Planetary and protostellar nuclear fission: implications for planetary change, stellar ignition and dark matter†

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The feasibility of thermal neutron fission and fast neutron fission in planetary and protostellar matter is calculated from nuclear reactor theory. Means for concentrating actinide elements and for separating actinide elements from reactor poisons are described. The implications of intermittent or interrupted planetary-scale nuclear fission breeder reactors are discussed in connection with observed changes in the giant outer planets and changes in the geomagnetic field. The concept that thermonuclear fusion reactions in stars are ignited by nuclear fission energy is disclosed. The suggestion is made that dark matter, inferred to exist in the Universe, might be accounted for, at least in part, by the presence of dark stars (not necessarily brown dwarfs) whose protostellar nuclear fission reactors failed to ignite thermonuclear fusion reactions.

1. Introduction

In 1939, Hahn & Strassmann (1939) reported their discovery of nuclear fission. Later in the same year, Flügge (1939) considered the possibility that self-sustaining chain reactions might have taken place under natural conditions sometime in the past within uranium ore deposits. Kuroda (1956) subsequently applied nuclear reactor theory (Fermi 1947) to demonstrate the feasibility that uranium ore deposits in nature might in the geological past have become critical and functioned as thermal neutron nuclear fission reactors. In 1972, French scientists discovered at Oklo in the Republic of Gabon, Africa, the fossil remains of an actual natural reactor (Baudin *et al.* 1972; Bodu *et al.* 1972; Neuilly *et al.* 1972). Recently, I developed the concept of planetary-scale natural nuclear fission reactors (Herndon 1992, 1993). This paper addresses the role of nuclear fission in the planetary and astronomical sciences.

2. Background

The giant planets, Jupiter, Saturn, and Neptune, radiate into space approximately twice as much energy as they receive from the Sun; Uranus, on the other hand, emits little energy other than absorbed solar energy (Pearl *et al.* 1990).

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Planetary scientists believed that they had considered all possible energy sources and concluded 'by elimination' that the excess emitted energy must be a relic left over from planetary formation about 4600 million years ago (Hubbard 1990). This view was first challenged by Herndon (1992) who suggested nuclear fission energy.

I have presented evidence for the occurrence of substantial quantities of uranium (and thorium) in the Earth's core and have demonstrated the feasibility for nuclear fission as an energy source for the geomagnetic field (Herndon 1993). Furthermore, I have suggested that polarity reversals of the geomagnetic field may have their origins in intermittent nuclear reactor output (Herndon 1993).

To my knowledge, there exists no observational data on protostars before the ignition of thermonuclear fusion reactions. However, the planet Jupiter represents in certain respects a reasonable protostar model (Hubbard 1990). Since before the discovery of nuclear fission, gravitational potential energy, released during protostellar collapse, has been assumed as the energy source for the ignition of thermonuclear fusion reactions in the stars (Bethe 1939; Gamow & Teller 1938; Leve 1953; Schwartzschild 1958). Protostar heating by the gravitational infall of matter is off-set by radiation from the surface which is a function of the fourth power of temperature. Generally, in numerical models of protostellar collapse, ignition temperatures, on the order of several million degrees Celsius, are not attained solely by the gravitational infall of matter; an additional shock wave induced sudden flare up is assumed (Hayashi & Nakano 1965; Larson 1984). The concept of planetary nuclear fission reactors, as applied to the giant gaseous planets and to the Earth's core (Herndon 1992, 1993), may also apply to protostars and forms the basis of the suggestion, made in this paper, that thermonuclear fusion reactions in stars, as in hydrogen bombs, are ignited by self-sustaining, neutron induced, nuclear fission.

3. Theoretical basis

The pressures that prevail in the deep interiors of planets are sufficiently great that the density of matter is essentially a function of atomic number and atomic mass (Herndon 1992). Actinide elements, being the most dense substances, would tend, by the action of gravity, to be concentrated at the planets' or protostars' centre and separated from less dense reactor poisons as shown by figures 1 and 2.

Figure 1 shows theoretical estimates of the density of several substances as a function of pressure calculated using a Thomas–Fermi–Dirac approach published by Salpeter & Zapolsky (1967). The pressure-density profile of a solar mixture of hydrogen and helium, applicable for example to Jupiter and to protostellar internal regions, designated $H_{10}He$ in figure 1, is one boundary-value reference. The pressure-density profile of nickeliferous iron, $Fe_{16}Ni$, is applicable to planetary cores, although the addition of lighter elements would certainly lead to a slight decrease in density. Nevertheless, the $Fe_{16}Ni$ curve serves as a useful reference for comparing the pressure-density profiles of actinides, represented in figure 1 by uranium mono-sulphide and uranium metal. Fission-product reactor poisons, as represented by the example of ^{149}Sm in figure 1, are less dense than uranium or compounds of uranium at all internal planetary pressures.

Figure 2 shows that, for elements with atomic numbers in the range $55 \leqslant Z \leqslant$

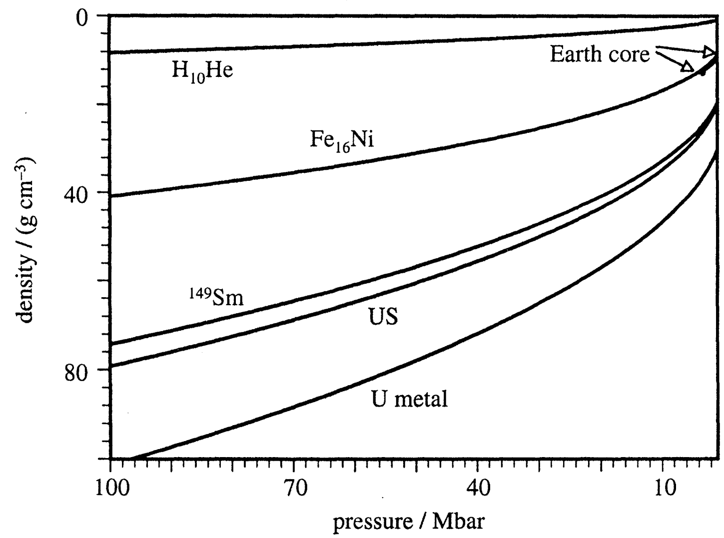

Figure 1. Theoretical pressure-density profiles of selected substances calculated using a Thomas–Fermi–Dirac approach (Salpeter & Zapolsky 1967). The applicability of the calculations relative to planetary interiors is demonstrated by the reasonable, although not perfect, agreement between the curve for $Fe_{16}Ni$ and the seismically-based estimate for the Earth's core (Dziewonski & Anderson 1981). Significantly, for the Thomas–Fermi–Dirac approach, errors are thought to decrease with increasing pressure (Stevenson & Salpeter 1976). This figure shows that uranium metal and uranium compounds, represented by uranium mono-sulphide (US), are more dense, at the pressures expected to prevail in planetary interiors, than any other substances including reactor poisons, as represented by the curve for ^{149}Sm. Rather than uranium settling out directly from H–He, some U-containing complex of iron and other elements would be expected to settle out first, with uranium subsequently settling out from that complex.

83, i.e. the most heavy stable-elements, the percent differences in density relative to uranium are substantial, ranging from 9–41%; a high degree of separation would be anticipated. Witness, for example, the fact that the inner core of the Earth separated by the action of gravity from the fluid core even though the density difference is less than 5% (Dziewonski & Anderson 1981). Moreover, the greater the planet mass or protostar mass, the greater the gravitational acceleration and, consequently, the greater the degree of separation. In addition, it should be noted that, before the onset of nuclear reactions, convection will not take place.

In suggesting nuclear fission reactors as energy sources for the giant planets, I applied nuclear reactor theory (Fermi 1947) to demonstrate the feasibility that a concentration of uranium hydride might in the past have become critical, capable of sustaining a nuclear chain reaction. Continued, but interrupted, functioning as a breeder reactor was suggested based upon the behavior of the Oklo natural reactor. In calculating nuclear fission feasibility for the giant planets, I considered only slow (thermal) neutron fission; this paper reports the feasibility for fast neutron, non-hydrogenous, planetary and protostellar nuclear fission and discusses the implications of intermittent or interrupted reactor operation.

The fundamental criterion for maintaining a nuclear chain reaction is that on the average at least one neutron produced in a fission event causes another fission to occur. This criterion, referred to as criticality or critical condition, is

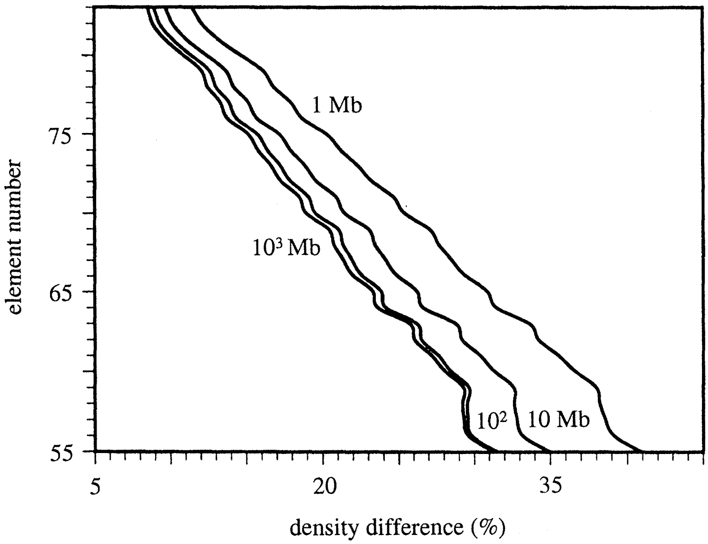

Figure 2. Percent difference in density between the heaviest stable elements and uranium calculated using a Thomas-Fermi-Dirac approach (Salpeter & Zapolsky 1967). This figure shows that the differences in density, relative to uranium, at pressures appropriate to the interiors of planets and protostars, are greater than the difference in density between the Earth's core and inner core ($< 5\%$) which separated by the action of gravity (Dziewonski & Anderson 1981). One would therefore expect a high degree of separation. At pressures greater those within the Earth's inner core region, *ca.* 3 Mbar, even higher degrees of separation would be expected. Fast neutron capture cross sections are considerably less than the fast fission cross-section of uranium, particularly for the high Z elements shown in this figure. Moreover, the high Z elements have negligible effect as neutron moderators. Whereas high degrees of separation are anticipated, fast neutron reactor dynamics require only modest degrees of separation.

described in nuclear reactor theory (Fermi 1947) by the unitary value of the neutron multiplication factor, k, where

$$k = k_{\infty} P. \tag{3.1}$$

P is a measure of the probability that neutrons will not be lost from the system and, being related to the geometry and mass of the reactor assembly, is always less than 1 except for an ideal, infinite assembly. For a system appropriate to planetary or protostar-scale reactors, P is approximately 1, so that

$$k = k_{\infty}. \tag{3.2}$$

The infinite multiplication factor, k_{∞}, is the ratio of the average number of neutrons produced in each generation to the average number of corresponding neutrons absorbed. As discussed by Herndon (1992), the expression for k_{∞} from nuclear reactor theory, applicable to slow (thermal) neutron, hydrogenous, planetary-scale, nuclear fission reactors, is given by

$$k_{\infty} = \eta \epsilon p f, \tag{3.3}$$

where ν is the average number of neutrons liberated for each neutron absorbed, ϵ is the fast fission factor, p is the resonance escape probability, and f is the thermal utilization factor. For fast neutron, non-hydrogenous, planetary-scale,

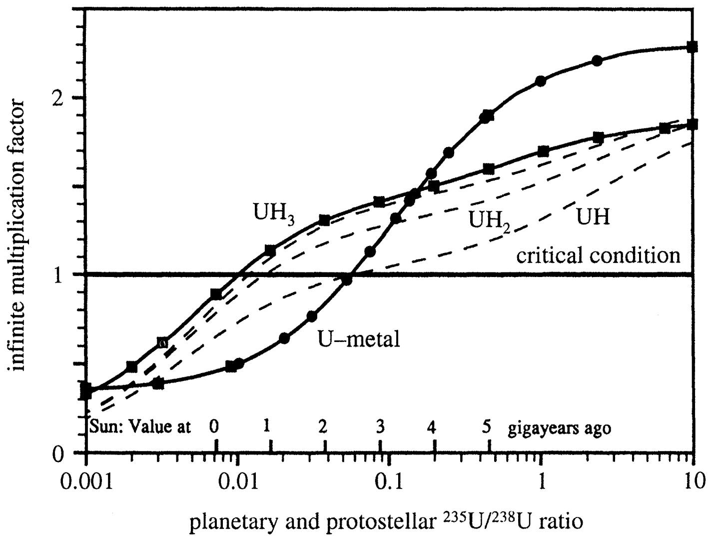

Figure 3. The infinite multiplication factor, k_∞, for fast and thermal neutron natural uranium reactors as a function of $^{235}U/^{238}U$ ratio. Corresponding times before present for terrestrial and presumed solar ratios are indicated as 'Sun value'. In a 'theoretically infinite' system, a nuclear chain reaction is possible when $k_\infty \geqslant 1$. Thermal neutron k_∞ curves for the indicated uranium hydride compounds are also shown. Solid k_∞ curves are based upon 27-group calculations which are the more sophisticated and accurate; 1-group results, indicated by dashed curves, are shown for comparison. At the time of formation of the Sun, between 4 and 5 billion years ago, the $^{235}U/^{238}U$ ratio was more than sufficient for an assemblage of a few kilograms or more of uranium to become supercritical and, gravitationally confined, to attain thermonuclear fusion ignition temperatures. Oak Ridge data points: •, Jordan & Turner (1992); ■, D. F. Hollenbach (personal communication).

nuclear fission reactors, equation (1.3) reduces to

$$k_\infty = \eta f. \tag{3.4}$$

Methods for calculating the components of k_∞ are described in numerous textbooks (Foster & Wright 1973; Lamarsh 1983).

For a natural reactor, k_∞ depends upon the ratio $^{235}U/^{238}U$ which, through radioactive decay, changes over time and which may also change as a consequence of nuclear fission reactions. Figure 3 is a plot of k_∞, expressed as a function of the time before the present that natural, terrestrial uranium would have the indicated $^{235}U/^{238}U$ ratio, assuming no nuclear transmutation except through radioactive decay. Figure 3 presents the k_∞ curve for the fast neutron fission of uranium metal. Because the ratio of fission cross-section to capture cross-section is significantly greater at high neutron energies, the fast reactor k_∞ curve shown is approximately the same for various uranium compounds, including U metal, USi, US, UO_2, UC, and possibly others. The k_∞ curve for the slow neutron fission of uranium hydride, UH_3, shown in figure 3, serves as a useful reference.

As discussed previously (Herndon 1992), if a substantial quantity of UH_3 (at least several kilograms) were to have accumulated before about 500 million years ago, that mass would have begun to function as a thermal neutron reactor; continued operation to the present, however, would depend upon the nature of the fuel breeding reactions involved, e.g. $^{238}U(n,\gamma)\ ^{239}U(\beta^-)\ ^{239}Np(\beta^-)\ ^{239}Pu(\alpha)\ ^{235}U$.

Similarly, as shown in figure 3, if a theoretically infinite quantity of uranium metal or, in fact, most compounds of uranium, were to have accumulated before about 2600 million years ago, that mass would have begun to function as a fast neutron reactor. Continued operation to the present, as in the thermal neutron case, would depend upon the nature of the fuel breeding reactions involved.

The importance of figure 3 is in showing that uranium, virtually irrespective of chemical state, would be capable of self-sustaining nuclear fission, if present in planetary cores and concentrated by gravity to the planets' centre before about 2600 million years ago. For protostars and the giant planets, the implication is that, even were the thermodynamic data on uranium hydrides to be incorrect, or if hydrogen was driven away from uranium by elevated temperatures, nuclear fission would nevertheless occur.

For the Sun, the requisite ratios, $^{235}U/^{238}U \geqslant 0.06$, have certainly existed during that star's lifetime, as inferred from terrestrial isotope ratios. Temporal specification based upon terrestrial isotope ratios is only relevant, within the framework of present knowledge, to the protostar that became the Sun. The k_∞ results presented in figure 3 are, however, generally valid for the indicated $^{235}U/^{238}U$ protostellar abundance ratios.

Approximately 2600 million years ago and earlier, the solar $^{235}U/^{238}U$ abundance ratio was sufficiently great for a 'theoretically infinite' uranium assemblage to become supercritical, as shown in figure 3 by the values of k_∞. Protostellar masses sufficient to gravitationally confine thermonuclear reactions, at least approximately 8% of the mass of the Sun, could likewise confine nuclear fission reactions and would permit the attainment of temperatures sufficiently high to ignite thermonuclear fusion reactions.

4. Implications of nuclear fission in the planetary sciences

Unlike previously envisioned planetary-scale energy sources that change gradually and in one direction through time, variable and interrupted energy output is possible from nuclear fission, as evidenced from investigations of the Oklo natural reactor (Maurette 1976). As known from nuclear reactor technology, various factors can shut down a nuclear reactor or can cause a nuclear reactor to run wild. One planetary nuclear reactor interruption mechanism envisioned relates to accumulations of reactor poisons effectively shutting down the geo-reactor for a period of time until the less dense reactor poisons diffuse from the region of the reactor sub-core (Herndon 1993). A similar mechanism may operate in the deep interiors of the giant planets and be the explanation of the differences in excessive luminosity referred to in § 2 above.

Changes occurring within the deep interior regions of the Earth are manifest as changes in the direction and/or intensity of the geomagnetic field and are evident over geologic time from palaeomagnetic investigations. Moreover, the consequences of such changes, although not yet understood, may affect surface phenomena, as suggested by apparent correlation of geomagnetic field reversals with species extinction (Hagiwara 1991; Kennett & Watkins 1970) and with major episodes of volcanism (Irvine 1989; Marzocchi 1990).

Likewise, changes may also be occurring within the giant planets; for example, during the past 120 years, significant variations have been noted in the appearance of turbulent features, particularly the Great Red Spot, in the atmosphere of Jupiter. In 1878 the Great Red Spot increased to a prominence not before recorded, but 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 (Peek 1958). Whether or not observed variations in Jupiter's turbulent features are due to changes in internal energy production is not known, but it is an interesting and important question.

Long-term monitoring indicates that gradual changes have occurred in the brightness of Uranus over the past thirty years (Lockwood *et al.* 1983). Continued monitoring is important to ascertain whether or not the observed brightening is solely a consequence of highly reflective polar regions and the 98° obliquity of that planet as suggested by some investigators (Conrath *et al.* 1991). Similar, long-term, more or less cyclic changes in the brightness of Neptune have been observed for almost two decades (Lockwood & Thompson 1991). It is important to establish whether or not the atmospheric variations observed in the giant planets are related to changes in internal energy production.

5. Implications of nuclear fission in the astronomical sciences

The traditional concept of stellar ignition through temperatures developed by gravitational infall of matter and protostellar collapse dynamics assumes the inevitability of thermonuclear ignition, except for those protostars having masses less than approximately 8% of the mass of the Sun. Such very low mass objects, called brown dwarfs, are thought to approach minimum internal pressure limits for gravitational thermonuclear fusion confinement (Liebert & Probst 1987).

A considerable body of evidence has now been accumulated suggesting that the Universe contains at least ten times more non-luminous matter than luminous matter (Trimble 1987). The nature of dark matter is unknown and represents an outstanding problem in astrophysics.

Dark matter might be accounted for, at least in part, by the presence of dark stars, but not necessarily brown dwarfs, whose protostellar nuclear fission reactors failed to ignite thermonuclear fusion reactions. Possible reasons for such failure include a too low $^{235}U/^{238}U$ ratio, inadequate confinement pressure, and the absence of fissionable elements.

Observational evidence, primarily based on velocity dispersions and rotation curves, suggests that spiral galaxies have associated with them massive, spheroidal, dark matter components, thought to reside in their galactic halos (Rubin 1983). Interestingly, the luminous disc stars of spiral galaxies belong to the heavy-element-rich Population I; the luminous spheroidal stars of spiral galaxies belong to the heavy-element-poor Population II. In spiral galaxies, the dark matter components are thought to be associated in some manner with the spheroidal heavy-element-poor Population II stars (Bacall 1986; van der Kruit 1986). The association of dark matter with heavy-element-poor Population II stars is inferred to exist elsewhere, for example, surrounding elliptical galaxies (Jarvis & Freeman 1985; Levison & Richstone 1985). Because of the apparent association of dark matter with heavy-metal-poor Population II stars, I suggest the possibility that these dark matter components are composed of what might be called Population III stars, i.e. stars devoid of fissionable elements, and, consequently, unable to sustain the nuclear fission chain reactions necessary for the ignition of thermonuclear fusion reactions.

The possible existence of a second mechanism for stellar thermonuclear ignition precludes the notion that the sole cause of ignition was the heat generated by gravitational potential energy release. Observational confirmation of protostellar ignition is clearly important, not only as relates to the question of stellar ignition, but as relates to the possibility of stellar non-ignition and the nature of dark matter in the Universe.

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