

## Nuclear Fission Reactors as Energy Sources for the Giant Outer Planets

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Of the giant planets, Jupiter, Saturn, and Neptune presently radiate into space approximately twice as much energy as they receive from the Sun; Uranus, however, emits little, if any, energy other than absorbed solar energy. Currently, speculative explanations for the energy sources involved propose gravitational potential energy release. The purpose of the present paper is to suggest the possibility of naturally occurring nuclear fission reactors in the giant outer planets. The discovery of a naturally occurring, terrestrial, nuclear fission, "breeder" reactor is reviewed. Quantitative estimates are made of the planetary energy release by nuclear fission and of the duration that present planetary power output levels could be sustained by nuclear fission energy.

Observations made from ground-based observatories, from high-altitude jet aircraft, and from Pioneer and Voyager spacecrafts show that Jupiter, Saturn, and Neptune presently radiate into space approximately twice as much energy as they receive from the Sun; Uranus, on the other hand, emits little, if any, energy other than absorbed solar energy [1–11]. Quantitative estimates of planetary thermal emission to absorption ratios are presented in Table 1.

Although observations of large excess radiant flux from the giant outer planets were confirmed over 20 years ago [12], explanations of the heat sources responsible are yet speculative. The central interior temperature of Jupiter, thought to be the highest of the internal temperatures of the gaseous planets, is estimated from numerical model calculations to be approximately 20 000 K [13, 14]. Because this temperature is more than two orders of magnitude too low for the occurrence of stellar-type thermonuclear fusion reactions involving nuclides of hydrogen and helium [15–18], other ideas of potential heat sources have been suggested. An idea has been discussed suggesting that a portion of the excess energy flux is caused by relic primordial heat originally produced by gravitational collapse during planetary formation [19]. Another idea that has been discussed suggests that a portion of the excess energy radiated into space is due to gravitational potential energy liberated during the precipitation of helium in the metallic hydrogen planetary core [20–24].

Table 1. Determinations of the ratio of radiated power to absorbed solar power for the giant gaseous planets

	Ratio	Ref.
<i>Jupiter</i>	2.7 ± 0.6	[1]
	1.9 ± 0.2	[3]
	2.0 ± 0.4	[5]
	1.67 ± 0.09	[6]
<i>Saturn</i>	2.5 (+ 1.3, -0.6)	[1]
	2.5 ± 0.6	[2]
	2.6 ± 0.9	[5]
	1.78 ± 0.09	[7]
<i>Uranus</i>	≤ 1.3	[5]
	< 1.24	[8]
	< 1.48	[9]
	< 1.27	[10]
	< 1.06 ± 0.08	[11]
<i>Neptune</i>	2.1 ± 0.5	[4]
	2.6 (+ 2.4, -0.9)	[5]
	2.85 ± 0.56	[10]
	2.7 ± 0.4	[11]

To date there is no proof or direct evidence for the ideas of gravitational energy release within the giant planets and for 20 years scientists have sought a non-gravitational energy source of sufficient magnitude to power the giant outer planets.

The purpose of the present paper is to suggest the possibility of naturally occurring nuclear fission, "breeder" reactors as energy sources for the giant planets. The discovery of a naturally occurring terrestrial nuclear fission breeder reactor is reviewed. A preliminary attempt is made to reveal the chemical states of certain actinide elements within the giant outer planets. A means of concentrating the actinide elements is discussed. The results of theoretical calculations are presented that support the feasibility of nuclear fission reactors in the hydrogenous planets, particularly in light of data obtained from the terrestrial naturally occurring nuclear fission reactor. Finally, the energetics and implications of possible planetary nuclear fission reactors are discussed.

## Terrestrial Nuclear Fission Reactors

In 1949, J. B. Orr published the idea of the possibility of self-sustaining nuclear reactors occurring naturally in terrestrial uranium deposits [25]. In 1956, P. K. Kuroda described theoretically the feasibility that a terrestrial uranium-water mineral assemblage in the geological past might undergo self-sustaining, neutron-induced, nuclear fission reactions [26-31]. Specifically, Kuroda applied nuclear reactor theory [32] to the geochemistry of uranium mineral formation to deduce the environment and the circumstances under which terrestrial uranium ore deposits might become natural fission reactors. Although the present-day natural isotope abundance of  $^{235}\text{U}$  (0.72%) is too diminished relative to  $^{238}\text{U}$  to permit its functioning as a water-moderated, self-sustaining, nuclear fission reactor, Kuroda recognized that the  $^{235}\text{U}$  isotope abundance would have been greater in the past. Imagining the crystallization of Johanngeorgenstadt pitchblende 2100 million years ago, Kuroda estimated that critical uranium chain reactions could have taken place if the molar ratio of water to uranium was on the order of 1 and the size of the pitchblende assemblage was at least about 1 m in thickness.

In 1972, evidence was discovered that the uranium deposit at Oklo in the Republic of Gabon, Africa, had in fact functioned in the geological past as a natural, self-sustaining, nuclear fission reactor [33-39]. The Oklo reactor began operating about 2000 million years ago under conditions very close to those described by Kuroda [26] and appears to have operated for a period as

long as 0.6 to 1.5 million years, shutting itself down when water necessary for neutron moderation was driven off. Moreover, the Oklo reactor not only consumed naturally occurring  $^{235}\text{U}$  as fuel, but acted as a "breeder", producing additional  $^{235}\text{U}$  by neutron capture in  $^{238}\text{U}$  and subsequent decay through  $^{239}\text{Pu}$ . Furthermore, nuclear fission in the Oklo reactor occurred not only by the thermal neutron fission of  $^{235}\text{U}$ , but also to a lesser extent by the fast neutron fission of  $^{238}\text{U}$  and  $^{239}\text{Pu}$  [38, 39].

The discovery of the natural fission reactor at Oklo proves that nuclear fission reactors can in fact occur in nature and justifies the theoretical approach used by Kuroda for predicting their occurrences [26]. Subsequent investigations of the Oklo natural fission reactor serve to extend the idea of naturally occurring thermal neutron reactors to include naturally occurring fast neutron "breeder" reactors.

## Planetary Chemical States of Actinide Elements

In Jupiter, atoms of hydrogen are about 1000 times more abundant than atoms of any other element, except the chemically unreactive element, helium. Within the limitations of present knowledge, there is no reason to believe that the bulk chemical composition of Jupiter differs greatly from the composition of the photosphere of the Sun, although elements heavier than helium may be enhanced by a factor of three to ten, relative to solar composition [40]. Saturn, like Jupiter, appears to be composed primarily of hydrogen and helium; however, Saturn is thought to consist of a greater proportion of heavy elements and a lesser relative proportion of hydrogen and helium than Jupiter. In Saturn, elements heavier than hydrogen and helium appear to be enhanced by a factor of ten to twenty, relative to the composition of the photosphere of the Sun [41-43]. In Uranus and Neptune, elements heavier than hydrogen and helium appear to be enhanced by even greater factors, relative to solar composition [44]. Nevertheless, hydrogen is the most abundant chemical element of each of the four giant outer planets. Uranium and thorium are the only two naturally occurring chemical elements at the present time whose atomic nuclei can be induced to fission or can undergo nuclear transmutation to become fissionable nuclei. Early in the history of the solar system at the time of the formation of certain meteorites, fissionable  $^{244}\text{Pu}$  was also present [45].

At the surface of the Earth, uranium and thorium occur in combination with oxygen as oxidized ore minerals. Likewise, in most meteorites uranium and tho-

rium occur associated with silicate-oxide minerals. The geochemical behavior of these actinide elements, however, is not entirely lithophile. Uranium and thorium display a distinctly nonlithophile character in the enstatite chondrite meteorites [46], which formed under highly reducing conditions [47]. Notably, certain minerals found in the enstatite meteorites, for example, oldhamite (CaS) and osbornite (TiN), are thermodynamically stable in a gas of solar composition at elevated temperatures and pressures [48]. It is of interest to make a preliminary attempt to ascertain the chemical states of uranium, thorium, and plutonium under conditions that might be expected to prevail within the giant outer planets.

In the laboratory actinide elements can exist in various chemical states, including metals, oxides (e.g.,  $\text{UO}_2$ ,  $\text{ThO}_2$ ,  $\text{PuO}_2$ ), and hydrides (e.g.,  $\text{UH}_3$ ,  $\text{ThH}_2$ ,  $\text{PuH}_2$ ). Using published data [49 – 58] and extrapolating to the relevant temperatures and pressures, I calculated boundary conditions on the thermodynamic stability of these three actinide metals, oxides, and hydrides in a medium of solar composition. The results of these calculations for uranium are presented in Fig. 1. For comparison, planetary interior pressure-temperature profiles, calculated by Podolak and Cameron [13] for solar composition models of the giant planets, are also shown in Fig. 1.

An important thermodynamic boundary condition shown in Fig. 1 is the interface between the region of stability of uranium metal and the region of stability of uranium hydride. Were oxygen not a component of

solar matter, that interface would extend to lower pressures and lower temperatures. With the intention of establishing boundary conditions, the most oxidizing conditions for solar matter were adopted for the calculations. The interfaces between the thermodynamic stability region of a uranium oxide ( $\text{UO}_2$ ) and the stability regions of uranium metal (U) and uranium hydride ( $\text{UH}_3$ ) thus calculated impose the most stringent possible boundary conditions with respect to uranium metal and uranium hydride stability. The interiors of gaseous planets, particularly Jupiter and Saturn, may in fact be less oxidizing, thus extending the metal and hydride stability regions to lower pressures and lower temperatures.

I also calculated boundary conditions on the thermodynamic stability regions of thorium and plutonium metals, oxides, and hydrides in a medium of solar composition. Although the thermodynamic stability regions were calculated using published data from different sources and extrapolating to the relevant temperatures and pressures, the resultant stability regions are remarkably similar for the three actinide elements and are approximately the same as the stability regions for the uranium species shown in Fig. 1.

### Accumulation of Actinide Elements in the Outer Planets

It is difficult theoretically to predict the manner by which uranium deposits form on the surface of the

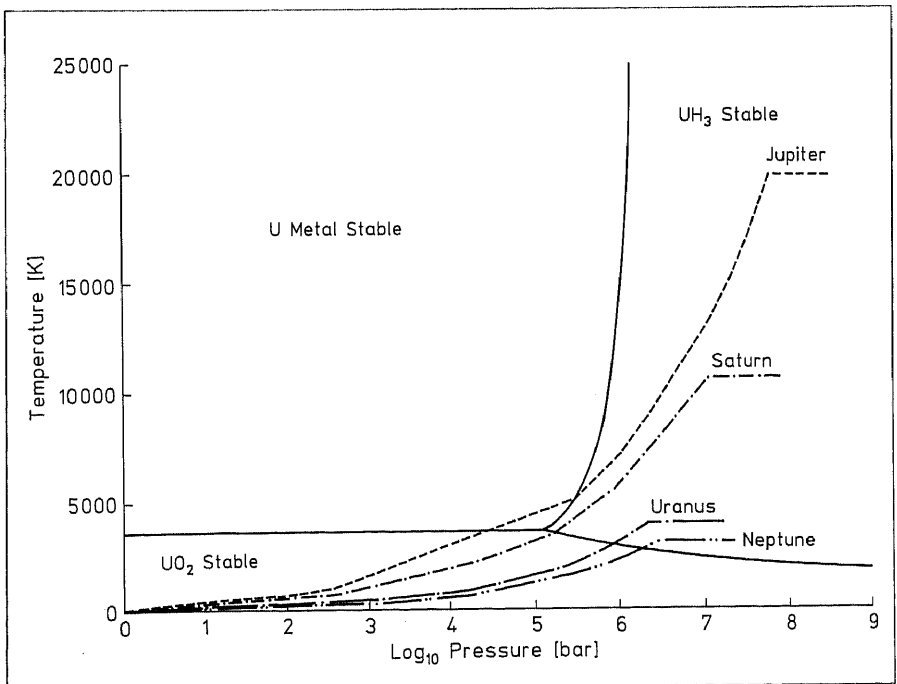


Fig. 1. Estimates of the regions of thermodynamic stability for uranium metal, uranium hydride, and uranium dioxide in a medium of the composition of the photosphere of the Sun. For reference, interior temperature-pressure profiles are shown for one set of numerical models of the giant gaseous planets [13]

Earth, even given the opportunity for first-hand field examination of the actual deposit. It is even more difficult theoretically to predict the manner by which uranium deposits might form in the much unknown, alien environments of the giant gaseous planets. Notably, these planets differ from the Earth in ways that may enhance the concentration of actinide elements. The giant outer planets, by virtue of their large masses, have higher than terrestrial gravitational acceleration. Larger gravitational acceleration would enhance concentration of the actinide elements by the action of gravity. Moreover, the giant gaseous planets have lower mean densities ( $0.7 - 1.6 \text{ g/cm}^3$ ) than the Earth ( $5.5 \text{ g/cm}^3$ ). Such density differences would favor gravitational segregation. Of particular importance, however, is the effect of great pressure. At ambient pressure the crystallographic (electronic) structure of minerals greatly influences their densities. By contrast, the pressures that prevail within the interiors of the giant gaseous planets are sufficiently great that the density of matter becomes a function almost entirely of atomic number and atomic mass [59 - 62]. The actinides have the greatest atomic numbers ( $Z \geq 90$ ) and greatest atomic masses ( $A \geq 232$ ) of the elements and thus would comprise the most dense matter within the massive, low-density, giant gaseous planets, as shown by examples of theoretical density as a function of pressure presented in Fig. 2. Moreover, heat produced by radioactive decay of the actinides may further assist in their concentration, particularly in the icy outer regions of these planets.

## Feasibility of Planetary Nuclear Fission Reactors

Nuclear reactors consist of an assemblage of fissionable nuclides (e.g.,  $^{235}\text{U}$ ) for fuel and a moderator (e.g.,  $^1\text{H}$ ,  $^2\text{H}$ , He, or C) for slowing neutrons to energies that can induce fission in the fuel. The Oklo natural reactor in Africa was presumably moderated by  $\text{H}_2\text{O}$ , as predicted by Kuroda [26]. The giant planets contain copious amounts of hydrogen, helium, and, to a lesser extent, carbon that might serve as potential moderators. In the Earth water is low in abundance and confined primarily to the outer crust and surface. In the giant planets, on the other hand, hydrogen and helium are present in great abundance throughout much, if not all, of the volumes of these planets. The presence of moderators, particularly hydrogen, throughout much of the volume of the giant planets is an especially favorable environment for the occurrence of natural nuclear fission reactors.

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. For a nuclear reactor to operate, this criterion, referred to as criticality or critical condition, is described theoretically [32] by the unitary value of the neutron multiplication factor,  $k$ , where

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

$P$ , a measure of the probability that neutrons will not be lost from the system, is related to the geometry and

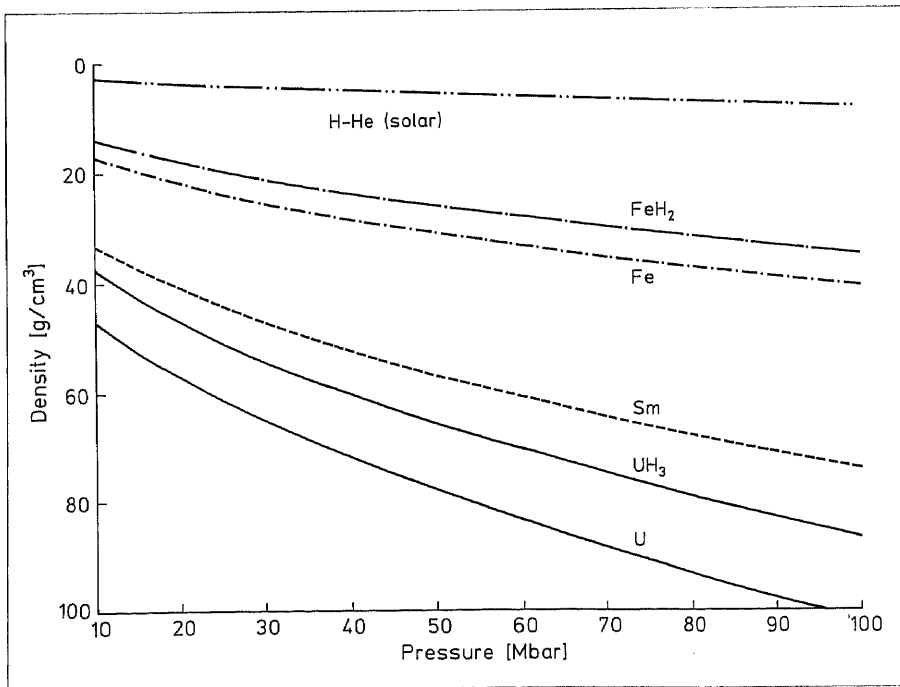


Fig. 2. Theoretical estimates of the density of several substances as a function of pressure in the range 10 - 100 Mbar, calculated using a Thomas-Fermi-Dirac approach given by [62]. At these pressures, U and  $\text{UH}_3$  are the most dense substances, denser than nuclear fission product "reactor poisons", represented by the example of Sm

mass of the reactor assembly and is numerically always less than 1. For a theoretically infinite system,

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

The infinite multiplication factor,  $k_{\infty}$ , is the ratio of the average number of neutrons produced in each generation to the average number of corresponding neutrons absorbed. In nuclear reactor theory,

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

where  $\eta$  is the average number of neutrons liberated for each neutron absorbed,  $\epsilon$  the fast fission factor,  $p$  the resonance escape probability, and  $f$  the thermal utilization factor. The methods for calculating the component factors of  $k_{\infty}$  are described in numerous references [63 – 68].

Calculation of the infinite multiplication factor is the means employed by Kuroda [26] for estimating the feasibility of a naturally occurring terrestrial nuclear reactor. In the natural nuclear fission reactor at Oklo, seams of uranium ore approximately 0.5 m in thickness constituted a more or less “theoretically infinite system”.

Figure 3 presents the results of  $k_{\infty}$  calculations that I made for a hydrogen-uranium assemblage represented by various molar H/U compositions and various  $^{235}\text{U}/^{238}\text{U}$  ratios. The uranium isotope ratios adopted are those of natural composition in times past. About 600 million years ago or earlier, as shown in Fig. 3, a hydrogen-natural uranium assemblage having a H/U

molar ratio of about 3 would have a  $k_{\infty}$  value greater than or equal to 1; thus, critical uranium chain reactions could have taken place in a theoretically infinite system. An upper limit on the minimum size of such a hydrogen-uranium assemblage is estimated to be on the order of 0.5 m in diameter. It is evident from Fig. 3 that, for a particular  $^{235}\text{U}/^{238}\text{U}$  ratio, the H/U molar ratio strongly controls whether or not the assemblage is critical. One might imagine that, as the nuclear chain reaction began to accelerate, the additional heat produced would tend to drive off hydrogen, thus lowering the H/U ratio, thereby decelerating the chain reaction. In the terrestrial analog, the Oklo natural reactor in Africa, the availability of  $\text{H}_2\text{O}$  presumably had a similar effect. It is interesting that the compound, uranium hydride ( $\text{UH}_3$ ), is itself an ideal combination of fuel and moderator, as shown in Fig. 3.

The above calculations, showing that the infinite multiplication factor for a hydrogen-natural uranium assemblage can exceed unity, support the feasibility of a naturally occurring thermal neutron reactor fueled by  $^{235}\text{U}$ . Experience teaches that the thermal neutron fission of  $^{235}\text{U}$  may initiate the production of other fissionable atoms. The results of investigations of the fission yield products of the Oklo terrestrial reactor demonstrate that fast neutrons did in fact produce additional fuel in that reactor. The functioning as a fast neutron “breeder” reactor is important because fuel sources other than  $^{235}\text{U}$  can be utilized. Also, obtaining a critical condition in a thermal neutron reactor moderated by hydrogen is constrained by the  $^{235}\text{U}/^{238}\text{U}$

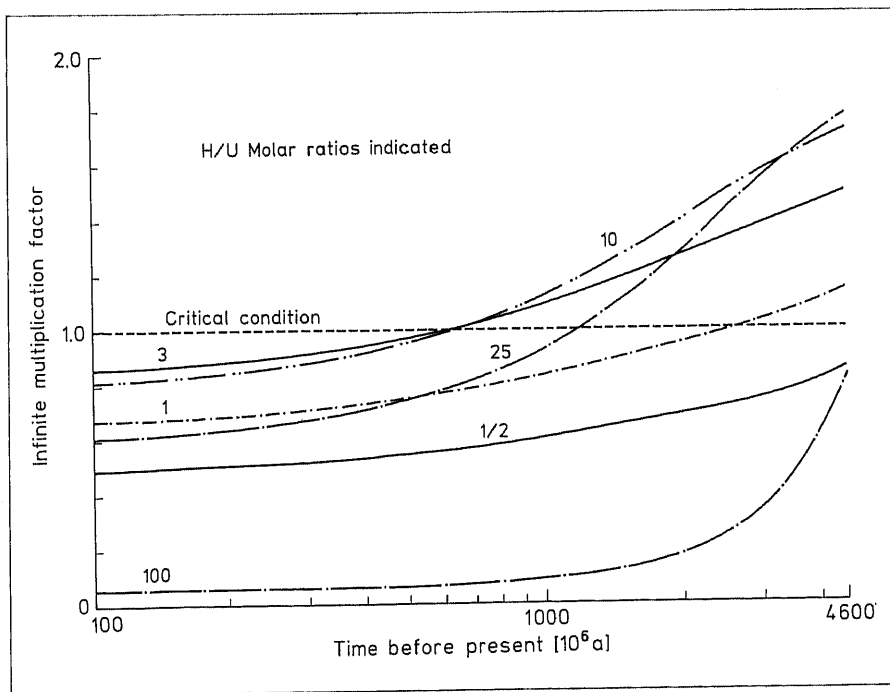
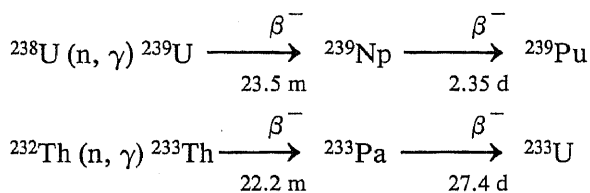


Fig. 3. The infinite multiplication factor  $k_{\infty}$ , for various hydrogen to uranium molar ratios for an assemblage of hydrogen and natural uranium in times past. Other neutron absorbers assumed present in solar proportion relative to hydrogen. In a “theoretically infinite system”, a nuclear chain reaction is possible when  $k_{\infty} \geq 1$

ratio in nature. In a fast neutron “breeder” reactor this constraint is obviated. This means that “breeder” reactors can function in the present, not only in times past when the  $^{235}\text{U}/^{238}\text{U}$  ratio was greater. Consequently, the feasibility for subsequent continued operation of such a reactor would depend upon the fuel produced, for example, by the following reactions:



## Removal of Fission Product Poisons

Nuclear fission reactors produce a variety of fission products. Some, for example,  $^{149}\text{Sm}$ , have high neutron capture cross-sections and are referred to as reactor poisons because accumulations of these can adversely affect reactor operation. In the interiors of the giant planets such reactor poisons might be removed from the reactor zone by the same mechanism suggested for the accumulation of actinide elements, namely, gravitational layering. In the interiors of the giant planets, the pressures are sufficiently great that the density of matter becomes a function almost entirely of atomic mass and atomic number [59–62]. Reactor poisons, being fission products, have atomic masses and atomic numbers that are roughly half those of their parent actinides. The poisons therefore would have considerably lower densities than the reactor fuel and would tend to layer above the more dense fuel, as shown in Fig. 2 for the example of  $^{149}\text{Sm}$ . That upper layer may be further removed or diluted by convection. Industrial experience, for example, observations of multi-kilogram gold-plus-glass liquids, shows that, in systems where heat is introduced from below by a considerably denser material, the convection produced will generally be constrained to the upper, less dense layer. In the interiors of the giant planets, the actinide fuels may tend to layer gravitationally, whereas the less dense reactor poisons may tend to be removed by convection.

## Planetary Reactor Energetics and Implications

The large excess energy flux from Jupiter has been observed for only about 20 years; excess energy flux from the other giant planets has been observed for

even less time. At present, it is not known whether the large excess energy flux from the interiors of the giant planets has persisted throughout the approximately 4 600 million years since planetary formation or whether the excess energy emissions began at some later times. It is not known whether the excess energy flux densities have varied or remained constant. Also, it is not known whether the excess energy emissions have been continuous or intermittent. Within the framework of present knowledge, one cannot even state with certainty the times at which the energy was produced that accounts for presently observed excess radiant energy emissions. Unlike the other giant planets, Uranus presently emits little, if any, energy other than absorbed solar energy [11]. Currently, there is no valid scientific basis for making assertions or assumptions as to the constancy or to the long-term history of excess energy emissions from the giant planets.

Nevertheless, it is of interest to estimate the magnitude of the energy release that is theoretically possible from naturally occurring nuclear fission reactors associated with the giant outer planets and to relate these values to the presently observed planetary energy emissions. From such an exercise, one may appreciate that naturally occurring planetary nuclear fission reactors could theoretically produce substantial internal power for long durations. As a first step toward this end, I assumed planetary compositions of unfractionated solar matter with present-day abundances of uranium and thorium converted entirely into fissionable isotopes. Numerical estimates of the nuclear fission energy release thus calculated are presented in Table 2 with values of the internal power production of the giant planets from a recent tabulation by Pearl et al. [11]. The outer planets deviate from solar composition, however, and estimates of the degree of fractionation, or heavy-element enrichment, vary considerably [40–44]. Figure 4, which incorporates the data from Table 2, shows,

Table 2. Internal power production of the giant gaseous planets. Also, for equivalent masses of solar composition, uranium content, thorium content, and estimated maximum energy production possible by nuclear fission assuming complete conversion of uranium and thorium into fissile isotopes

Parameter	Jupiter	Saturn	Uranus	Neptune
Planetary internal power [W] (from [11])	$3.4 \times 10^{17}$	$8.6 \times 10^{16}$	$3.4 \times 10^{14}$	$3.3 \times 10^{15}$
Uranium content [g] (based on [69])	$1.0 \times 10^{20}$	$3.1 \times 10^{19}$	$4.7 \times 10^{18}$	$5.5 \times 10^{18}$
Thorium content [g] (based on [69])	$3.7 \times 10^{20}$	$1.1 \times 10^{20}$	$1.7 \times 10^{19}$	$2.0 \times 10^{19}$
Maximum fission energy solar mass equivalent [W s]	$3.7 \times 10^{31}$	$1.1 \times 10^{31}$	$1.7 \times 10^{30}$	$2.0 \times 10^{30}$

for various heavy-element enhancement factors, the durations that nuclear fission energy alone might theoretically power the giant gaseous planets at their present power levels. The times would obviously be extended were other energy sources involved, for example, gravitational potential energy release. The theoretical criticality results for a thermal neutron chain reaction, shown in Fig. 3, would tend to imply the necessity for some reactor operation more than about 600 million years ago to initiate fuel "breeding". At such times the abundances of uranium and thorium would have been greater than at present. Assuming present-day abundances in the calculations may lead to an underestimate; assuming 100 % conversion may lead to an overestimate. The values adopted for the calculations are equivalent to assuming abundances of uranium and thorium 600 million years ago and assuming a 96 % conversion factor. Such a value for the conversion factor may not be unreasonable for planetary nuclear reactors, considering the high matter densities and high neutron fluences that might be involved and considering the mechanism suggested in the present paper for removal of reactor poisons. In any case, disparities of more than a factor of two exist between estimates of the abundances of the actinides [69, 70]. To minimize overestimation, the lowest abundance estimates were used in the calculations. It is important to emphasize that the output energy of a naturally occurring nuclear reactor need not be constant. Various factors can alter the power output, for example, changes in the fuel composition, changes in

the fuel to moderator ratio, physical changes in the positioning or dimensions of fuel, changes in pressure or temperature, accumulations in the fuel of elements with high neutron capture cross-sections, and possibly other effects. It is tempting to speculate that Uranus' low excess radiated power, relative to that of Jupiter, Saturn, and Neptune, may be the result of nuclear reactor shutdown, for example due to one or more of these factors. It is likewise tempting to speculate that higher levels of reactor operation in times past might have caused elevated temperatures and, consequently, losses of hydrogen and helium from the giant planets. The idea of the possibility that naturally occurring planetary nuclear fission reactors are responsible for internal energy production in the giant planets is suggested for the first time in the present paper. The feasibility of that suggestion is supported by the theoretical results presented and is reasonable to consider because neutron moderators, especially hydrogen, occur in far greater abundance in the giant planets than in the Earth. The strongest evidence in support of this idea, however, is the discovery of an actual, naturally occurring, terrestrial, nuclear fission "breeder" reactor. Future deep probe missions to the giant planets should be equipped to investigate the origin and nature of the excess internal energy production.

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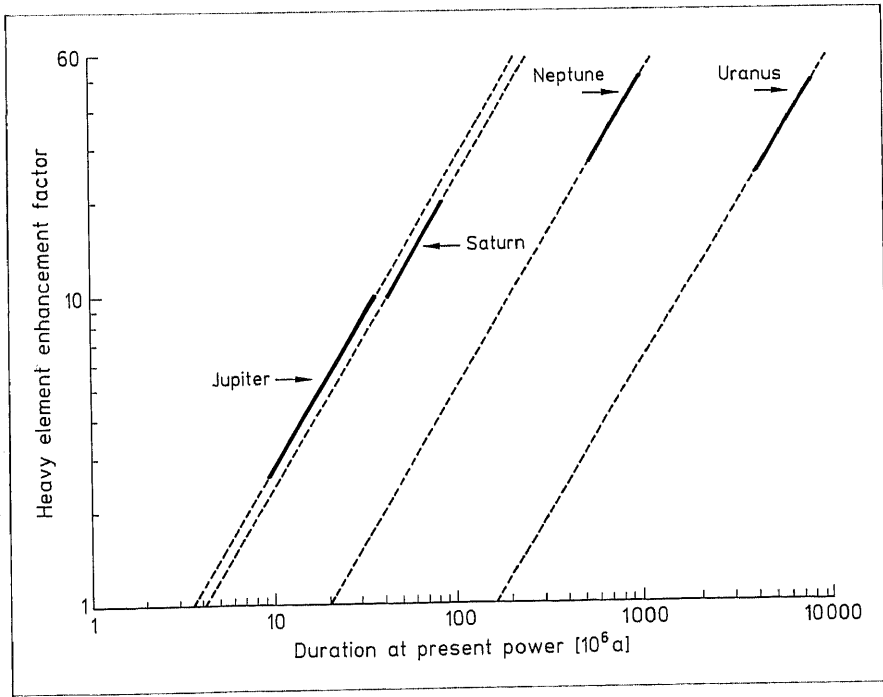


Fig. 4. The duration that present planetary power output levels could be sustained by nuclear fission energy as functions of the heavy-element ( $Z > 2$ ) enhancement factor, relative to solar composition. The solid portion of each line shows the range of heavy-element enhancement factors considered in planetary models [40 - 44]

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