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and Neon Isotopes in the Earth**

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**The Early Sun: Precursor to Helium
and Neon Isotopes in the Earth**

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Abstract

The sources and emissions of mantle gases from the Earth containing high $^3\text{He}/^4\text{He}$ ratios, as compared to the atmospheric value, while the $^{20}\text{Ne}/^{22}\text{Ne}$ ratios are often similar to their atmospheric ratios, has attracted much attention. This paper proposes that gases bearing these isotopic ratios were formed during the early stages of the development of the Sun from the solar nebula. Particularly, ^{22}Ne was abundant in the solar nebula and was carried to the accreting planets by SiC and graphite particles. Helium-3 was formed by a nuclear fusion reaction during the Sun's pre-main-sequence phase. Subsequent neutron absorption converted ^3He to ^3H (tritium) which would have been soluble in the Fe cores of the accreting planets and iron meteorites. A proposed model suggests that the Earth's core still contains $> 99\%$ of this primordial ^3He .

Introduction

The study of helium, neon and other noble gases venting from the Earth has been an intriguing scientific investigation and given new insight into the convective processes within the Earth. In particular the measurements of the isotopic ratios for He with two stable isotopes, ^3He and ^4He , and Ne with three stable isotopes, ^{20}Ne , ^{21}Ne and ^{22}Ne , have been fruitful when compared with the atmospheric isotopic ratios of these gases. Such studies recognize that ^4He is constantly being released from U and Th-bearing ores and a small amount of ^3He is produced from neutron absorption from Li-bearing ores producing a $^3\text{He}/^4\text{He}$ ratio of $\sim 10^{-8}$. The neutron production results from α -particle bombardment of mineral oxides. The He isotopic ratios of many terrestrial gases are shown in Fig. 1. Only a limited set of nuclear reactions are known to produce Ne isotopes within the Earth, such as the small amount of ^{21}Ne produced by spallation of surface rocks from energetic cosmic rays (Niedermann et al., 1993). Consequently, neon gases venting from the Earth must be isotopic mixtures of various cosmic neon sources, some of which are shown in Fig. 2.

Gases collected from terrestrial vents record varying He and Ne isotopic ratios. Two potential mechanisms have been advocated for the placement of these gases within the Earth, namely: (1) primordial gases with varying isotopic ratios were occluded within the accreting bodies which formed the Earth and were subsequently entombed (Allègre, et al., 1993), or (2) the gases were transported to the Earth after its formation, such as by interplanetary dust particles (IDPs) (Anderson, 1993).

The IDPs are characterized by the retention of solar-wind elements with high $^3\text{He}/^4\text{He}$ ratios of $\sim 4 \times 10^{-4}$ and high $^{20}\text{Ne}/^{22}\text{Ne}$ ratios of 12-13. IDPs with such isotopic compositions have been detected in cores from deep oceanic sediments. Anderson postulates that these sediments are subducted into the mantle and release these gases very slowly. These gases are carried, subsequently, by upwelling magma to vent at the

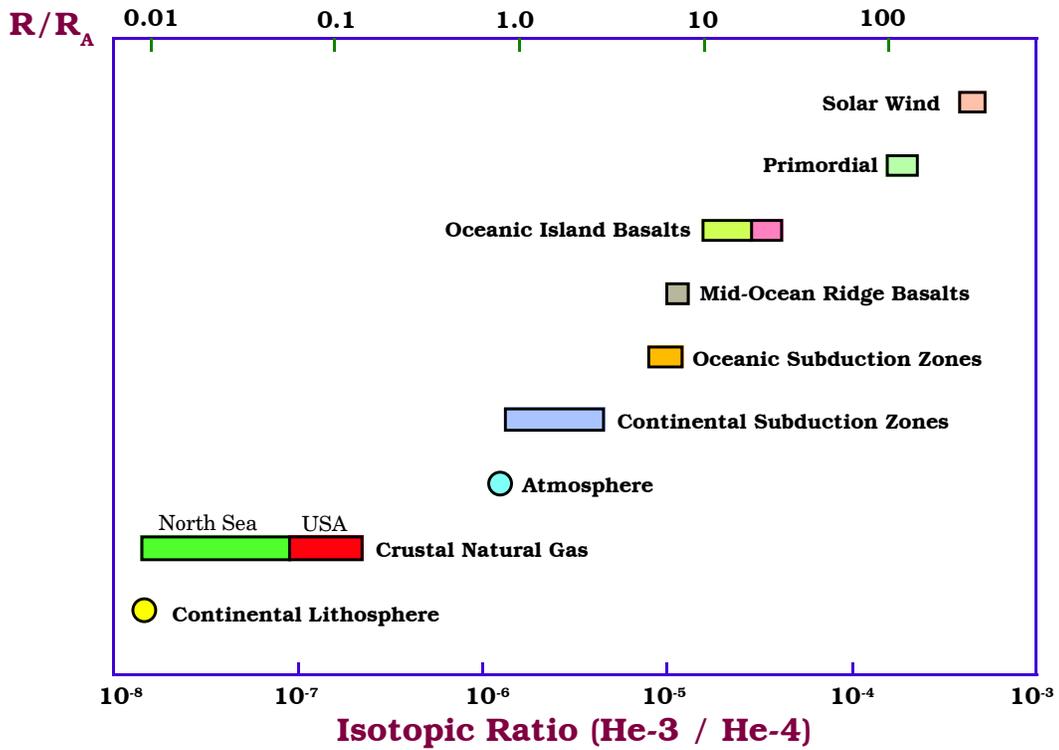


Figure 1. Helium isotopic ratios for major natural resources; R/R_A = isotopic ratio of a sample compared to the Earth's atmospheric ratio.

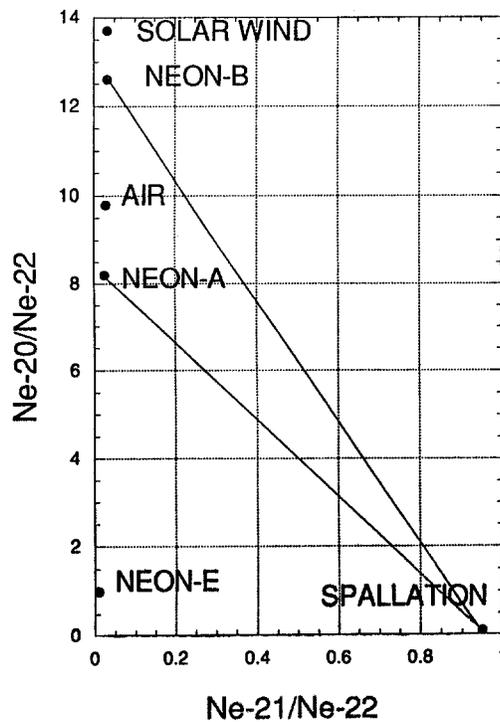


Figure 2. Neon isotopic ratios for several natural resources.

intraplate volcanoes. Recently, Hiyago (1994) has measured the rate of diffusion of He and Ne in IDPs and found, however, that these gases would be evolved from the subducting slabs at very shallow depths before the gases could enter the mantle.

Gases evolved from intraplate volcanoes, such as Loihi in the Hawaiian Island chain, display high $^3\text{He}/^4\text{He}$ ratios up to $30\times$ the atmosphere ratio while the $^{20}\text{Ne}/^{22}\text{Ne}$ ratios at 9.8 are nearly coincident with the atmospheric ratio (Allègre et al., 1993). Detailed studies (Valbracht, et al., 1994) have shown that these noble gaseous isotopic ratios are indicative of stage 1 buildup of oceanic island systems. The mid-ocean ridge basalts (MORB) display moderate $^3\text{He}/^4\text{He}$ ratios (8×10^{-6}) and high $^{20}\text{Ne}/^{22}\text{Ne}$ ratios (~ 13). In order for the IDPs to supply the intraplate volcanoes a large isotopic loss of ^{20}Ne must occur while the ^3He is retained in the magma. Such a scenario is difficult to construct. Consequently, many investigators have postulated a layered-mantle in which the upper mantle supplies magma to the mid-ocean ridges while a lower mantle supplies magma plumes to the active intraplate volcanoes and in past epochs to the large igneous provinces which have risen to the Earth's surface. The source of these plumes is postulated to be the core-mantle boundary, CMB, between the molten outer core and the lower mantle. This boundary is characterized by a layered mixture, often called the D''-layer, probably a dispersed mixture of molten metal and magma. It is speculated that the noble gases could be trapped within this layer during geologically significant time-scales, or some of the gases could be stored within the core (Davies, 1990). Because metallic core formation occurred very early in the history of the Earth (Fearn, 1989) and differentiation of incompatible minerals from the magma occurred during the Archean Epoch, the noble gases must have been transported and buried deep within the Earth by the Earth-forming planetesimals; consequently, these gases would be of primordial origin.

In order to advance the hypothesis of a primordial origin for these gases buried within the Earth, it is necessary to consider the following questions, namely: (1) How

was the Earth formed; (2) what was the isotopic composition of the primordial gases; (3) how were the gases transported to the primitive Earth; and (4) how are the gases stored in the core or the lower mantle?

This study reviews some of the contemporary concepts regarding the formation of our solar and planetary system and advances several scenarios for the transport and storage of the noble gas, He and Ne, within the Earth.

Formation of the Pre-Solar Nebula

Astronomical observations indicate that star formation is an evolutionary process in which new stars are constantly being formed and old stars, such as red giants, are continually being destroyed (Fowler 1984). Following the destruction of a star, usually by a supernova explosion, the debris is well-mixed into the surrounding molecular cloud and becomes incorporated into a newly forming star. During the life of a star, hydrogen fuel is converted by nucleosynthesis reactions to form both ^3He and ^4He and ^4He atoms combine to form chemical elements with ever-increasing atomic number and weight. The heavier atomic number elements, beyond ^{56}Fe , cannot be formed by ^4He addition only, but require additional neutrons. These neutrons are supplied by neutron stars within which the high density, 10^{10} g/cm^3 , forces the proton nucleus to combine with an electron. These neutrons are captured by the existing elements and form the long-lived, heavy isotopes such as ^{235}U , ^{238}U and the short lived ^{244}Pu (118 Myr half-life) (Cameron 1993). Such a supernova explosion apparently occurred in the pre-solar nebula approximately 125 Myr before the formation of our Sun.

During a supernova explosion, very high energy protons are formed also which are postulated to form ^{22}Na from the spallation of Al nuclei. The β decay of ^{22}Na (2.6 yr half-life) forms ^{22}Ne . Evidence for this reaction has been obtained from the gases evolved at rather low temperatures from graphite spherules in meteorites. This ^{22}Ne contains only

small traces of the other Ne isotopes; i.e., $^{20}\text{Ne}/^{22}\text{Ne} = 10^{-2}$ and $^{21}\text{Ne}/^{22}\text{Ne} = 10^{-4}$ (Anders and Zinner 1993).

Several additional supernovae may have formed and disintegrated before the present solar system (BSS) formed. Finally, at ~ 2 Myr BSS an AGB star (asymptotic giant branch) of 1–3 solar masses reached the end of its lifetime and exploded. An AGB star has completed its H-burning stage and most of its He-burning phase. During this latter period, the nucleosynthesis reaction $^{18}\text{O}(^4\text{He})^{22}\text{Ne}$ occurred; thus, another source of isotopically pure ^{22}Ne was created. Evidence of this synthesis has been found during the degassing at high temperatures of SiC spherules obtained from meteorites, yielding Ne-E(H). Also produced during this event was the isotope ^{26}Al , half-life 1.07 Myr.

The explosion of an AGB is known to trigger the formation of new stars and is believed to have created the birth of our present solar system, as described in the following section.

Formation of the Solar System

Molecular clouds of a pre-solar nebula, containing all the remnants of previous stars in the vicinity, began to assemble into clusters, possibly due to the influence of electromagnetic fields because gravity alone could not hold such clouds together. The collapse of these clouds and the formation of stars and disks apparently follow an evolution path which requires ~ 10 Myr. Observations of newly forming stars, such as the T-Tauri group, together with computer modeling has given new insight into these processes. Eventually, the star attains a main-sequence burning phase, as shown in Fig. 3 in which the log of the relative luminosity is a monotonic function of the inverse log of the stellar surface temperature. A newly formed star transits a pre-main sequence phase, as shown for a mass 3 star in Fig. 3, in which the luminosity of the star decreases, but the surface temperature remains constant. Eventually the luminosity remains constant while the surface temperature increases as it approaches the main sequence line.

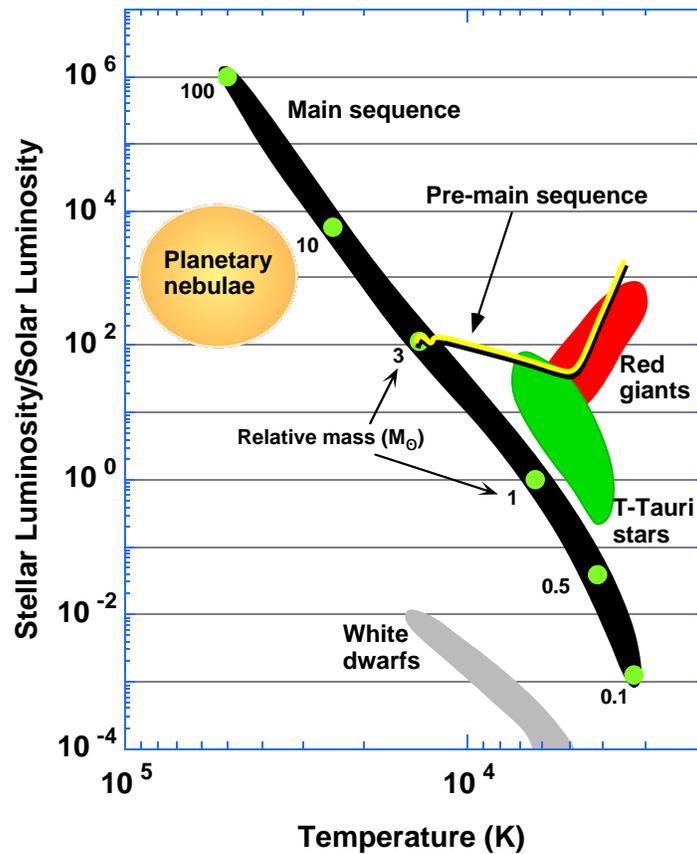


Figure 3. The Hertzsprung-Russell diagram (Wasson, 1985) showing the evolution from birth to death of a star. All stars originate along a pre-main sequence line, shown schematically for the mass 3 star, requiring 1-10 Myr to reach the main sequence line.

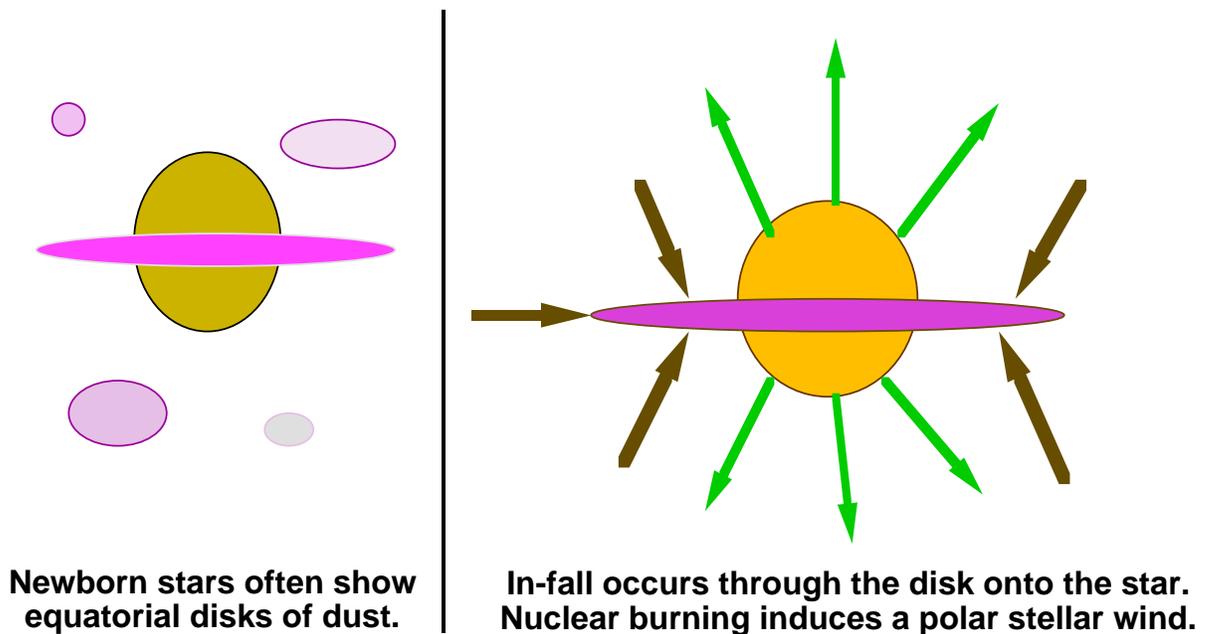


Figure 4. Stages in the development of a pre-main sequence star: (a) A nebula cloud collapses to a central sphere and is usually surrounded by a disk of gas and dust; (b) In-fall of gas and dust proceeds initially onto the disk, then on to the embryonic Sun. A stellar wind originates from the polar axes and gradually spreads toward the disk.

Shu, et al. (1993) proposed that a pre-main sequence star transits four stages of evolution. In the initial phase, (a) the molecular cloud collapses to form one or more cores. In phase 2, (b) the protostar with a surrounding nebular disk forms at the center of the cloud as the dust and gases begin to collapse from the inside upon the core, as shown in the left panel of Fig. 4. In phase 3, (c) a stellar wind originates along the polar axes as in-fall continues through the disk to the equator of the star. During this phase nearly 2–3 times the mass of the final star follows these paths and is lost to space, as shown on the right side of Fig. 4. In phase 4, (d) it is believed that the stellar wind gradually spreads from the polar region to lower latitudes and eventually reaches the equator where it overwhelms the in-falling material and the process terminates revealing a newly formed star with a circumsolar disk. Disks of dust surrounding newly formed stars have been observed with the Hubble Space Telescope.

As the processes described above are proceeding, nuclear fusion reactions are initiated within the protostar. In Fig. 5 the probabilities of nuclear fusion reactions among the light atoms are plotted as a function of their kinetic temperature. The primary reaction in a main sequence star, $p(p, e^+v)^2\text{H}$, has very low probability and can only occur in the core of stars which have enormous gravity to confine the protons long enough to accomplish significant H-burning; however, in a newly formed star nebula this density has not been obtained. As a result, the nuclear reaction which does occur is deuterium-burning, i.e., $^2\text{H}(p, \alpha)^3\text{He}$, using the protium in which the deuterium/hydrogen ratio is $\sim 2.5 \times 10^{-5}$.

Deuterium burning in protostars has been visualized to proceed in 4 stages (Stahler and Walters, 1993). In the first stage (a) at low mass density, accreted deuterium is fed to the burning center by convective eddies, as shown in the left panel of Fig. 6. Eventually, (b) a radiative barrier appears eliminating the D supply to the center. In stage 3, (c) the depleted interior continues to burn until all the D is exhausted. As in-fall continues, (d)

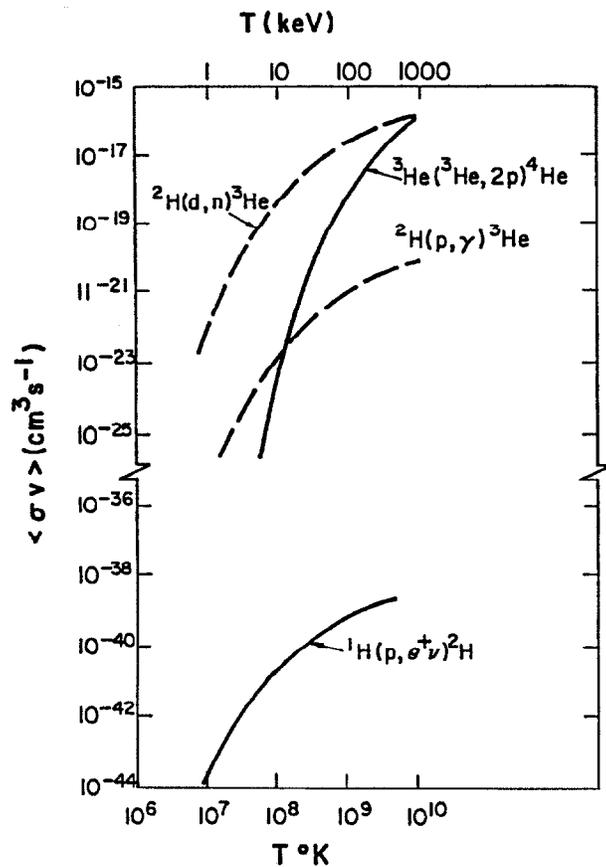


Figure 5. Probability of the nuclear fusion of hydrogen isotopes in the early Sun as a function of the ion temperature.

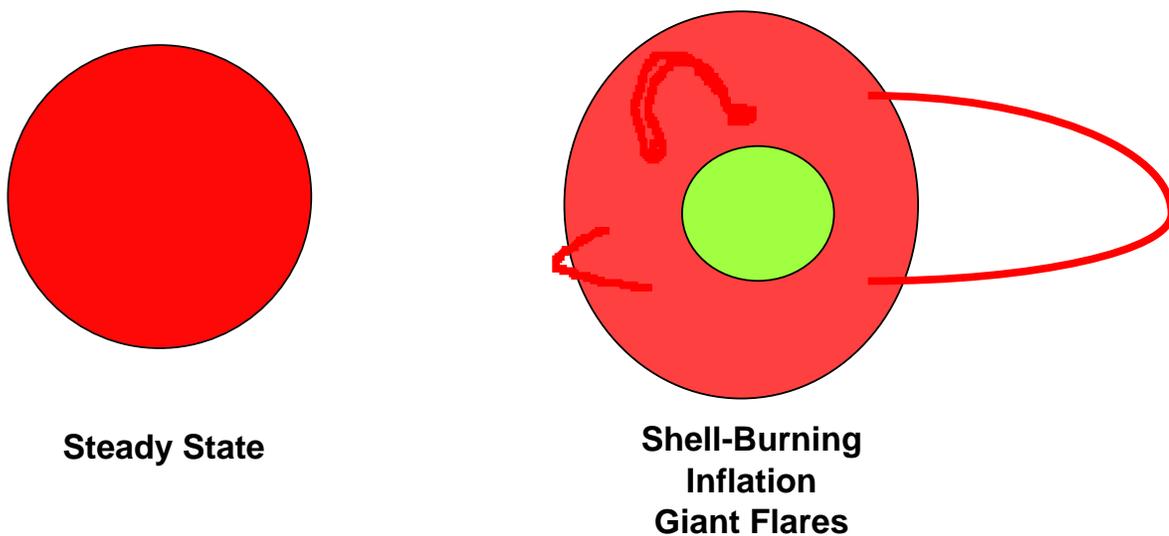


Figure 6. Deuterium-burning phase in the pre-main sequence star: (a) initially deuterium burns homogeneously throughout the star; (b) as D is consumed in the central portion newly accreting D ignites as an outer shell.

the density increases and deuterium ignites as a shell surrounding the core, in stage 4, as shown on the right panel of Fig. 6. At this stage the protostar swells in volume and becomes very active, forming flares which may extend to nearly the radial distance from the Sun to the Earth.

Newly formed stars become luminous when deuterium-burning is initiated. When such observations are plotted on the pre-main sequence-luminosity diagram, a birthline for the formation of stars is obtained (Stahler and Walter, 1993).

Based upon this contemporary scenario for the formation of our solar system, a model for the development of the Earth can be postulated.

Accretion of the Planets and Other Bodies in the Solar System

At the present development of astronomical observations for newly formed stars which exhibit disks, the development of planetesimals can not be observed because the dust in the disk is too opaque. Consequently, the formation of planetesimals must be inferred from observations of the planets and asteroids in the solar system and from particle-gas dynamics calculations of a protoplanetary nebula. Using such computational techniques, Cuzzi, et al. (1993) modeled a disk configuration of particles at 1 AU circulating at orbital velocities – tens of km/s in a cold nebula gas, 280 K, as a function of particle size and the density of particles in the gas. Their results indicated that because of the particle drag, the gas attained nearly the same velocity and became convective. As a result of this turbulence, small particles, < 1 cm, were unable to accrete as a result of gravitational instability. For large planetesimals to form on a reasonable time scale, the “seed” particles had to be 10 m in size. Clearly, the initial accretion into planetesimals from the nebula dust requires an additional energy mechanism, perhaps electromagnetic waves or flares from the newly formed Sun. Additionally, their results indicated that outward transport of solid chips and volatiles is possible and can be coupled with inwardly

directed transport of larger particles, leading to significant radial compositional mixing and localized mass enhancement.

Entrapment of He and Ne Isotopes in the Proto-Earth

Based upon the previously discussed information, a scenario for the occlusion of He and Ne within the Earth is proposed.

1. Reservoirs of nearly isotopically pure ^{22}Ne were a constituent of the pre-solar nebula. Similarly, isotopically pure ^3He was formed during the initial deuterium-burning of the pre-main sequence phase of the Sun.
2. The early Sun was surrounded by a disk of dust particles which subsequently formed the planets and asteroids. Initiation of nucleosynthesis in the early Sun created a solar wind which bathed the dust particles in an atmosphere composed of high ^3He and ^{22}Ne isotopic ratios as compared to the primordial concentration of these isotopes.
3. During the active stage of the early Sun giant flares heated the dust and in the high H concentration of the solar wind, many of the chondritic particles were chemically reduced to the Fe-Ni alloys which later formed the iron cores of the terrestrial planets and the iron meteorites. This heating and chemical reduction is evidenced by the formation of iron cores in all the terrestrial planets and extended out to the inner periphery of the asteroid belt where iron asteroids have been detected. Temperatures must have reached 1400°C , occasionally, in order to form the homogeneous Fe-Ni alloys identified in the metallic meteorites.
4. The heated iron and chondritic particles had the opportunity to adsorb these solar wind gases. Experimental evidence has shown that He and Ne dissolve in molten materials of synthetic chondritic compositions (Matsuda et al., 1993).

Conversely, the solubility of He in the molten Fe or Ni is extremely small as shown by experimental data and confirmed by theoretical molecular interpotential models (Wolfer et al., 1989). Hence, little He and Ne would be expected in the Earth's core.

5. Although He has limited solubility in Fe, hydrogen has significant solubility in Fe (Smithells, 1992), Fig. 7, and the solubility increases with temperature even in the liquid phase. The significance of this information is that the isotope ^3H (tritium) had a high probability of formation in the early solar nebula based upon the following scenario. As previously noted, ^3He was the product of deuterium-burning. At the same time, the heavy fissionable isotopes were in abundance, such as ^{235}U , ^{244}Pu etc. Many of these heavy isotopes were self-fissionable creating neutrons which would fission additional isotopes, creating neutron multiplication. In addition, neutrons could be produced by energetic proton bombardment of nebula particles. Kim and Marti (1992) suggested that during accretion, the solar nebulae material were exposed to a neutron fluence of $> 10^{16}$ n/cm². In such an environment, ^3He which has a high neutron absorption cross-section had a high probability to form tritium via the nuclear reaction $^3\text{He}(n, p)^3\text{H}$. Hence, tritium (a hydrogen isotope) would dissolve also in the Fe phase.

Once tritium dissolved in the Fe alloy, it would quickly decay (half-life, 12.3 yr) to ^3He which would be insoluble in the alloy. The irradiation of steels by energetic neutrons often forms He which precipitates as small bubbles along vacancy imperfections. Similar He bubble formation occurs from tritium dissolved in steel. Such reactions have been extensively studied in nuclear reactor technology (Schroeder et al., 1985).

Because no known predecessor of ^{22}Ne would dissolve in the core, it is suggested that the Ne enriched in ^{22}Ne dissolved solely in the molten chondritic phases.

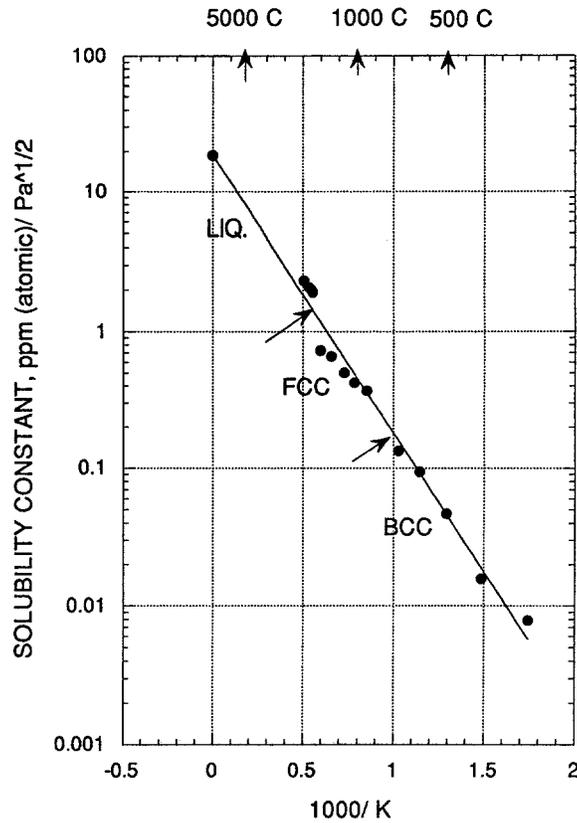


Figure 7. Solubility constant for the dissolution of H in Fe as a function of reciprocal temperature.

6. It is proposed, therefore, that at 1 AU small iron particles absorbed tritium while chondritic bodies in their vicinity absorbed the ²²Ne enriched Ne when these particles were heated for short periods.

Agglomerates of meter-size bodies of these heterogenous mixtures were formed during the period when the release of collisional and gravitation energies were small and any heating by ²⁶Al decay was too small to cause extensive melting of the agglomerates; perhaps short pulses of electromagnetic heating were sufficient to cause the formation of planetesimals with metallic cores surrounded by silicate shells. These planetesimals gradually accreted to form the metallic cores of the terrestrial planets with their silicate shells, as proposed by Taylor (1991).

Following the formation of the planetary metallic cores, the orbits of planetesimal-size chondritic bodies in the asteroid belt, were perhaps perturbed and subsequently accreted as a veneer over the terrestrial planets, as proposed by Dreibus and Wänke (1984). Consequently, the siderophile elements in the veneer were never in contact with the iron alloys in the core.

The accretional and gravitational energies of the final planetesimal bombardment of the Earth were sufficient to heat the original silicate shell and release most of the noble gases to the atmosphere with Ne having an excess of the ^{22}Ne isotope as compared with the solar value. In the core of the Earth, the ^3He bubbles would migrate very slowly from the molten outer core. Eventually arriving at the core-mantle boundary, these bubbles could become entrapped in the D'' layer (an emulsion of molten silicate and metallic phases). Perhaps the episodes of large igneous plumes were initiated by the release of ^3He gas from this layer.

Qualitative Assessment of He and Ne Entombed Within the Primitive Earth

A primitive Earth composed of a metallic core surrounded by a shell of chondritic silicate minerals has been proposed. The core contained nearly isotopically pure ^3He and dissolved H-isotopes. The shell contained dissolved noble gases enriched in ^3He and ^{22}Ne . Most of the noble gases in the molten shell were probably released to the atmosphere during subsequent accretion of the Earth. Some of these gases containing enriched ^3He and ^{22}Ne were sequestered, however, within the Earth and continue to be released. Qualitative assessments were made in order to set boundaries on this scenario.

Helium-3 Assessment

The unique implacement of ^3He within the core was suggested as a means of prolonging its escape and was based upon the solubility of tritium, ^3H , in the Fe-Ni alloy of the core. Although the solubility of H_2 in Fe-Ni alloys has not been extensively measured, the solubility of H_2 in Fe has been measured in two solid and the liquid phases. A graph, Fig. 7, of the log (solubility constant) as a function of the reciprocal temperature indicates that the solubility is only slightly affected by the particular phase, but increases monotonically with temperature. The equation of the solubility constant, S , is

$$\log S = -2.013(10^3/T) + 1.273 \quad (1)$$

$$\text{where } S = \text{atomic ppm H/Fe}(P)^{-1/2}, (P = \text{Pa}, T = \text{K}). \quad (2)$$

The pressure in the pre-planetary nebula has been estimated to be $\sim 10^{-4}$ atm, mostly H_2 during chondrule formation and $10^{-6} - 10^{-3}$ atm during asteroid formation (Kerridge and Anders, 1988). A pressure of 10 Pa (10^{-4} atm) was assumed for this study. These same authors estimated also that the nebula temperature was 1800–2000 K during formation of calcium-aluminum-inclusions. Based upon these values of T and P and Equation 1, the H/Fe ratio was calculated to be 1.9×10^{-5} during the time of the Earth's core formation. The D/H ratio in the Fe would be nearly the cosmological background value, estimated to be 2.5×10^{-5} . The fraction of the deuterium which would undergo nuclear fusion while transiting the early Sun and yield the $^3\text{He}/\text{D}$ ratio carried by the solar wind might have been similar to the ^4He in the present solar wind, i.e. $\sim 5\%$. This ^3He is assumed to absorb neutrons and form tritium which would decay back to ^3He in the core. The Earth's inner-core contains 1.73×10^{21} k moles Fe and the outer core an additional 3.6×10^{22} k moles of Fe; therefore, the potential ^3He trapped in the Earth's inner core could have been $\sim 4 \times 10^{10}$ k moles [1.2×10^{11} kg (^3He)] and 8.6×10^{11} k mole ^3He (2.6×10^{12} kg ^3He) in the outer core.

This calculated ^3He residing initially in the core and mantle would have continuously escaped, eventually to the atmosphere; however, because He escapes to outer space by diffusion, a total inventory of ^3He is not possible. It is often suggested that this primordial gas may be venting at intraplate volcanoes and during the eruption of large plumes which form near the CMB. Intraplate volcanoes release $\sim 1 \text{ kg } (^3\text{He})/\text{yr}$, or $4.5 \times 10^9 \text{ kg } (^3\text{He})$ if released at the present rate since the formation of the Earth. Additionally, large plumes, such as the Ontong-Java Plateau have been suggested to have released $\sim 3.6 \times 10^6 \text{ km}^3$ of magma (Coffin and Eldholm, 1993). If this magma released ^3He at the same composition as MORB, $\sim 4 \text{ kg } (^3\text{He})/20 \text{ km}^3$ (of magma), then the ^3He release for 10 such events could have been $\sim 7 \times 10^7 \text{ kg } (^3\text{He})$. Combining the volcanic plus plumes, one obtains a total release of primordial ^3He to the atmosphere of $4.5 \times 10^9 \text{ kg}$. When compared to the total ^3He entombed ($2.6 \times 10^{12} \text{ kg}$), one finds that only 0.2% of the stored ^3He has been released and $> 99\%$ remains in or near the core.

^{22}Ne

No known ancestors of Ne have been identified as soluble in the Earth's metallic core; therefore, Ne will be assumed to have been transported to the Earth with the chondritic bodies which formed the lower mantle. During accretion much of the neon was released, forming a permanent constituent of the atmosphere; however, some of the neon was sequestered, perhaps in SiC or graphite chondrules, into the lower mantle. The solubility of noble gases in basaltic type melts under pressure has been demonstrated (Matsuda et al., 1993). Hence, Ne under pressure in the lower mantle has remained dissolved and is only released through vents tapping deep mantle sources.

The Earth's atmosphere contains $\sim 7.2 \times 10^{19} \text{ cm}^3$ (STP) of Ne composed of the three isotopes; namely: $^{20}\text{Ne} - 2.9 \times 10^{15} \text{ moles}$, $^{21}\text{Ne} - 8.61 \times 10^{12} \text{ moles}$, $^{22}\text{Ne} - 2.97 \times 10^{14} \text{ moles}$. The concentration of ^{21}Ne is small and its formation by spallation was not considered here; consequently, this isotope is not considered in this global estimate.

Several types of Ne-bearing chondrules with unique isotopic signatures have been discovered in chondritic meteorites. Neon-B, Fig. 2, with a high ^{20}Ne content ($^{20}\text{Ne}/^{21}\text{Ne} = 12.5$ and $^{21}\text{Ne}/^{22}\text{Ne} = 0.0335$), has been attributed to a solar source (Podosek, 1978), while Neon-A with high ^{22}Ne ($^{20}\text{Ne}/^{22}\text{Ne} = 8.125$, $^{21}\text{Ne}/^{22}\text{Ne} = 0.025$) has been classified as “planetary” because it was found in carbonaceous chondrites. The occurrence of nearly pure ^{22}Ne (Neon-E) in SiC and graphite particles was discussed previously; however, the quantity of this material is unknown, hence, Neon-A, which probably contained a large amount of Neon-E is a more likely identifiable source for the ^{22}Ne in the Earth. Based upon this assumption, Ne isotopic ratios in the atmosphere can be obtained from a mixture of 62% Neon-A and 38% Neon-B.

The amount of chondritic material required to supply the quantities of ^{20}Ne and ^{22}Ne to the Earth’s atmosphere was determined based upon the experimental measurements of samples from the Deccan Flood Basalt, which has an enhanced $^3\text{He}/^4\text{He}$ ratio of 14 times atmospheric. This sample was selected for this computation because it may be more pristine than meteoric samples which may contain solar wind gases. The ^{20}Ne content of this basalt is $\sim 4 \text{ n cm}^3/\text{g}$ (Basu et al., 1993). (^{22}Ne was not determined but the $^{20}\text{Ne}/^{22}\text{Ne}$ ratio will be assumed to be the atmosphere value.) Measurements of the partition of noble gases He and Ne between olivine and basalt melts indicated that this ratio is in the range of 0.01 – 0.08 (Hiyagon and Ozima, 1986). Hence, $> 90\%$ of the Ne and He were extracted into the molten plume.

An estimate of the partition of the Ne between the melt and its release to the atmosphere was estimated, as follows. Contemporary measurements of gases evolving from active Hawaiian volcanoes (Greenland, 1988) indicate that the magma contains 0.016–0.022 wt% CO_2 . The $\text{CO}_2/^3\text{He}$ ratio is $\sim 2 \times 10^9$ for contemporary MORB; hence, the Hawaiian Island molten basalt contains $\sim 2.3 \times 10^{-15}$ mole (^3He)/g. Quantitative measurements of young, cooled Hawaiian lavas, which were crushed in a vacuum system

to release the entrapped gases, yielded ^4He in the range of $(1 - 5) \times 10^{-8} \text{ cm}^3(\text{STP})/\text{g}$ with a $^3\text{He}/^4\text{He}$ ratio of $\sim 8\times$ atmospheric (Kurz et al., 1987); hence, the measured ^3He concentration remaining is 2.5×10^{-17} mole (^3He)/g, which is 10^{-2} less than the gases in molten magma.

The above ratio of degassing was utilized for the Ne in the Deccan Flood Basalts to indicate that the Ne content in the pre-planetary chondritic material was $\sim 400 \text{ n cm}^3(\text{STP})/\text{g}$. At a density of 3.3 Mg/m^3 this chondritic material would have a Ne content of 6×10^4 mole (^{20}Ne)/ km^3 . In order for the atmosphere to obtain its present inventory of ^{20}Ne , nearly $5 \times 10^{10} \text{ km}^3$ of this chondritic material would be required, which would be composed of 2/3 material bearing Neon-A, and 1/3 material bearing Neon-B. If this chondritic material were mixed into the lower mantle, it would constitute only 8% of this molten mantle. This small amount of meteoric material bearing this neon would be difficult to detect; consequently, the described scenario for the emplacement of Ne in the primitive Earth is reasonable.

Summary

Contemporary astrophysical models of the early Sun were examined and relatively large quantities of the isotopes ^3He and ^{22}Ne have been identified uncontaminated by sibling isotopes. Mechanisms were proposed for the incorporation of these isotopes during the accretion of the Earth. The ^3He was visualized to be stored within the Earth's metallic core. Qualitative inventory analysis indicates that $< 1\%$ of the ^3He has degassed from the core over the age of the Earth. The ^{22}Ne was sequestered in the pre-solar nebula in SiC and graphite modules and perhaps incorporated in meteorites as a constituent known as Neon-A. Only 8% of the Earth's molten mantle, composed of this meteoric material containing Neon-A, would be required to degass and form the present Ne inventory in the atmosphere. Traces of these entombed ^3He and ^{22}Ne gases continue to vent from the Earth.

Acknowledgement

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