Nuclear reactor at the core of the Earth! – A solution to the riddles of relative abundances of helium isotopes and geomagnetic field variability

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The quest for the origin and understanding relative abundances of ^{3}He and ^{4}He isotopes and the origin and cause for variability of geomagnetic field has been a continuing activity. Helium gas is attributed to primordial origin or to radioactive decay of various unstable isotopes. The geomagnetic field attributed to a geodynamo is observed to show variability and also reversibility in its sign. Can there be a common origin or cause for these and other geological observations?

Helium, the lightest of the noble gases, was identified in the Sun in 1868, during a solar eclipse in India. A spectrometer was used for the first time in the study of the chromosphere around the Sun, the chromosphere's spectrum among other bright stripes, contains a yellow line that, at the time, was thought to correspond to sodium. The French astronomer Janssen proved that the yellow line did not belong to sodium, but was probably the line of a new element. Lockyer and Frankland confirmed Janssen's results and proved that the bright yellow line could not have an earthly origin. Frankland proposed the name 'helium' after the Greek word 'Helios' for Sun. This stripe was later detected in the spectra of many other stars and, in 1882, Palmieri observed it in gases erupting from Vesuvius.

The search for helium in the Earth was not very productive until 1895, when William Ramsay examined the gas produced by a Norwegian ore (cleveite) when treated with acids, and proved the existence of helium on Earth. Ramsay made this discovery after the work of Hillebrand in 1888, that stated that the boiling of uraninite with dilute sulphuric acid produced considerable amounts of an inert gas.

Amongst some eight isotopes (^{3}He to ^{10}He), only two isotopes ^{3}He and ^{4}He are stable, with abundances 0.0001373% and 99.9998633%, respectively in helium gas. The other isotopes decay by b^- and neutron emission. That is, the Earth's atmosphere contains fewer than one and a half rare ^{3}He atoms for every million atoms of ^{4}He. In crustal fluids, which include groundwater, the ratio is even less. But in mantle fluids, this ratio of ^{3}He to ^{4}He is about eight times greater than in the air. When geophysicist Mack Kennedy found high ratios of ^{3}He to ^{4}He in the San Andreas fluids, it was a clue to their deep origin.

The composition and abundance of various materials in the Earth are inferred from samples of volcanic eruptions, meteorites, etc. The conventional model of the Earth envisions an onion-like shell structure grossly divided into the crust, upper and lower mantle and a solid innermost core surrounded by a fluid core; this model is based on seismic data. Geophysicists[1,2] have hypothesized that the inner and outer cores are mainly composed of a nickel–iron metal alloy similar in composition to that of ordinary chondrites. Herndon[3] has proposed that the core of the Earth 'consists not of nickel–iron metal, but of nickel silicide'. This suggestion was based on studies of the rare enstatite meteorites; for example, the Abee meteorite. He noted that the Earth 'as a whole has a state of oxidation similar to certain highly reduced enstatite chondrites' and that 'the consequence of this state is to lead to fundamentally different interpretations of seismic data'. Based on this chemical consideration, he observed that '... one may expect at the centre of the Earth, one or more high density, high temperature precipitates. The highest density and most important high density, high temperature precipitate would be uranium or a compound thereof'[4] and that it may 'lead to... a subcore within the inner core'[5]. He went on to state that 'the tentative assignment of uranium as a monosulphide is not unreasonable'[5]. Details of the resulting subcore of the inner core are discussed in Herndon[5].

Within 15 years after the first man-made fission reactor, scientists were thinking about the possibility of naturally occurring nuclear reactors. According to Cowan[6], in 1953 George Wetherill, UCLA and Mark G. Inghram, University of Chicago, had studied the possibility of sustained nuclear reaction in natural uranium deposits. Subsequently, the first detailed published study[7] in 1956 by Paul Kuroda, a Japanese physicist, had suggested that nuclear reactions could occur on or in planets. Kuroda had determined the detailed requirements for any likely natural reactor. He showed that uranium 235 would have been more abundant in the past (as much as 3% instead of 0.7% as at present in uranium) and this would have been sufficient to trigger nuclear fission reactions. He laid out in detail the approximate age range for a natural reactor, the uranium concentration, ^{235}U/^{238}U ratio requirements and other aspects[8]. However, he could not find a match for his natural reactor model amongst the Earth's then known uranium ores.

During the late 1950s and early 1960s, the ^{235}U/^{238}U ratio in hundreds of uranium ores from around the world were measured, to detect any change in it. Any reduction in this ratio would indicate that some ^{235}U had fissioned some time in the past. Of the hundreds of ores investigated, none had a ^{235}U/^{238}U ratio outside the generally accepted value of 0.007202 ± 0.00006. However, on 2 June 1972 a French analyst (H. Bouzigues) while working at the Pierrelatte nuclear fuel processing plant, during routine mass spectrometry measurements of the value of ^{235}U/^{238}U ratio in uranium ore samples, observed a tiny change in the ratio (0.00717, compared to a normal value of 0.00720). So precisely known was this ratio that this small difference was sufficient to suggest something strange had occurred. At first it was thought that some used nuclear fuel had inadvertently slipped into the processing plant. However, this was quickly ruled out by detailed analysis.

Cowan, the Head of Nuclear Chemistry Division at Los Alamos Scientific Lab noted that[6] 'finally, the discovery of the (natural) reactor involved an investigative *tour de force* worthy of the best sleuths in

detective fiction'. In fact Cowan's article in *Scientific American*[6] is an interesting concise summary of what all transpired. Two important facts came together for the epoch-making discovery[6]: (a) 'the isotopic composition of uranium is thought to be a constant of the solar system in any one era. ... While chemical processes can make one region rich in uranium and leave another region poor, … there seemed to be no plausible mechanism in nature that might selectively remove one isotope to the extent observed in the depleted ore'; and (b) 'elements that are characteristic products of nuclear fission were abundant in the depleted vein, but they were almost absent elsewhere in the ore body'. A careful check on the source materials traced the uranium ore back to a very high concentration uranium deposit present in a mine-site at Oklo in Gabon, southwest Africa. A detailed investigation detected the presence of all the conditions necessary for large quantities of ancient (no longer radioactive) fission product waste embedded in the natural uranium ore, confirming that natural nuclear fission reactions had taken place at Oklo some 1700 million years ago. This first physical evidence of such a natural reactor – sometimes referred to as a fossil reactor – confirmed that a natural nuclear chain-reaction had occurred on the surface of the Earth and had run for hundreds of thousands of years, generating relatively high temperatures and also consuming several tons of uranium during that time. The radioactive remains of the natural nuclear fission reaction were held in place by the surrounding geology. It may be noted that[6] 'eventually six reactor zones were identified in the Oklo pit'. The researches of the French scientists showed clearly that what Kuroda had postulated could indeed occur.

As was pointed out later by Herndon, the nuclear reaction at Oklo stopped only when it ran out of water. Had it not been for this, the nuclear reaction would have continued for countless millions of years more. Scientists had discovered that the Oklo reactor had not only consumed uranium-235, but it had also produced additional uranium-235 by neutron capture. The Oklo reactor was thus a 'breeder' reactor which was able to generate additional fuel for its own use! These discoveries served to prove that long-term self-sustaining nuclear fission reactions are possible in nature.

Herndon discussed the feasibility of a nuclear-fission reactor at the centre of the Earth as the energy-source for the geomagnetic-field[4], based on the evidence for the existence within the Earth's core of substantial quantities of uranium and thorium leading to the accumulation of uranium in the core of the Earth, functioning as a nuclear fission breeder reactor. He had noted that 'if uranium and thorium exist in the core of the Earth as elements or compounds, as evidence indicates, the actinides (a) would be the most dense matter in the Earth, (b) would tend to concentrate at the centre of the Earth, (c) would tend to be separated on the basis of density from less dense reactor poisons, and (d) if accumulated 3000 million years ago, would be able to initiate self-sustaining nuclear fission chain reactions which may continue to the present through fuel breeding reactions'[4].

Hollenbach and Herndon[9] have recently noted that 'nuclear fission provides a viable mechanism for the deep-Earth production of ^{3}He', giving 'evidence of deep-Earth nuclear fission. A nuclear fission geo-reactor is clearly an acceptable alternative to previously postulated energy sources for the geomagnetic field...'. The conceptual reactor is said to consist of 'an actinide subcore, surrounded by a subshell, possibly fluid or slurry, composed of fission products and lead from radioactive decay that is expected to exist at the centre of the inner core of the Earth... . A nuclear fission geo-reactor will produce a plethora of charged particles and copious amounts of ionizing radiation. One might wonder whether the geomagnetic field might originate, in some yet unspecified manner, from this assemblage rather than from fluid motions in the main core of the Earth'. They note that 'if the rate of production of fission products exceeds their rate of removal by gravitationally driven diffusion, the power output of the geo-reactor would decrease and the reactor might eventually shut down, … and ultimately shutting down the Earth's magnetic field. As the fission products diffuse out ... and the actinide fuel diffuses inward, the reactor restarts' and also that 'the frequent but, irregular, variability in intensity and direction of the Earth's magnetic field may be understandable from (such a) fissionogenetic energy-production standpoint'.

The detailed methodology of study by Hollenbach and Herndon[9] involved use of the SCALE code of the Oakridge National Lab; this code is used in nuclear reactor theory calculations, widely. The authors studied the behaviour of the geo-reactor under three conditions: (a) zero-power state, (b) 3TW power generation with removal of fission products migrating out of the system, and (c) 3TW power generation with no migration of fission products. Further details are to be found in Hollenbach and Herndon[9].

How does one verify that such a reactor is actually at work? It is in this context that Hollenbach and Herndon[9] note that 'an independent verification of the presence of fission deep inside the Earth would be the detection of fission and decay products from sources deep inside the Earth... . Helium would be the most likely of these elements to be detected at the surface'. Then they go on to exploit results from fission physics. They note that tritium [^{3}H] – an isotope of hydrogen – is a major ternary fission product of actinides. Whereas ^{4}He is a product of radioactive decay of actinides and their daughters, ^{3}He is the daughter product of decay of ^{3}H, with a 12.32 year half-life. A large fraction of ^{3}H can migrate several kilometers, escaping the reactor zone before it decays to ^{3}He. Hollenbach and Herndon have calculated the cumulative ^{3}He/^{4}He ratio as a function of time of the geo-reactor simulation for case (b) which provided values of the order of 1.4×10^{-6} to about 7 times that value. These values closely match the observed ^{3}He/^{4}He ratio on the surface of the Earth, to which we have referred to earlier.

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