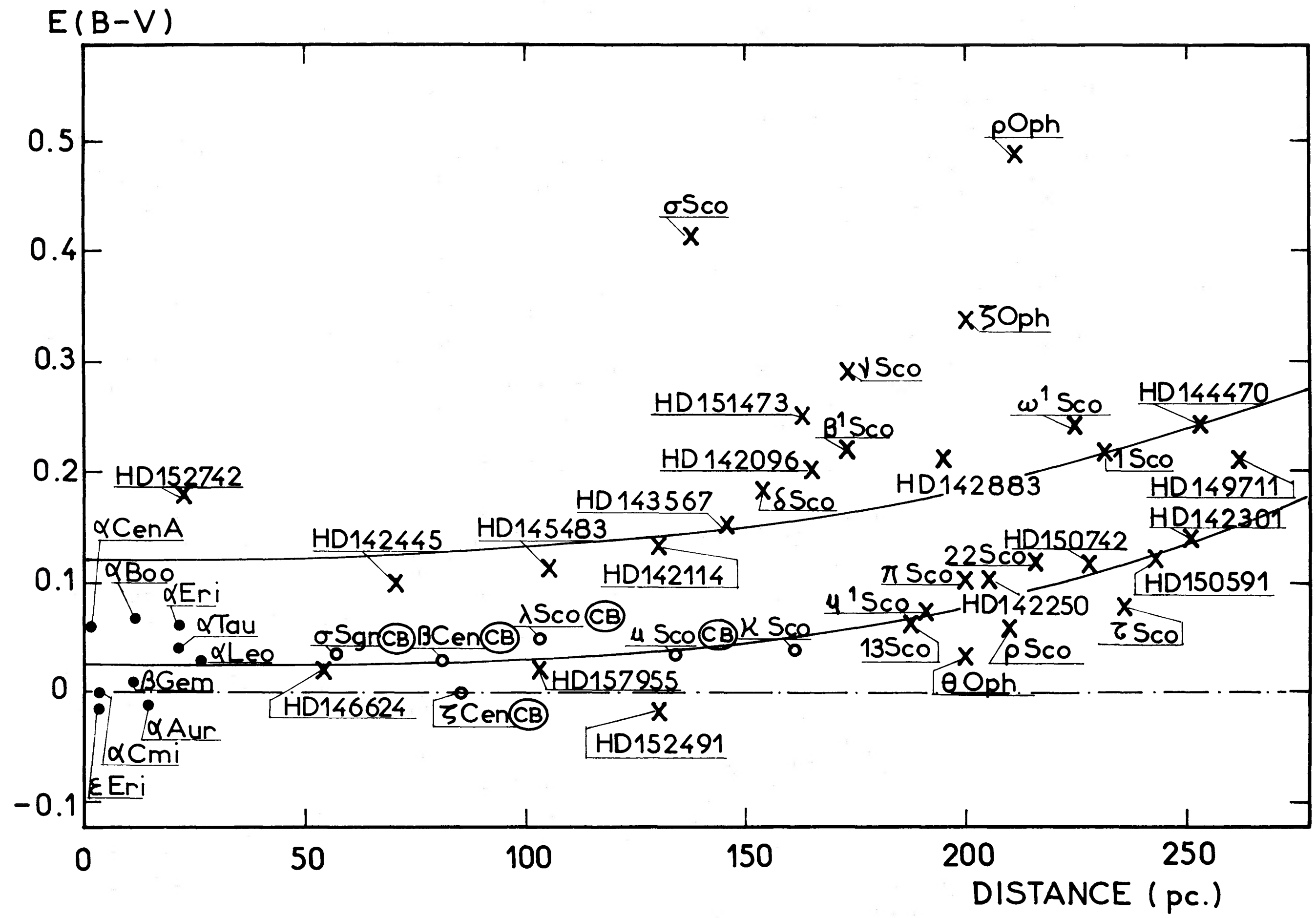

FIG. 5.—Reddening of three samples of stars with respect to their distance: (i) filled circles (●) are for the nearby stars of Fig. 1; (ii) open circles (○) are for the stars near (but out of) the angular region of the candidate cloud (among them the closest stars of Bohlin's sample are marked CB); (iii) crosses (×) are for the stars in the direction of the candidate cloud—some are displayed on Fig. 4; the others, marked by their HD numbers and listed in Table 3, are taken from Deutschman *et al.* (1976). The distribution of this last group seems to indicate the existence of two reddening phases independent of the distance up to almost 200 pc. These phases are emphasized by the two parallel lines separated by roughly 0.1 magnitude in $E(B-V)$.

selected stars in Deutschman, Davis, and Schild 1976). Bohlin (1975) found that the low N(H) values (corresponding to a low reddening) were related to the nearest stars of his sample (labeled CB in Figs. 4 and 5); he concluded that the absorbing material should be at a distance of 160 pc. This conclusion does not seem valid since other nearer stars (HD 152742, 142445, 145483, 142114, 143567) in the direction of the candidate cloud are significantly more reddened than the CB stars [the $E(B-V)$ value of HD 152742 is questionable as indicated by Deutschman, Davis, and Schild 1976 since "photometry disagrees with both spectral type and luminosity"]. The low reddening of the CB stars of the Bohlin sample is therefore attributable to their location out of the direction of the cloud. Thus the question of distance should be transformed into an angular problem. Note also that reddening is independent of distance for the stars out of but near the cloud (including α Cen A); possibly the reddening material is very close to the Sun.

The reddening distribution of the stars in the direction of the candidate cloud seems to indicate the existence of two distinct phases: (*a*) a phase with a low reddening, equivalent to the one observed in front of the CB stars; (*b*) a high reddening phase that has an $E(B-V)$ value ~0.1 mag greater than the previous phase. Both distributions show that reddening is roughly independent of distance; consequently, the reddening should be local, and the candidate cloud should be close to the Sun. The steady increase of the two distributions in this region of the sky can be related to the $E(B-V)$ versus distance relation established by Schild, Neugebauer, and Westphal (1971), who found in the same region of the sky that there should be an increase of 0.06 mag in $E(B-V)$ over 200 pc.

The two different phases in the direction of the cloud can be explained if the cloud were in an inhomogeneous phase. Mészáros (1973) proposed an evolution model for interstellar clouds of low mass

($M < 200\ M_\odot$) in which clouds aged $3 \times 10^7 < t < 5 \times 10^7$ years are unstable and develop blobs and holes. The two-phase pattern could be a signature of this predicted instability. Although the analyses of the reddening may not constitute clear evidence of the presence of a nearby candidate cloud, the existence of such a cloud is not precluded by the observational results.

c) *Distance of the Nearby Cloud*

The distance of this cloud can be roughly estimated as follows: since the UV flux geometry remains stable for approximately 10^7 years, the total displacement of the deuterium atoms should be $L_D \sim 0.02$ pc. We have shown that under such conditions the approximate interstellar density scale height in the vicinity of the Sun is $L \sim 0.02$ pc. In the two-phase model of the interstellar medium, since Mészáros (1973) showed that an interstellar cloud breaks down at densities $n_H \approx 3.5\ \text{cm}^{-3}$ to evolve rapidly into the intercloud phase, reaching at its outside boundary densities of the order of $n_H \approx 0.5\ \text{cm}^{-3}$; and since $0.1\ \text{cm}^{-3}$ is the value for the solar system density, the edge of the cloud should be then at a distance of ~ 0.03 pc from the solar system.

This estimation of cloud distance (0.03 pc) should represent a lower limit, since during the last 10^7 years the cloud was, on the average, much closer to the Sco-Oph association (the average relative motion of these stars is $\sim -5\ \text{km s}^{-1}$, as compared to the $-15\ \text{km s}^{-1}$ for the candidate cloud). Presumably the radiation pressure mechanism was more efficient in the past. On the other hand, this cloud cannot be farther than $\sim$1–2 pc from the Sun because then this model would not explain any depletion in deuterium on the α Cen A line of sight since α Cen A is at a distance 1.3 pc (Fig. 6). The cloud could be at a greater distance only if its original deuterium abundance is less than 2×10^{-6} times that of hydrogen, which seems a very remote possibility.

The cloud could be located at a shorter distance from the solar system. Using the analysis of the line of sight of ζ Oph (Herbig 1968), we may estimate the blob densities. From the observed abundances of atomic and molecular species in different ionization stages, Herbig (1968) placed the absorbing cloud at 15–50 pc from the star and estimated a thickness of $\sim$0.15 pc and a density ~ 500–$900\ \text{cm}^{-3}$. According to *Copernicus* observations of H_2 and HD (Spitzer, Cochran, and Hirshfeld 1974) and C II (Morton 1975), if the cloud were 100 pc from the star, where the UV flux from ζ Oph is equivalent to the interstellar UV flux (Witt and Johnson 1973), its density would be $n_H \sim 10^4\ \text{cm}^{-3}$ and its thickness only 0.05 pc. In the proposed model, the cloud is much closer to the Sun, and fewer constraints are necessary to Morton's (1975) discussion concerning the UV flux irradiating the cloud. By using this estimation of blob density and thickness, assuming an average of one blob on a given line of sight, and the estimation of the angular dimension of the cloud as $\sim 40°$, we may conclude that the cloud would be more elongated along the line of

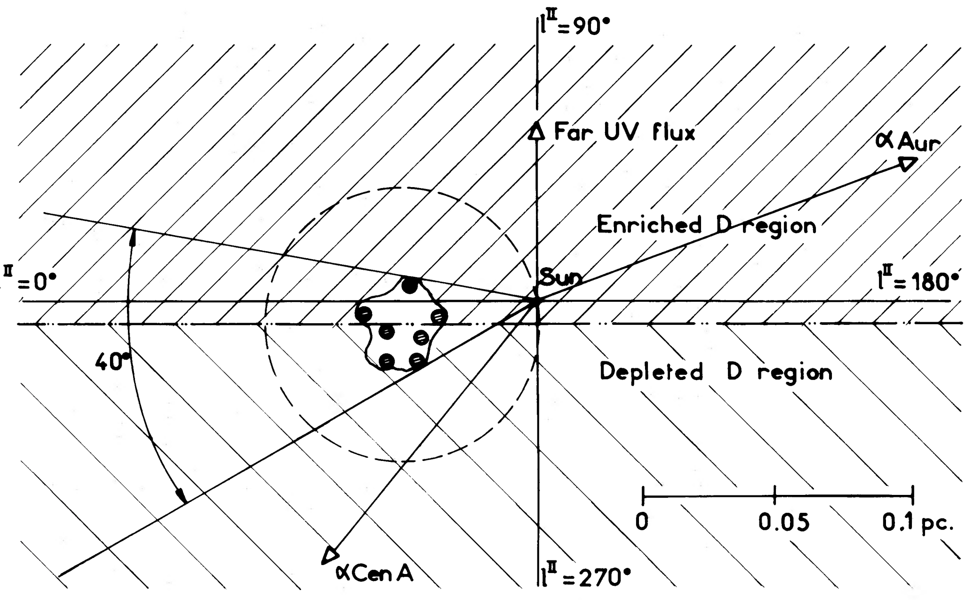

FIG. 6.—Projection of the first candidate cloud on the galactic plane at a distance of 0.03 pc. The solid lines are the assumed cloud boundaries at $n_H = 0.5\ \text{cm}^{-3}$ (blobs are represented to illustrate the two-phase structure of the cloud as deduced from the reddening analysis). The dashed circle represents the assumed $n_H = 0.1\ \text{cm}^{-3}$ level. The net UV flux responsible for the selective radiation pressure mechanism is also represented as a vector in the $l^{II} = 90°$ direction. Since the enrichment or depletion of deuterium is a function of both the UV flux and the density gradients, one can distinguish two regions separated on this figure by the thin line. From this schematic representation it is quite clear that, if such a mechanism works, the cloud is unlikely to be more than 2 pc from the Sun due to the very low D/H value observed on the α Cen A line of sight which must be mainly inside the depleted zone.

sight if it were located nearer to the solar system. Under such conditions a strong limitation is obviously to place the cloud at less than 0.01 pc. At this distance the cloud would be cigar-shaped (length 10 × thickness). Therefore, the region in which the cloud should be is reasonably between 0.01 and 2 pc from the Sun.

d) *Is the Scorpius-Ophiuchus Cloud the Only Possible Candidate?*

The previous analysis assumes that the Sco-Oph cloud explains both the local density gradient and the deuterium abundance variations. Recently, Adams and Frisch (1977) suggested the presence of another cloud to explain their *Copernicus* observation of the velocity vector of the interplanetary hydrogen. They found a velocity of -21 ± 2 km s^{-1}, slightly higher than ~ -15 km s^{-1} proposed by Hobbs (1969*a*) and Morton (1975). Furthermore, they showed that a weak component around -20 km s^{-1} seems to exist in front of some stars in the same region of the sky. This component may be connected with the local interstellar medium. This observation was correlated with the 21 cm survey of the region (Sancisi and Van Woerden 1970; see Fig. 4) that also displays a weak (10%) component, with a heliocentric velocity of -20 km s^{-1}. Sancisi and Van Woerden (1970) mapped the weak component and described a filamentary shape of 2° width in the same region and located it in front of ν Sco, β^1 Sco, and ω^1 Sco, but not in front of the other stars listed in Table 2. The velocity vector of this component seems to match the velocity measured locally inside the solar system. However, the velocity evaluation inside the solar system is certainly model-dependent, and there are no obvious reasons why the velocity measured at a given location of the edge of a cloud should be equal to the average velocity of the whole cloud. Considering this description, we find that such a candidate might be a low-density clump ($n_H \sim 0.1$ cm^{-3} i.e., the solar system value) and would be (1) very elongated (35 pc, to account for $n_H \sim 10^{20}$ cm^{-2}, i.e., 10% of the column density of the first candidate cloud); (2) very thin (1 pc thick, to account for the 2° angular diameter); (3) located just at the edge of the solar system since the local density decreases in the direction of the nearby stars opposite to the cloud; and (4) with a velocity vector aligned along its longest dimension. Furthermore, this configuration is not stable over a time long enough to satisfy the separation mechanism, and so is unable to explain the observed D/H ratio.

A more likely possibility is that the cloud is smaller but with a density $n_H > 0.5$ cm^{-3} and consequently more compact, more stable, and very close to the solar system. In this case, the second candidate is almost identical to the previous one. This cloud is less dense than the first candidate by about a factor 10 (its density should be $\sim 10^3$ cm^{-3}), but it should be located at the same distance ($\sim$0.03 pc).

Throughout this analysis we have concentrated on observable cloud candidates (column density $n_H > 10^{19}$ cm^{-2}). At present we cannot exclude an "invisible" candidate with a column density $n_H \sim 10^{17}$–10^{18} cm^{-2} (its column density cannot be less because of the α Cen A measurement). Taking into account cloud stability conditions presented by Field, Goldsmith, and Habing (1969), Mészáros (1972) shows that its minimum acceptable density should be $n_H \sim 3.5$ cm^{-3}, and, in consequence, its thickness should be $\sim$0.1 pc. In fact, such a "small" candidate cloud, which has to be compact like the previous candidates, would meet the requirements previously discussed.

Finally, nothing prevents these candidate clouds from being simply parts of the first one. Such a situation implies in depth a picture similar to the one inferred from the reddening analysis: the cloud could be in a blob-and-hole phase (Mészáros 1973).

V. IMPLICATIONS OF THE PRESENCE OF A NEARBY CLOUD

The existence of a very close (0.03 pc in the Sco-Oph direction) and possibly dense ($n_H > 10^4$ cm^{-3}) cloud as shown in Figure 6 seems to be consistent with the observations of the nearby interstellar medium, such as those of the gas embedding the solar cavity. Moreover, a nearby cloud would offer a reasonable explanation of the strong variation of the D/H ratio with respect to the considered line of sight.

Besides the necessity of observing the interstellar gas to confirm the presence of a nearby cloud, other implications are that (*i*) the actual interstellar deuterium abundance and its origin should be reexamined; (ii) this nearby cloud might manifest its presence in perturbations of comet orbits and these effects should be investigated; (iii) the encounter of the solar system with an interstellar cloud could have some effect on the planetary climate, which will be briefly discussed here.

a) *Implications of the Observations of the Interstellar Gas*

The presence of the nearby cloud should be confirmed by new observations.

The D/H ratio measured in the interstellar gas embedding the solar system should be much larger than the low value found in the α Cen A direction, of the order of D/H = $(3 \pm 2) \times 10^{-5}$ (note that the D/H ratio in the solar system would be low if the stellar wind mechanism or the planetary nebula one are valid proposals).

The D/H ratio should also be high in lines of sight other than along that of α Aur if they are within 90° of the vector sum of the far-UV fluxes.

The hydrogen column densities observed in various lines of sight should show unambiguously the density gradient given in § II.

The observation of the interstellar medium toward nearby stars (within 30 pc) in the direction of our candidate cloud should confirm its existence.

The proposed selective radiation pressure mechanism could also act upon other chemical species. Other observational anisotropies would be clear proof of the proposed mechanism.

b) *Deuterium Abundances, Origin, and Evolution*

The large variations of the deuterium abundance observed in the interstellar medium should be taken into account in the models regarding its evolution and its origin. A more complete discussion is presented in a forthcoming paper (Audouze *et al.* 1978); however, if the interstellar D/H ratio is lower than the previous estimate of (1–1.5) $\times 10^{-5}$, it should be related to a somewhat higher density of the present universe $\rho > 3\ 10^{-31}$ g cm^{-3} if deuterium was produced during the big bang (e.g., Wagoner 1973). But even with an interstellar D/H value of 2×10^{-6}, the corresponding density of the universe is not high enough to close the universe.

c) *Other Astrophysical Implications*

Encounters between clouds and the solar system could have induced significant accretion processes within the solar system. In this respect, Fahr (1971) and Fahr, Lay, and Blum (1976) have evaluated the gravitational focusing of the interstellar hydrogen by the Sun and the planets in the direction opposite to that of the interstellar matter flow. A significant increase of density due to collisions could have been produced by this effect around the Sun, leading to the generation of long-period comets. Thus, the D/H ratio in long-period comets could be predicted to be lower than that in the cloud since the focusing effect would be less efficient on deuterium atoms due to the selective radiation pressure mechanism, induced by the solar flux, just because in a cloud of $n_{\rm H} \sim 10^3$–10^4 cm^{-3} the interplanetary medium would be optically thick for the hydrogen, and not the deuterium, Lα line.

The presence of a nearby cloud should also affect short-period comets. If such a cloud entered the solar system, it should induce some perturbations on the orbits of these objects, perhaps similar to those used by Brady (1972) to support the hypothesis of the presence of a tenth planet. If the cloud is at a distance of 0.1 pc from the solar system, there should be no sizable perturbations to be measured. However, if the cloud is as close as 10^{-3} pc (i.e., $\sim$100 AU), a precise evaluation of its distance by these perturbation methods would be possible.

Finally, as noted by Talbot and Newman (1977), an encounter between the solar system and an interstellar cloud may have further important astrophysical implications. The accretion of interstellar matter could slightly increase the metal abundance of the solar surface. A model including the effects of previous cloud encounters may shed light on the solar neutrino problem (Newman and Talbot 1976; Auman and McCrea 1976); such an effect might also be incorporated in models of chemical evolution of galaxies.

d) *Climatic Effects of the Encounter of a Nearby Cloud with the Solar System*

Several investigators have proposed that important climatic changes such as the occurrence of ice ages with a period of about 10^8 years, could be related to the passage of dense interstellar clouds across the solar system. For example, Hoyle and Lyttleton (1939) found that the luminosity of the Sun can be enhanced by accretion processes of the interstellar cloud material on the solar surface. McCrea (1975) has claimed that only very dense clouds, $10^5 < n_{\rm H} < 10^7$ cm^{-3}, can induce significant effect on the solar luminosity, while Begelman and Rees (1976) have argued that less dense clouds, $\sim 10^3$ H cm^{-3}, could also affect the terrestrial climate by isolating the Earth from the solar wind.

One possible area of investigation of the forthcoming results of *Viking* regarding the Martian climatology would be to correlate any major climate change on Mars (e.g., the massive water flows that occurred in the past) with the occurrence of an ice age on Earth. A simultaneous climatic change on these two planets might be the signature of an encounter with an interstellar cloud.

VI. CONCLUSION

Two basic observations regarding the nearby interstellar medium—the existence of a hydrogen gradient and the anisotropy of the UV (950 Å) flux—have been used in this paper to propose a scenario to account for the large D/H variations observed toward α Cen A and α Aur (Dupree, Baliunas, and Shipman 1977). A particular motivation for this work was to try to account for the high D/H ratio found in front of α Aur. The most likely mechanism seems to be deuterium separation by selective radiation pressure. The two basic observations are strong arguments in favor of a mechanism in which the geometrical configuration of the close interstellar medium has remained stable for at least $\sim 10^7$ years. Such a stable density gradient implies the existence of a nearby ($d < 2$ pc) interstellar cloud. The interstellar reddening and the absorption-line observations in the Sco-Oph region do not contradict the presence of a nearby cloud in this direction. The presence of such a cloud would then imply a high interstellar D/H ratio inside the solar system. Further investigations would provide essential data to support this hypothesis or that of planetary nebula mechanism such as that described in § III*a*.

The presence of a nearby cloud might also affect the physical conditions inside the solar system. Some tentative predictions can be made of the deuterium content in long-period comets, and, as stated in many reports, an encounter with a cloud might not only affect the neutrino flux released from the Sun but also have some drastic influence on the terrestrial climate in the next 10^4 years.

The observations and analyses mentioned here suggest the presence of a very close interstellar cloud which should encounter the solar system in the "near" future. However, the complexity of the interstellar medium is not completely understood, it would not be surprising if the situation is far more complicated than indicated in this paper.

This analysis relies heavily on the new and important information from the *Copernicus* observations. We are therefore very much indebted to the Princeton group, especially Drs. D. G. York and T. P. Snow. We are very grateful to Dr. A. K. Dupree who has communicated to us her very important results prior to publication. We would like to thank Drs. M. Jura, J. Lequeux, J. L. Puget, and D. G. York for fruitful discussions, and Mrs. J. Caro, Mrs. R. Osman-Jouchoux, and Mrs. Noël-Giraud for their efficient help in the presentation of the manuscript. We acknowledge some useful remarks provided by Drs. T. Montmerle and C. Ryter. Last but not least, we thank an unknown referee for his very constructive criticisms and valuable comments.

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Note added in proof.—Dr. G. Michaud has kindly pointed out to us that if the radiative flux is spatially constant in the neighborhood of our cloud and if the medium is stable enough to make the diffusion equation applicable, the proposed mechanism of separation of deuterium from hydrogen runs into difficulty: the effect of density in the diffusion velocity exactly cancels the increase in the deuterium density. However, radiative forces might be, for example, spatially dependent, in which case this separation mechanism is still possible. This point is currently under investigation.

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