Noble Gases and Earth's Accretion

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Earth probably accreted in two stages corresponding to conditions before and after the removal of gas from the nebular disk. Helium and neon in the mantle primarily record a solarlike component likely incorporated during the first stage by solution into a magma ocean blanketed under a massive protoatmosphere of molecular hydrogen and helium. The heavier noble gases primarily reflect a meteoritic (planetary) component trapped in accreted planetesimals. This model provides a possible explanation for the reduced and oxidized accretion stages inferred from siderophile elements and may explain why the present mantle appears to be too oxidized to be in equilibrium with the core.

Planets form from material left behind in residual accretion disks once infall of the collapsing source clouds is complete. Such disks experience a two-stage history involving the separation of minor condensed dust from the major reservoir of hydrogen and helium. The first stage begins with the segregation of small solid objects into a central plane within a thick surrounding nebular gas atmosphere. The accretion process leading to planets begins in this environment and proceeds through a later gas-free stage, with the transition at any radial position occurring when the nebular gas (>98% of the mass of the nebula) has dissipated at that radius either because of blow-off by the intense T-Tauri ultraviolet luminosity and extreme winds generated by the young star or because of truncation of the inward nebular flow of gas by accretion onto proto–Jupiter-like giant planets (*1*). The difference between the rocky, volatile-depleted planets in the inner solar system and the gas giants Jupiter and Saturn is widely understood to be related to the terrestrial planets' proximity to the sun. It is not clear, however, if this difference is the result of (i) dissipation of the nebular gas before the formation of planetary nuclei of sufficient mass for massive protoatmosphere co-accretion or (ii) blow-off of such atmospheres after (or at some later stage during) accretion. The existence of Jupiter is consistent with the latter scenario because accretion is expected to run faster closer to the sun.

Here, we show that co-accretion of a massive prototerrestrial H_2-He protoatmosphere on Earth is consistent with the preservation of noble gas isotopes in the deep interior and therefore that the growth of at least one of the terrestrial planets, Earth, was probably initially similar to the accretion of Jupiter and Saturn. In general, the detailed relation between the (radially dependent) time scales of nebular gas dissipation and planetary accretion throughout the solar system (and even the physical mechanism of dissipation itself) remains unclear from theoretical considerations. The record carried by noble gas isotopes may provide useful constraints on this problem.

Massive Solar-Composition Protoatmosphere

The accretion of a massive solar-composition atmosphere onto a growing planetary nucleus is an unavoidable consequence of accretion in the presence of gas once a protoplanet attains a mass roughly 10% that of Earth's (*2*). Several accretion models suggest that Earth reached this point as rapidly as 100,000 years after the completion of the main phase of solar accretion (*3*). The absence of residual solar-type atmospheres surrounding the terrestrial planets today does not mean that such atmospheres never existed: The intense T-Tauri wind and ultraviolet luminosity of the T-Tauri sun would have totally removed even the heaviest gas (*4*).

To find evidence of the massive protoatmosphere that surrounded the proto-Earth during accretion, it is necessary to look for traces of gases retained in the solid Earth since the time of accretion. A massive blanketing atmosphere would have trapped the energy of accretion, leading to the formation of a magma ocean into which solar composition gases would have dissolved. Once incorporated into the silicate Earth, the abundance pattern and isotopic compositions of such gases would have remained observable, even if most gas was lost at later times, provided only that (i) the noble gases preserved their relative abundances as the mantle degassed and (ii) the residual abundances were not diluted by other contributing sources (other than radiogenic changes).

Mizuno *et al.* (*5*) initially raised the possibility that solar Ne might be preserved in the mantle, recording an episode of solar gas solution into a magma ocean during accretion. However, early studies of Ne in mid-ocean ridge basalts (MORBs) did not find a solarlike signature in the $^{20}Ne/^{22}Ne$ ratio (*6*). It is now known this was the result of swamping of the indigenous mantle component with atmospheric Ne. Subsequent studies have shown that the Ne isotopes measured in a variety of mantle-derived samples trend away from the atmospheric $^{20}Ne/^{22}Ne$ ratio (9.8) toward a solarlike composition (13.8) (*7*), representing the indigenous composition of Ne in the mantle (*8–13*). However, the case for a first-stage magma ocean scenario is much stronger if He is also taken into account.

Solar and Planetary Noble Gases

Indigenous or trapped noble gases in primitive chondrites have a distinctive abundance pattern related to mass in which He is depleted by six orders of magnitude relative to Xe (which is itself depleted by about five orders of magnitude with respect to its solar abundance). This composition comprises several components, some of which have been traced to populations of interstellar grains [graphite, SiC, and microdiamond (*14*)]. Preferential destruction or degassing of these components can lead to variations in the abundance pattern and isotopic composition of the trapped gas. The abundances and isotopic composition of the bulk gas trapped in solid phases in the most primitive carbonaceous chondrites provide a rough upper limit proxy for the bulk reservoir of nebular solids from which the terrestrial planets formed and provide a baseline for determinations of cumulative degassing resulting from the transformation of primitive nebular dust aggregates into fully accreted and differentiated planetary reservoirs. For historical reasons, the bulk component in primitive carbonaceous chondrites is known as "planetary" because its abundance pattern is similar to that of the noble gases in Earth's atmosphere. There are thus two basic solar system noble gas components, "solar" and "planetary," corresponding essentially to the free gas and the gas trapped in solid phases in the nebula, respectively.

Primitive ^3He in the Earth

The inferred ^3He abundance in the deep Earth is in a range similar to that observed in primitive carbonaceous chondrites (*15*). This similarity has been attributed to the presence of a primitive undegassed reservoir

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(*16*) preserved since the early stage of Earth's accretion when the planetary nucleus was not large enough to support impact energies over the threshold for degassing (*17*). It has remained a mystery, however, how such a primitive undifferentiated reservoir could have been preserved against degassing during the energetic later stages of accretion, core formation, and subsequent mantle convection. An alternate explanation for high ^{3}He and solarlike Ne values in the mantle is that the subduction of fine extraterrestrial particles rich in solar wind composition has injected solar He and Ne into the mantle (*18*). This interpretation, however, is controversial (*19*).

Helium-3 in the plume source. The high-^{3}He reservoir in the mantle has been identified by the acronym PHEM (primitive helium mantle). As low ^{4}He/^{3}He ratios are characteristic of large volcanic provinces, such as Hawaii, thought to be associated with deep-mantle plumes, a simple explanation for the high-^{3}He source is that it represents a zone in the deep Earth (likely the lower mantle) comprised of relatively undegassed mantle entrained by rising plume diapirs at some point during ascent (*20*).

The lowest observed hot-spot ^{4}He/^{3}He ratio presumably associated with a deep-mantle plume (~2.2 × 10^4) is from Loihi (*10*, *20*), but it probably does not represent the pure end-member component in the lower mantle because of mixing with upper mantle He. Poreda and Craig (*11*) and Farley *et al.* (*21*) used trends in ^{143}Nd/^{144}Nd, ^{87}Sr/^{86}Sr, and ^{206}Pb/^{204}Pb to trace the mixing and inferred that end-member PHEM has a ratio of ^{4}He/^{3}He ~ (1.7 ± 0.3) × 10^4 (~43 ± 8 times the atmospheric ^{3}He/^{4}He ratio R_a).

A lower limit on the initial (early Earth) abundance of ^{3}He in the plume source is obtained by assuming a closed system with undepleted U and Th abundances. For an unfractionated ^{232}Th/^{238}U ratio of 3.9, the equation for decay over 4.55 billion years is

$$\left(\frac{^{4}\mathrm{He}}{^{3}\mathrm{He}}\right)_{\mathrm{closed}} = \left(\frac{^{4}\mathrm{He}}{^{3}\mathrm{He}}\right)_{\mathrm{initial}} + 18.7\left(\frac{^{238}\mathrm{U}}{^{3}\mathrm{He}}\right)_{\mathrm{present}} \qquad (1)$$

For the initial ^{4}He/^{3}He ratio, we choose an inferred initial solar nebular value of 3.1 × 10^3 (*22*). Our calculation is relatively insensitive to the exact value chosen within the range between the present day value of the solar wind (~2 × 10^3) and the planetary composition (~7 × 10^3) (*23*). For a primitive mantle ^{238}U abundance of 5.4 × 10^{13} atoms/g [21 parts per billion (*24*, *25*)] and the present-day PHEM ^{4}He/^{3}He ratio, we infer a post-accretion ^{3}He source abundance of 7.3 × 10^{10} atoms/g [range of 6 × 10^{10} to 9.3 × 10^{10}, see also (*24*)]. For an open system, the initial ^{3}He abundance must be higher, so this estimate is a lower limit.

Helium-3 in primitive accreted bodies. The ^{3}He abundance in primitive accreted nebular matter that is free of a solar component can be determined from differences in the ^{4}He/^{3}He and ^{20}Ne/^{22}Ne ratios between the indigenous trapped component and the solar surface exposure component in carbonaceous chondrites (*26*) (Fig. 1). Estimation of the baseline abundance of trapped ^{3}He in primitive accreted matter requires measurements free of significant cosmogenic and solar wind contamination from regolith and free-space exposure. Only a few meteorites satisfy this requirement. Many of the carbonaceous chondrites surveyed by Mazor *et al.* (*15*) contain dominant solar wind, cosmogenic ^{3}He, or both; use of these abundances can lead to an overestimate of the amount of trapped ^{3}He in an undegassed primitive reservoir. The abundance of indigenous planetary ^{3}He varies from ~1.5 × 10^{11} atoms/g in C1 chondrites to ~7.5 × 10^{10} atoms/g in C2 meteorites (Fig. 1). The best reference for the pure planetary component is Haripura (Fig. 1). Meteorites with high ^{3}He as a result of solar wind addition (Fig. 1) are the C2 chondrites Nawapali and Mokoia.

Helium-3 in the deep Earth is likely to have been degassed because of (i) volatile depletion in Earth's nebular source reservoir, (ii) early metamorphic degassing in planetesimals, (iii) degassing during planetary accretion, and (iv) degassing as a result of convection. None of these effects can be precisely determined; however, shock experiments (*17*) suggest that only 2% of trapped gases survived accretion. The fraction of primitive gas remaining may be less than 1%. Inferred ^{36}Ar and ^{130}Xe abundances in the plume source (*25*) indicate that the fraction left is ~10^{-2} to 10^{-3} (Fig. 2). This amount of degassing will also have been the case for He. Thus, we infer a probable initial ^{3}He abundance of >10^{13} atoms/g. This value is two orders of magnitude higher than the planetary abundance in primitive C chondrites; therefore, ^{3}He in the plume source cannot be an accreted primitive trapped component. The ^{3}He in the mantle must instead be attributed to some additive mechanism, either solar wind implantation onto nebular precursor materials or magma ocean equilibration with a massive protoatmosphere.

Solar ^{3}He/^{22}Ne and Planetary-Like ^{36}Ar/^{130}Xe in the Mantle

Honda *et al.* (*10*) inferred a solarlike ^{3}He/^{22}Ne ratio of the mantle source of the Hawaiian plume. Jacobsen (*25*) obtained a similar result using a non–steady-state transport model for the MORB and deep plume source reservoirs, input data from measured ^{4}He/^{3}He and ^{20}Ne/^{22}Ne ratios for both reservoirs, and ^{40}Ar/^{36}Ar and ^{136}Xe/^{130}Xe ratios for the MORB source. In the model it is assumed that

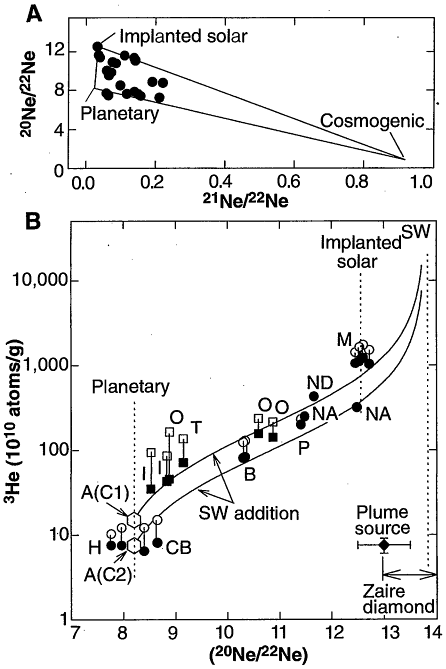

Fig. 1. (**A**) The ^{20}Ne/^{22}Ne ratios for chondrites (solid circles) (*15*) can be corrected for cosmic ray spallation by projection from the cosmogenic component onto the line connecting planetary and implanted solar components in a Ne three-isotope plot. (**B**) The ^{3}He abundance data (*15*) for carbonaceous chondrites—(C1: squares) Ivuna (I), Orgueil (O), and Tonk (T), and (C2: circles) Boriskino (B), Cold Bokkeveld (CB), Haripura (H), Nawapali (NA), Nogoya dark (ND), Pollen (P), and Mokoia (M)—plotted against spallation-corrected ^{20}Ne/^{22}Ne. Mixing is shown (solid curves) between indigenous trapped (planetary) gas and the solar wind (SW) end member [^{3}He/^{22}Ne = 3.5 and ^{20}Ne/^{22}Ne = 13.8 ± 0.1 (*7*)]. The indigenous trapped ^{3}He level for a meteorite type is obtained by projection of the mixing curves to the planetary Ne component [^{20}Ne/^{22}Ne = 8.2, ^{3}He/^{22}Ne = 0.25 (close to that for Haripura) (*15*)]. The ^{20}Ne/^{22}Ne ratio in the implanted solar particle flux component differs from that in SW because of the presence of isotopically fractionated subcomponents (Fig. 3). Total (open symbols) and spallation-corrected (filled symbols) ^{3}He values are connected by vertical lines. The baseline estimate of trapped ^{3}He in primitive nebular matter is based on the planetary component of the C2 chondrites [A(C2)] (*36*). Plume-source ^{20}Ne/^{22}Ne is ~13.0 ± 0.5, with the highest measured value of 13.5 ± 0.5 (range shown by arrow) obtained for a Zaire diamond (*9*). This implies that the mantle has a close-to-solar composition distinct from the implanted particle composition of ^{20}Ne/^{22}Ne < 12.5 (*7*). The plume-source ^{20}Ne/^{22}Ne is plotted together with the ^{3}He concentration estimated for the plume source. This ^{3}He concentration is identical to that for the planetary component of carbonaceous chondrites.

there is a leaky connection between the two mantle reservoirs and that the upper reservoir can degas. Coupling of the U,Th–He, U,Th–Ne, K-Ar, and U-Xe systems yields present-day abundances and residence time histories in both reservoirs. A key input assumption in the model is that all of the noble gases degas congruently. This assumption is justified if the noble gases behave as highly incompatible elements during melt extraction from the mantle to form MORBs. In this case, any interelement fractionation in the trace component remaining in the residue is overprinted by the composition of the material leaking in from the plume reservoir. Results for this model (Fig. 2) imply a distinct two-component structure of mantle gas. The ^{3}He-^{22}Ne system preserves solarlike relative abundances (^{3}He/^{22}Ne = 3.5), the ^{36}Ar/^{130}Xe ratio is close to the planetary value, and the ^{22}Ne/^{36}Ar ratio is intermediate between the solar and planetary value.

The solarlike ^{3}He/^{22}Ne ratio obtained from the transport model is based on input Ne data for the MORB source reservoir and agrees with the estimate of Honda *et al.* (*10*), which is based on closed-system isotopic evolution and He and Ne isotopic data from Hawaii. The plume source pattern cannot be explained by differential solubility of noble gases from an atmosphere with a planetary noble gas pattern. In this case the isotopic composition of Ne should also be planetary (Fig. 3), which it clearly is not.

Discussion

The ^{3}He excess in the deep Earth is thus readily explained as a two-component mixture similar to that observed in the C2 chondrites Mokoia and Nawapali (Fig. 2). These meteorites and the plume-source noble gas patterns can be described as hybrids, with solarlike ^{3}He-^{22}Ne and planetary ^{36}Ar-^{84}Kr-^{130}Xe. The solar components in Mokoia and Nawapali are attributable to solar wind addition (Fig. 1). Sasaki (*27*) suggested that the solar component in Earth may be attributable to capture of an ancient intense solar wind by primordial dust before accretion. We think this is unlikely. Any exposure-derived solar-type component must be different from that in Mokoia (Fig. 3), principally because mantle Ne does not exhibit a spallation enhancement of ^{21}Ne as observed in Mokoia and other macroscopic objects exposed to cosmic radiation. Solarlike He (and Ne) in Mokoia is a result of implantation during surface exposure to the solar and galactic particle flux, leading to unavoidable production of spallogenic ^{21}Ne. Earth's precursor materials cannot have been similarly exposed because the range of ^{21}Ne/^{22}Ne ratios in the plume source (*8–13*) imply that there is only a small ^{21}Ne excess relative to that in the solar wind (Fig. 3). Modeling of the noble gas isotope systems in the mantle (*24, 25*) is consistent with this excess being a nucleogenic effect from the ^{18}O + α = ^{21}Ne + n reaction (α, alpha particle; n, neutron) over the course of Earth's history.

Lunar fines and some breccia components of carbonaceous meteorites (such as Nogoya dark), however, plot close to the implanted solar component (similar to Nawapali) in Fig. 3 and do not exhibit significant excess ^{21}Ne relative to the plume source. These components appear to represent (i) surface material rich in a solar wind component and (ii) regolithic sediments of solar-wind–rich dust. Four arguments disfavor this type of component as an explanation for the solar component in the terrestrial mantle. First, the correlation of a solar wind component with brecciation in C2 meteorites, and its absence in the unbrecciated C2 meteorite Y791198, indicates that the dust coagulation zone of the nebula was well shielded from the solar wind during the formation of centimeter- to meter-scale objects, plausibly by the extended atmosphere of the disk (*28*). Second, some ^{20}Ne/^{22}Ne ratios in the mantle may be higher than in the implanted solar component (Fig. 3). Third, modeling of the He-Ne isotopic evolution implies that the initial ^{21}Ne/^{22}Ne ratio (4.5 billion years ago) in the mantle-plume end member plots on the mass fractionation line in Fig. 3 and is substantially lower than that in the implanted solar component (*24, 25*). Fourth, the ^{3}He/^{22}Ne ratio in chondritic materials rich in a solar wind component is significantly lower than the solar value because of

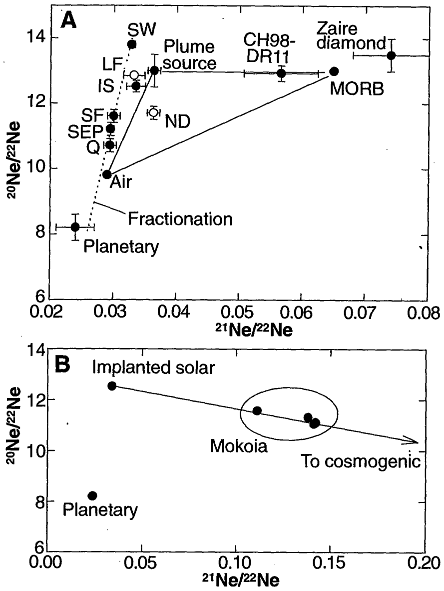

Fig. 3. (**A**) A Ne three-isotope plot showing mixing trends (solid lines) for plume- and MORB-derived gases (*8–13*) in relation to other compositions for air, solar wind (SW) (*7*), solar flares (SF) (*38*), solar energetic particles (SEP) (*7*), "Q" (*35*), planetary and implanted solar (IS) Ne (*15, 26*), the C2 chondrite Nogoya dark (ND) (*39*), and lunar fines (LF) (*40*). Also included are ^{20}Ne/^{22}Ne ratios for MORB sample CH98-DR11 (*12*) and a Zaire diamond (*9*). The dotted line connecting planetary Ne and SW represents mass fractionation (*41*). The plume and MORB-derived mantle materials (*8–13*) trends diverge from the air composition, which is a pervasive contaminant, and imply indigenous contamination-free ^{21}Ne/^{22}Ne ratios of ~0.036 for a plume and ~0.065 for MORBs, respectively, for ^{20}Ne/^{22}Ne = 13.0. The plume source composition was obtained by modeling all other noble gas isotope systems as a result of growth of nucleogenic ^{21}Ne from the reaction ^{18}O + α = ^{21}Ne + n over the course of Earth's history (*24, 28*). (**B**) Samples of the C2 chondrite Mokoia (*15*).

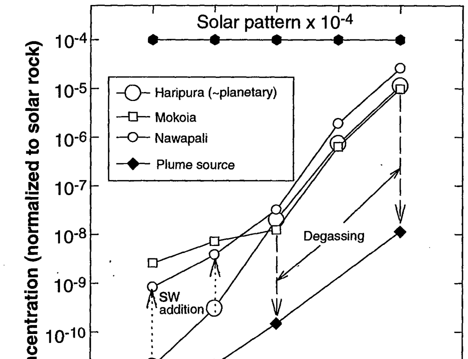

Fig. 2. Solar-normalized noble gas abundance plot showing component mixing in primitive meteorites in comparison with abundances inferred for the plume source in the deep Earth. Haripura represents the planetary component of noble gas distribution in primitive accreted nebular matter. Data are shown normalized to "solar rock" [solar abundances from (*37*) given in atoms per 0.2 g of Si because a typical mantle rock contains about 0.2 g of Si per gram of rock] (*37*). Mokoia and Nawapali represents the hybrid pattern caused by trapping of implanted SW leading to excess ^{3}He and ^{22}Ne (dotted arrows). As shown in Fig. 1, the ^{3}He concentration estimated for the plume source is identical to that for the planetary component of carbonaceous chondrites (that is, primitive accreted matter). Combining the ^{3}He concentration estimated for the plume source with plume-source ^{3}He/^{22}Ne, ^{3}He/^{36}Ar, and ^{3}He/^{130}Xe ratios obtained by modeling of all the radiogenic noble gas systems in the Earth (*25*), we obtain the plume source pattern shown (solid diamonds). The ^{3}He/^{22}Ne ratio indicates the presence of a solar component, whereas ^{36}Ar and ^{130}Xe suggest that a planetary component is dominant for these in the Earth. Comparison of the plume-source pattern (using ^{36}Ar and ^{130}Xe) with that of Haripura (close to the planetary pattern) suggests that the extent of degassing (dashed arrows) of the planetary component in the deep Earth is about two to three orders of magnitude greater relative to primitive matter (with a planetary pattern).

fractionation in the solar wind and preferential diffusive or erosive loss of He from surfaces (as in Nawapali, Fig. 2).

A plausible explanation for the solar component in Earth is the solution of noble gases from a massive solar composition protoatmosphere into an underlying magma ocean. The presence of solarlike $^{20}Ne/^{22}Ne$ ratio in the mantle and the inferred (*8–13*) solarlike (*10*) $^{3}He/^{22}Ne$ ratio provide support for this scenario. The massive protoatmosphere must have been accreted from the nebular gas before its dissipation in the vicinity of 1 astronomical unit (AU) from the sun and would require the rapid accretion of Earth (Fig. 4). The orbit of an inner solar system protoplanet with a rapidly growing massive protoatmosphere would be expected to decay rapidly as a result of viscous coupling to the nebula (*3, 29*). Therefore, the proto-Earth would have grown into a gas-rich planet and spiraled into the sun had not the gas accretion process been terminated.

The levels of the two gas components in the plume source do not constrain the mass of the proto-Earth at the time of the stage transition because the noble gases are not conserved in the system. Certain moderately siderophile element abundances in the mantle may reflect the same two-stage accretion history consistent with the noble gases. These elements appear to have been conserved in the silicate Earth after a stage transition and therefore provide a mass scale for the inferred changeover. In the heterogeneous accretion model, most of Earth's mass (~80 to 90%) is accreted in a reducing stage, followed by an oxidized stage during which the remaining mass is added (*30*). One problem with this notion is that the physical explanation for the change in the chemistry of accreting materials is not clear. The idea of an initial reducing stage is consistent with partitioning in a magma in equilibrium with a dense H_2-He atmosphere. This model provides a possible explanation: the Fe^{2+}-silicate components of the magma ocean could be reduced by dissolved hydrogen, forming a metallic Fe melt that segregates into the core. A two-stage model may also be needed to explain the problem that the oxygen fugacity of the present-day upper mantle scatters roughly about the quartz-fayalite-magnetite buffer and may be out of equilibrium with the metallic fluid that formed most of the core (*31*). If mantle siderophiles record the same stage transition implied by the noble gases, then ~80 to 90% of the accretion of Earth and close to ~100% of the formation of its core would have to have taken place within the epoch when the proto-Earth was co-accreting a massive protoatmosphere. Observations of protostars imply that this time scale is less than ~3 million years (*32*), which tends to favor fast accretion models involving gas-drag and density-wave effects such as those proposed by Ward (*33*).

The planetary gas component in Earth's mantle may have accreted during the second stage (Fig. 4). However, the inferred planetary abundances of ^{36}Ar and ^{130}Xe are possibly too high to have been transported by any accretion mechanism involving high-energy impacts (as would be likely for the last 10% of accretion), and therefore, the planetary component may partially represent a remnant of a "primitive accretion core," as suggested by Ahrens (*17*), rather than strictly a second-stage addition.

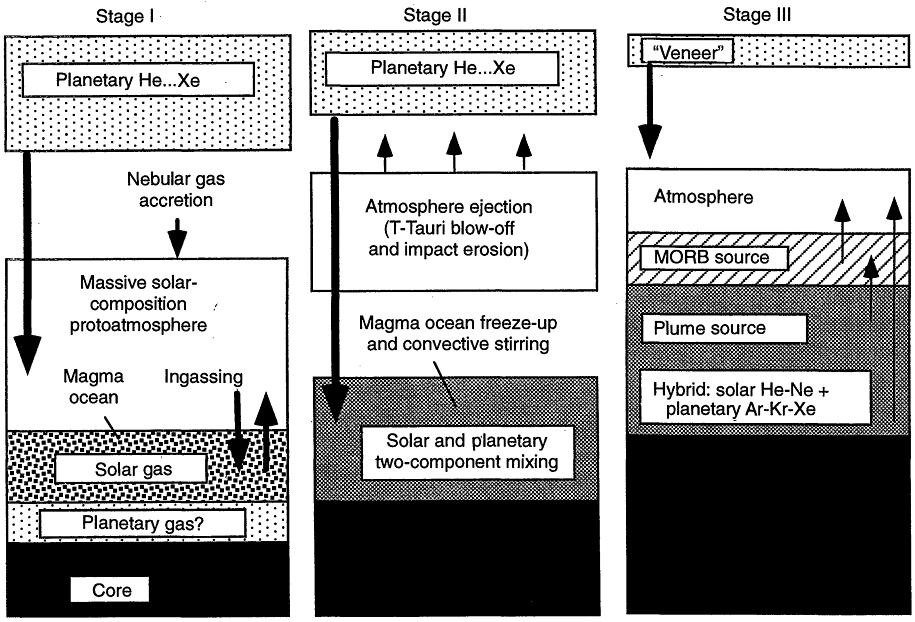

Fig. 4. Schematic three-stage evolution of Earth's core-mantle-atmosphere system during accretion. Stage I is initiated when the proto-Earth grows to sufficient size to accrete a massive solar-composition (H_2-He) protoatmosphere directly from the nebular gas. Under these conditions, the blanketing effect of the massive protoatmosphere supports a global magma ocean into which solar gases dissolve and through which metal rains out to form the proto-core. This scenario is suggested as the origin of the solar component in the deep Earth. Continued accretion of planetesimals (containing planetary noble gases) occurs during all stages, but this gas is totally overwhelmed by the solar gas reservoir exchanging with the magma ocean during stage I. Stage II follows when the massive protoatmosphere is removed by the proto-sun, after which the magma ocean freezes by rapid heat loss in a "naked" (no atmosphere) phase. The hybrid two-component structure of the noble gases in Earth is established as a result of the continued accretion of planetesimals. The final and present stage III is initiated when the solar ultraviolet luminosity falls to a level at which an atmosphere can be retained and grows by mantle degassing and "late veneer" accretion of volatile-rich objects scattered from the outer nebula (C1 meteorites and comets) (*42*).

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20. Poreda and Craig (*11*) and Farley *et al.* (*21*) identified the PHEM as having ^{3}He/^{4}He in the range 35 to 50 R_a, where R_a is the reference composition of atmospheric He (^{3}He/^{4}He = 1.40×10^{-6}). The highest measured ^{3}He/^{4}He ratios are from Loihi, Hawaii: 32 ± 1 R_a (*10*). Other mantle-plume hot spots showing transport of primitive-type He to the surface are Yellowstone [H. Craig, J. E. Lupton, J. A. Welhan, R. Poreda, *Geophys. Res. Lett.* **5**, 897 (1978); B. M. Kennedy, M. A. Lynch, J. H. Reynolds, S. P. Smith, *Geochim. Cosmochim. Acta* **49**, 1251 (1985)], Iceland [B. G. Polak, V. I. Kononov, I. N. Tolstikhin, B. A. Mamyrin, L. V. Khabarin, *Proc. Int. Assoc. Hydrol. Sci.* **119**, 17 (1976); R. Poreda, J.-G. Schilling, H. Craig, *Earth Planet. Sci. Lett.* **78**, 1 (1986)], Samoa (*21*), Afar [B. Marty *et al.*, *Geochem. J.* **27**, 219 (1993)], Reunion [D. Graham, J. Lupton, F. Albarede, M. Condomines, *Nature* **347**, 545 (1990)], Juan Fernandes [K. Farley, A. R. Basu, H. Craig, *Contrib. Mineral. Petrol.* **115**, 75 (1993)], Siberia [A. R. Basu *et al.*, *Science* **269**, 822 (1995)], and Deccan [A. R. Basu, P. R. Renne, D. K. DasGupta, F. Teichmann, R. J. Poreda, *Science* **261**, 902 (1993)]. The surface expression of plume-driven melting, however, is geochemically complex and generally not isotopically primitive for Nd, Sr, and Pb (*34*). This complexity is, however, not unexpected in view of the entrainment of ambient material penetrated during diapiric ascent of plumes. The "primitive" He signal is strong simply because ^{3}He is about two orders of magnitude more abundant in the deep source relative to entrained mantle at higher levels (*24, 25*). There are two types of hot spots, high ^{3}He and low ^{3}He, and it turns out that the high-^{3}He hot spots are larger in volume (that is, big ocean islands), and they may be derived from the mantle-core boundary, whereas low-^{3}He hot spots (R_a lower than 8) are possibly derived from recycled oceanic crust.
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22. This is based on agreement between a D/H estimate for Jupiter corrected for a cometary component (for correction of ^{3}He derived from D burning in the present solar wind) and a rough correction of the so-called meteoritic "Q" composition (*35*) for isotopic fractionation.
23. A precise constraint on the solar wind composition (after D burning) has been obtained from analyses of lunar minerals rich in a solar wind composition, which imply (^{4}He/^{3}He)$_{SW}$ = (2.23 ± 0.07) × 10^{3} (*7*). Precise determinations of ^{4}He/^{3}He in the planetary He in carbonaceous chondrites imply a value of (7 ± 1) × 10^{3} [E. Anders, D. Heymann, E. Mazor, *Geochim. Cosmochim. Acta* **34**, 127 (1970); P. M. Jeffrey and E. Anders, *ibid.*, p. 1175; J. H. Reynolds, U. Frick, J. M. Neil, D. L. Phinney, *ibid.* **42**, 1775 (1978)].
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26. "Neon B" represents Ne implanted into carbonaceous chondrite surfaces exposed to the solar wind: ^{20}Ne/^{22}Ne = 12.52 ± 0.18 and ^{21}Ne/^{22}Ne = 0.0335 ± 0.0015 [D. C. Black, *Geochim. Cosmochim. Acta* **36**, 347 (1972); *ibid.*, p. 377].
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28. K. Metzler, A. Bischoff, D. Stöffler, *Geochim. Cosmochim. Acta* **56**, 2873 (1992). Recently reported in situ laser spot analyses of Ne isotopes in Murchison have been interpreted as evidence for the exposure of small objects to the protosolar wind during an early stage of accretion [D. S. Woolum, K. Kehm, C. M. Hohenberg, K. Poelstra, E. Guntalilib, *Lunar Planet. Sci.* **XXVI**, 1519 (1995)] but are also consistent with heterogeneous distribution of "Q" Ne (T. Nakamura, K. Nagao, N. Takaoka, *ibid.*, p. 1027). The presence of gas in the nebula would act as a very efficient shield for dust from solar wind irradiation [K. R. Housen and L. L. Wilkening, *Proc. Lunar Planet. Sci. Conf.* **11**, 1251 (1980)].
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30. E. Jagoutz *et al.*, *Proc. Lunar Planet. Sci. Conf.* **10**, 2031 (1979); H. Wänke, G. Dreibus, E. Jagoutz, in *Archean Geochemistry*, A. Kröner *et al.*, Eds. (Springer-Verlag, Berlin, 1984), pp. 1–24; H. E. Newsom, in *Origin of the Earth*, H. E. Newsom and J. H. Jones, Eds. (Oxford Univ. Press, New York, 1990), pp. 273–288; H. Palme and H. St. C. O'Neill, *Geochim. Cosmochim. Acta* **60**, 1106 (1996). The main observation supporting the scenario is the similar depletion factor of about 11 for several moderately siderophile elements (Fe, Ni, Co, and W) that have a wide range of siderophility.
31. The problem of the apparent disequilibrium of the mantle with respect to the core remains unresolved after three decades since it was raised by A. E. Ringwood [*Geochim. Cosmochim. Acta* 30, 41 (1966)], who concluded that "the mean oxidation state of the mantle is not now, nor has it ever been, in equilibrium with the metallic iron." Studies of the oxygen fugacity of the mantle [H. St. C. O'Neill and V. J. Wall, *J. Petrol.* **28**, 1169 (1987); B. J. Wood and D. Virgo, *Geochim. Cosmochim. Acta* **53**, 1277 (1989)] have confirmed Ringwood's observations and indicate that the present mantle is about 4 log-bar units more oxidizing than the iron-wüstite buffer. It remains unclear, however, whether this might be explained by core partitioning at high temperature or high pressure [C. Ballhaus, *Earth Planet. Sci. Lett.* **132**, 75 (1995)].
32. A time scale for gas dissipation in the neighborhood of 1 million years is consistent with observational constraints on the dissipation of gas in residual disks [M. F. Skrutskie *et al.*, *Astron. J.* **102**, 1749 (1991); B. Zuckerman, T. Forville, J. H. Kastner, *Nature* **373**, 494 (1995)]. The oldest observed massive (~0.1 solar mass) gas disk surrounding a near–solar mass T-Tauri star (GM Aurigae, ~2 million years old) implies that gas disks may survive up to a few million years [D. W. Koerner, A. I. Sargant, S. V. W. Beckwith, *Icarus* **106**, 2 (1993)].
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34. S. R. Hart, E. H. Hauri, L. A. Oschmann, J. A. Whitehead, *Science* **256**, 517 (1992).
35. R. Wieler, in *Noble Gas Geochemistry*, J. Matsuda, Ed. (Terra, Tokyo, 1994), pp. 31–41.
36. C1 chondrites have about two times more trapped ^{3}He [A(C1) in Fig. 1] than do C2 chondrites [A(C2)]. C1 chondrites appear to have formed in the cool outer asteroid belt. Presumably C2 material formed in a reservoir that experienced warmer conditions closer to the sun. The provenance of Earth's parental solid reservoir in the inner nebula likely had lower ^{3}He than the planetary component of C2 chondrites, which therefore provides an upper limit on Earth's preaccretionary trapped ^{3}He budget. Similar or higher inferred initial levels of ^{3}He in the plume source in the deep Earth indicates that ^{3}He is far too abundant (by ~10^{3}) to be primordial trapped gas. We interpret the agreement between ^{3}He in the plume source and primitive matter to be fortuitous and infer ingassing of ^{3}He by two to three orders of magnitude by addition of a solar component.
37. N. Grevesse and A. Noels, in *Origin and Evolution of the Elements*, N. Prantzos, E. Vangioni-Flam, M. Casse, Eds. (Cambridge Univ. Press, Cambridge, 1993), pp. 15–25. Solar abundances for noble gas index isotopes normalized to "solar rock" are (in atoms per 0.2 g of Si) ^{3}He = 3.86×10^{21}, ^{22}Ne = 9.65×10^{20}, ^{36}Ar = 4.0×10^{20}, ^{84}Kr = 1.10×10^{17}, and ^{130}Xe = 8.80×10^{14}. The ^{3}He abundance is estimated for the solar source composition (before D burning), based on an estimated isotopic composition of ^{4}He/^{3}He = 3.1×10^{3}. Our choice for the "planetary" noble gas abundances in primitive nebular matter are from the C2 chondrite Haripura (*15*) (in atoms per gram): ^{3}He = 7.5×10^{10}, ^{22}Ne = 2.96×10^{11}, ^{36}Ar = 8.1×10^{12}, ^{84}Kr = 8.1×10^{10}, and ^{130}Xe = 1.0×10^{10}. The ^{3}He datum includes a small correction for spallogenic He.
38. M. N. Rao, D. H. Garrison, D. D. Bogard, G. Badhwar, A. V. Murali, *J. Geophys. Res.* **96**, 19321 (1991).
39. D. Heymann and E. Mazor, *ibid.* **72**, 2704 (1967).
40. C. M. Hohenberg, P. K. Davis, W. A. Kaiser, R. S. Lewis, J. H. Reynolds, *Proc. Apollo 11 Lunar Sci. Conf.* **2**, 1283 (1970).
41. Samples plotting to the right of the dotted mass-fractionation line connecting planetary Ne and SW in Fig. 3 are enriched in ^{21}Ne as a result of either cosmic ray spallation or the reaction $^{18}\mathrm{O} + \alpha = {}^{21}\mathrm{Ne} + n$. Samples plotting close to the implanted solar composition [such as lunar fines, Nogoya dark, and the Nawapali sample, indistinguishable from the implanted solar composition (*15*)] shown in Fig. 2 represent the composition of implanted solar corpuscular radiation (mixture of SW, SF, and SEP), with an additional small component of cosmogenic ^{21}Ne from spallation due to the high-energy solar and galactic particle flux during the exposure. All of these compositions have ^{20}Ne/^{22}Ne ratios significantly lower than that of the bulk SW composition [13.8 ± 0.1 (*7*)] because of the presence of the isotopically fractionated high-energy subcomponents (SEP and SF), which are apparently enhanced by preferential erosive sputtering of the dominant low-energy surface-sited component (*7*). The mantle ^{20}Ne/^{22}Ne ratio appears to be distinct from implanted-type compositions and closer to the bulk solar composition, as suggested by the highest measured ^{20}Ne/^{22}Ne ratios for MORB sample CH98-DR11 (*12*) and a Zaire diamond (*9*).
42. As shown in Fig. 3, the isotopic composition of air Ne looks like a simple mixture between solarlike degassed Ne from the mantle and planetary-like Ne from a late volatile-rich veneer (atmospheric Kr and Xe are also isotopically mass fractionated compared to their solar and meteoritic isotope compositions, possibly as a result of fractionation in a cometary ice component of the late veneer).

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