maxwellian for energies greater than about 0.22 eV and less than 0.57 eV. The charge exchange sources contribute very little to the total hot density on the dayside. The $O^+ + H_2$ reaction is the dominant source of the nonthermal H.

Given a distribution function at the exobase level one can find the corresponding exospheric density distribution of H as a function of altitude by using Liouville's theorem[17]. We calculated the exospheric density distributions, using the distribution functions shown in Figs 1 and 2 and assuming (1) that the distribution functions are isotropic and (2) that there is spherical symmetry. Only ballistic and outgoing (escaping) hyperbolic orbits were included in our calculations. This should be a fairly good assumption because, for Venus, satellite particles will be rapidly removed by charge exchange with energetic solar wind or ionosheath protons. The calculated exospheric densities for the nightside are shown in Fig. 3. The total hydrogen altitude distribution (cold and hot maxwellians), has almost the same shape as density distribution *c* (the cold maxwellian plus our calculated nightside distribution), although the absolute magnitude is somewhat larger. We also calculated the total exospheric altitude distributions for the dayside but do not show them here because of space limitations and because the agreement between our calculated altitude distribution and the one deduced by Anderson[1] agree even better (~20%) than shown for the nightside case.

Note that, in comparing the results of these calculations with the Mariner 5 data, the atmospheric and ionospheric conditions were different during the Mariner 5 encounter and the Pioneer Venus observations and furthermore, the ionospheric densities are highly variable and only model values of H_2 are available. The calculations presented here indicate, within the limitations just mentioned, that reactions (1), (3) and (4) are the major sources of the 'hot' component of Venus hydrogen corona. On the nightside the charge exchange reactions are important because the ion temperatures are high and the H^- densities are greater than on the dayside. There are preliminary indications, from the Pioneer Venus ion mass spectrometer results[10], that there is a significant night-time hydrogen bulge; if the night-time 'cold' hydrogen densities are greater than the values assumed in these calculations, the importance of reaction (4) will increase further. Contrary to earlier suggestions[9], most or at least a significant fraction of the nightside hot hydrogen population is apparently produced locally.

As the Pioneer Venus Ly α intensity results become available, more quantitative comparisons can be carried out. The nightside Venus ionosphere is highly variable, with apparent time scales of the same order as the hot hydrogen lifetime ($\sim 10^3$ s) and therefore, orbit to orbit comparisons between the measured Ly α intensities and ionospheric parameters can be used to check the validity of the basic mechanisms suggested in this work.

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A weak interaction model for Io and the jovian magnetosphere

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Four features of the interaction between the satellite Io and the surrounding jovian magnetosphere place constraints on the atmosphere of the satellite and on the nature of the interaction: (1) the atmosphere must be at least partly an exosphere so that sodium and other non-volatile atoms sputtered from the surface of the satellite could escape[1,2]; (2) the atmosphere should be dense enough for a detectable ionosphere to form showing a leading–trailing asymmetry[2,3]; (3) the atmosphere should provide an electrically conductive path to produce the electric currents which eventually cause the Io-related decametric radio emissions[4,5]; (4) the conductivity of the ionosphere should not be large enough to short out the electric field seen by the satellite, as pronounced absorption of energetic particles is observed[6–8]. Before the Pioneer 10 encounter it was pointed out[9] that erosion by the co-rotating magnetosphere caused atmospheres on the galilean satellites with surface pressures in the range 10^{-5}–10^{-9} mbar, if they exist, to be stable only if they are continuously replenished and therefore likely to be associated with "venting or the presence of non-hydrous ices on the surface". Alternatively, if the surface is covered with non-volatiles and/or water ice, the atmospheric pressure would be very low and controlled by sputtering due to the impact of magnetospheric plasma and energetic particles on the surface[9]. In any case, the interaction with the magnetosphere is likely to be 'weak' as it is for Mercury[10], that is, the magnetic field and plasma sweep into and past the satellite being affected mainly by the additional inertia of newly formed ions (provided the satellite is non-conducting and non-magnetic). We substantiate these arguments here using the recent Voyager observations, and suggest that the interaction between Io and the magnetosphere can be understood if the atmosphere of Io were largely exospheric in nature and controlled by the vapour pressure of SO_2 ice which covers the surface.

The discovery of volcanic activity on Io by Voyager 1 (ref. 11) confirms that venting of gas from beneath the surface must be an important source of gas in the atmosphere. By analogy with the gaseous products of terrestrial volcanoes (ignoring the H_2O and N_2 which probably have an external origin) one might expect CO_2 and SO_2 to predominate together with smaller amounts of SO_3, H_2S, CO, A, He, H_2 and Cl_2 (ref. 12). The behaviour of such volatiles, if ejected from the volcanoes on Io, can be studied in terms of a vapour pressure versus temperature diagram as shown in Fig. 1. Evidently CO_2 and several other possible constituents such as CH_4, CO and N_2 have such high vapour pressures that they would tend to completely dominate the atmosphere if they were present in the volcanic ejecta in any significant amounts. However, Voyager 1 observations of energetic heavy ions in the jovian magnetosphere indicate that S and O ions are dominant and C and N ions (other than those of obviously solar origin) are essentially absent[8]. Furthermore, SO_2^+ ions and their dissociation products were detected by the plasma experiment[13] and an SO_2 absorption feature was identified on the surface of the satellite by the IR and radiometry experiments[14]. Accordingly, we conclude that the gaseous emission from the Io volcanoes is almost entirely SO_2 and that the other components commonly found in terrestrial volcanoes are absent or very depleted.

To understand how this would affect the atmosphere of Io we should consider the situation where the surface of the satellite is uniformly covered with SO_2 frost and the atmospheric pressure is determined locally by the surface temperature (the effects of

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pressure gradients in inducing lateral flows are neglected). Figure 2 shows that the pressure should vary from $\sim 1.3 \times 10^{-3}$ mbar on the equator at the subsolar point ($T = 140$ K) to an exospheric level ($< 2 \times 10^{-8}$ mbar) at elongations exceeding 80° from the subsolar point ($T < 100$ K). This maximum pressure exceeds the upper limits obtained from occultation measurements[15] but as these only apply to the limb, a detectable atmosphere would not be expected. The major constituents of the atmosphere should be essentially frozen out on the dark side of the satellite and over the whole surface during eclipses. However, ^{40}Ar, He and H_2, all of which could be expected to be present in volcanic ejecta in small amounts, could in principle survive such low temperatures and would provide most of the atmosphere in such situations. The argon could conceivably condense very close to the poles of Io and consequently have a very low average vapour pressure. This is not possible for hydrogen and helium. The evaporative and magnetospheric losses of these constituents must be severe enough to prevent them from becoming dominant. In fact, the ionisation time scale in the hot dense plasma which constitutes the magnetospheric environment of Io is sufficiently short (less than the orbital/rotation period of the satellite) that there is little chance for these constituents to accumulate. Similarly, secondary products such as O_2, which could be produced as a result of photolysis[16] or the effects of energetic magnetospheric particles, would also be lost rapidly.

We now consider the interaction between the magnetospheric plasma and magnetic field and the atmosphere of Io and in particular the abovementioned constraints on the interaction. The approximately exospheric (column content $\leqslant 10^{15}$ cm^2) nature of the atmosphere shown in Fig. 2 allows for the direct escape of sputtered material over a large part of the surface. As pointed out by Johnson *et al.*[2] a relatively dense 'ionosphere' can be produced in such a rarified atmosphere if the ionisation is due to the presence of a flux of relatively soft (10–10^2 eV) electrons, which are known to exist in the magnetospheric plasma torus (refs 3, 18, and H. E. Johnson and W. I. A. unpublished data). However, much of the ionosphere may not be as significantly affected by recombination as assumed by these authors because

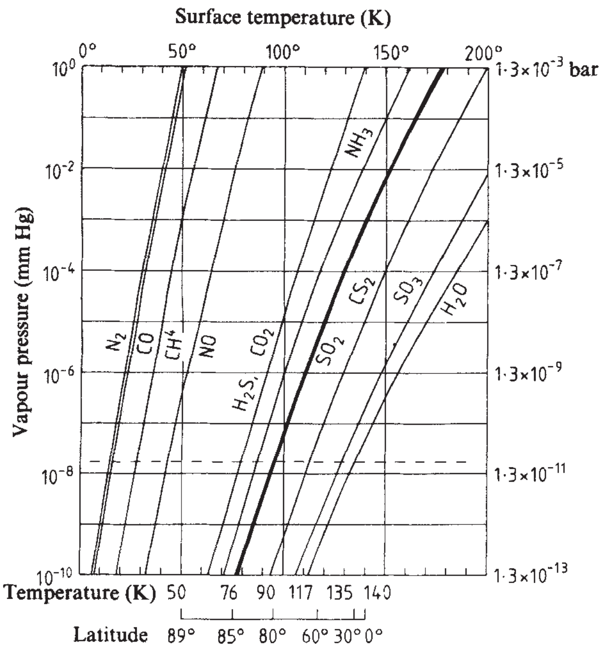

Fig. 1 The vapour pressures for various possible atmospheric constituents of Io as function of surface temperature. The curves are extrapolated from the data of refs 36, 37. The upper limit of the surface pressure determined by stellar occultation measurement is $\approx 10^{-4}$ mbar (ref. 15); and the broken line marks the exospheric limit of 3×10^{-8} mbar. The surface temperatures at various latitudes (θ) with a $(\cos\theta)^{1/4}$ dependence are marked in the bottom of the diagram.

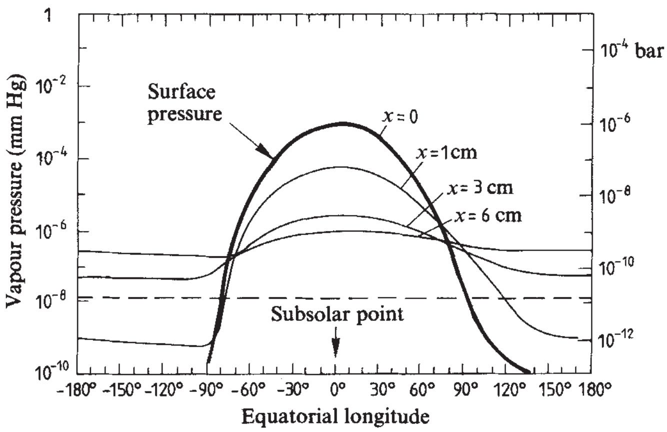

Fig. 2 The variations of SO_2 vapour pressure on Io as a function of longitude from the subsolar point. The curve for $x = 0$ is approximated from the numerical results of Sinton[38] and the curves for $x \neq 0$ are derived by assuming the surface material has thermal inertia 1.3×10^4 erg cm^{-1} s^{-1} K^{-1}, heat capacity 10^7 erg K^{-1} g^{-1}, a density of 0.1 g cm^{-3}, and thermal conductivity 1.7×10^2 erg cm^{-1} K^{-1} s^{-1}. Differing values of x correspond to differing thicknesses of a fine dust layer which could conceivably exist on parts of the surface at least.

the convective removal time is shorter than the dissociative recombination time except in regions where the plasma density is $\gg 10^5$ cm^{-3} or the atmosphere is sufficiently dense to prevent rapid motion of the plasma. In these circumstances, the plasma density is controlled by convection giving rise to the leading–trailing asymmetry observed at the limb[3]. Obviously, over the subsolar point where the atmospheric density is large, the structure of the ionosphere must be much more complex and depends on the orbital phase of Io.

As the atmosphere of Io is mainly exospheric the interaction with the magnetosphere is correspondingly weak except in the vicinity of the subsolar point where the surface pressure is relatively large. This implies that the incident magnetic field lines to a large extent cross the satellite relatively freely and the energetic particles they carry with them can suffer absorption on the surface as required by the observations[7,8]. However, the interaction should be capable of producing a fairly large electric current ($\sim 10^6$–10^7 A) to account for the Io-related decametric radio emissions. That is, a drag must be exerted on the corotating plasma and the magnetic field correspondingly stressed, so that a disturbance in the form of an Alfvén wave propagates in both directions along the field lines towards the planet[4,5,19]. This could be to a large extent the result of ion–neutral collisions (Pedersen conductivity) in the dense atmosphere surrounding the subsolar point, in which case a very strong longitudinal control of the radio emissions might be expected. However, note that the effect of ion mass pick-up, which has previously been overlooked in this connection (although alluded to in ref. 9)), could make a significant if not dominant contribution in this respect.

The effects of ion mass pick-up in the presence of a magnetic field have been considered in contexts other than the Io–magnetosphere interaction, notably the interaction between the solar wind and comets[20,21], the ionospheres of Mars, Venus and Mercury[22–25] and the interstellar gas[26,27]. The processes involved can be understood using the mass and momentum conservation equations for the plasma which are good approximations in the circumstances of interest here:

$$\frac{dn}{dt} = q \tag{1}$$

$$\frac{d}{dt}(nmV) = nm\frac{d\mathbf{V}}{dt} + mq\mathbf{V} = \mathbf{j} \times \mathbf{B} \tag{2}$$

$$\mathbf{E} + (\mathbf{V} + \mathbf{B}) = \mathbf{j} \times \mathbf{B}/ne \tag{3}$$

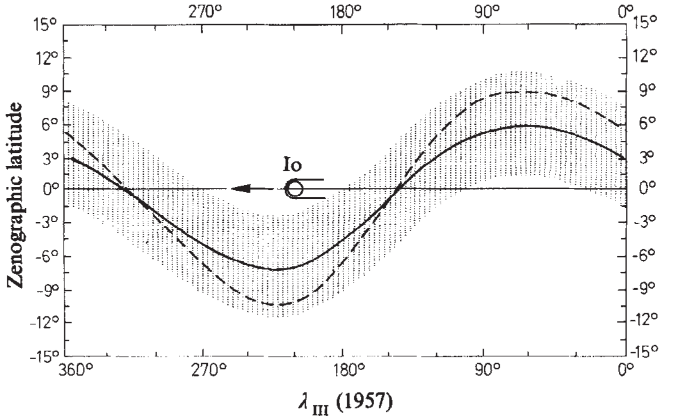

Fig. 3 Geometrical relationship between the corotating thermal plasma disk and the orbital position of Io. The shaded region represents the sulphur ion nebula with thickness equal to one jovian radius[32–34]. The solid curve indicates the central plane of the plasma disk, and the broken line the magnetic equator according to the Goddard Space Flight Center O_4 magnetic field model[35]. The direction of motion of Io in the rotating frame of the jovian magnetosphere and the convection pattern of the ionospheric plasma are also sketched. A current directed outward from Jupiter is generated in the extended atmosphere of Io to accelerate the newly created satellite ions into corotational motion. Io periodically crosses the plasma disk/magnetic equator at System III longitudes $\lambda_{III} \approx 120°$ and 315°.

n is the plasma density, **V** is its velocity, m is the mean ion mass, q is the effective source strength due to ionisation of neutrals, **E** is the electric field, **e** the charge on an electron, and **j** and **B** are the electric current and magnetic induction respectively. As a first approximation, we neglect the effects of plasma pressure gradients and ion-neutral collisions and note that q must be proportional to the neutral density N regardless of the ionisation process. These equations, together with Maxwell's equations and suitable boundary conditions, determine the behaviour of the plasma. The two terms on the left of equation (2) can be regarded as sources of electric current, the first of which involves the deceleration and acceleration of the plasma (that is the polarisation current) and the second describes the effects of mass loading due to pick-up or loss of plasma by ionisation of neutrals and recombination or absorption, respectively. The latter term is negligible in most ionospheric situations but not in the case under consideration.

Taking $q = \alpha N$ with α and also **V** constant to a first approximation, we find from equation (1) that

$$\begin{aligned} n' &= (\alpha N_0 H/V) \exp(-z/H) \text{ upstream} \\ &= \alpha N_0 H/V(1-\exp(-z/H)) \text{ downstream} \end{aligned} \qquad (4)$$

where n' is the additional plasma density produced by ionisation of neutrals, z is the height above the surface of Io (for normal incidence), and N_0H is the column content of the atmosphere. These solutions are, of course, highly idealised but they demonstrate certain basic features of the interaction, notably the upstream–downstream asymmetry and the relationship between the scale heights of the ionosphere and neutral atmosphere. To produce the additional plasma density of 5×10^3 cm^{-3} observed on the upstream side of Io by Pioneer 10 (which, as it used a refraction technique, was unable to detect the uniform ambient magnetospheric plasma) α must be 2.5×10^{-5} s^{-1} for $N_0 H \approx 10^{15}$ cm^{-2}.

Clearly it is not easy to predict the form of the electric current distribution resulting from such an interaction as it requires a knowledge of the precise form of the flow field as well as the sources and sinks of plasma and if full three-dimensional treatment is warranted. However, one can estimate the magnitude of a typical component of the current associated with mass pick-up (equation (2)) as simply

$$I = \dot{M}V/BL \qquad (5)$$

Here $\dot{M}$ is the total mass picked up by the magnetosphere and L is a length which is of the order of the diameter of Io. We estimate that if $\dot{M} \approx 2.5 \times 10^5$ g s^{-1} on the upstream side of Io then with $V = 57$ km s^{-1} and $L = 4{,}000$ km, the corresponding electric current induced is $I \approx 2 \times 10^6$ A. For the whole interaction, including the downstream region, the electric current may be significantly larger. The effective ionospheric conductance associated with ionisation of the exosphere is $\Sigma = I/EL \approx 5$ S and the energy dissipation is $IEL \approx 8 \times 10^{18}$ erg s^{-1}. Note that the effects of the inertial term on the left hand side of equation (2) tend to reduce the current density on the upstream side of the satellite where the plasma decelerates by a factor of order $(1 + X^2)^{1/2}$ where $X = \omega L'/V$, L' is a characteristic length, and ω is the gyrofrequency of the newly created ions in the ambient magnetic field. This reduction is significant on the upstream side as $L' \approx H$ and $X \approx 1$, but there is no diminution of the current overall as all the freshly produced ions must be accelerated eventually up to the corotational speed of the magnetosphere relative to Io. It can be seen that equation (5) also applies to the Io torus of more extensive structure.

All aspects of the interaction between Io and the jovian magnetosphere can, therefore, be accounted for if the atmosphere has the properties indicated in Fig. 2 and we suggest that ion mass pick-up is an important ingredient of this interaction. These arguments lead to some interesting conclusions on the variation of the nature of the interaction with both the jovian longitude and the Io phase. As the dense regions of the atmosphere influence the interaction the phase of Io in its orbit must be important as, for example, the subsolar point is on the leading–trailing side of the satellite at western–eastern elongations respectively. Also the fact that the jovian plasma sheet is not coplanar with the orbit of Io (see Fig. 3) should lead to a jovian longitudinal control of the currents produced by the interaction if the total ionisation rate is the determining factor and this is controlled by the density of the corotating magnetospheric plasma. Note that the plasma torus need not instantaneously coincide with the equilibrium position shown since it can oscillate in position along the magnetic field with a frequency $\sqrt{3}\Omega/2\pi$, where $2\pi/\Omega$ is the rotational period of Jupiter. This is not commensurate with the (relative) orbital period of Io and hence the addition of fresh plasma with random phase will tend to supress the oscillations. Nevertheless, the oscillatons should be completely absent only at longitudes $\lambda_{III} \approx 120°$ and 350° where Io crosses the jovian magnetic equator.

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Note that several of our conclusions have been reached independently in papers submitted later than our original manuscripts. In particular, we refer to the discovery of SO_2 gas on Io by Pearl *et al.*[28] and the identification of SO_2 frost on the surface by Fanale *et al.*[29]. Smith *et al.*[30], Pearl *et al.*[28] and Kumar[31] have also drawn attention to the fact that the atmosphere of Io should be spatially inhomogeneous.

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Accretion of nitrogen during the growth of planets

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The $^{15}N/^{14}N$ ratio measured in nitrogen of the terrestrial atmosphere is, or was, apparently widespread in the inner Solar System. Such an observation might suggest that this value (3.61×10^{-3}) represents that of proto-solar material. However, I argue here that the original ratio was at least 20% lower, the presently observed value having resulted from significant isotopic fractionation, presumably caused by nebular condensation processes.

First, I will summarise what we know about $^{15}N/^{14}N$ of inner Solar System objects, expressing these values as per cent deviations from the terrestrial atmospheric value. The Moon is highly depleted in volatiles, and identification of indigenous lunar N, free from either terrestrial contamination or cosmic ray spallation products, has consequently been very difficult. The best estimate for the lunar $^{15}N/^{14}N$ ratio is between +1 and +4% relative to air[1].

The martian atmosphere is highly enriched in ^{15}N, about +62% relative to air[2]. However, it has been argued that this value has resulted from selective escape of ^{14}N from the martian upper atmosphere[2]. When allowance is made for this fractionation, a starting composition close to the terrestrial value is derived[2]. Because of the model dependence of the fractionation calculations, it is not possible to assign realistic uncertainty limits to the initial $^{15}N/^{14}N$ ratio. A large uncertainty is also associated with the $^{15}N/^{14}N$ ratio found for the atmosphere of Venus. The value measured by Pioneer Venus is within 20% of that of terrestrial air[3].

Different groups of stony meteorites have significantly different N isotopic compositions[4,5], although the actual nature of the relationship between $^{15}N/^{14}N$ ratio and chemical–petrographic classification is unclear. Referring to Fig. 1 of ref. 5, ordinary chondrites and carbonaceous chondrites of petrologic types 3 and 4 lie close to the terrestrial value (−0.3 to +2.0% and −4.3 to +0.2%, respectively). Carbonaceous chondrites of petrologic types 1 and 2 are enriched in ^{15}N by up to 4.6% (with one large anomaly, Renazzo, at +17.2%), the degree of enrichment roughly correlating with increasing N content[5]. Enstatite chondrites, on the other hand, are depleted in ^{15}N (to −4.3%), with a rough tendency for $^{15}N/^{14}N$ to decrease with increasing N content[5]. Whatever the cause(s) of these isotopic patterns, the trend of the meteoritic data suggests that the present compositions reflect fractionations, in different directions, of a starting composition close to that of the terrestrial atmosphere. Apparently, formation of organic matter in carbonaceous chondrites and inorganic nitrides in enstatite chondrites favoured heavy and light isotopes, respectively.

This picture of isotopic uniformity in the inner Solar System is disturbed when we turn to the only other repository of N analysed so far: the solar wind, believed to represent the composition of the solar convective zone[6]. These analyses have been made using solar wind ions implanted in the lunar surface during the past 4 Gyr, and have revealed that $^{15}N/^{14}N$ in the Sun has increased substantially over the lifetime of the Moon[7]. The actual magnitude of the change is still not established precisely but is known to be at least 30%, from −19% (ref. 8) to +11% (ref. 1) relative to air. Whatever the cause of this change, possibly nuclear reactions in the solar convective zone[7], it seems clear that the solar atmosphere must have had an initial $^{15}N/^{14}N$ ratio at least 19% lower than terrestrial air. It is therefore difficult to avoid the conclusion that this lower value must also have characterised the proto-solar nebula. This in turn leads to the conclusion that the value observed or inferred for the Earth and other planetary objects must represent the result of significant isotopic fractionation.

It is unlikely that we can specify, at this time, how such fractionation occurred. The fact that its magnitude was apparently independent of either the size of the planetary object (radii varying from some tens of kilometres[9] to more than 6,000 km) or its degree of volatile depletion (from about 10^{-7} to 10^{-3} g N per g) suggests that N, and presumably other volatiles, were accreted by early forming planets, and planetesimals, in the form of a solid component of volatile-rich condensate. Isotopic fractionation apparently took place between this component and the reservoir from which it condensed, rather than during accretion. The magnitude and sign of the fractionation suggest gas–solid equilibration at very low temperature rather than kinetic effects or isotopically selective loss of gas.

Because neither the nature of the N-rich condensate nor its temperature of formation is known, it is not possible to determine whether the fractionation factor associated with the condensation reaction(s) is adequate to provide the degree of fractionation implied here. Calculated fractionation factors[10] for isotopic exchange between simple N compounds imply an equilibration temperature significantly below 273 K. Equilibration at such low temperatures in the nebula seems intuitively unlikely but similar temperatures are suggested by the enrichment of the Earth and carbonaceous chondrites in deuterium, relative to its abundance in the primitive solar nebula[11–13].

The condensation/accretion scenario suggested here is qualitatively consistent with the model of Anders and Owen[14], which proposes acquisition of the Earth's volatiles via a veneer of composition similar to that of carbonaceous chondrites of petrologic type 3, which also provide a reasonable match in $^{15}N/^{14}N$ ratios[5]. However, the magnitude of the fractionation suggested here, between the volatile-carrier and its parental reservoir, implies a temperature of formation significantly lower than the 400–450 K inferred by Anders and Owen for carbonaceous chondrite material[14].

The hypothesis presented here is potentially testable as it leads to three observational predictions. First, the $^{15}N/^{14}N$ ratio in Jupiter, which should directly reflect that of proto-solar material, will be found to be at least 19% lower than terrestrial air. Second, the $^{15}N/^{14}N$ ratio in the present solar wind will be found to be about 11% greater than in air (more if we do not measure it soon). Third, isotopic fractionation of N during condensation may have been accompanied by similar fractionation of any other volatile elements condensing at the same time. If such elements, or the appropriate fractions of them, can be isolated for analysis, similar heavy isotope enrichments may be detected. In fact, the deuterium mentioned above may constitute such evidence; however, the relationship between the provenance of nitrogen and that of hydrogen in early Solar System objects remains a topic for further study.

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