

# Fractionation of Noble Gases by Thermal Escape from Accreting Planetesimals

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Received November 11, 1985; revised January 16, 1986

A model for the selective loss of noble gases by thermal escape of the gases from planetesimals as they grow to form the terrestrial planets has been developed. The initial elemental and isotopic abundance ratios are assumed to be solar. Competition between gravitational binding and escape determines the degree of fractionation that occurs. Two classes of planetesimals can be formed on a time scale consistent with modern models of accretion. One class is depleted in neon and, in some cases, partly in  $^{36}\text{Ar}$ . The other class is neon rich. Subject to the validity of some assumptions regarding loss of planetary atmospheres following collisions between very large embryo planets and a strong radial dependence in the rate of accumulation of neon-rich planetesimals, the mechanism can account for all known properties of the noble gas volatiles on the terrestrial planets except one. This is the  $^{36}\text{Ar}/^{38}\text{Ar}$  ratios for Earth and Mars which are predicted to be much lower than observed. This failure is probably fatal for the hypothesis. © 1986 Academic Press, Inc.

## 1. INTRODUCTION

Table I summarizes what is known about the endowment of the terrestrial planets, Venus, Earth, and Mars, in nonradiogenic noble gases (Owen *et al.*, 1977; Donahue and Pollack, 1983; von Zahn, 1984). The most significant property of these gases is the extreme fractionation they have undergone, a fractionation that results in a reduction in the ratio of neon to xenon by more than three orders of magnitude from the solar abundance ratio. The table also shows that the atmosphere of the Earth is about 150 times richer in the noble gas volatiles than is the atmosphere of Mars (with due allowance for the relative masses of the planets). A partial exception is xenon; the factor is only about 50 in the case of  $^{132}\text{Xe}$ , and the xenon isotopic ratios are conspicuously different on Mars and on Earth. And there is about 100 times as much argon and 50 times as much neon on Venus than there is on Earth, but only two or three times as much krypton and xenon. The krypton situation on Venus is still somewhat confused. In this paper it will be assumed that

the Pioneer Venus and Venera 13/14 mass spectrometers, which agree with each other, give the correct values. The Venera mass spectrometer team now attributes the large krypton abundances that they reported on the Venera 11 and 12 missions to a contamination by preflight calibration gas (Istomin *et al.*, 1983). Only the high values reported by the gas chromatograph on Venera 13 and 14 remain unexplained. Thus it will be assumed that there is  $1.65 \times 10^4$  times as much  $^{36}\text{Ar}$  and  $10^4$  times as much  $^{20}\text{Ne}$  (per gram of planetary mass) on Venus as there is on Mars but only 250 times as much  $^{84}\text{Kr}$  and  $^{132}\text{Xe}$ . As for isotopic ratios,  $^{20}\text{Ne}/^{22}\text{Ne}$  and  $^{21}\text{Ne}/^{22}\text{Ne}$  appear to be somewhat lower in the planetary atmospheres than they are on the sun. On the other hand the ratio for  $^{36}\text{Ar}$  and  $^{38}\text{Ar}$  is remarkably stable throughout the solar system. A further degree of complexity is that volatile compounds of H, C, N, and O seem to be depleted on Mars to the same extent as the noble gases, whereas they are almost equally abundant on Venus and the Earth.

In this paper an attempt will be made to reproduce the features of Table I by invoking

TABLE I  
NONRADIOGENIC NOBLE GASES ON TERRESTRIAL  
PLANETS: VOLUME ABUNDANCE RATIOS

|                                   | Sun             | Venus           | Earth             | Mars               |
|-----------------------------------|-----------------|-----------------|-------------------|--------------------|
| $^{20}\text{Ne}/^{22}\text{Ne}$   | 13              | 11.8 ± 0.7      | 10                | $10^{+4.3}_{-3.3}$ |
| $^{21}\text{Ne}/^{22}\text{Ne}$   | 0.05            | <0.06           | 0.035             | —                  |
| $^{20}\text{Ne}/^{36}\text{Ar}$   | 40              | 0.16–0.2–0.3    | 0.57              | 0.15–0.4–0.6       |
| $^{36}\text{Ar}/^{38}\text{Ar}$   | 5.35            | 5.55 ± 0.6      | 5.21              | 5.26 ± 0.5         |
| $^{36}\text{Ar}/^{84}\text{Kr}$   | 2500            | 1200–2500       | 48                | 10–30–90           |
| $^{36}\text{Ar}/^{132}\text{Xe}$  | $7 \times 10^4$ | $2 \times 10^4$ | $1.5 \times 10^3$ | $2.7 \times 10^2$  |
| $^{129}\text{Xe}/^{132}\text{Xe}$ | 1               | —               | 0.95              | 2.5                |
| $^{84}\text{Kr}/^{132}\text{Xe}$  | 28              | 10–17           | 30                | 10                 |

Note.  $^{36}\text{Ar}$  Venus/Earth = 100; Earth/Mars = 165;  $^{84}\text{Kr}$   $1.67 \times 10^{-12}$  g/g on Earth.

ing a simple mechanism for selective loss of noble gases from accreting planetesimals. Even though the mechanism succeeds in accounting for most of the known characteristics of the noble gas inventories on the three planets it develops two serious problems. One of these is the prediction of a significantly lower  $^{36}\text{Ar}/^{38}\text{Ar}$  ratio on Venus and especially on Earth and Mars than has been observed. The second but more tractable problem is to account for the very low abundance of noble gases, particularly neon, on Mars. Furthermore, the mechanism offers no credible explanation for the fractionation pattern of noble gases trapped in meteors.

Despite these problems, a discussion of the mechanism and an analysis of the reasons for its apparent shortcomings seems to be worthwhile. One reason is that it has a large measure of plausibility and does succeed in reproducing many of the observed features of the noble gases on terrestrial planets without many ad hoc assumptions. More important, perhaps, its failures demonstrate how severe are the constraints placed on any mechanism by the conflicting requirement set forth in Table I. It is important to emphasize the need to explain all of these properties, isotope ratios as well as the full set of observed elemental abundance ratios, for all three planets and not only for one or two as well as for meteors. It is not adequate to develop a model that

merely produces an atmosphere on Venus that is rich in noble gases, for example. Venus is rich in neon and argon compared to Earth, but not in krypton and xenon. But Mars is conspicuously deprived of all four elements. All of these properties, along with the isotope ratios, are very difficult to explain, and it is this fact that this paper emphasizes.

For the purpose of this exercise the following assumptions will be made:

(1) That as planetesimals grow rapidly to a mass of about  $10^{24}$  they become enveloped in noble gas atmospheres in which the relative elemental and isotopic abundances are solar;

(2) That the inventory of  $^{84}\text{Kr}$  on the planetesimals contributing to the noble gas endowment of the planets is the same on all of them and has some suitably chosen value equal to or greater than the terrestrial abundance of  $1.66 \times 10^{-12}$  g/g relative to the mass of the planetesimal.

The first assumption would be justified if, for example, the noble gases in the solar nebula had been physically absorbed in the dust grains of the nebula and were released during the collisions leading to the growth of the planetesimals. In this picture other volatiles, for the most part, would remain chemically bound in this solid phase until the mass of the planetesimals exceeded  $10^{26}$  g. It is recognized that there are problems with this assumption in that the heating generated by collisions between relatively small planetesimals may be insufficient to release the noble gases. It is also unclear whether the solar nebula would have cleared during this early phase of planetesimal growth. The spirit of this exercise is to determine whether the mechanism for fractionation has promise and only then to examine these underlying assumptions carefully. It will be shown that to ask of the mechanism developed in this paper that it produce the degree of fractionation required for the noble gases and also accommodate a large primordial abundance of

volatiles such as nitrogen or carbon in the atmospheres of the growing planetesimal is to ask for more than it can deliver. Because noble gases absorb extreme ultraviolet radiation moderately well but radiate poorly, it may, nevertheless, be necessary to invoke a modest admixture of a good radiator, such as  $\text{CO}_2$ , in the atmosphere in order to achieve exospheric temperatures low enough to prevent blow off (Rasool *et al.*, 1966). The second assumption together with the first assures that all planetary material begins with the same noble gas inventory per unit mass and recognizes that loss of krypton will be negligible.

The planetesimals are supposed to lose their noble gas atmospheres by the classical thermal escape process of Jeans escape. But at the same time they are supposed to be growing in size as they collide with each other. At each accretional collision the atmospheres of the colliding partners coalesce. The escape parameters then change and escape becomes more difficult. It will be assumed that by the time the planetesimals begin to lose an appreciable fraction of their neon the solar nebula has been cleared from the region where they are growing. Thus the picture of accretion here is that it takes place in a gas free environment. An attempt will be made to account for the properties specified in Table I with an economy of planetesimal species and to restrict the initial values for the  $^{84}\text{Kr}$  endowment to one, if possible. This paper attempts to answer two questions. Is the characteristic time for planetesimal growth such as to permit selective loss of the lighter noble gases before the planetesimals become so massive that further loss of noble gases is strongly inhibited? And, if so, is it possible to assemble these planetesimals in such a way as to endow Venus, Earth, and Mars each with its peculiar noble gas inventory without being forced to call upon implausibly different planetesimal populations for each of these three planets?

It will turn out that the answer to both questions is affirmative. The time constants

for loss of noble gases, neon and heavier, is sufficiently great that if planetesimals grow to a mass of about  $10^{24}$  g in  $10^4$  or  $10^5$  years they will retain all of their initial noble gas inventory at that stage. If the time for subsequent growth to about  $10^{26}$  g is sufficiently long (about  $10^7$  years), complete loss of neon and partial loss of the argon isotopes will occur. (These time scales are reasonable, according to current models for accretion.) On the other hand, a somewhat more rapid growth rate can produce a population of planetesimals that will still have retained most or all of their initial endowment of neon when their mass has grown to about  $10^{26}$  g. Loss of gas—even of neon—occurs so slowly from planetesimals larger than  $10^{26}$  g that the inventory becomes frozen at that stage. Thus it is feasible to assemble the planets out of two kinds of planetesimals—a class, by far the most abundant, that have lost all of their neon and some argon, and a very small number of neon rich planetesimals.

The mechanism plausibly explains the relative *elemental* abundances of the noble gases and even the relative abundances of the neon isotopes. Unfortunately, it is not so successful in accounting for the relative abundances of the two isotopes of nonradiogenic argon. The strong mass dependence of the loss mechanism produces very different histories for two constituents whose mass difference is large and two whose masses are nearly equal. In the former case a lighter constituent which is initially dominant disappears almost completely before an appreciable amount of the heavier constituent begins to be lost. This is the case for the elements neon, argon, and krypton. For isotopes of a given element loss of the lightest will be accompanied by a significant loss of the heavier. But the departure of the lighter is sufficiently favored that, when it must be appreciably fractionated relative to a heavier element, significant reduction in isotope ratios will be entailed. Because a severe fractionation of  $^{36}\text{Ar}$  relative to  $^{84}\text{Kr}$  must occur, especially

for Earth and Mars, this model calls for the ratio of  $^{36}\text{Ar}$  to  $^{38}\text{Ar}$  to be less than unity on Earth and Mars and appreciably less than the solar value on Venus, whereas in fact it remains close to the solar value of about 5 in the atmospheres of all three planets.

## 2. LOSS OF GAS FROM PLANETESIMALS

### a. Jeans Escape

The abundance of each noble gas constituent of a planetesimal's atmosphere is

$$N_i = n_{i0}H \quad (1)$$

where  $H$  is the average scale height of the mixture near the surface and  $n_{i0}$  is the density of the constituent at the surface.

Above the homopause,  $z_h$ , each gas assumes its own scale height. At the critical level for escape,  $z_c$ , the escape flux of each species is

$$\phi_i = n_{ic}u_{ic}, \quad (2)$$

where

$$u_{ic} = (1 + \lambda_{ic})U_i e^{-\lambda_{ic}/2} \sqrt{\pi} \quad (3)$$

$$\lambda_{ic} = r_c/H_{ic}, \quad (4)$$

$$U_i = \sqrt{2kT/m_i}, \quad (5)$$

and  $r_c = r_0 + z_c$ , where  $r_0$  is the planetesimal radius.

The differential equation governing the behavior of gas  $i$  is

$$dN_i/dt = -\phi_i. \quad (6)$$

Consider first the case in which one constituent is dominant so that

$$n_{1c} \gg n_{ic}$$

and

$$n_{1h} \gg n_{ih},$$

for all  $i \neq 1$ . In this case the abundance of the dominant gas evolves linearly with time

$$N_1(t) = N_1(0)(1 - t/\tau_1), \quad (7)$$

where

$$\tau_1 = N_1(0)/n_c u_1. \quad (8)$$

and  $n_{ic}$  has the constant value  $n_c$  which defines the critical level. Every other constituent is controlled by the differential equation

$$dN_i/dt = -n_{ic}u_i. \quad (9)$$

If the flux is sufficiently small that the distribution of species  $i$  above the homopause can be approximated by diffusive equilibrium,

$$n_{ic} = (n_{i0}/n_{10})n_{1h}(n_{1c}/n_{1h})^{s_i}, \quad (10)$$

$$= (N_i/N_1)n_h(n_c/n_h)^{s_i}, \quad (10')$$

with

$$s_i = m_i/m_1. \quad (11)$$

Then

$$dN_i/dt = (N_i/N_1)n_h(n_c/n_h)^{s_i}u_i, \quad (12)$$

where  $n_h$  is the total density at the homopause and both  $n_h$  and  $u_i$  are constant in time. The loss rate increases as  $N_1$  (and  $n_{10}$ ) decrease with the time constant  $\tau_1$  because of the reduction in altitude of the homopause. The solution of (12) is

$$N_i(t) = N_i(0)(1 - t/\tau_1)^{A_i}, \quad (13)$$

where

$$A_i = (u_i/u_1)(n_c/n_h)^{(s_i-1)}. \quad (14)$$

When the mass ratio  $s_i$  is large  $A_i$  will be a very small number and loss of the minor constituent negligible until constituent 1 has almost vanished. On the other hand, for isotopes of the major constituent  $A_i$  will be fairly close to unity, and appreciable loss of minor isotopes will occur during the main phase of the decay of the major isotope. In Section IIb the assumption that the flux is small will be examined. What matters is how  $n_{ic}u_i$ , as expressed in (12), compares with the limiting flux

$$\phi_{li} = (b_i/H_1)(N_i/N_1)(1 - m_i/m_1), \quad (15)$$

where

$$b_i = D_i n_1, \quad (16)$$

and  $D_i$  is the diffusion coefficient for species  $i$ .

Eventually sufficient loss of the major constituent will have occurred that

$$n_{1h} = n_{2h}, \quad (17)$$

where species 2 could be one of the isotopes of species 1 or another element. This will occur at time  $t_a$  when  $N_1 = N_2$ , or

$$(1 - t_a/\tau_1) = [N_1(0)/N_2(0)]^{1/(A_2-1)}. \quad (18)$$

After species 2 begins to control the altitude of the homopause the ratio of  $n_{1c}$  to  $n_{1h}$  begins to increase as the distance between  $z_h$  and  $z_c$  decreases.

During the time that

$$n_{2h} = n_h > n_{1h},$$

but

$$n_{2c} < n_{1c} = n_c.$$

$n_{1h}$  varies with time in expression (10) and so (10') is not valid. Instead

$$n_{2c} = n_h(n_c/n_h)^s(N_2/N_1)^s, \quad (19)$$

where  $s = m_2/m_1$ , and instead of (12) the loss of  $N_2$  is governed by

$$dN_2/dt = -n_h(n_c/n_h)^s(N_2/N_1)^s u_2, \quad (20)$$

where  $i = 2$ . The solution of this differential equation is

$$N_2^{1-s} = A_2 N_1^{1-s} + N_1^{1-s}(t_a)(1 - A_2), \quad (21)$$

or

$$N_2(t') = N_2(t_a) \left\{ [1 + A_2(1 - t'/\tau_{1a})^{1-s} - 1] \right\}^{1/(1-s)}. \quad (22)$$

where  $N_1$  still varies linearly with time because species 1 continues to control the critical level.  $N_2(t_a)$  is the quantity of species 2 left at the time ( $t_a$ ) that condition (17) occurs,  $t'$  is  $t - t_a$ , and

$$\tau_{1a} = N_1(t_a)/n_c u_1. \quad (23)$$

Eventually, at time  $t'_b$  another critical point is reached at which

$$n_{1c} = n_{2c} = n_c/2, \quad (24)$$

where  $n_c$  is the total density at the exobase. This occurs when

$$n_{10} = n_{20}(n_c/n_h)^{1-s}/2, \quad (25)$$

that is, when

$$N_1 = N_2(n_c/n_h)^{1-s}/2, \quad (26)$$

or

$$(1 - t'_b/\tau_{1a})^{1-s} [1 - A_2 2^{s-1} (n_c/n_h)^{(1-s)^2}] = (1 - A_2) 2^{s-1} (n_c/n_h)^{(1-s)^2}. \quad (27)$$

Thereafter species 2 controls both the homopause level and the critical level; species 1 is relegated to the role of a minor species. The roles of 1 and 2 are reversed,

$$N_2 = N_2(t_b)(1 - t''/\tau_2), \quad (28)$$

$$t'' = t - t'_b,$$

$$\tau_2 = N_2(t'_b)/n_c u_2, \quad (29)$$

and, provided the flux of species 1 is small enough that it departs little from diffusive equilibrium above the homopause,

$$N_1 = N_1(t'_b)(1 - t''/\tau_2)^{B_1}, \quad (30)$$

with

$$B_1 = u_1/u_2(n_c/n_h)^{(1-s)/s} \quad (31)$$

If the mass ratio is large (as for  $^{20}\text{Ne}$  and  $^{36}\text{Ar}$ , say)  $B_1$  will be large and species 1 will disappear quickly compared to species 2. A schematic of the behavior of the two species is shown in Fig. 1. Numerical examples will be developed in Section IIe where it will be shown that in the cases of interest here the loss of neon is rapid after argon comes to control the entire region above

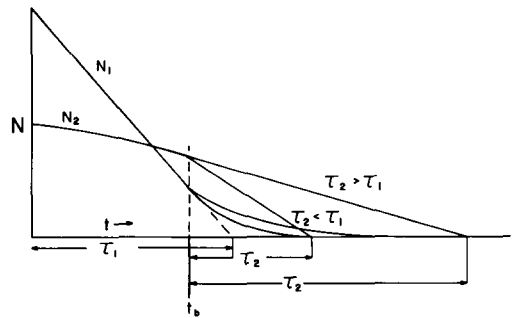


FIG. 1. Surface densities of species 1 and 2 as functions of time for  $m_2/m_1 \geq 1.5$ . Cases in which  $\tau_2$  is greater than and less than  $\tau_1$  are illustrated.

the homopause. The reservoir of neon,  $N_1$ , at time  $t'_b$  is smaller than the reservoir of argon,  $N_2$ ,  $u_1$  is larger than  $u_2$  and, even though  $n_{1c}$  is less than  $n_{2c}$ , the rate of loss of  $N_1$  is much larger than that of  $N_2$ . Obviously this treatment becomes invalid when the densities of any species becomes so small that it would formally vanish below the exobase. For example, equation (30) cannot represent the decay of  $N_1$ , at times  $t''$  comparable to  $\tau_2$ . The treatment is also defective around the critical times,  $t_a$  and  $t'_b$ .

### b. Test for Limiting Flux

The assumption that the flow of species 1 is controlled at the exobase and not by diffusion in the lower atmosphere when species 1 no longer controls the critical level is not always a safe one. In fact it is false when species 1 is neon and species 2 is argon. The relevant test is to compare

$$\phi_{11} = (b_1/H_2)(N_1/N_2)(1 - m_1/m_2) \quad (32)$$

with  $n_{1c}u_1$ . Diffusion will control if

$$(b_1/H_2)(1 - m_1/m_2) < n_h(n_c/n_h)^{1/2}u_1. \quad (33)$$

If, indeed, the flux is diffusion limited  $n_1$  will decrease with altitude above the homopause much more rapidly than under diffusive equilibrium and (19) will no longer be valid. In this case

$$dN_1/dt = -\phi_1, \quad (34)$$

for which the solution is

$$N_1 = N_1(t_b)(1 - t''/\tau_2)^{B'_1}, \quad (35)$$

$$\begin{aligned} B'_1 &= b_1(1 - m_1/m_2)/H_2n_cu_2 \\ &= b_1(m_2 - m_1)g/kTn_cu_2. \end{aligned} \quad (36)$$

$B'_1$  turns out to be of order  $10^4/u_2$ , in cgs units, for the cases of interest here. Since  $u_2$  is always less than  $30 \text{ cm sec}^{-1}$  (when species 2 is argon)  $B'_1$  is always considerably larger than unity. Thus even under limiting flux conditions the final loss of species 1 is rapid.

### e. Characteristic Times for Accretion and Escape

$\tau_i$  can be either less than or greater than  $\tau_1$ , depending on the relative abundance of the two species and the ratio of their effusion velocities, which in turn is a strong function of the planetesimal mass,

$$\tau_i/\tau_1 = N_iu_i/N_1u_1, \quad (37)$$

where  $N_i$  is reckoned at the time species  $i$  begins to control the exobase. Because  $u_i/u_1$  increases rapidly as the mass of the planetesimal grows, it is possible for  $\tau_i$  to be less than  $\tau_1$  for small planetesimals and greater when their mass is large. But, even though  $\tau_2$  may be less than  $\tau_1$ , no important loss of gas  $i$  would occur until gas 1 is almost exhausted if  $m_i$  is appreciably larger than  $m_1$ . Thus, in principle, it is possible that planetesimal growth can be rapid enough that virtually all of both kinds of gas remain bound to the accreting planetesimal until it has grown so large that  $\tau_i$  is greater than  $\tau_1$ . Thereafter, if the rate of growth should decrease, some or all of gas 1 could be lost without any loss of gas  $i$ , or all of gas 1 lost and some of gas  $i$  as well, before the planetesimals become so large that further escape would be inhibited and the composition frozen. At issue is whether the time scales involved are reasonable.

To address this question it is useful to relate lifetimes and other properties of the noble gas species to the escape parameter for that species evaluated at the surface, to the exospheric temperature and to the initial abundance  $N_i(0)$  chosen for the noble gases. It is demonstrated in the Appendix that the lifetimes for  $^{20}\text{Ne}$  and  $^{36}\text{Ar}$  can be expressed numerically in terms of  $\lambda_{10}$  for  $^{20}\text{Ne}$  in the form

$$\tau_1 = 4.3 \times 10^{10} \sqrt{\lambda_{10}} e^{\lambda_{1c}}/(1 + \lambda_{1c}) \quad (38)$$

$$\tau_2 = 1.07 \times 10^9 \sqrt{\lambda_{20}} e^{\lambda_{2c}}/(1 + \lambda_{2c}) \quad (39)$$

where

$$\lambda_{10} = r_0/H_1 \quad (40)$$

$$\lambda_{20} = (36/20)\lambda_{10} \quad (41)$$

and the relationship between  $\lambda_{ic}$  and  $\lambda_{i0}$  is given by A(8) in the Appendix. In evaluating (A11) numerically in the forms (38) and (39) the initial abundance ratio of  $^{20}\text{Ne}$  to  $^{84}\text{Kr}$  is taken to be  $10^5$  and the ratio of  $^{36}\text{Ar}$  to  $^{84}\text{Kr}$  2500. While these ratios are solar they could be any appropriate value reflecting some fractionation of the gas from the solar nebula that may have occurred prior to the formation of these putative planetesimal atmospheres. No significant change in the conclusions that follow would occur, except in the numerical values of the species lifetimes.  $\tau_1$  and  $\tau_2$  are plotted as functions of  $\lambda_{10}$  in Fig. 2.  $\tau_2$  is less than  $\tau_1$  for  $\lambda_{10}$  less than 8, where the two lifetimes have equal values of  $4 \times 10^{11}$  sec or  $10^4$  years. For larger planetesimals the  $^{36}\text{Ar}$  lifetime is greater than that of  $^{20}\text{Ne}$ . A situation thus exists where  $\lambda_{10}$  can increase with time as accretion proceeds in such a way that neon

can be lost but massive loss of argon prevented.

Because the escape parameters for isotopes of a given element are nearly equal the lifetime curves for  $^{22}\text{Ne}$ ,  $^{21}\text{Ne}$ , and  $^{38}\text{Ar}$  will almost parallel  $\tau_1$  and  $\tau_2$ , respectively, but at much smaller values. The lifetime for  $^{84}\text{Kr}$  at a specified value of  $\lambda_{10}$  is the  $^{20}\text{Ne}$  lifetime at  $4.2\lambda_{10}$  multiplied by  $10^5$ . It becomes larger than  $\tau_1$  at  $\lambda_{10} = 6$  and then becomes so large as  $\lambda_{10}$  increases that loss of  $^{84}\text{Kr}$  is very slow and never a factor in the scenario proposed here.

The exospheric temperature is treated as a free parameter to accommodate a range of possible extreme ultraviolet luminosities for the early sun and a range of locations in the solar system at which planetesimal growth can occur. The planetesimal mass,  $M_p$ , is a function of  $\lambda_{10}$  and  $T$  since, according to (A9)

$$r_0^2 = 3k\lambda_{10}T/4\pi m_i G. \quad (42)$$

Figure 3 shows  $M_p$  as a function of  $\lambda_{10}$  for various values of  $T$ .

#### d. Blowoff

It is important to determine whether the escape rate of the dominant species can ever be great enough that "blowoff" of the noble gas atmosphere will occur and become an important process for the range of conditions envisioned in this paper. Blowoff takes place when the dominant gas is the escaping species and its outflow velocity becomes supersonic below the exobase (Walker, 1977, 1982). The sonic level is located at  $r_{1s}$  for an atmosphere dominated by species 1 where

$$\lambda_{1s} = \lambda_{10}(r_0/r_{1s}) = 2 \quad (43)$$

According to (40) this occurs when

$$\lambda_{10} = 2g(\lambda_{10}) \quad (44)$$

or at an escape parameter of 7.8. This is almost exactly where  $\tau_1$  and  $\tau_2$  are equal. Since it will be a fundamental assumption in Section 3 that accretion is so rapid that essentially none of the original noble gas at-

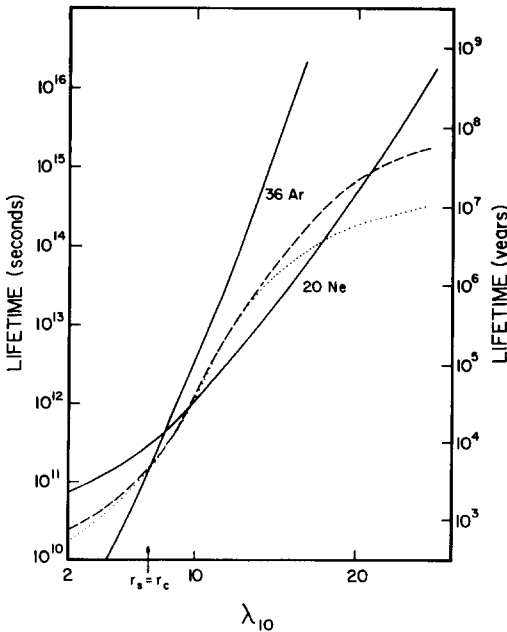


FIG. 2. Time constants for loss of  $^{20}\text{Ne}$  and  $^{36}\text{Ar}$  as functions of the escape parameter for  $^{20}\text{Ne}$  at the surface of the planetesimal,  $\lambda_{10}$ . The value of  $\lambda_{10}$  at which the sonic level coincides with the exobase is marked. Dashed and dotted lines are sample planetesimal accretion times.

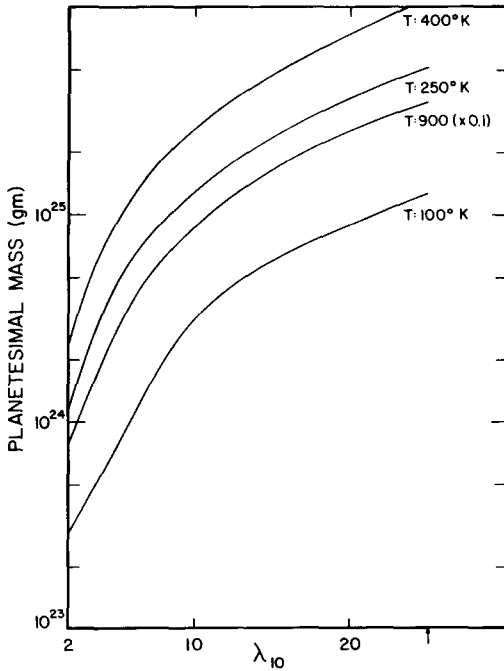


FIG. 3. Planetesimal mass versus escape parameters  $\lambda_{10}$  for various exospheric temperatures.

mosphere can be lost when  $\lambda_{10}$  is less than 8, blowoff would not appear to be of concern.

In any event fluid dynamics and kinetic theory are merely two ways of describing the same phenomenon, and the escape flux of the dominant component can always be computed either by calculating it at the sonic level or by using expression (3). The characteristic of blow off that is really important is that the escape flux of the major component can sometimes be large enough to carry along other more massive species. In that case the description used here would be incorrect in that it assumes that the scale heights of the minor constituents above the homopause are those of gases in hydrostatic equilibrium. In a recent elegant discussion Hunten (1985) has shown that the flux of a second species is given by

$$\phi_2 = (x_2/x_1)(\phi_1 - \phi_{11}), \quad (45)$$

where  $x_i$  are mole fractions and  $\phi_{11}$  is the "limiting flux" given by (32). When  $\phi_1$  is

large compared to  $\phi_{11}$  the minor species cannot diffuse downward rapidly enough to be contained in the gravitational field and it too expands rapidly outward.

The limiting flux for minor constituents  $^{21}\text{Ne}$ ,  $^{22}\text{Ne}$ , and  $^{36}\text{Ar}$  diffusing in the escaping flow of  $^{20}\text{Ne}$  were compared with the  $^{20}\text{Ne}$  escape flux as  $\lambda_{10}$  was varied. In Fig. 4 the range of parameters  $\lambda_{10}$  and  $T$  for which blowoff of a minor species will occur is located to the left and above the curves plotted for  $m_1 - m_i = 16, 2$  and 1. Blowoff of  $^{36}\text{Ar}$  will not occur. But blowoff of  $^{22}\text{Ne}$  and  $^{21}\text{Ne}$  certainly comes into play as planetesimals grow from  $\lambda_{10}$  of about 10 to 14, depending on  $T$ . This should be kept in mind when planetesimal growth is slow enough that all the neon will be lost—as will be the case for most of the planetesimals considered in this model. It makes no difference whether the minor isotopes stream away along with  $^{20}\text{Ne}$  or take their turn after most of the  $^{20}\text{Ne}$  is gone. On the other hand, blowoff may be useful in obtaining the proper isotope ratios for the planetesimals that grow at some intermediate rate so that they can lose a fraction but not all of their neon. This mode of growth could produce the population of planetesimals that are in this paper will be designated "neon rich." An issue will be whether the observed fractionation pattern for the neon isotopes can be reproduced. The answer may depend on whether  $^{21}\text{Ne}$  and  $^{22}\text{Ne}$  escape along with

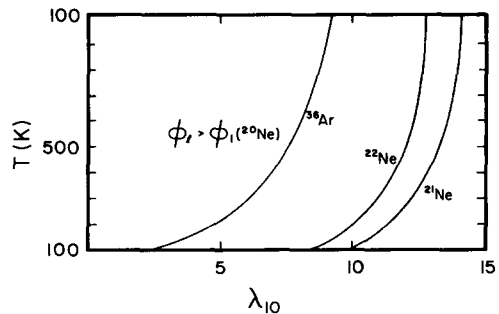


FIG. 4. Temperature-escape parameter domains for mass fractionation of  $^{36}\text{Ar}$ ,  $^{22}\text{Ne}$ , and  $^{21}\text{Ne}$  in blowoff of  $^{20}\text{Ne}$ .



TABLE II  
ATMOSPHERIC ESCAPE PARAMETERS

|                    | <sup>20</sup> Ne | <sup>21</sup> Ne | <sup>22</sup> Ne | <sup>36</sup> Ar | <sup>38</sup> Ar |
|--------------------|------------------|------------------|------------------|------------------|------------------|
| $\lambda_{10}$     | 14               | 14.7             | 15.4             | 25.2             | 26.6             |
| $\lambda_{ic}$     | 5.86             | 6.30             | 6.78             | 14.0             | 15.13            |
| $u_1/u_0$          | 1                | 0.76             | 0.58             | 0.011            | 0.47             |
| $A_1$              |                  | 0.48             | 0.23             | 6.9(-6)          | 0.28             |
| $B_1$              |                  | 2.04             | 4.0              | 5450             | 3.45             |
| $(1 - t_2/\tau_1)$ |                  | 2.25(-3)         | 0.036            | 0.025            | 0.085            |

<sup>20</sup>Ne at the effusion velocity  $u_1$  or at their own particular effusion velocity.

### e. Numerical Discussion

Thus the most critical range of  $\lambda_{10}$  for the fractionation mechanism is from 10 to 20. Table II lists various critical quantities when  $\lambda_{10}$  is 14 and  $n_1/n_c$  is  $10^4$ . Species 1 is taken to be <sup>20</sup>Ne for the other neon isotopes and for <sup>36</sup>Ar, but to be <sup>36</sup>Ar for <sup>38</sup>Ar. The decay exponents  $A_i$  are the heavy neon isotopes are fairly large and an appreciable loss of those isotopes would have accompanied the escape of <sup>20</sup>Ne. Similarly, a significant loss of <sup>38</sup>Ar would have occurred while <sup>36</sup>Ar was escaping. On the other hand the planetesimals would have retained virtually all of their argon while the neon isotopes were disappearing. The behavior of the neon and argon isotopes during a  $10^{12}$ -sec interval centered at  $10^{13}$  sec, which is  $\tau_1$  for <sup>20</sup>Ne, is illustrated in Fig. 5. The first species to supercede <sup>20</sup>Ne, first at the homopause and then at the exobase, would have been <sup>22</sup>Ne. Following the discussion in Section IIa and using the data from Table I it can be shown that condition (18) for equality of <sup>20</sup>Ne and <sup>22</sup>Ne at the homopause would have been reached when 0.036 of  $N_1(0)$  remained. At that time  $N_1(t_a) = N_2(t_a)$ . Application of condition (22) shows that after a further reduction of <sup>20</sup>Ne by a factor of 0.74 to 0.027 of its original value the densities of the two isotopes would have been equal at the critical level. During the time between  $t_a$  and  $t'_b$  the abundance of <sup>22</sup>Ne would have decayed only by a factor of 0.93 according to (28). At  $t'_b$  the <sup>22</sup>Ne

abundance would thus have been 0.033 times the initial <sup>20</sup>Ne abundance. Thereafter, since  $B_1$  is 4, the residue of <sup>20</sup>Ne would have disappeared quickly according to (30),

$$N_1 = N_1(t'_b)(1 - t''/\tau_2)^4. \quad (46)$$

Then <sup>22</sup>Ne would have been the dominant gas since the <sup>36</sup>Ar abundance would have remained unchanged at 0.025 times the initial <sup>20</sup>Ne abundance while all of this was going on. After parity of <sup>20</sup>Ne and <sup>22</sup>Ne had occurred at the exobase at time  $t_c$  the <sup>22</sup>Ne would have decreased following (28) by a factor of  $5.8 \times 10^{-3}$ , according to the equivalent of (27) for the <sup>36</sup>Ar-<sup>22</sup>Ne pair, before its density at the exobase became equal to that of <sup>36</sup>Ar there. (The <sup>22</sup>Ne abundance would then have been only  $1.9 \times 10^{-4}$  times the original <sup>20</sup>Ne abundance.) Thereafter <sup>36</sup>Ar would have controlled escape

$$N_3 = N_3(t'_d)(1 - t'''/\tau_3), \quad (47)$$

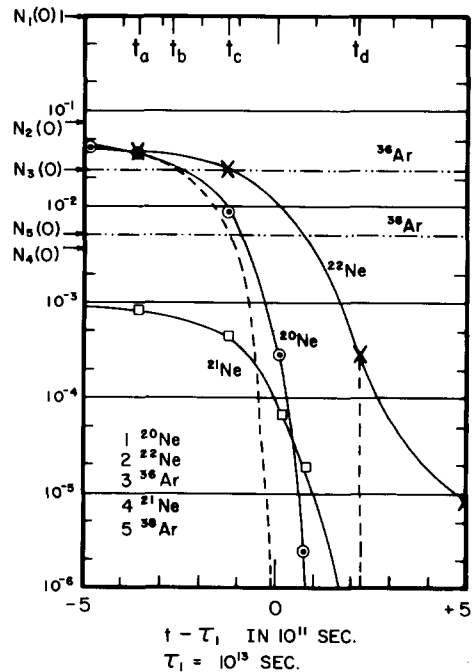


FIG. 5. Behavior of neon and argon isotopes relative to the initial abundance of <sup>20</sup>Ne retained as a function of time during  $10^{12}$ -sec interval centered at  $\tau_1$  for <sup>20</sup>Ne.

while

$$N_2 = N_2(t_d''')(1 - t'''/\tau_3)^{5450}, \quad (48)$$

where  $N_3(t_d''')$  is the  $^{36}\text{Ar}$  abundance at  $t_d$  when it becomes dominant at the exobase  $N_3(t_d''')$  is virtually identical with  $N_3(0)$ . The lifetime ( $\tau_3$ ) of  $^{36}\text{Ar}$  when  $\lambda_{10}$  is 14 is  $4.4 \times 10^{14}$  sec.

According to the equivalent of (18) parity of  $^{36}\text{Ar}$  and  $^{38}\text{Ar}$  at the homopause would have occurred when only 0.097 of the original  $^{36}\text{Ar}$  remained,  $4.3 \times 10^{13}$  before  $t = \tau_3$ . The decay of the argon isotopes is shown in Fig. 6 during the  $12 \times 10^{13}$ -sec interval around  $t = \tau_3$ . Further decay in  $^{36}\text{Ar}$  by a factor of 0.76 and in  $^{38}\text{Ar}$  by a factor of 0.93 would have resulted in equality at the exobase. At this time the abundance of  $^{36}\text{Ar}$  would have been 0.065 and of  $^{38}\text{Ar}$  would have been 0.078 of the original  $^{36}\text{Ar}$  value.

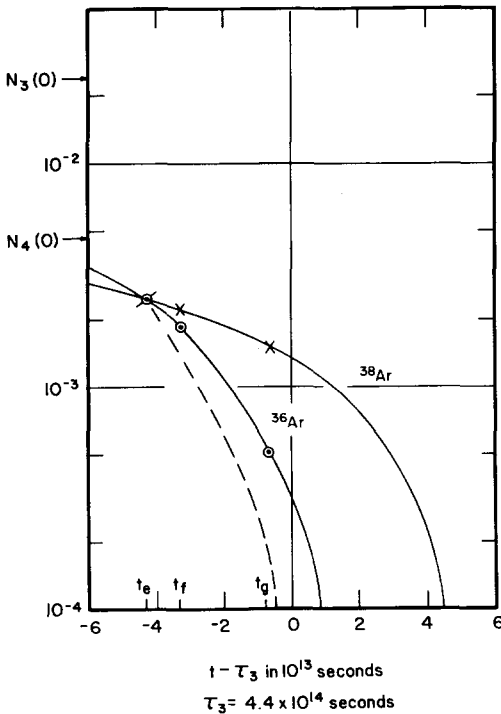


FIG. 6. Behavior of the argon isotopes (relative to the initial  $^{20}\text{Ne}$  abundance) near  $\tau_3$ . Times are marked where the isotopes are equal in density at the homopause and the exobase and where the  $^{36}\text{Ar}$  abundance is reduced to 2% of its original value.

The  $^{36}\text{Ar}/^{38}\text{Ar}$  ratio would have already been less than unity. In the next stage of decay a decrease in  $^{38}\text{Ar}$  by a factor of  $f$  would have been accompanied by an  $f^{3.45}$  decrease in  $^{36}\text{Ar}$  since  $B$  for  $^{36}\text{Ar}$  and  $^{38}\text{Ar}$  is 3.45. Thus, for example, to achieve a fractionation of  $^{36}\text{Ar}$  by 0.02 of its original abundance—which is the case for Earth— $^{38}\text{Ar}$  would only have been reduced to 0.33 of its original abundance (0.06 of the original  $^{36}\text{Ar}$  abundance). This condition occurs at the time marked  $t_g$  in Fig. 6. The  $^{36}\text{Ar}/^{38}\text{Ar}$  ratio would have been reduced from 5.35 to 0.32.

### 3. DISCUSSION

If the growth of a planetesimal can be characterized by an accretion time scale such as the one suggested by the dashed line in Fig. 2 virtually no  $^{20}\text{Ne}$  nor any other noble gas would have been lost until  $\lambda_{10}$  reached a value of about 10 about 30,000 years after accretion began. If this growth had occurred where  $T$  was between 100 and  $400^\circ\text{K}$  the planetesimal mass would then have been between  $3 \times 10^{24}$  and  $3 \times 10^{25}$  g. Suppose then, for some reason, the rate of accretion had been retarded so that some 30 million years would have been required for  $\lambda_{10}$  to grow from 10 to 21, in the way suggested by the dashed line. The planetesimal could have lost all or a portion of its neon and even some of its argon during this phase of its growth. According to Fig. 3 the planetesimal mass would then have been between  $10^{25}$  and  $10^{26}$  g. All relevant time constants increase so rapidly with  $\lambda_{10}$  when  $\lambda_{10}$  is greater than 20 that no further escape of the noble gases by this process could have occurred during the later stages of accretion of planetesimals to planetary size. The planetesimal's endowment of noble gases at this stage would constitute its eventual contribution to the planetary atmosphere.

This mechanism can accommodate two distinctly different families of planetesimals, one of them depleted in neon, and even to some extent in  $^{36}\text{Ar}$ , and the other

retaining most if not all of its original supply of gas and, consequently, rich in neon. The two classes will be called Type 1 and Type 2. The second class of planetesimals are those that would have grown rapidly enough to maintain their accretional lifetime below the  $^{20}\text{Ne}$  curve until they met an object so large that the combined  $\lambda_{10}$  was greater than 20 or so. A range of possibilities exists. Such planetesimals must either have been gas poor compared to Type 1 planetesimals or still of low mass when they were captured by objects so large that the combined  $\lambda_{20}$  was greater than 20. Otherwise they would have supplied the planets with too much neon. This means that they only would have begun to accrete when most planetesimals were already 10 or more million years old with average masses greater than  $10^{25}$  g, and that they would have grown rapidly to a mass between 1 and  $2 \times 10^{24}$  g ( $8 < \lambda_0 < 12$ ) in about  $10^4$  years and in a region of the solar system where  $T$  could be about  $100^\circ\text{K}$ . Then it would have been necessary that they be captured by a larger and older planetesimal, so that the resultant  $\lambda_{10}$  would have been at least 20. The population of planetesimals of Type 1 and Type 2 could have contained a wide range of objects whose "average" histories would have approximated the scenario described here. To account for the lower than solar  $^{20}\text{Ne}/^{22}\text{Ne}$  ratio for the planets, Type 2 planetesimals must be assumed to have lost a small amount of  $^{20}\text{Ne}$ . The time scales for the planetesimals to grow to the mass ranges involved appear to be consistent with present day models of accretion (Wetherill, 1985).

Tables IIIa–c specify the amount of gas relative to terrestrial  $^{84}\text{Kr}$  that must be supplied by these two classes of planetesimals to endow the three terrestrial planets with their present supply of noble gases. A satisfactory outcome can be obtained with the mechanism except for  $^{38}\text{Ar}$ . An appreciable loss of  $^{36}\text{Ar}$  from Type 1 planetesimals must occur—especially on those that are destined for Earth and Mars—to reduce the

ratio from the solar value of 2500 to  $^{84}\text{Kr}$  to about 50. The consequence is the drastic reduction in the  $^{36}\text{Ar}/^{38}\text{Ar}$  ratio that was discussed in Section IIe. This is a serious, and apparently disabling flaw in the mechanism.

Type 1 planetesimals acquired by Venus must have suffered considerably less loss of  $^{36}\text{Ar}$  than those from which the Earth accreted. This could have occurred if their average rate of growth between 10,000 and 35 million years after accretion began, during the crucial period when neon and argon were escaping, was faster than the average rate for the terrestrial Type 1 planetesimals. The result would have been complete loss of neon but less severe depletion of argon. Venus also would need to have acquired more Type 2 planetesimals or bigger ones than the Earth to account for its excess  $^{20}\text{Ne}$ . Because there would have been little if any loss of  $^{36}\text{Ar}$  in the Type 1 planetesimals of Venus, the  $^{38}\text{Ar}$  anomaly is not as serious for Venus, but there is certainly no way to make the  $^{36}\text{Ar}/^{38}\text{Ar}$  ratio larger than solar, as the observations suggest (Table 1).

Table IIIc shows the requirement for Mars. They are similar to those for the Earth's planetesimals, except that they are scaled by a factor of about  $10^{-3}$ . The  $^{38}\text{Ar}$  problem persists.

#### 4. THE NUMBER OF PLANETESIMALS

The entries in Tables IIIa–c are in units of the amount of  $^{84}\text{Kr}$  in the Earth's atmosphere ( $10^{16}$  g). If the average abundance of  $^{84}\text{Kr}$  on a Type 1 planetesimal was  $1.66 \times 10^{-12}$  g/g and the average mass of such a planetesimal was  $4 \times 10^{25}$  g, then 150 planetesimals would have been needed to supply the Earth with its  $^{84}\text{Kr}$ . Of course virtually the entire mass of the Earth ( $6 \times 10^{27}$  g) would then have been supplied by these planetesimals, since the contribution of Type 2 planetesimals to the planet's mass is negligible. From the information in Table III the numbers of planetesimals of each type needed to supply each planet can be determined once the average  $^{84}\text{Kr}$  abundance and the average "terminal" planetes-

TABLE III  
 ABUNDANCE OF NOBLE GAS ISOTOPES ON PLANETESIMALS RELATIVE TO  $^{84}\text{Kr}$

|           | $^{20}\text{Ne}$  | $^{22}\text{Ne}$   | $^{21}\text{Ne}$   | $^{36}\text{Ar}$   | $^{38}\text{Ar}$   | $^{84}\text{Kr}$     |
|-----------|-------------------|--------------------|--------------------|--------------------|--------------------|----------------------|
| (a) Earth |                   |                    |                    |                    |                    |                      |
| Needed    | 29                | 2.9                | 0.1                | 51                 | 10                 | 1                    |
| Initial   | $10^5$            | 7770               | 380                | 2500               | 470                | 1                    |
| Type 1    | 0                 | 0                  | 0                  | 50                 | 132                | 1                    |
| Type 2    | 30                | 2.7                | 0.13               | 1                  | 0.2                | $4 \times 10^{-4}$   |
| Total     | 30                | 2.7                | 0.13               | 51                 | 132                | 1                    |
| (b) Venus |                   |                    |                    |                    |                    |                      |
| Needed    | 1000–1500         | 85–130             | $\leq 5-7.5$       | 5000               | 900                | 2.5                  |
| Initial   | $2.5 \times 10^5$ | 19,000             | 960                | 6250               | 1030               | 2.5                  |
| Type 1    | 0                 | 0                  | 0                  | 5000               | 960                | 2.5                  |
| Type 2    | 1000              | 105                | 3.5                | 37                 | 17                 | $1.5 \times 10^{-2}$ |
| Total     | 1000              | 105                | 3.5                | 5000               | 960                | 2.5                  |
| (c) Mars  |                   |                    |                    |                    |                    |                      |
| Needed    | 0.012             | —                  | —                  | 0.03               | 0.01               | $10^{-3}$            |
| Initial   | 100               | 7.7                | 0.38               | 2.5                | 0.5                | $10^{-3}$            |
| Type 1    | 0                 | 0                  | 0                  | .03                | 0.11               | $10^{-3}$            |
| Type 2    | 0.012             | $9 \times 10^{-4}$ | $4 \times 10^{-5}$ | $3 \times 10^{-4}$ | $6 \times 10^{-5}$ | $1.2 \times 10^{-7}$ |
| Total     | 0.012             | $10^3$             | $4 \times 10^{-5}$ | 0.03               | 0.11               | $10^{-3}$            |

imal mass is decided upon. (Terminal in this sense means that no further gas loss occurred and not that growth stopped). The choice of terminal mass is restricted by the requirement that the value of  $\lambda_{10}$  at which the argon abundance is frozen be about 20 and reached after 10 to 30 million years of growth. The terminal planetesimal mass is determined from Fig. 3, given the value of  $\lambda_{10}$  at which the planetesimal growth curve crosses the  $^{20}\text{Ne}$  lifetime curve in Fig. 2, terminating all loss of gas, and the gas temperature assumed. The requirements for planetesimals of Type 2 are likewise set by Tables IIIa–c, the average  $^{84}\text{Kr}$  abundance assumed and the planetesimal mass when it was captured by a much larger body.

In Table IVa it is assumed that virtually the entire planet was made of Type 1 planetesimals. This means that for some reason the planetesimals of Venus would have contained an average of 2.5 times as much  $^{84}\text{Kr}$  as did the Earth's planetesimals. It is very difficult to imagine how this could have happened given the gravitational mix-

ing of bodies that must have occurred during accretion. Hence it would seem to be preferable to assume that Type 1 planetesimals had a larger supply of  $^{84}\text{Kr}$  per unit mass than the present Earth does. Tables IVb and c show the requirements if Venus and Earth both acquired Type 1 planetesimals with 10 times the present terrestrial  $^{84}\text{Kr}$  abundance per unit mass. The average mass of all Type 1 planetesimals is taken to be the same. Only 10% of the Earth and 25% of Venus would consist of Type 1 and 2 planetesimals. The rest of each planet would have been built out of gas-poor planetesimals. These may have lost their atmospheres as a result of massive collisions of the sort visualized by Cameron (1983). The difference between Earth and Venus would be that Venus happened to have acquired 2.5 times as many of these planetesimals as the Earth did. Venus also must have accumulated 17 as many Type 2 planetesimals as the Earth did. Because of the greater abundance of gas per unit planetesimal mass the lifetimes are increased by an order

of magnitude for the Type 1 planetesimals of Tables IVb and c. It is necessary then to assume their characteristic growth time is represented by the dotted curve in Fig. 2. Table IV shows how it would be possible to accommodate a smaller number of more massive Type 1 planetesimals by virtue of their growing with a higher exospheric temperature. The table also shows the conditions that Type 2 planetesimals would need to satisfy if they were 0.1 times as rich in gas. The lifetime for escape of neon is reduced by an order of magnitude for these type 2 planetesimals and so they would need to grow to  $10^{24}$  g in only little over 300 years.

There is a very serious problem in ac-

counting for the noble gases in the atmosphere of Mars with this mechanism (or any unified mechanism for the terrestrial planets). Small fractions of planetesimals would be needed. To supply the  $9 \times 10^{12}$  g of  $^{84}\text{Kr}$  on Mars only 0.15,  $1.5 \times 10^{-3}$ , and  $6 \times 10^{-3}$  respectively, of the Type 1 planetesimals of Tables IVa–c are needed. Even more unmanageable is the case with the neon-rich planetesimals of Type 2.  $8 \times 10^{-4}$  of the  $10^{24}$  g Type 2 planetesimals of Tables IVa and b or  $8 \times 10^{-3}$  of the gas-poor Type 2 planetesimals of Table IVc are required. If the scenario suggested by Table IVc should closely approximate the way the two large terrestrial planets acquired their noble gases then a variation that would account

TABLE IV  
NUMBER AND CHARACTERISTICS OF NOBLE GAS PLANETESIMALS

| Type      | Number | $M_p$ (g)            | $^{84}\text{Kr}$ ( $1.66 \times 10^{-12}$ g/g) | $T$ (°K) | $\lambda_{10}$ | Time (years) |
|-----------|--------|----------------------|--|----------|----------------|--------------|
| (a) Earth |        |                      |  |          |                |              |
| 1         | 150    | $4 \times 10^{25}$   | 1  | 250      | 21             | 30M          |
| 2         | 2      | $1.2 \times 10^{24}$ | 1  | 100      | 6              | 3300         |
| Venus     |        |                      |  |          |                |              |
| 1         | 150    | $4 \times 10^{25}$   | 2.5  |          |                |              |
| 2         | 75     | $1.2 \times 10^{24}$ | 1  |          |                |              |
| (b) Earth |        |                      |  |          |                |              |
| 1         | 15     | $4 \times 10^{25}$   | 10   | 300      | 18             | 35M          |
| 2         | 2      | $1.2 \times 10^{24}$ | 1  | 100      | 6              | 3300         |
| Venus     |        |                      |  |          |                |              |
| 1         | 37     | $4 \times 10^{25}$   | 10   |          |                |              |
| 2         | 75     | $1.2 \times 10^{24}$ | 1  |          |                |              |
| (c) Earth |        |                      |  |          |                |              |
| 1         | 6      | $10^{26}$            | 10   | 600      | 21             | 30M          |
| 2         | 24     | $10^{24}$            | 0.1  | 100      | 6              | 325          |
| Venus     |        |                      |  |          |                |              |
| 1         | 15     | $10^{26}$            | 10   |          |                |              |
| 2         | 750    | $10^{24}$            | 0.1  |          |                |              |
| (d) Earth |        |                      |  |          |                |              |
| 1         | 60     | $10^{26}$            | 10   | 600      | 21             | 30M          |
| 2         | 2      | $1.2 \times 10^{24}$ | 10   | 100      | 6              | 33K          |
| Venus     |        |                      |  |          |                |              |
| 1         | 60     | $10^{26}$            | 10   |          |                |              |
| 2         | 30     | $1.2 \times 10^{24}$ | 10   |          |                |              |
| Mars      |        |                      |  |          |                |              |
| 1         | 6      | $10^{26}$            | 10   |          |                |              |
| 2         | 2      | $7 \times 10^{22}$   | 10   | 100      | 2              | 10K          |

for Mars would require three Type 2 planetesimals to collide with one Type 1 planetesimal of the sort in Table IVc, whose mass was  $10^{26}$  g. Then this conglomerate would have collided with an embryo Mars. After the collision only about one-half a percent of the gaseous envelope was retained. An alternative is the later, as Mars grew to its final mass of  $6.5 \times 10^{26}$  g, erosion of the atmospheres following collisions between planetesimals or some other process drove off all but 0.5% of this atmosphere.

An unattractive feature of the first three models of Table IV is that they involve different initial gas abundances for the planetesimals involved. They also require that Earth and Venus acquire different numbers of Type 1 planetesimals despite gravitational mixing during accretion. An obvious improvement is to assume that all planets were built of Type 1 planetesimals like those of Table IVc. The requirements are listed in Table IVd. Venus and Earth would have represented an agglomeration of the equivalent of 60 such Type 1 planetesimals, and Mars of 6. The excess gas accumulated in this case could have been lost during this climactic large body impacts (Cameron, 1983) that are featured in Wetherill's (1985) accretion scenario. In these collisions all but 10% of the Earth's noble gas atmosphere, all but 75% of that of Venus and all but 0.1% of that of Mars must have been lost. This scheme accommodates the same pristine noble gas abundance ( $1.66 \times 10^{-11}$  g/g of  $^{84}\text{Kr}$ ) in the grains from which planetesimals of both types are made. However, this is possible only if the two neon-rich planetesimals that were acquired by Mars grew only to  $7 \times 10^{22}$  g during the  $10^4$  years before they were absorbed by embryo planets or planetesimals with  $\lambda_{10}$  greater than the critical value of 21.

The time scale suggested in Tables IVc and d calls for the stabilization of the atmosphere on the Type 1 planetesimal after 30 million years. In the numerical simulation performed by Wetherill (1985), the Mars-

like planet emerged after about 9 million years. This hardly seems to be a serious disagreement in view of the primitive nature of the models now being generated and the statistical nature of Wetherill's exercise. The final stabilized stage of the gas-rich  $10^{26}$ -g planetesimal could have occurred at  $\lambda_{10} = 16$  and  $10^7$  years, for example, if the gas temperature appropriate for the growing Type 1 planetesimals was about  $600^\circ\text{K}$ .

The solar abundance of nitrogen is almost the same as that of neon and carbon about 5 times as abundant. It is obviously not possible to avoid catastrophic loss of gaseous forms of nitrogen along with neon and argon if it is allowed to be present in the atmospheres of the planetesimals. It is for this reason that it was assumed that for the most part those elements were chemically bound to the solid phase of the planetesimals until their masses became greater than  $10^{26}$  g. Most of whatever atmospheric  $\text{CO}_2$  may have been present could have been retained even if an appreciable loss of argon had occurred.

##### 5. CONCLUDING REMARKS

Many refinements would have to be incorporated in this model if it were to be developed further as a serious candidate to account for the atmospheric composition of the terrestrial planets. The relationship among exospheric temperatures, solar eu fluxes and location of the planetesimals in the solar system would have to be established. Accommodation of possible changes in exospheric (and lower atmospheric temperature) with time during the several tens of millions of years of planetesimal growth would have to be made. The change in temperature that would occur when argon replaced neon as the dominant gas in the upper atmosphere would have to be taken into account. The issue of the nature and stability of a heavy, efficiently radiating species in the infrared would need to be faced. A convincing justification for excluding other atmospheric species—nitro-

gen in particular—would need to be produced. A quantitative understanding of the effect of shock heating of atmospheres of colliding planetesimals on the composite atmospheres would clearly be needed. No doubt there would be other issues. Unfortunately, it does not seem to be worthwhile to be concerned about them in the context of developing this mechanism further.

A generic difficulty for all models, including this one, that attempts to account for noble gas fractionation after degassing of solid planetary material has occurred is to account for the fractionation patterns found in meteorites. How to achieve the requisite fractionation for parent bodies that never grew to masses much larger than  $10^{24}$  g and how to reincorporate these gases in the interior of the parent bodies so that they can be trapped in meteorites is a serious problem for such models. Such difficulties led to attempts to understand fractionation before or during the adsorption of noble gases from the solar nebula in the grain that later accrete to form planetesimals and planets such as those of Pollack and Black (1982).

The mechanism discussed in this paper can account for almost all known properties of noble gases in terrestrial planetary atmospheres. Nevertheless, it does not seem that the proposal is a viable one in its present form, mainly because the fractionation of argon relative to krypton that must occur for planetesimals destined for Earth and Mars could not have been obtained through the Jeans escape process without a drastic change in the argon isotope ratio. Although contortions are necessary to account for the great differences in the noble gas abundances between Venus and Mars, those suggested here have a measure of plausibility. It is hard to imagine how any mechanism can avoid some such acrobatics in view of the scale of the effects that must be explained. The failure of the mechanism because of its inability to account for just one aspect of this complicated problem demonstrates the burden of complexity that must be borne by the eventual successful

theory. The possibility that noble gas loss and fractionation occurred during the planetesimal phase of accretion—even when the planetesimals were of the size of the present day Mars—is probably worth further exploration. The gas loss mechanism will need to be one less sensitive to small mass differences among constituents—especially for heavier elements—than Jeans escape. Some form of hydrodynamic escape or blowoff may have been involved. Choice of the atmospheric constituents will need to be made carefully, however, to account for the selective fractionation of noble gases. The impression persists that there are important implications for planetogenesis contained in the noble gas results. It is certain that they are still not understood.

#### APPENDIX

The species lifetimes depend on  $N_i(0)$  and  $u_i$  at  $r_{ic}$  where

$$r_{ic} = H_i \ln(N_i(0)/n_c H_i). \quad (A1)$$

Expressing the initial abundance in terms of  $r_0$ ,

$$N_i(0) = \gamma_i \rho r_0 / 3, \quad (A2)$$

where  $\gamma_i$  is the initial abundance in atoms per unit mass of planetesimal matter whose density is  $\rho$ , allows (A1) to be written

$$r_{ic} = r_0 g(\lambda_{i0}) \quad (A3)$$

where

$$g(\lambda_{i0}) = 1 + \ln(\gamma_i \rho / 3 n_c / \gamma_{i0} + \ln \lambda_{i0} / \lambda_{i0}). \quad (A4)$$

Numerically

$$g(\lambda_{i0}) = 1 + 16.86 / \lambda_{i0} + \ln(\lambda_{10} N_i(0) / N_1(0)) / \lambda_{i0} \quad (A5)$$

$$= 16.86 / \lambda_{i0}, \quad (A6)$$

where  $\rho$  is  $5.3 \text{ g cm}^{-3}$ ,  $n_c$  is  $10^8 \text{ cm}^{-3}$ , the initial krypton abundance is taken to have the terrestrial value of  $1.66 \times 10^{-12} \text{ g/g}$ , and

$$\lambda_{i0} = \lambda_{10}(m_i/m_1). \quad (A7)$$

Obviously

$$\lambda_{ic} = \lambda_{i0}/g(\lambda_{i0}). \quad (\text{A8})$$

If  $U_i$  is written in the form  $\sqrt{2H_i g}$  or  $2\sqrt{2r_0 g/\lambda_{i0}}$  it follows that

$$U_i = r_0 \sqrt{8\pi\rho G/3\lambda_{i0}} \quad (\text{A9})$$

and

$$u_i = r_0 \sqrt{2G\rho/3} (1 + \lambda_{ic})e^{-\lambda_{ic}/\sqrt{\lambda_{i0}}} \quad (\text{A10})$$

It then follows that using the expression to be expressed as (A2) for the initial abundance allows the species lifetime  $\tau_i = N_i(0)/n_c U_i$  to be expressed as

$$\tau_i = \gamma_i \sqrt{\rho/6G\lambda_{i0}} e^{\lambda_{ic}/n_c} (1 + \lambda_{ic}) \quad (\text{A11})$$

#### ACKNOWLEDGMENTS

George Wetherill suggested that I investigate this mechanism during a sabbatical year that I spent at the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. I thank him for his suggestion, encouragement, criticism, and hospitality. Donald Hunten and J. C. G. Walker read and effectively criticized early drafts. Many of their suggestions have been incorporated in the final presentation. This material was based upon work supported by the National Science Foundation under Grant ATM-8116689 and by NASA under Contract NAS2-9126.

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