and Gottlieb for Earth (*11*). Eddy conduction has also been considered by Dickinson (*12*). In principle, rapid vertical motion can enforce an adiabatic (negative) temperature gradient all the way to zero Kelvin, where the density also falls to zero. Some difficulties about the concept were pointed out by Hunten (*13*), and many of them have been resolved by Izakov (*14*); in particular, eddy conduction is inevitably accompanied by eddy heat dissipation, which almost certainly offsets and may even overcome the cooling. In principle, the relatively small difference can be of either sign; perhaps there is net cooling for Venus and Mars (CO_2), net heating for the sun and Jupiter (hydrogen), and near cancellation for Earth. [As Dickinson and Ridley pointed out (*8*), a coherent circulation transports heat and matter without dissipating energy at high altitudes; but it predicts much too high a temperature on the nightside.] An upper bound to the cooling rate, or a minimum requirement on the eddy diffusion coefficient K, can be derived by neglecting the eddy heating. With a little over 3 erg cm^{-2} sec^{-1} for 120 km (Table 2), we find that K should be at least 2×10^7 cm^2 sec^{-1}, which is in the range obtained for the dayside by von Zahn *et al.* (*15*). Such a large value is incompatible with the circulation regime as proposed by Dickinson and Ridley.

The cold thermosphere found for Mars on the Viking mission (*16*) is in accord with the idea that there is net eddy cooling in CO_2 atmospheres. The higher temperature of the dayside Venus thermosphere now becomes the anomaly; perhaps the heating efficiency should be increased again from the very low value (0.1) adopted by Dickinson and Ridley.

Altitude profiles of the densities of major gases at the antisolar point are shown in Fig. 4a. The solid lines represent fits to data. The dashed lines are downward extrapolations to below the homopause, based on the temperature profile (*17*) shown in Fig. 4b. Both CO and O are present in the thermosphere entirely as photolysis products of CO_2, since their mixing ratios are orders of magnitude greater than at the cloud tops. Moreover, any recombination is negligible to well below 100 km (*18*). The global mean downward fluxes of CO and O must therefore be equal at all heights considered here. The level at which their number densities become equal is therefore a special one, a "homopause" for whatever vertical transport processes are operating.

Our downward extrapolation of the nightside data places the homopause at 117 km, where the CO_2 density is about 10^{13} cm^{-3}, and the diffusion coefficient for CO in CO_2 is $D = 2.5 \times 10^5$ cm^2 sec^{-1} (*19*). If the homopause is formed by eddy mixing, K would also be 2.5×10^5 cm^2 sec^{-1}; for a vertical velocity v, D is divided by the scale height to give $v \sim 1$ cm sec^{-1}. These values, derived by extrapolation, are uncertain by at least a factor of 3. A height-dependent K, as found for the dayside by von Zahn *et al.* (*5*), is another possibility. The present crude state of analysis does not permit us to say whether this estimate of K is inconsistent with the larger requirement for heat conduction. We hope that further analysis, once we have a complete set of orbits for the nightside, will elucidate the true nature of the homopause and energy balance.

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Implications of the Gas Compositional Measurements of Pioneer Venus for the Origin of Planetary Atmospheres

Abstract. *Comparisons are made between the volatile inventories of the terrestrial planets, including Pioneer Venus data, and the predictions of three classes of theories for the origin of planetary atmospheres. Serious difficulties arise for the primary atmosphere and external source hypotheses. The grain accretion hypothesis can account for the trends in the volatile inventory from Venus to Earth to Mars, if volatiles were incorporated into planet-forming grains at nearly the same temperature for all of these planets, but at systematically lower pressures in the regions of planet formation farther from the center of the solar nebula.*

The Pioneer Venus spacecraft carried several mass spectrometers and a gas chromatograph, which measured the abundance of gaseous species in the upper and lower atmospheres. Species detected included several rare gases as well as N_2, H_2O vapor (below the clouds), and CO_2, the dominant atmospheric constituent. In this report, we compare the absolute abundances and the ratios of these species with their counterparts for Earth, Mars, chondritic meteorites, and the sun in order to assess the validity of alternative hypotheses for the origin of planetary atmospheres.

Tables 1 and 2 summarize currently available data on the absolute abundances and ratios of constituents of the volatile inventory of five classes of solar system objects (*1*, *2*). The absolute abundances refer to the ratio of the mass of a given volatile species to the object's total mass. In the case of the planets, of necessity, we took stock only of material outgassed into the atmosphere over the planet's lifetime, including material currently residing in near-surface reservoirs or known to be lost subsequently to space (*2*). However, in the case of the meteorites, we counted, again of necessity, nuclides capable of forming volatile compounds that are present throughout the mass of the object. The important trends displayed in Tables 1 and 2 are summarized below. (i) The absolute abundances of N_2 and CO_2 are essen-

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tially the same for Venus and Earth. However, the martian abundance of N_2 is lower. (ii) The absolute abundance of ^{36}Ar and the ratio ^{36}Ar/^{14}N decrease systematically by several orders of magnitude from Venus to Earth to Mars. (iii) A similar sharp increase occurs for ^{40}Ar/^{36}Ar (*3*). (iv) The ratios of the primordial rare gas species (for example, ^{20}Ne/^{36}Ar) are very similar for the terrestrial planets and chondritic meteorites. These ratios differ considerably from ones appropriate for the sun and presumably the primordial solar nebula, from which the planets and meteorite parent bodies were formed. We examine below how alternative theories may account for these four trends.

There are three classes of theories for the origin of planetary atmospheres: the primary atmosphere hypothesis, the external source hypothesis, and the grain accretion hypothesis. We outline each of these hypotheses and compare their predictions with the results in Tables 1 and 2.

According to the primary atmosphere model, the planets captured gaseous material after they had formed, either from the primordial solar nebula or an early intense solar wind. In either case, the elemental and isotopic compositions would be essentially those present in the sun today. This model has the attractive feature of possibly offering an explanation for the systematic increase in the absolute abundance of nonradiogenic Ar and the other rare gases from Mars to Earth to Venus: nebular and solar wind densities can be expected to increase with decreasing distance from the center. However, both the ratio of one rare gas species to a second rare gas species and the ratio of the rare gases to N and C that characterize the terrestrial planets depart by orders of magnitude from that expected for solar elemental abundances. One might attempt to circumvent this problem by postulating that the capture phase was followed by an epoch during which large quantities of the gases escaped by thermal evaporation from the top of the atmospheres, with the lighter gases escaping preferentially. Although this postulate is qualitatively consistent with the rare gas fractionation pattern with respect to solar abundances, it must require that the extensive fractionation resulted in essentially the same rare gas ratios for Venus, Earth, Mars, and the meteorites' parent bodies despite significant differences in these bodies' gravity and position (and hence probably their exospheric temperatures). Also, it fails to account for the direction of the fractionation pattern of the ^{36}Ar/^{14}N and ^{36}Ar/^{12}C ratios. We conclude that the primary atmosphere hypothesis does not appear to account for the volatile inventories of Tables 1 and 2 or even the rare gas subset in these tables.

The external source hypothesis postulates that the terrestrial planets formed from volatile-depleted material and that, subsequent to formation, a superficial layer of volatile-rich materials was added (*4*). The added material originated elsewhere in the solar system, such as the asteroid belt or the Oort cloud of comets, where lower solar nebula temperatures permitted vola-

Table 1. Volatile abundances (gram per gram).

Object	Instrument*	Ne	Non-R Ar†	Kr	Xe	R Ar†	N_2	CO_2	H_2O
Venus	Pioneer LNMS		$(5 \pm 4) \times 10^{-9}$	$<4 \times 10^{-10}$		$(5 \pm 4) \times 10^{-9}$	$(2 \pm 1) \times 10^{-6}$		
Venus	Pioneer BNMS		$\sim 8 \times 10^{-9}$			$\sim 7 \times 10^{-9}$			
Venus	Pioneer GC	$(2 \pm 1) \times 10^{-10}$	$(8 \pm 2) \times 10^{-10}$	$<4 \times 10^{-11}$		$(8 \pm 2) \times 10^{-10}$	$(2.1 \pm 0.1) \times 10^{-6}$	$(9.5 \pm 0.1) \times 10^{-5}$	$(6 \pm 1) \times 10^{-8}$
Venus	Venera 11 and 12 MS	$(6 \pm 1) \times 10^{-10}$	$(7 \pm 2) \times 10^{-9}$	$(2 \pm 0.4) \times 10^{-10}$		$(7 \pm 2) \times 10^{-9}$	$(2.8 \pm 0.3) \times 10^{-6}$	9.4×10^{-5}	
Venus	Venera 11 and 12 GC		$(2 \pm 1) \times 10^{-9}$			$(2 \pm 1) \times 10^{-9}$	$(1.5 \pm 0.37) \times 10^{-6}$	9.7×10^{-5}	$<6 \times 10^{-9}$
Earth		1.1×10^{-11}	4.6×10^{-11}	2.9×10^{-12}	1.6×10^{-11}	1.1×10^{-8}	2.4×10^{-6}	1.6×10^{-4}	2.8×10^{-4}
Mars		$(4 \pm 2.5) \times 10^{-14}$	$(2.2 \pm 0.3) \times 10^{-13}$	$\sim 2 \times 10^{-14}$	$\sim 9 \times 10^{-15}$	$(5.4 \pm 0.8) \times 10^{-10}$	4×10^{-8} to 4×10^{-7}	$>3.5 \times 10^{-8}$	$>5 \times 10^{-6}$
Meteorites	Ordinary chondrites		3×10^{-12} to 1×10^{-9}						
Meteorites	Carbonaceous chondrites		4×10^{-10} to 1×10^{-9}						
Sun		1.7×10^{-3}	1.0×10^{-4}	9.7×10^{-8}	1.7×10^{-8}		1.3×10^{-3}	1.3×10^{-2}	9.5×10^{-3}

*LNMS, large probe neutral mass spectrometer; BNMS, bus neutral mass spectrometer; GC, gas chromatograph; MS, mass spectrometer †Non-R Ar is the nonradiogenic Ar (^{36}Ar + ^{38}Ar); R Ar refers to radiogenic Ar (^{40}Ar).

Table 2. Atomic ratios.

Object	Instrument*	^{40}Ar/^{36}Ar	^{38}Ar/^{36}Ar	^{20}Ne/^{36}Ar	^{84}Kr/^{36}Ar	^{132}Xe/^{36}Ar	^{13}C/^{12}C	^{36}Ar/^{12}C	^{36}Ar/^{14}N	^{15}N/^{14}N	N/C
Venus	Pioneer LNMS	1.2 ± 0.1	0.2	0.5 ± 0.3	$\leqslant 0.02$		0.012 ± 0.001	$(6 \pm 5) \times 10^{-5}$	$(7 \pm 6) \times 10^{-4}$	$(3.6 \pm 1) \times 10^{-3}$	0.07 ± 0.05
Venus	Pioneer BNMS	~ 1									
Venus	Pioneer GC			0.6 ± 0.3	<0.01			$(8 \pm 2) \times 10^{-6}$	$(1 \pm 0.2) \times 10^{-4}$		0.07 ± 0.003
Venus	Venera 11 and 12 MS	~ 1.2	0.2	0.2 ± 0.1	0.01 ± 0.005		0.011 ± 0.001	$(6 \pm 2) \times 10^{-5}$	$(7 \pm 2) \times 10^{-4}$		0.09 ± 0.01
Venus	Venera 11 and 12 GC				0.02 ± 0.01			$(2 \pm 1) \times 10^{-5}$	$(3 \pm 1.5) \times 10^{-4}$		0.05 ± 0.01
Earth		292	0.2	0.5	0.036	2.9×10^{-2}	0.011	3×10^{-7}	5×10^{-6}	3.6×10^{-3}	0.05
Mars		3000 ± 500	0.2 ± 0.02	0.5 ± 0.3	0.03 ± 0.02		0.011 ± 0.0005	$<6 \times 10^{-6}$	2×10^{-7} to 2×10^{-6}	$(6.1 \pm 0.5) \times 10^{-3}$	
Meteorites	Ordinary chondrites and carbonaceous chondrites		0.2	~ 0.2	0.022 ± 0.007	$(3 \pm 1) \times 10^{-2}$		$(8.5 \pm 3.5) \times 10^{-9}$	$(4 \pm 3) \times 10^{-7}$		0.03 ± 0.02
Sun				31	0.00027	1.4×10^{-5}		8.4×10^{-3}	2.7×10^{-2}		0.31

*For an explanation of these abbreviations, see Table 1.

tiles to condense. The volatile-rich bodies had their orbits altered to ones crossing those of the terrestrial planets and subsequently collided with them. This model has a number of attractive features. As there is a postulated common source of volatile-rich material, atomic ratios of rare gases and ratios of N to C can be expected to be the same for Venus and Earth, as is observed. Moreover, since the probability of a stray body colliding with Venus is roughly the same as the probability of one colliding with Earth (*5*), the absolute abundance of N and C should be nearly the same for these two planets, consistent with the data.

Unfortunately, the external source hypothesis has some serious problems. Foremost among these is the strong gradient in the absolute abundance of nonradiogenic Ar and the other rare gases: their abundances increase by about a factor of 200 from Mars to Earth and about 20 to 200 from Earth to Venus. But, using the estimates given in (*5*) of the impact probability per unit area of objects having a wide variety of initial orbits, including one that initially only crosses Venus's orbit, we find that the absolute abundances of the rare gases should differ by no more than a factor of 2 between Venus and Earth and that their abundances for Mars should be smaller by no less than a factor of 3 than for Earth. Finally, note the large differences in the $^{36}Ar/^{12}C$ ratio between Venus and the chondritic meteorites. The latter generally are assumed to approximate the volatile-rich impacting objects envisioned by the external source model.

One could try to circumvent some of the above difficulties by postulating that the volatile addition event is followed by a hydrodynamic loss to space of the added material, with the amount of loss increasing dramatically from Venus to Earth to Mars. This postulate appears to be particularly attractive in light of one obvious difference between Earth and Venus, namely, Earth has a moon. One might appeal to the moon-forming event as a physically reasonable deus ex machina to provide a singular degassing event for Earth. Such a postulate accounts for the trends in the absolute abundance of the rare gases as well as their nearly constant atomic ratios with respect to one another. However, in this event, there should also be a large gradient in the N_2 and CO_2 abundances between Venus and Earth, contrary to the data of Table 1. In summary, the external source model has some serious problems.

The grain accretion hypothesis attributes the volatile inventory of planets to the incorporation of volatiles into the grains and planetesimals that subsequently accreted together to form the planet. It is helpful to use our present understanding of the incorporation of volatiles into meteorites as a guide. When present in significant amounts, the C, N, and H_2O in meteorites are located within chemical compounds, as intimate parts of these compounds. On the other hand, the rare gases have less of an intimate relation to the materials within which they are occluded (*6*). There is a diversity of opinion on how the rare gases became incorporated within the material that formed the meteorites' parent bodies, but several of the more prominent concepts share the following properties: the amount of rare gas incorporation is proportional to the surface area of their hosts, is proportional to the partial pressure of the rare gas, and depends exponentially on temperature. These concepts include physical adsorption (*7*), solid-state dissolution (*8*), and some as yet unknown process, found in organic synthesis experiments (*9*). In all these cases, fractionation patterns and absolute abundances similar to those observed in chondritic meteorites are found, although the magnitude of the fractionation and the abundances are very temperature-sensitive.

The generally accepted concept of the early solar system is that the time of volatile incorporation was a "cooling down" phase in the evolution of the solar nebula and that a strong temperature gradient existed in the region of the terrestrial planets. The immediate notoriety given the Pioneer Venus rare gas data stemmed from the contradiction of the precepts of the standard picture by these data. The nature of this conflict is that, on the basis of such a model, one would expect a strong decrease in the abundance of ^{36}Ar on Venus relative to that on Earth by virtue of the nebula being hotter in the region of Venus than in the region of Earth, exactly opposite to the observed trend.

However, if one is willing to make certain other assumptions about the conditions within the solar nebula at the time the volatiles were incorporated into solar system objects, many of the trends shown in Tables 1 and 2 can be accounted for in terms of the grain accretion hypothesis. Because the incorporation of the rare gases and C, N, and H_2O depended upon two different sets of processes, the ratio of rare gas to C or N will vary with position in the nebula. Assume for a moment that a given unit mass of material had a fixed proportion of C, N, and H_2O, independent of position in the nebula. The amount of rare gases incorporated into the unit mass is proportional to the nebular pressure and decreases exponentially with temperature. If the temperature was fairly isothermal at the time of volatile incorporation, the pressure effect will dominate and therefore the $^{36}Ar/^{12}C$ and $^{36}Ar/^{14}N$ ratios will increase with decreasing distance from the center of the nebula, in accord with the results of Table 2. Furthermore, with fairly constant temperature conditions, the rare gas fractionation pattern and the fractional amount of C and N contained within a unit mass may also have been approximately constant and hence account for the similarities in these quantities among the volatile inventories of Venus, Earth, Mars, and meteorites.

In order to quantitatively reproduce the results in Tables 1 and 2 with the grain accretion hypothesis, we need to allow for differences in the efficiency of outgassing as well as for pressure gradients in the solar nebula. It is useful to distinguish between two periods of outgassing. Most of the volatiles, except ^{40}Ar (*3*), may have been placed into planetary atmospheres at an early time, when the planets underwent extensive internal differentiation (*10*). In a more episodic fashion, in association with more localized volcanism or tectonic activity, or both, subsequent outgassing took place to the present, which particularly affected the amount of outgassed ^{40}Ar (*10*). Let P, e_1, and e_2 be, respectively, the ratios of the nebular pressure, the efficiency of early outgassing, and the efficiency of later outgassing for a given object to the corresponding values for Earth. If the $^{36}Ar/^{14}N$ ratio is taken to be 20 times larger for Venus than Earth, which seems to be the most likely value, then the data of Tables 1 and 2 for these two planets can be reproduced by setting $P = 20$, $e_1 = 1$, and $e_2 = 1/15$. If instead the $^{36}Ar/^{14}N$ ratio is larger by as much as a factor of 200 as suggested by the mass spectrometer results, $P = 200$, $e_1 = 1$, and $e_2 = 1/1.5$. The somewhat less efficient later outgassing for Venus might be attributed to the more plastic behavior of the near-surface rocks, due to the higher surface temperature (*11*). The martian volatile inventory can be best fit with $P \cong 1/40$ to $1/20$, $e_1 \cong 1/5$ to $1/20$, and $e_2 \cong 1/20$, where we have made the reasonable assumption that $e_1 \gtrsim e_2$. The much lower outgassing efficiencies for Mars than Earth may be due to the former's smaller mass, which led to less extensive melting of the planet and less extensive reworking of near-surface materials (*10, 12*).

According to the above discussion, the grain accretion hypothesis requires sharp decreases in the nebular gas pressure and fairly constant temperatures from the region where Venus formed to that for Earth to that for Mars. Currently available laboratory data suggest that temperature differences of no more than several tens of degrees Kelvin would be permitted by either the adsorption or solid-state dissolution mechanism of rare gas incorporation in order to keep the fractionation pattern the same, with temperatures of about 150 and 500 K required, respectively (*8*). Are such constraints on the nebular conditions reasonable? We believe they are. The required circumstances could obtain in one of two possible scenarios: one involving the instantaneous structure of the solar nebula, and the other involving the entropy evolution of the inner solar system. Regarding the first, current models of solar system formation may be characterized by three stages (*13*): initially, there is no central condensation and temperatures are fairly isothermal, but the pressure gradients are quite shallow. As a central condensation that is to become the sun forms, pressure gradients build up dramatically, but the temperature gradients remain small because the central condensation is not yet a dominant energy source. Finally, the sun becomes the dominant energy source and both the nebular pressure and temperature gradients become steep. If the grain accretion hypothesis is correct, then it would appear that volatile incorporation occurred during the second stage of nebular development. The second scenario is one where the volatile incorporation in the terrestrial planets was not coeval but rather occurred (or was terminated) at essentially the same temperature for each of the planets. If the entropy of the inner regions was higher than that of the outer regions, the required pressure differences could be realized without implying a high instantaneous pressure gradient.

The grain accretion hypothesis is not without problems. Much more work needs to be done on nebular evolution to determine whether the pressure-temperature conditions required under either scenario can be realized. Moreover, a reasonable way must be worked out to yield the observed significant variations in bulk density among the terrestrial planets. This probably will require that not all of the planet formation took place during the epoch of volatile incorporation; that the grains of the volatile stage accreted to planetesimals prior to the next stage, so that they no longer equilibrated with the solar nebula; and that planet formation was not accomplished until well into the next stage, so that the volatiles were not segregated toward the center of the planets.

If the grain accretion hypothesis is correct, then we can make several interesting inferences. As the ratios of the rare gases for the chondritic meteorites are similar to those for the terrestrial planets, their volatiles were formed in a region of the solar nebula having a very similar temperature to that characterizing comparable regions for the planets. Hence, nebular pressure was also the dominant factor in determining their $^{36}Ar/^{12}C$ and $^{36}Ar/^{14}N$ ratios. On the basis of the values for these ratios given in Table 2, we infer that the nebular pressure in the region where these meteorites' parent bodies formed could not be much lower than that where Mars formed. Thus, an origin in the asteroid belt is to be favored over one much farther out. Because only modest temperature differences are permitted at the time of volatile incorporation, an amount of H_2O not much less than that for Earth was incorporated into Venus. In this case, the amount of H_2O in the Venus atmosphere at the present time is much less than the initial endowment and substantial sinks are required. Both reincorporation into the lithosphere (*11*) and early rapid exospheric escape (of H) (*14*) need to be critically reevaluated to determine the plausibility of this inference. Finally, it appears to be reasonably safe to use the N/C ratio but not the $^{36}Ar/^{12}C$ ratio found for other objects to infer the amount of CO_2 outgassed over the history of Mars. Using the model parameters given above, we obtain an amount equal to $\sim$ 1 to 3 bars, enough to create much warmer conditions in the early history of Mars (*15*). Also, by analogy to terrestrial H_2O/N_2 ratios, Mars outgassed an amount of H_2O equivalent to an ice layer 80 to 160 m deep, uniformly covering the planet. Such an amount could supply enough H_2O to carve the fluvial channels observed on the Mariner 9 and Viking spacecrafts (*15*).

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Ultraviolet Night Airglow of Venus

Abstract. *The night airglow spectrum of Venus in the ultraviolet is dominated by the* $v' = 0$ *progressions of the gamma and delta bands of nitric oxide. The bands are produced by two-body radiative recombination of nitrogen and oxygen atoms. Since the source of these atoms is in the dayside thermosphere, the night airglow is a tracer of the day-to-night thermospheric circulation. The airglow is brightest at equatorial latitudes, and at longitudes on the morning side of the antisolar meridian.*

During the early orbits of the Pioneer Venus orbiter mission, the ultraviolet spectrometer experiment detected ultraviolet emissions from the dark limb of Venus. These were tentatively identified (*1*) as the Cameron bands of carbon monoxide excited by the precipitation of charged particles into the Venusian thermosphere. Since then, the orbit's periapsis has traversed the dark side of the planet, and we have obtained spectra of the night airglow. These spectra are dominated by bands of the nitric oxide delta and gamma systems, confirming an earlier detection of some members of the delta band system from the Earth-orbit-