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Examining the Overlooked Implications of Natural Nuclear Reactors

J. Marvin Herndon

On April 7, 1972, scientists at the French Atomic Energy Establishment at Pierrelatte discovered a 0.4% anomaly in the uranium isotopic ratio of a sample of natural uranium. In a masterful example of analytical detective work, the French scientists traced the anomaly to a particular area of a uranium mine located at Oklo in the Republic of Gabon. In that area they found uranium that was deficient in U-235 and was accompanied by fission-produced isotopes of Nd and Sm. On September 25,1972, the French Atomic Energy Commission announced their conclusion that self-sustaining nuclear chain reactions had occurred on Earth about 2000 million years ago [Neuilly et al., 1972]. Later, other natural nuclear fission reactors were discovered in the region [Gauthier-Lafaye et al.,1996.

Today, sufficiently thick, 0.5-m seams of uranium ore would be unable to initiate self-sustaining neutron chain reactions because the proportion of U-235 in natural uranium is too low. But 1800 million years ago, when nuclear fission activity began in Oklo, the proportion of U-235 in natural uranium was more than four times greater, thereby resulting in deposits that could achieve a self-sustaining neutron chain reaction. Subsequent studies showed that not only had areas in the Oklo deposit functioned as thermal neutron reactors, as predicted by Kuroda [1956], but they had also functioned as fast neutron breeder reactors, producing additional fissile material in the form of plutonium and other transuranic elements. Breeding fissile material results in possible reactor operation continuing long after the U-235 proportion in natural uranium would have become too low to sustain neutron chain reactions.

The discovery of the intact remains of natural nuclear reactors has profound scientific implications, especially in proving the existence in nature of an energy source capable of producing more than an order of magnitude more energy than radioactive decay alone. Curiously, the subject appears never to have been addressed in the pages of

Science or the *Journal of Geophysical Research*.

Gauthier-Lafaye et al. [1996] have recently reviewed the considerable body of work done characterizing the conditions and consequences on the environment of the natural reactors at Oklo. The natural reactors are important as natural analogs to nuclear waste repositories mainly as Oklo is the only known occurrence in the world where actinides and fission products have been in a near-surface geological environment for an extremely long period of time. The implications of Oklo, however, extend far beyond the surface regions of the Earth.

Planetary Reactors

In the late 1960s, astronomers discovered that Jupiter radiates into space about twice as much energy as it receives from the Sun. Later, Saturn and Neptune were also found to radiate prodigious quantities of internally generated energy. That excess energy production has been described by Hubbard [1990] as "one of the most interesting revelations of modern planetary science." Stevenson [1978], discussing Jupiter, stated, "The implied energy source ... is apparently gravitational in origin, since all other proposed sources (for example, radio-activity, accretion, thermonuclear fusion) fall short by at least two orders of magnitude...." Similarly, more than a decade later, Hubbard [1990] asserted, "Therefore, by elimination, only one process could be responsible for the luminosities of Jupiter, Saturn, and Neptune. Energy is liberated when mass in a gravitationally bound object sinks closer to the center of attraction ... potential energy becomes kinetic energy ....."

Having knowledge of Oklo, Herndon [1992] realized a different possibility and proposed the idea of planetary-scale nuclear fission reactors as energy sources for the giant planets. The feasibility was demonstrated in part using the same calculations employed in the design of commercial nuclear reactors and employed by Kuroda [1956] to predict conditions for the natural reactors that were later discovered at Oklo. Subsequently, Herndon [1993, 1994] extended the concept to non-hydrogenous planets, especially the Earth.

The state of oxidation of the deep interior of the Earth is comparable to that of certain highly reduced enstatite chondrite meteorites [Herndon, 1993,1996,1998]. In those meteorites, as much as half of the uranium occurs in the portion corresponding to the Earth's core. Uranium or a compound thereof would be expected to precipitate from the Earth's core at relatively high temperatures and, at the pressures involved, would be the densest substance and would tend to collect at the center of the Earth. Uranium or a compound thereof, if accumulated more than about 2000 million years ago, would be capable of self-sustaining neutron chain reactions, even in the absence of moderators. Because density at such pressures is mainly a function of atomic number and atomic mass, fission fragments-including reactor poisons-being lighter would tend to diffuse radially outward away from the reactor subcore [Herndon, 1996]. A similar mechanism may be applicable to other planets.

Geomagnetic Reversals and Planetary Changes

Unlike traditional, globally important energy sources, which change gradually and in only one direction overtime, planetary-scale nuclear fission reactors may be capable of variable or intermittent operation like the Oklo reactors. As inferred from Oklo and reactor technology, changes in nuclear reactor energy production can result from changes in composition and/or position of fuel, moderators, and neutron absorbers. Paleomagnetic investigations (augmented by geological, paleobiological, and geochronological studies) and magnetometer measurements of the ocean floor have established that the Earth's magnetic field reverses polarity frequently, but quite irregularly, with an average time between reversals of about 200,000 years. The cause of geomagnetic reversals has not yet been established. Herndon [1993] has suggested that the variable and intermittent changes in the intensity and direction of the geomagnetic field have their origin in nuclear reactor variability.

Significantly, the geomagnetic field has been in existence at least 3000 million years and certainly during the time period natural reactors could begin to operate and breed fissile material. The following schematically illustrates one possible mechanism for geomagnetic field reversals and excursions:

Nuclear fission consumes actinide fuel and produces fission fragments, some of which have high neutron capture cross-sections. Fission products may be removed from the reactor sub-core region by diffusion and gravitational layering based on density at the prevailing pressures. One might imagine instances in which the rate of production of fission fragments exceeds the rate of their removal. In such instances, the power output of the reactor would decrease and the reactor might shut down, eventually shutting down the Earth's magnetic field. After a period of time had elapsed for fission fragments to diffuse to regions of lower density, the reactor output would increase, and the Earth's magnetic field would reestablish itself either in the same direction or in the reverse direction.

Changes may also be occurring in the giant planets. Atmospheric turbulence in the giant planets appears to be driven by internal energy sources. Jupiter, Saturn, and Neptune produce prodigious amounts of energy and display prominent turbulent atmospheric features. Uranus, on the other hand, radiates little, if any, internally generated energy and appears featureless.

In the summer of 1878, Jupiter's Great Red Spot increased to a prominence never before recorded and, late in 1882, its prominence, darkness, and general visibility began declining so steadily that by 1890 astronomers thought that the Great Red Spot was doomed to extinction. Changes have been observed in other Jovian features, including the formation of a new lateral belt of atmospheric turbulence. Changes have been also observed in the atmosphere of Neptune. It is important to establish whether these atmospheric changes are due to changes in internal energy production that may be related to changes in nuclear reactor output [Herndon, 1994].

Astrophysical Implications

At the beginning of the 20th century, understanding the nature of the energy source that powers the Sun and other stars was one of the most important problems in physical science. Initially, gravitational potential energy release during protostellar contraction was considered, but calculations showed that the energy released would only be sufficient to power a star for a few million years; life has existed on Earth for a longer time. The discovery of radioactivity and the developments that followed led to the idea that thermonuclear fusion reactions power the Sun and other stars. As stellar thermonuclear reactions require ignition temperatures on the order of a million degrees Kelvin, gravitational potential energy release during protostellar contraction of dust and gas was assumed to be responsible for attaining ignition temperatures. No other energy source of sufficient magnitude was known at the time.

Since the 1960s, in numerical models of protostellar collapse, thermonuclear ignition temperatures are not attained solely by the gravitational in fall of matter, an additional shock wave-induced sudden flare-up is assumed. The difficulty in attaining thermonuclear ignition temperatures is understandable as protostar heating by the gravitational in fall of matter is offset by radiation from the surface, which is a function of the fourth power of temperature. The idea that thermonuclear reactions in stars are ignited by gravitational potential energy release during protostellar contraction is an idea that began before the discovery of nuclear fission and has been carried into the present, although there are clearly difficulties. Herndon [1994] has suggested that thermonuclear reactions in stars are ignited by energy mainly from nuclear fission chain reactions.

Astrophysicists traditionally assume that stars will attain thermonuclear ignition temperatures through gravitational collapse during formation and, consequently, will be as luminous as stars are observed to be. The exceptional brown dwarfs, stars with masses less than 0.08 solar mass, are thought to be unable to sustain thermonuclear fusion reactions and are, therefore, considered by many as non-luminous candidates for dark matter. Dark matter, which may be 10 times more abundant than luminous matter, is thought to surround luminous galaxies like a halo and to be necessary for maintaining the dynamic stability of luminous galactic structures.

The idea that stars, like thermonuclear bombs, are ignited mainly by nuclear fission energy opens the door to the possibility of stellar non-ignition. As noted by Herndon [1994], dark matter in the universe might be accounted for, at least in part, by the presence of non-brown-dwarf-size, non-luminous dark stars whose protostellar nuclear fission reactors failed to ignite thermonuclear fusion reactions. Possible reasons for such failure include too low a proportion in uranium of U-235, and, interestingly, the absence of fissionable elements. The apparent association of dark matter with low-metallicity stars suggests the possibility that galactic-halo dark matter may be composed of zero-metallicity dark stars, thus devoid of the fissionable elements necessary to ignite thermonuclear fusion reactions.

Summary and Historical Perspective

The French discovery at Oklo proves that in the geological past natural nuclear reactors can and did occur.

Subsequent investigations prove that natural nuclear reactors can and did produce additional fissile material through breeding reactions. Implications from Oklo include the concept of planetary-scale nuclear fission reactors as energy sources for the giant planets and for the terrestrial planets and the idea that reversals and changes in the geomagnetic field have their origins in variable or intermittent nuclear reactor output. Implications from Oklo also include the concept that thermonuclear reactions in protostars are ignited mainly by nuclear fission energy and the idea of the dark matter possibility of stellar non-ignition. In an October 1, 1996, Eos editorial titled "Why History," Ed Cliver, Ruth Liebowitz, and Sam Silverman point out that, "The historical depths of a scientist's knowledge should encompass at least the last major turning point in their field ... hence the need for long-term perspective." Sometimes one benefits from reexamining former thinking in light of new implications, especially new implications as fundamental as those arising from the natural nuclear reactors at Oklo. Clearly, the French discovery at Oklo, Gabon, is one of the most important yet overlooked discoveries of modern geoscience.

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