Reports

Interstellar Cloud Material: Contribution to Planetary Atmospheres

Abstract. *A statistical analysis of the properties of dense interstellar clouds indicates that the solar system has encountered at least a dozen clouds of sufficient density to cause planets to accumulate nonnegligible amounts of some isotopes. The effect is most pronounced for neon. This mechanism could be responsible for much of the neon in Earth's atmosphere. For Mars, the predicted amount of neon added by cloud encounters greatly exceeds the present abundance.*

Several investigators have considered the implications for Earth's climate (*1–4*) and stellar surface abundances (*5, 6*) of encounters between the solar system and dense interstellar clouds. Talbot and Newman (*6*) have estimated the frequency of such encounters on the basis of a statistical study of current observations. We discuss here the direct effect of these encounters on planetary atmospheres.

The early investigators considered only conditions for which the interstellar material was effectively collisionless. In contrast, we are concerned only with those relatively few encounters for which the density is large enough so that the gas particles have mean free paths much smaller than the scale of the problem and the fluid approximations are valid. This means that we everywhere underestimate the effects because of the neglected encounters. Since the pioneering paper of Hoyle and Lyttleton (*2*), investigators who have considered the problem have concluded that accretion from the general interstellar medium is negligible and that accretion from most interstellar clouds (hydrogen number density $n \sim 1$ to 100 cm^{-3}) is negligible. This conclusion was further reinforced in the discussion by Talbot and Newman (*6*); however, as they emphasized, there have been a few encounters (16 out of about 900) with clouds with extreme properties such that they should have had significant influences upon the solar system. The knowledge that most cloud encounters (884 out of about 900) have had no effect should not bias one against the realization that a small fraction of the encounters may have been important.

We adopt lower-limit values for quantities to emphasize that the interstellar medium has almost certainly had some effect upon planetary atmospheres. These results are sufficiently contrary to the conventional view held by solar system scientists that this approach is required.

Upon encountering a dense interstellar cloud, a planet of radius R will accumulate hydrogen (mostly H_2 molecules) at a rate at least as large as that given by its geometrical cross section multiplied by the apparent flux:

$$\dot{M} \gtrsim \pi R^2 V(r) n(r) m_H \qquad (1)$$

where V is the velocity of the gas relative to the velocity of the planet at that planet's distance from the sun, r, and m_H is the mass of H_2. Gravitational attraction of the material toward the planet produces an additional mechanism that might enhance this rate, but the theory for such gravitational accretion is uncertain, especially for the situation in which the particle-particle mean free path is much greater than the radii of the planets. The geometrical cross section is a lower limit.

For interstellar cloud densities far from the sun and less than about 3000 cm^{-3}, $n(r)$ scales with distance from the sun roughly as $r^{-3/2}$ inside the solar "accretion radius," $r_c = GM_\odot/c_e^2$. Here G is the gravitation constant, $M_\odot$ is the mass of the sun, and the effective sound speed c_e (in kilometers per second) is given by $(v^2 + c_\infty^2)^{1/2}$, where v is the speed of the solar system with respect to the interstellar medium and c_∞ is the sound speed in the cloud far from the sun. In this expression for r_c we assume that the material is gravitationally attracted by the sun. The interstellar gas behaves as a fluid provided that the particle-particle mean free path λ is less than the characteristic length scale of the flow, r_c. We will be concerned only with those situations where $(\lambda/r_c) = c_e^2/GM_\odot n\sigma = 0.75\, c_e^2 n^{-1} < 1/30$, a condition which guarantees that the fluid approximation is valid (we use for σ, the H_2 collision cross section, $= 10^{-16}$ cm^{-2}). (In the present local interstellar environment, $\lambda/r_c \sim 3000$.) For $r < r_c$ (r is in astronomical units), the average V will be a little larger than the free-fall velocity $42.2\ r^{-1/2}$ km sec^{-1}. If the solar system has spent a time Δt (in millions of years) in clouds that produce a density at Earth's orbit, $n_\oplus$, then the total amount of material accreted from the interstellar medium during its lifetime by a planet a distance r from the sun is

$$M_{acc} \geq 3 \times 10^{18} (R/R_\oplus)^2 r^{-2} \Sigma(n_\oplus/10^4)\Delta t \qquad (2)$$

where the summation is over classes of clouds. Equation 2 is essentially equivalent to what one obtains with the Bondi-Hoyle (*3*) accretion column argument, but we restrict ourselves to cases where the gas behaves as a true fluid.

The results of our computations for $n_\oplus$ and Δt are given in Table 1 for interstellar clouds classified by their mean density far from the sun, n_∞. The total numbers of encounters with clouds of each class, N_e, are deduced from the analysis presented in (*6*). The present solar wind and the heating and ionization by the accretion luminosity act in opposition to the accretion flow (*6*); N_a shows our estimate of the number of encounters of each class for which the relative velocity v is low enough to allow accretion onto the solar surface. The internal velocity dispersions of these dense clouds, c_∞ are $\lesssim 0.5$ km sec^{-1}. The accretion luminosity which would result is L_{acc}. The unit $10^{-2}\ L_\odot$ roughly corresponds to the solar ultraviolet flux; since the accretion luminosity would peak in that wavelength region (*4*), the influence on the planetary radiation environment could be substantial. The duration of individual encounters of each class is given by $\Delta t/N_a$ (it is accidental that the three Δt values are approximately equal).

One may well be concerned over whether material actually accretes onto the sun, or whether it forms an accretion disk which prevents it from moving in toward the solar surface. That question is important for the sun, but it does not affect our argument. We have considered (in the relatively small number of cases N_a) only those circumstances where (i)

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the interstellar material pressure overwhelms the outward dynamic pressure of the solar wind (by at least a factor of 100) and (ii) the inflow rate of neutral H_2 is faster than the photoionization rate by the sun even if 10 percent of the accretion luminosity were in the form of ionizing photons [the details of these considerations may be found in (6)]. If material does not fall onto the sun, the accretion luminosity will be lower. The material must go somewhere; it does not have sufficient energy to leave the solar system on its own, because the solar wind does not have enough momentum to push it out [item (i) above] and solar radiation pressure is inadequate. No matter what happens to it (probably an accretion disk of some sort), the mean density will be greater than if the material had gone onto the solar surface. We deduced this from the observation that, owing to angular momentum, the accreting material falls toward the central gravitational field source more slowly than if it had no angular momentum [because it is a fluid with dissipation, it will lose energy and slowly move inward; our case is an unexotic example of accretion disks, which have been extensively discussed for x-ray stars and black holes (7)]. The important point is that lower radial velocities mean higher densities, and hence more material is encountered by a planet. As before, we take the lower-limit case by assuming that the material does go onto the solar surface at the highest possible rate and therefore the lowest possible density.

Although we see from Table 1 that the sum in Eq. 2 could be quite large, we adopt a conservative (low) value for the density at Earth for each class of cloud and count only those few with conditions that qualify for inclusion in N_a; this gives a value of 5 for the sum $\Sigma(n_\oplus/10^4)\Delta t$. This quantity is unlikely to be less than 3, but it is probable that it is appreciably greater than the nominal value of 5. This number would be increased if we were to include the effects of those very many cloud encounters (over 90 percent of N_e) for which the density is not sufficient to allow accretion onto the sun but which nevertheless enhance the density at 1 A.U. For planets with magnetic fields, the degree of ionization of the cloud material that occurs in those cases will significantly affect planetary accretion. The analysis used to derive N_a shows that less than half of the N_e encounters would produce ionization zones as large as 1 A.U.; that is, it is probable that most of the N_e encounters will bathe the planets in a neutral gas with $n_\oplus > 10$ cm^{-3}; nevertheless, to be on the conservative side, we consider only the small number N_a. For them, $n_\oplus > 3 \times 10^3$.

Table 1. Values of parameters for encounters with interstellar clouds.

n_∞ (cm^{-3})	$n_\otimes$ (cm^{-3})	N_e	N_a	Δt ($\times 10^6$ years)	L_{acc} ($10^{-2} L_\odot$)
10^1 to 10^2	$\sim 4 \times 10^4$	800	2	~ 1	$\sim 10^{-2}$
10^2 to 10^3	6×10^3 to 10^6	120	5	~ 1	10^{-3} to 0.3
10^3 to 10^4	3×10^3 to 10^7	16	7	~ 1	10^{-3} to 3

Table 2. Possible contributions of cloud material to present-day planetary atmospheres; acc, accreted abundance normalized by multiplication by the factor $10^6\ M_{acc}/M_{atm}$; atm, contemporary atmospheric abundance. Abundances are in parts per million by mass.

Element	Venus		Earth		Mars	
	Acc	Atm (15)	Acc	Atm (16)	Acc	Atm (17)
H	41	~ 1.7	2250	~ 2170	5.2×10^4	<239
He	11	$\sim 2.3 \times 10^{-2}$	620	0.72	1.45×10^4	?
C	1.6	2.7×10^5	87	136	2050	2.6×10^5
N	6.5×10^{-2}	<6000	3.6	7.6×10^5	85	1.6×10^4
O	4.4×10^{-1}	7.3×10^5	24	2.3×10^5	550	7.0×10^5
Ne	9×10^{-2}	?	4.8	12.7	110	~ 1.7
^{36}Ar	4.5×10^{-3}	?	0.24	43.8	5.8	6.0
^{38}Ar	9.0×10^{-4}	?	5×10^{-2}	8.2	1.2	~ 1
^{40}Ar	1.0×10^{-6}	?	5.5×10^{-5}	1.29×10^4	1.2×10^{-3}	2×10^4
Kr	5.0×10^{-6}	?	2.7×10^{-4}	0.39	6.2×10^{-3}	~ 0.4
Xe	9.0×10^{-7}	?	4.8×10^{-5}	3.3	1.1×10^{-3}	~ 0.1

The amounts of material added and its significance vary considerably from planet to planet. For the massive jovian planets, which have presumably retained their original composition closely resembling that of the interstellar medium, the effect should be small; too little is known about their moons to provide a reasonable basis for comparison. The escape rates of volatiles from Mercury are too fast to allow a meaningful buildup of atmosphere, although during a cloud encounter Mercury may develop an atmosphere which is rapidly lost afterward. Traces of these temporary atmospheres may be found in the poorly heated polar regions, especially in polar craters as suggested for the moon (8); however, in what follows we consider only Venus, Earth, and Mars.

For $n_\infty \gtrsim 3000$ cm^{-3}, the distance dependence of the particle density is much less steep than the $r^{-3/2}$ which leads to Eq. 2; it is in fact almost flat near 1 A.U. At lower cloud densities $n(r) \propto r^{-3/2}$ varies from 1.6 $n_\oplus$ for Venus to 0.5 $n_\oplus$ for Mars. For Venus, Earth, and Mars the factor $(R/R_\oplus)^2 r^{-2}$ in Eq. 2 stands in the ratios 1.73:1.00:0.12, yielding mass additions of 2.6 10^{19} g for Venus, 1.5 10^{19} g for Earth, and 1.8 10^{18} g for Mars. Much more important in evaluating the significance of cloud encounters for those planets are the masses of their atmospheres, M_{atm}, which stand in the ratios 89:1.0:4.9 $\times 10^{-3}$. The relative contributions M_{acc}/M_{atm} are 5×10^{-5} for Venus, 3.0 10^{-3} for Earth, and 0.07 for Mars. If the interstellar material accumulated is distributed among the various elements in the abundance ratios of the primitive solar system (9), the effect on the contemporary atmospheres of these planets of admixing the appropriate fraction of interstellar matter is as shown in Table 2.

The bulk of the cloud material consists of H_2 and He, and for all three planets the amount that could have been added by cloud encounters exceeds the present-day atmospheric abundances. Although both elements are light enough to gravitationally escape, their fate during and after encounter will differ because of atmospheric chemistry. The He concentration should build up during encounters and decay away afterward on time scales short as compared to the interval between encounters. By comparison, H_2 can participate in radical chemistry involving OH, HO_2, and other "odd hydrogen" species, and eventually become tied up in H_2O (water) which will not escape directly. The input of H_2 during encounters could balance the continuous losses for Earth and Mars and provide a source of H_2 to the Venus atmosphere.

Although not a large mass of H_2 is added, if it is efficiently converted into H_2O, the H_2O vapor abundance at very high altitudes will be greatly enhanced over the present value, and this will alter the atmospheric absorption and reflection properties. This would affect the climate during those episodes (10).

About 1 percent of the cloud material

is in the form of dust, so that some 1.5×10^{17} g of dust (H_2O ice or silicate grains, or both) should have been accreted by Earth during time intervals totaling about 3×10^6 years. The flux of interstellar dust averaged over the age of the solar system is $\sim 6 \times 10^{-12}$ g cm^{-2} year^{-1}, which is well below the value of $\sim 2.10^{-9}$ g cm^{-2} year^{-1} of dust influx found in lunar soils (*11*), and thus most of that probably originated in the solar system. Evidence consistent with our predictions indicating occasional enhancements in the flux of dust has been found in lunar core samples (*12*). During encounters, the predicted interstellar flux is about 8×10^{-9} g cm^{-2} year^{-1}, four times the average dust flux deduced from lunar soil. During these episodes the average rate of dust loading for Earth is $\sim 5 \times 10^{10}$ g year^{-1}. This value is comparable to the dust loading from other sources, such as volcanism, which have been suggested to have significant effects on Earth's climate. Material would be injected at the top of the atmosphere so that its residence time is longer than that of particulates from most terrestrial sources, and the high-altitude tail of the particulate distribution will be strongly affected.

The cosmic abundances of C, N, and O are high, but for N and O we estimate small interstellar contributions relative to the large amounts present in the atmosphere (Table 2). We expect the amount of C from the interstellar medium to equal or exceed the C present in the form of CO_2 in the present atmosphere of Earth, but most terrestrial CO_2 is locked up in carbonates. When the complete C budget of Earth is considered rather than just the atmospheric portion, the contribution from cloud encounters is insignificant. Of the three planets considered, Mars is the most susceptible to interstellar C input but in the present calculations the contribution is <1 percent.

The most striking case is that of Ne. The minimum amount of Ne we expect to have been added from clouds is 37 percent of that present in the terrestrial atmosphere. We conclude that a substantial fraction of Earth's atmospheric Ne is probably of interstellar origin. In view of our estimate above that $\Sigma n_{\oplus}\Delta t \sim 5$ was at the low end of the expected range, it is not at all improbable that virtually all of the Ne present in Earth's atmosphere was added by the interstellar medium.

The Ne mixing ratio on Venus is not known. It could provide a test of these ideas.

For Mars, the interstellar contribution is predicted to be more than 50 times the present atmospheric content of Ne. This surprising result may indicate that (i) interstellar encounters have not contributed as much material as our estimates suggest, (ii) the abundance of Ne in interstellar material is smaller than currently believed, or (iii) there has been substantial Ne loss by Mars. McElroy *et al.* (*13*) assumed an exospheric temperature of 400°K for Mars in their discussion of the differential escape of ^{15}N and ^{14}N. That temperature would not lead to an appreciable gravitational escape rate for mass 20, and, since neon does not form significant amounts of molecular ions, the escape mechanism involving fragments of dissociative recombination reactions is inapplicable. However, the understanding of the interaction of the solar wind with the martian atmosphere is not yet sufficient to rule out a continuous loss of Ne, nor is the history of the martian exospheric temperature known.

It has been suggested (*14*) that the sinuous channels on Mars imply that a dense atmosphere prevailed in earlier epochs. This atmosphere has either been lost from the planet or the material is currently tied up in the martian polar caps. Our Ne discrepancy may provide alternative evidence for atmospheric loss. Since it seems unlikely that significant amounts of atmospheric Ne could be tied up in CO_2 and H_2O ices, we suggest that the Ne abundance indicates that most of an earlier dense atmosphere was lost from the planet rather than condensed on its surface. At present, there is no reason to relate the loss mechanism to the cloud encounters but such external mechanisms should not be excluded from future investigations.

Measurement of the amount of ^{20}Ne in the martian atmosphere should shed new light on this question. The estimate given is based upon a measurement of ^{22}Ne and an assumed $^{20}Ne/^{22}Ne$ ratio of 10.

There are many uncertainties associated with the several different ways of explaining this Ne discrepancy, so no definite conclusion may be drawn. Our purpose is to state what we believe to be a significant problem; we do not yet see the solution.

The Ar isotopic abundances are shown in Table 2. Terrestrial atmospheric Ar is predominantly ^{40}Ar, due to the decay of ^{40}K, but cosmic argon is mostly ^{36}Ar and ^{38}Ar. Thus, although the total amount of Ar present in Earth's atmosphere is many orders of magnitude larger than that which we expect to have accumulated from encounters with interstellar clouds, most of that is ^{40}Ar; ~ 0.5 percent or more of the present amount of ^{36}Ar and ^{38}Ar could have been added during encounters with dense interstellar clouds.

As with Earth, most of the Ar on Mars is ^{40}Ar from the decay of ^{40}K. However, for Mars the interstellar contribution to ^{36}Ar and ^{38}Ar is predicted to be almost exactly equal to the amount present in the atmosphere. Gravitational escape of species as heavy as Ar is certainly not expected; thus it is reasonable to expect most of the accumulated Ar to have remained. In view of the large uncertainty in the Ar abundance of the primitive solar system (*9*), which we use for the interstellar cloud abundance, we cannot draw firm conclusions from Ar alone. However, our results indicate that interstellar cloud material is a nonnegligible factor in the Ar budget of Mars.

Heavier species are too rare in the interstellar medium to have dramatic effects on bulk atmospheric properties, although the possible accumulation of interstellar material bearing products of very recent nucleosynthesis should not be overlooked. In such a case, a cloud encounter would be revealed by the presence of short-lived radioactive elements.

Interstellar cloud material can make significant contributions to the evolution of the H_2 budgets of Venus, Mars, and Earth. With planetary accumulation of interstellar material at rates at least as large as our lower bounds, then at least the Ne and Ar abundances of Mars and Earth have been influenced by the material. For Mars, the Ne abundance may be an indication that there has occurred substantial atmospheric loss of atomic mass 20 after the formation of the planet. It is also possible that our estimates of the amounts of accumulated interstellar material are too large; however, we have taken pains to underestimate this contribution and we still find a discrepancy.

The problems of the evolution of planetary atmospheres are clearly made more complex by the consideration of uncertain episodic phenomena of external origin, but we believe that we should not ignore the effects of encounters between the solar system and dense interstellar clouds.

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DNA Structure: Evidence from Electron Microscopy

Abstract. *The contour lengths of ϕX174 DNA duplex and RNA-DNA hybrid molecules were measured by several commonly used electron microscopic techniques. The countour length of the hybrid molecules corresponds to a rise of 2.5 to 2.6 angstroms per base pair, as expected for the A conformation, while the length of ϕX174 duplex DNA similarly measured corresponds to a 2.9-angstrom rise, very different from 3.4 angstroms of the classic B form. Thus any chromatin structure parameter based on electron microscopy and a rise of 3.4 angstroms must be reappraised. The possibility that DNA in dilute solution also has a rise of 2.9 angstroms and a screw of 10.5 base pairs per turn is discussed.*

The structure of DNA in dilute solution has not been proved to correspond exactly to any of the helical forms observed under conditions necessary for x-ray crystallography. These conditions require that DNA be oriented in very high concentration, and in less than 100 percent relative humidity. The x-ray studies reveal two steriochemical families, A and B (*1*), which differ in the orientation of the base pairs relative to the sugar-phosphate backbone; transitions from the A to B patterns are observed upon changing the ionic conditions and hydration of the DNA fibers. Because the classic Watson-Crick B structure having a rise of 3.4 Å per base pair and a screw of 10.0 base pairs per turn is found at higher relative humidities as compared to the A form, it is generally assumed that this classic B structure is retained when these DNA concentrates are dispersed into dilute solution. Little direct experimental evidence for this assumption exists, however, and recent energy calculations suggest otherwise (*2*). It is therefore important to establish the helical parameters, the rise and screw, of DNA under normal laboratory conditions. Furthermore, because electron microscopy (EM) is commonly used to measure the mass per unit length of DNA, an accurate measurement of the rise of DNA as it is visualized by the common EM techniques is important to many studies.

Now that the exact size of the ϕX174 genome is known (revised to 5386 base pairs) (*3*) measurement of its length by EM provides a direct means of measuring the average rise of DNA prepared by these techniques. Furthermore, such values might reflect the rise of DNA in dilute solution if changes in length which may occur during the preparation and dehydration of the DNA could be eliminated or understood. One probe into such changes would be a parallel measurement of the length of ϕX174 RNA-DNA hybrid circles synthesized from single-stranded ϕX174 DNA and *Escherichia coli* RNA polymerase (*4*). These hybrid molecules are always found in the A helix form in x-ray studies and appear to remain so even in dilute solution (*5*). Their length divided by 5386 base pairs should correspond to the A helix rise of 2.55 Å. A second test would be to determine whether or not open covalently closed DNA circles become supertwisted during preparation for EM. Because of the spiral nature of the DNA double helix, any change in its length should also be accompanied by a change in the rate at which the two strands wrap about each other, that is, the screw. Any such changes, therefore, would be seen as a supertwisting of a formerly covalently closed DNA circle.

This report describes such a study. With the use of the ϕX174 strain that has been sequenced, several different EM techniques were applied to measure both ϕX174 DNA duplex and RNA-DNA hybrid circle lenths. Whereas measurement of the ϕX174 hybrid length yielded a value in agreement with the A helix rise, measurement of the DNA duplex circles yielded a rise of 2.9 Å, very different from the 3.4 Å of the classic B form. Furthermore, covalently closed, open DNA circles remained untwisted during these EM procedures. These results support the suggestion that DNA in dilute solution also has a rise close to 2.9Å. Furthermore, this finding will require reevaluation of any chromatin parameter based on EM and a rise of 3.4 Å.

ϕX174 (amber 3) double-stranded DNA was prepared for electron microscopy by several different preparative procedures (Fig. 1 and Table 1): (i) direct absorption on carbon supporting films in a physiologic salt mixture followed by slow dehydration with water-ethanol washings and tungsten shadow-casting (*6*), (ii) absorption onto carbon supports followed by brief washing with dilute ammonium acetate buffer, drying in air, and tungsten shadow-casting, and (iii) surface spreading on a cytochrome c film (*7*) followed by picking up on plastic supports and shadow-casting with carbon-platinum.

Absolute molecular lengths were measured with the aid of a ruled grating verified in this laboratory (*8*) to have 54,800 lines per inch (1 inch = 2.54 cm). The grating was used in two ways: (i) consecutive sets of micrographs of the grating and of the sample were taken (*9*) and the DNA lengths were related to the mean grating spacing set-by-set, and (ii) a copper grid supporting the sample and a grid carrying the grating were sandwiched together and photographed simultaneously; the length of each molecule was related to the grating spacing in the same micrograph (Fig. 1A).

The length of ϕX174 duplex DNA prepared by direct absorption onto carbon supports, slow dehydration, and tungsten shadow-casting yielded values of 2.9 ± 0.05 Å and 3.0 ± 0.10 Å for the average rise by the two methods of measurement. Both DNA directly mounted and blotted dry from dilute ammonium acetate solutions and DNA surface spread with cytochrome c had lengths corresponding to a 2.9 ± 0.10 Å rise.

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