Hydrological Sciences - Journal - des Sciences Hydrologiques, **36**, 1, 2/1991

Water in the Universe

VINCENT KOTWICKI
Engineering and Water Supply Department, PO Box 1751, Adelaide 5000, Australia

Abstract Water appears to be one of the most abundant molecules in the Universe. It dominates the environment of the Earth and is a main constituent of numerous planets, moons and comets. On a far greater scale it possibly contributes to the so called "missing mass" of the Universe and may initiate the birth of stars inside the giant molecular clouds. This paper gives a brief description of water and ice environments with an emphasis on their possible origin and subsequent development in the Solar System. Expanding the scope of hydrology to cover phenomena encountered on other celestial bodies is postulated and discussed.

L'eau dans l'Univers

Résumé L'eau semble être la molècule la plus rêpandue dans l'Univers. Elle règne dans l'environnement terrestre et est une composante principale de nombreuses planètes, satellites et comètes. A une beaucoup plus grande échelle, elle pourrait se trouver à l'origine de la "masse manquante" de l'Univers et participer à la naissance des étoiles dans de gigantesques nébuleuses. L'article fait une brève description de différents milieux constitués par l'eau ou la glace, en mettant l'accent sur leur probable origine et leur développement dans le Système Solaire. L'extension de l'hydrologie aux phénomènes existant sur d'autres planètes y est viverment défendue et discutée.

INTRODUCTION

Where do rivers come from? Although to a mind educated in modern earth sciences the answer appears to be relatively simple nowadays, a surprisingly wide gamut of astonishing concepts can be heard from the general public, even now, when the question is suddenly cast to the wind. One should not be startled, however: as Biswas (1970) narrates, throughout the centuries billions of human beings and all the powers of ancient philosophy have not been able to arrange the jigsaw pieces of the hydrological cycle into one clear picture. Some hints on the ceaseless circulation of water could be found in Ecclesiastes (*c.* 350 BC) and Lu'Shi Chun Qiu (239 BC) but the details were probably poorly understood. The principle of the hydrological cycle was presumably grasped by Theophstratus (371–288 BC) whose ideas were adopted by a few, especially Vitruvius (50–26 BC). Centuries later Perrault (1674)

Open for discussion until 1 August 1991

reviewed numerous concepts of his predecessors and rationally came to the right conclusion, but it is Mariotte (1620–1684) who should be named the father of quantitative hydrology: in 1684 he conclusively proved that rainfall is the source of water discharged by springs and rivers.

Where do the oceans come from? Many and strange theories have been advanced, yet if someone claims to know the answer, the only thing certain is that he is bound to be wrong, as the proportions of water which have terrestrial and extraterrestrial origin are so far unknown. Other questions emerge from this: for example, is there more or less water on Earth as eons pass? There is nothing constant in nature but, frankly, the direction of the change is not known.

What is the origin, quantity and purpose of water in the Cosmos? Such questions were not being asked several years ago. But now, it begins to appear that somebody (perhaps hydrologists?) will have to deal with the most important substance of this Universe.

ORIGIN OF WATER

Speculations on the origin of our Universe have recently gone as far as proposing a primordial vacuum, in which virtual particles materialized randomly from quantum fluctuations of space over an infinite period of time, until one particular particle with exactly zero energy emerged, absorbing an unlimited amount of energy from the vacuum, and exploded, thus creating our Universe in an event commonly referred to as the Big Bang. It is further speculated that an infinite number of Universes with very different properties could have emerged simultaneously: water, therefore, is not necessarily to be found in all of them.

The development of our Universe has been successfully described in mathematical terms from 10^{-35} s after its creation, which supposedly happened some 15 billion years ago. The consensus generally exists that the Big Bang created two elements only: some 80% of hydrogen and 20% helium, which in time formed into galaxies and generations of short-lived stars. All the chemical elements - oxygen, carbon, iron and the rest - of which man and the Earth are made, were built up from these primordial elements by nuclear transmutations inside stars which existed before the Solar System was formed. As shown by the abundance of heavier elements, our Sun is an n-generation star and it is often enunciated that the Solar System is built from the ashes of dead stars. Interestingly, some ancient scripts (Neher, 1975) say that twenty six attempts, all of which were destined to fail, precede the present genesis, and that the world of Man was created from the debris of the previous worlds.

Synthesis of oxygen and other heavier elements continues today in two basic types of stars. Firstly, inside stars more massive than the Sun, destined to become supernovae, silicon, neon, carbon, oxygen and iron are formed by thermonuclear fusion during the short lifetime of these blue giants, in the ever-increasing temperatures and pressures which are necessary to release the energy required to support their collapsing outer layers. When atoms for the exothermic fusion become no longer available, these stars implode, producing most of the elements of the Mendeleev table in an instant. Their shattered outer layers explode, dissipating a mist of stellar material, and injecting heavy elements into other interstellar clouds which have a mass exceeding by millions of times that of the Sun, and which contain a significant proportion of water molecules. Alternatively, in the case of those medium-size stars similar to our Sun which slowly swell to become red giants, when their surface cools, atoms of oxygen, silicon and metals condense into grains of silicate rock and water. These so-called planetary nebulae disperse into other molecular clouds from which in time, new generations of stars condense. Perhaps they in turn have a watery baptism: as Bailey (1987) notes, powerful stellar winds and outflows from young stars produce dense decelerating shells which are an excellent environment for the growth of large interstellar grains by coagulation. In this way, the customary sprinkling of planets and comets may be added to a newborn star. The circumstellar disks can in turn be partially evaporated (Stern *et al.*, 1990) when stars leaving the main sequence enter a luminous phase.

The cosmological engine works on a grand scale: each second tens of supernovae (on average one supernova per century in a galaxy, our last SN 1987A in the Large Magellanic Cloud) burst in the Universe, discharging millions of Earth's masses of enriched material into space. Whether the mechanism works on the recently discussed anthropic principle - saying that the Universe is just (surprisingly and incomprehensibly) right for us - is unknown and may remain a matter of personal belief for a considerable span of time. In the meanwhile, many will be busy trying to prove or disprove the controversial Gaia hypothesis (Lovelock, 1989), which proclaims the Earth a living organism, still evolving and shaping the environment of the planet to its own advantage. The concept of the Intelligent Universe (Hoyle, 1983) will appeal to others. One can expect that more such ideas will see the light of day. Pro and contra concepts will fall thick and fast; the nature and role of water is likely to remain a focal point of any such considerations.

WATER ON EARTH

The Earth, a "water planet" contains some 0.07% water by mass or 0.4% by volume. Left to itself in space, this water would create a sphere 2400 km in diameter, big, but smaller than numerous icy bodies in the Solar System. Many publications quote, with small variations (except for the residence times which vary widely from author to author and which recently have received more attention), the contents of Table 1 as the summary of water resources of the Earth (which is strictly speaking incorrect, as large quantities of water in the crust and mantle should also be taken into account if the water balance of the planet is contemplated). It is interesting to note that the first scientific reasoning on the water balance of the Earth came from the realms of celestial orbits: it can be traced to Copernicus (1543), who, as well as being a keen astronomer, had also a good grasp of hydrology, contemplating in the opening chapters of his revolutionary book how the Earth forms a single sphere with water and concluding that there is little water in comparison with land, even though more water perhaps appears on the surface.

Table 1 *Water balance of the Earth's hydrosphere*

Water storage	*Amount* 10^3 km^3	*Surface equivalent* m	*Flux* * 10^3 km^3	*Mean residence time*
Total	1.46×10^6	2862	E=520	2800 years
Oceans	1.37×10^6	2650	E=449	3100 years
Inactive groundwater	56×10^3	110		
Frozen water	29×10^3	57	R=1.8	16000 years
Active groundwater	4×10^3	8	R=13	300 years
Lakes	230	0.45	E=3	76 years
Soil water	65	0.13	E+R=85	280 days
Atmosphere	14	0.03	P=520	9 days
Rivers	1.2	0.002	R=36	12 days
Biological water	0.7	0.001		7 days

** R = runoff; E = evaporation; and P = precipitation.*

Table 1, based here on Kalinin (1968), encompasses both the zones of active groundwater exchange and inactive groundwater, but it should be remembered that the total amount of water under our feet is much larger (see Table 2). Kalinin, well aware of this fact, quotes Vernadski who in 1936 estimated this quantity as 1.3×10^9 km^3 for a 20–25 km crust thickness, including water in various states and bonds with minerals, and Makarenko who in 1966 evaluated that a 5 km crust contains 1.9% of free gravitational waters, 5.1% physically bound water and 5% chemically bound water. Both these estimates represent approximately the volume of the world ocean. Deles came to a similar figure of 1.2×10^9 km^3 for all water in the ground in 1861 (Pinneker, 1980). Fyfe *et al.* (1978) maintain that the crust, which has a mass of 2.3×10^{25} g, must contain about half the mass of water that is in the

Table 2 *Estimates of inactive water in the crust and the mantle of the Earth*

Author	*Layer*	*Total mass* kg	*Inactive water* %	*Volume* (10^{15} m^3)
Deles (1861)	*Water in ground*			1200
Vernadski (1936)	*Crust (25 km)*			1300
Poldervaart (1957)	*Crust*			80
Vinogradow (1959)	*Mantle*			2000
Makarenko (1966)	*Crust (5 km)*		10.1	60
Kalinin (1968)	*Crust (5 km)*			56
Lvovich (1974)	*Crust (5 km)*			70
Ganapathy & Anders (1974)	*Crust and mantle*		0.11	4400
Fyfe et al. (1978)	*Crust*	23×10^{21}	3	700
Fyfe et al. (1978)	*Mantle*	4×10^{24}	0.03	1200
Anderson (1989)	*Crust*			60
Ahrens (1989)	*Mantle*			2800

oceans and that the mantle (mass 4×10^{27} g) would need a water content of 0.03% to carry the equivalent of the hydrosphere mass. Thus, they say, the mass of water in the hydrosphere, crust or mantle appears to be similar. Subduction carries water to depths of hundreds of kilometres at a rather fast rate: the proportions of water returning to the surface or bound as the result of presumed cooling of the planet are presently unknown. It seems possible (Van Andel, 1985) that the Earth's surface is losing water to the mantle through subduction of oceanic sediments and crust. Geomorphologically, the circulating water is a powerful transporting agent, possibly critical for ore deposition. The first direct evidence of this is the Kola Peninsula Bore, which at the depth of 12 km shows surprisingly large quantities of hot, highly mineralized water.

The origin of water on Earth is by no means certain and numerous mechanisms have been advocated. They fall into three basic groups: condensation of the primary atmosphere, outgassing of the interior, and extraterrestrial fallout.

The condensation theory, once universally sanctioned, has fallen into disfavour as current models of the primordial nebula and evolving Earth require that the primary atmosphere consisted mainly of hydrogen, helium, ammonia and methane. This atmosphere would have been blown away by the intense solar wind during the so called T-Tauri stage of the protosun. Adherents of the condensation theory tended also to forget that no Earth's atmosphere could hold all the waters of the planet in suspension: for example, the atmosphere now holds only 0.001% of the world ocean volume.

Present composition shows that the atmosphere is secondary, and suggests both its geological and biological origin. Similarly, the hydrosphere is believed to be outgassed (Rubey, 1951) and condensed from the interior of the planet. However, this theory needs further investigation, as in fact there should be (Van Andel, 1985) some 20 to 40 times more water on Earth, depending on which meteorite material would have been its main component. In this respect one should not ask: "Where does the water come from?" but "Where is the missing water?". The latter is perhaps the question which planetologists should ask more often.

Historically the timing of the emergence of the oceans was a matter of considerable dispute: according to Kuenen (1950) oceans were created early and rapidly in the Earth's history, Rubey (1951) promoted a continuous steady accumulation, whereas Revelle (1955) was of the opinion that they were formed late and rapidly. Water outgassed from the interior of the planet comes from at least two sources: from surfacing terrestrial and oceanic basalts and from volcanic eruptions. Schopf (1980) calculates that some 0.25×10^9 km^3 of water was released from basalts during the last 3.5 billion years and concludes that basalts alone cannot explain the emergence of oceans. Quoting existing evidence, he says that the majority of outgassing happened between 4.6 and 2.5 billion years ago. New research (Staudacher & Allegre, 1982) indicates that the Earth outgassed rapidly, in some 50 million years after its accretion. Further developments in this area are summarized in Holland (1984b) and Kump (1989). Pinneker (1980, and references therein) estimates that 3.4×10^9 km^3 of water evaporated from the mantle, which he considers the source of all natural water on Earth.

As Meier (1983) recognizes, the questions of outgassing and of tectonic movement of water are of importance for hydrologists in refining global water balance calculations. They are also of prime interest for planetologists: as Condie (1989) explains, the volatile contents and especially the water content of planetary mantles and the rate of volatile release are important in controlling the amount of melting, fractional crystallization trends and the viscosity of planetary interiors which in turn affect the rate of convection and heat loss which are important in terms of evolutionary state.

Some do not agree with the outgassing scenario altogether: Hoyle (1978), implicitly stating that water resides on the surface of our planet only, expressed a view that the ocean and the carbon dioxide present nowadays in the limestone rock have not come from outgassing from the Earth. They were, he argued, later additions, a residue from the accumulation of Uranus and Neptune, which happened to cross the Earth's orbit during some 300 million years after the formation of the Solar System.

It is now well established that the Earth, both in geological and in present times, is exposed to various cosmic collisions (Shoemaker, 1984; Alvarez, 1987). Extraterrestrial origin of the Earth's water is, therefore, possible, and comets (Whipple, 1976, 1978; Chyba, 1987) are commonly targeted as the potential water supplier. Estimates of the quantity of water acquired in this way in the early stages of the evolution of the Earth range from 4 to 40% (Chyba, 1987) or more (Hoyle, 1978) of the world ocean volume. Some data (Frank *et al.*, 1964) seemed to suggest that this amount might have been further supplemented by some 1 km^3 $year^{-1}$ in the form of as many as 10^7 mini-comets, each with a mass of about 10^5 g, hitting the Earth's atmosphere each year. This particular hypothesis has been disproved (Kerr, 1989). However, one should not doubt that recent water acquisitions are plausible. Ahrens (1989) points out that the Earth continues to accrete material containing water and puts the water budget of the mantle in the range of at least two world oceans.

Considering other exotic sources of water, the Sun loses some 4×10^{12} g s^{-1} of its matter in the form of solar wind, whose ionic composition reflects probably that of the solar corona which contains 0.77% of oxygen. This suggests that some 3×10^{10} g s^{-1} of potential water is emitted into space: in the lifetime of this star it amounts to a mass equal for example to some 10 billion 10 km diameter comets. As Taylor (1982) points out, hydrogen from the solar wind could be an additional source of water from the reduction of FeO. This would apply to all terrestrial planets and the Moon which is often classified as a terrestrial planet. Another possibility (Pinneker, 1980) is that water forms in the atmosphere, where, at a height of 250–300 km, atoms of hydrogen and oxygen may form molecules of water. A vastly greater amount is, however, probably lost from the Earth to interplanetary space.

How long will the water on Earth last? Whereas Kulp (1951) estimates that 1.0×10^9 km^3 have so far dissociated into hydrogen and oxygen and vanished into space, Shiklomanov & Sokolov (1983) state that, at present, there are no grounds to speak about any significant positive or negative water exchange between the Earth's atmosphere and space. The escape rate seems indeed to be low. Kasting

(1989) using a one dimensional globally-averaged model to calculate the escape of hydrogen, concludes that the present atmosphere is marginally stable with respect to water, and with the present escape rate, it will take some 7 billion years to lose the world ocean. This corresponds to a water escape rate of 7 m^3 s^{-1}. As Kasting further explains, because the Sun is currently increasing its luminosity by about 1% every 100 million years, the critical solar flux for water loss could be reached within about one billion years, much shorter than the five billion years during which the Sun is expected to remain in the main sequence. This is not to say that time is running out right now, but ultimately, water loss will become a problem for the wellbeing of our planet and its inhabitants.

WATER IN THE SOLAR SYSTEM

The Solar System, as usually defined, extends 6×10^9 km from the Sun to the orbit of its outermost known planet, Pluto. Technically, the gravitational sphere of influence of the Sun reaches about halfway to the nearest star, some 2×10^{12} km, and changes in time as stars change their position. The Solar System is distinctively well defined, the distance to the nearest star exceeds 3000 times its diameter, but definitely not unique. So far astronomers have found some 10^{11} galaxies more or less similar to our Milky Way galaxy. There are, on average, 10^{11} stars in a galaxy and many of them may possess planets.

It is now usually accepted that members of the Solar family assembled from the cold solid and gas particles of the spinning Solar nebula in the relatively short time of 100 million years (Weatherill, 1980). They passed through periods of intensive bombardment, vertical differentiation of bigger bodies, outgassing, and other processes in the formation of what is presently called the Solar System. A significant amount of primordial water might have been lost in this process. It is widely accepted (Torbett, 1989) that in the order of 90% of icy planetismals have been sufficiently gravitationally deflected by close approaches to protoplanets to have been ejected from the Solar System into interstellar space. As these are unlikely to be seen again, an inventory of the remainder will be made.

Planets

In increasing distance from the Sun there are four terrestrial planets, (Mercury, Venus, Earth and Mars) followed by four gaseous giants (Jupiter, Saturn, Uranus and Neptune). The small icy Pluto closes the system (Table 3) as the existence of a long-sought-after Planet X (Whitmire & Matese, 1985) has not been confirmed yet.

Starting from the terrestrial planets, there is no evidence of the presence of water on Mercury, either now or in the past. Its outgassing must have been quite complete, with every molecule of water decomposed by ultraviolet solar radiation and swept away by solar wind. The planet lacks atmosphere and resembles our Moon, both in size and in its heavily cratered surface.

Table 3 *Planets*

Planet	*Diameter (km)*	*Known moons*	*Mass (Earth = 1)*	*Density (Water = 1)*	*Distance from the Sun (A.U.)*	*Albedo*
Mercury	*4 878*	-	*0.055*	*5.5*	*0.387*	*0.06*
Venus	*12 103*	-	*0.81*	*5.2*	*0.723*	*0.76*
Earth	*12 756*	*1*	*1.0*	*5.5*	*1.0*	*0.29*
Mars	*6 794*	*2*	*0.11*	*3.9*	*1.523*	*0.16*
Jupiter	*142 800*	*16*	*318*	*1.3*	*5.202*	*0.34*
Saturn	*120 000*	*17*	*95*	*0.7*	*9.538*	*0.33*
Uranus	*52 400*	*15*	*15*	*1.3*	*19.181*	*0.5*
Neptune	*50 500*	*10*	*17*	*1.7*	*30.038*	*0.5*
Pluto	*2 284*	*1*	*0.002*	*1.9*	*39.44*	*0.5*

A.U. - Astronomical Unit = 150 000 000 km

Venus, although a twin planet of the Earth in size, has surprisingly little water in its carbon dioxide atmosphere, an equivalent of a 0.1 m deep layer. However, no water exists on its mainly calcite surface which, with a temperature of 650 K and clouds of sulphuric acid overhead, resembles a classical vision of Hell. The question of water on Venus is dilemmatic and by no means answered completely (Donahue *et al.*, 1982; Greenspoon, 1987; Kasting, 1988). If Venus once had water, where is it now? And if Venus never had oceans, why not? It is likely that Venus had an amount of water comparable to that of the Earth; however, with the runaway greenhouse process, the oceans evaporated and the water dissociated by solar radiation. In this case the oxygen was absorbed by the rocks and the free hydrogen escaped into space. The other alternative is that perhaps Venus formed so close to the Sun that water from the solar nebula never condensed on the planet. In this case Venus should, however, contain some water of later cometary origin. To make things more difficult, no trace of free oxygen has been found in the Venusian atmosphere. The recent Magellan mission will search by radar for evidence of ancient ocean terraces, river beds and deltas or other features which would point towards the past existence of running water on its surface.

Mars, the only planet to which a manned flight is presently envisioned, is a red, frigid wasteland, similar to some of our stony deserts (for example the Strzelecki Desert in Australia). Estimates of the amount of water outgassed from Mars based on the composition of the atmosphere range from 6 to 150 m, but numerous erosional and depositional landscapes and several indicators of ground ice suggest that at least 500 m of water have outgassed (Carr, 1987). Some possible sources of surface runoff include, for example, volcanic interactions with ground ice, geothermal melting of ground ice, eruption of water under pressure from confined aquifers or cometary impacts. This implies significant groundwater resources, estimated between 1.2×10^7 and 6×10^7 km^3 (Risner, 1989). At the surface, some 2.3×10^6 to 9×10^6 km^3 of water ice can be found at the poles, under the layer of solid carbon dioxide which sublimates in summer. The carbon dioxide atmosphere which Mars is losing at the rate of 1–2 kg s^{-1} contains 10 μm of water, close to saturation at night temperatures (200 K). Hydrological cycle models indicate that Mars has an active but nearly static hydrological cycle, dominated by water recharge in the ice-covered poles. Groundwater flows play a major role in this system. Significant progress in understanding of these phenomena is expected through the Martian Surface and Atmosphere Through Time (MSATT) project (NASA, 1989).

Asteroids, also called minor planets, are located mainly between the orbits of Mars and Jupiter. They range in size from the 900 km diameter Ceres downwards, and although orbits of more than 4000 of them have been computed and an estimated 20 000–30 000 smaller bodies were discovered by the Infrared Astronomical Satellite, their total mass is of the order of only 0.003 of the Earth's mass. The amount of water in them ranges from 0.5%, typical for siliceous meteorites, to 20%, characteristic for carbonaceous chondrites, the most primitive meteorites which comprise about 70% of all observed meteorite falls on Earth. Although not plentiful by astronomical standards (10^{20} kg?), water in the minor planets may prove valuable in future space exploration.

Jupiter, the biggest planet, whose mass is greater than that of all of the other planets put together, hides its interior under a dense layer of ammonia ice crystals, revealing in breaks deeper layers of clouds, including both those of water and water ice. Although the planet is about 70% hydrogen, it also contains huge quantities of oxygen, nitrogen, carbon, silicon, aluminium and other heavy elements. The amount of water is, however, hard to estimate. Two processes are worth mentioning apart from water acquisition from primordial nebula: firstly, Jupiter's allocation of comets must be greater than that of any other planet and secondly, if Jupiter has a rocky core (estimated to be some 14 times heavier than the Earth), such a core should have perspired its water at one time or another. More details will be known in the early 1990s, when the Galileo spacecraft will spend 20 months in orbit around Jupiter and will release a probe into its turbulent atmosphere.

Saturn, the most beautiful celestial body known, owes its splendour to spectacular celestial display of frozen water. Its eminent rings are poor reflectors of sunlight at certain near infrared wavelengths, which indicates water ice. Particles of rings vary in size from grains to blocks tens of metres in diameter, while their thickness is only 100–150 m. The atmosphere of the planet is 94% hydrogen and 6% helium. Under layers of haze, ammonia and ammonia polysulphide, blue water clouds can also be seen. The planet has the lowest density in the Solar System, and it has been quipped that Saturn would float on water if a suitable ocean could be found. The Cassini probe, expected to be launched in 1993, will orbit Saturn and drop a probe into the atmosphere of its moon Titan.

Uranus and Neptune are similar in size and supposedly in composition: Tarbett (1989) says that, compositionally speaking, they can be considered as giant collections of comets. The three-layer model of these planets features a gaseous atmosphere, a liquid ocean and a rocky core. The two-layer model, preferred after Voyager missions, has a superdense atmosphere containing up to 50% water, and a rocky core. Undoubtedly, the interior of these planets is one of the most intriguing in the Solar System: some theories suggest, for example, a superheated ocean, some 8000 km deep.

Pluto is a unique world, in a class of its own in the Solar System. Detailed calculations of its orbit (taking into account chaos theory) cannot reveal its origin, and over time Pluto has been considered to be a planet, an escaped moon of either Neptune or Uranus, a comet, or a gigantic asteroid, signalling possibly a new asteroid belt. Newest observations (Hebest, 1989) allow us to deduce that Pluto consists of three-quarters rock and one-quarter water ice. No assignment is planned to this intriguing planet. With conventional engines, the mission would require some 70 years to complete, but with ion engines, presently tested, the trip would take two months, which would make Pluto an extremely attractive target.

Moons

Moons, the largest of them shown in Table 4, display extraordinary variety, and offer some clues to the origin of our planetary system. Foreshadowing the Voyager 2 results, Prentice revived and extended the 1796 vintage Laplace theory on the formation of the Solar System (Maddox, 1989). This proposed a spherical nebula which rotated more and more rapidly as it contracted under its own gravity and shed rings of gas which gave rise to planets and, in a similar way, moons. Distribution of water in this primary nebula is probably reflected in the contemporary composition of moons.

Mercury and Venus have no satellites, Mars has two tiny, rocky, asteroid-like moons and the Earth technically forms a double planet system with its companion. Although, as can be seen in Taylor (1975, 1982), oxides are plentiful on the Moon's surface, H_2O is not one of them. Water is effectively absent from the Moon, and any trace of it (the unique "rusty" rock sample comprised of geothite FeO.OH) appears to be terrestrial contamination. This led

***Table 4** Largest moons in the Solar System*

Planet	*Satellite*	*Mean diameter km*	*Density g cm^{-3}*	*Albedo*	*Ice/rock ratio*
Earth	*Moon*	*3 476*	*3.3*	*0.1*	*rock*
Jupiter	*Io*	*3 630*	*3.5*	*0.6*	*silicates/sulphur*
	Europa	*3 140*	*3.1*	*0.6*	*70 km ice crust 100 km water mantle*
	Ganymede	*5 276*	*2.0*	*0.4*	*ice/rock 50/50*
	Callisto	*4 820*	*1.8*	*0.2*	*300 km ice crust 1000 km water mantle*
Saturn	*Mimas*	*390*	*1.4*	*0.7*	*ice*
	Enceladus	*500*	*1.2*	*1.0*	*ice/rock 60/40*
	Tethys	*1 050*	*1.2*	*0.8*	*ice*
	Dione	*1 120*	*1.4*	*0.5*	*ice/rock*
	Rhea	*1 530*	*1.3*	*0.6*	*ice/rock 50/50*
	Titan	*5 130*	*1.9*	*0.2*	*ice/rock 50/50*
	Iapetus	*1 440*	*1.2*	*0.5*	*ice*
Uranus	*Miranda*	*500*	*1.2*	*0.3*	*ice*
	Ariel	*1 160*	*1.5*	*0.4*	*ice/rock*
	Umbriel	*1 100*	*1.5*	*0.2*	*ice/rock*
	Titania	*1 600*	*1.5*	*0.3*	*ice/rock 40/60*
	Oberon	*1 600*	*1.5*	*0.3*	*ice/rock 40/60*
Neptune	*Triton*	*2 720*	*2.1*	*0.7*	
	1989 N1	*200*		*0.1*	
	Nereid	*240*		*0.1*	
Pluto	*Charon*	*1 192*	*1.3*	*0.5*	*ice/rock*

some to declare that the Moon is waterless "millions of times more than the Sahara Desert", although, on one occasion, the Apollo 15 mission detected an unexplained cloud of water vapour near its surface. Chyba (1987) thinks that several sources of lunar water during the past 2 billion years (including recent cometary impacts) probably each supplied 10–100 km^3 of water. Its complete absence testifies to a high efficiency of ejecta, atmospheric blow-off, photo-dissociation and destruction by solar wind (although some water may remain in polar cold traps). A first lunar private mission, planned for 1992, wants to find out from the Moon's polar orbit whether the deep polar craters hold water ice which has evaporated from the lunar surface. Any quantity of water on the Moon would be welcome both for human settlements and as a source of rocket fuel. However, frozen, uncharted oceans begin only when we reach the icy moons of the gaseous giants.

Jupiter has four big satellites, known since the first telescope was invented. Each of them is unique. Io, like Venus, is a medieval vision of Hell, lying in the deadly sphere of Jupiter's radiation, where one metre of lead would be a barely acceptable shield for humans. A gravitational resonance between all three of Io, Europa and Ganymede causes the whole body of Io to flex and the resulting friction produces heat, melting its silicate interior and producing spectacular volcanic eruptions of sulphur. Europa itself is smooth like a billiard ball: no craters are visible, presumably smoothed out by a 100 km deep ocean underlying the solid ice crust. Ganymede, the third satellite, is the largest moon in the Solar System, and is known to exhibit faulting. In this case, the ice, however, is the faulting material. Callisto, with its surface 4 billion years old, and its appearance of dirty ice, is the most heavily cratered body known. It is believed that it has a 300 km ice crust overlying a 1000 km mantle of water or soft ice, and a solid silicon core. Although frozen now, moons of Jupiter, especially Europa, were covered by a liquid ocean when a younger Jupiter emitted more energy than it does now. This would also imply that they had a significant atmospheric pressure to raise the boiling point: otherwise at least a thin ice layer would have to exist on their oceans.

Saturn has the most beautiful collection of icy satellites in the Solar System. The innermost, Mimas, is a regular frosty moon, dominated by the Herschel crater, 130 km in diameter, with an icy peak 6 km high. Enceladus has the distinction of being the most reflective body in the Solar System: it may be still geologically active, with soft ice eruptions due to the gravitational effect of Dione. Tethys in its early stages of evolution consisted of pure water, which on freezing and expansion created the Ithaca Chasm, a huge trench 100 km wide and 4.5 km deep, extending around its globe from its north to south pole. Dione is roughly the same size as Tethys but is much denser, suggesting a higher rock content: this is further confirmed by the significantly lower albedo. Rhea, of which images of greatest resolution were taken, shows an icy world, with numerous craters left after the "big bombardment". Titan is the only satellite with an atmosphere, which, contrary to previous beliefs, is composed of nitrogen rather than methane. Much has been written concerning its surface temperature of 94 K, which is close to the triple point of methane which could form seas, rivers, cliffs and icebergs on Titan. However any resemblance to Earth conditions is rather superficial and variations in temperature are probably too small. Iapetus closes the big array, and consists of almost pure ice, showing striking differences in brightness. Its leading hemisphere is dark, with an albedo of 0.04, resembling the Martian miniature moon Phobos, while its trailing edge is bright, with an albedo of 0.5.

The moons of Uranus are generally darker and show remarkable diversity. Miranda, which has barely enough gravitational pull to form a sphere, has a complex geological terrain, dominated by three enormous ovals, huge fracture zones, steep terraces and cliffs 10–20 km high. Ariel, the brightest Uranian moon, shows evidence of resurfacing by volcanic processes of a relatively warm plastic mixture of ice and rock. Both Miranda and Ariel have an unexpected degree of geological activity for such small bodies, which should be rather permanently frozen. Umbriel, the darkest moon, is exceptional for its almost total blandness. The 4 billion old surface of Titania, rich in water ice, shows evidence of global tectonics of an initially liquid interior which forms plates and cracks on expansion. Oberon is quite similar both in size and appearance to Titania, showing an ancient surface after the "big bombardment". All Uranian moons contain more rock and less water than predicted by existing models of the solar nebula and this fact cannot be readily explained.

"The most mysterious thing encountered during the Voyager 2 trip", Triton of Neptune, was thought to be a static, eternally frozen world. It turned out to be only the third object in the Solar System to have active volcanoes, spewing nitrogen ice particles kilometres high. Triton has few craters. One explanation is that its surface melted completely, another that some kind of large-scale deposition took place. Large flat areas of liquefied and refrozen water resemble volcanic calderas on Earth. The complex topography of Triton and its relatively high density will keep theoreticians occupied for years.

Charon, a companion of Pluto, has a strong spectral line at 2 μm, which is characteristic of water ice. Because of its low gravity, the primary allotment of methane probably escaped into space, exposing its mantle of water ice.

The total amount of water in the moons of the Solar System is of the order of 1.5×10^{11} km^3, that is some 100 times the mass of the world ocean. Contemplating nine polymorphs of ice discovered on Earth, one can wonder how many different forms of solid water will be found on those moons.

Comets

Every 76 years during the past 200 000 years a black object, now peanut shaped and 15 km long, ventures near the Sun, exhibiting on most occasions a fabulous tail by losing some 1% of its mass during each rendezvous. Comet Halley is the best known, but tens of other comets are observed each year, implying both a large quantity and continuous supply.

Where do comets come from? Aristotle asserted that they form in the atmosphere, Hevelius believed that they originated in the Solar System, and Kepler surmised that they form between the stars. Our dilemma is: are they a by-product of the formation of the Solar System or do they fly freely throughout the Universe, contributing to the so-called "missing matter"? Do they initiate the birth of stars in giant molecular clouds which have a mass exceeding a million times the mass of our Sun?

The current wisdom is that 10^{11} comets (a hundred billion is a favoured number in astronomy, meaning "many") circumnavigate the Sun in a static "Oort" cloud (Oort, 1950) stretching halfway to the nearest star. The gross mass is guesstimated to be between 0.1 and five Earth's masses. Some scientists speculate that it may exceed the mass of Jupiter. New information puts rather useful boundaries on our creativity: Anderson & Standish (1986) analysing Pioneer 10 data, limit the suggested mass of any hypothetical belt of comets immediately beyond Neptune to less than five Earth masses.

Nevertheless, such a simplified view faces many challenges (Theokas, 1988; Bailey, 1989). The spiral arms of our Galaxy may be full of cometary material, with clusters of comets captured by our Sun from time to time. However, evidence on the origin of comets is scarce, as comets trapped in the inner Solar System "forget" the direction from which they came. As a lack of sampling material (to determine the deuterium to hydrogen ratio and hence the origin of a comet) allows for too many speculations, picking up a sample from a comet has currently a high priority. In July 1990, the European space probe Giotto which swept past the eye of Halley's Comet in 1986 was successfully redirected to fly within 965 km of comet Grigg-Skjelierup in 1992. The Comet Rendezvous and Flyby (CRAF) project will be launched by NASA in 1995 with a task of firing a penetrator into the crust of a comet.

Amount of water in the Solar System

On our local (very local, indeed) scale, water appears to be in sufficient quantities to satisfy any conceivable needs of the present and future inhabitants of the Solar System. From the whole mass of this cosmic entity, 2×10^{33} g, of which 99.87% is concentrated in the Sun, the amount of water in planets, moons and comets, at 10^{29} g, is a formidable quantity, exceeding 20 times the mass of the Earth or some 100 000 times the mass of the world ocean. Based on existing knowledge, the ratio of the mass of the Sun to the mass of all other objects in the Solar System to the mass of water is of the order of 20 000:20:1. What should be remembered is that the present estimates of the mass of comets may be very conservative and that one day it may be found that they outweigh the Sun.

Just for illustration and a homely comparison, it can be visualized that water circulates in the Solar System in a manner which to some extend resembles our beloved Earth's hydrological cycle. One can imagine that water droplets (comets) form a cloud (Oort cloud) from which they fall to the centre of gravity if specific conditions are met. They can fall onto the Sun and evaporate, blown away by the solar wind back towards their place of rest. The cloud itself can lose or gain some comets from other stars or from molecular clouds through which our Sun passes. Comets falling towards the Sun can be intercepted and find temporary storage on planets and their moons; however, they eventually evaporate back to the cloud, and then a comet one day appears again.

WATER IN THE UNIVERSE

Everyone who ever studied astronomy for their employment or enjoyment knows that the Universe is big. What conclusions could be drawn from this fact in respect to water?

As hydrogen (from Greek "hudor", meaning "water") is so plentiful in the Universe, the synthesis of water depends on the supply of oxygen. The quantity of this element, recalculated from Press & Siever (1978) and shown in Table 5, is probably underestimated. Just recently, for example, astronomers have found that oxygen exists in the so-called "cooling flows", a heavy rain of gas which is falling into many galaxies from the supposedly empty space around them. The amount of this intergalactic "rainfall" can be anything from one to 1000 solar masses per galaxy each year, which is sufficient to double the mass of the largest galaxy over the lifetime of the Universe.

In any case, oxygen is the third most abundant element in the Universe, ranked between the inert gases helium and neon. What is more, oxygen reacts readily with the most abundant hydrogen, creating water, which in turn is one of the most stable chemical molecules. It should not be surprising then if water is found to be one of the most common molecules in this Universe. If, for example comets, which are mostly water ice, form a significant constituent of the "missing mass" which may account for 90% of the Universe, the remote uncharted (albeit mostly frozen) oceans are truly unimaginably big.

Just how big they are remains largely unclear. Considering the visible Universe, stars are numerous (at 10^{22} their quantity exceeds the number of grains of sand on Earth) and in various stages of development. Many of them may possess planets, which seem to be a standard by-product of star formation. Seas, lakes and rivers are more likely to be found in spiral arms of galaxies. The nuclei of galaxies are more star-compacted and have much less stable (and hence suitable) conditions for planet formation and development.

Knowledge of "dark matter" or "missing mass" is still very incomplete. The critical density of the Universe (necessary to stop the Big Bang expansion) works out at about 3 atoms m^{-3}. All matter detected to date falls short of

Table 5 *Abundance of the principal elements in the Universe expressed as the number of atoms relative to a base of 1000 atoms of oxygen (recalculated from Press & Siever, 1978)*

Element	*Atomic number*	*Atomic weight*	*Abundance in the Universe*
Hydrogen	*1*	*1*	*2 000 000*
Helium	*2*	*4*	*150 000*
Oxygen	*8*	*16*	*1 000*
Neon	*10*	*20*	*400*
Nitrogen	*7*	*14*	*300*
Carbon	*6*	*12*	*160*
Silicon	*14*	*28*	*45*
Magnesium	*12*	*24*	*42*
Iron	*26*	*56*	*28*
Sulphur	*16*	*32*	*17*

this critical value by a factor of about ten: as there is also ten times as much dark matter exerting its gravitational influence as there is matter in the form of bright stars, it can be concluded that the bright stars represent only 1% of the Universe. If the Sun were a typical star, the amount of water which could be attributed to the visible matter would be significant ($>10^{25}$ Earth masses) although dispersed: a glass of water requires on average 10^{21} km^3 of space to materialize. If dark matter prevails, this amount would be much greater.

Giant molecular clouds with densities from 100 to 10 000 atoms cm^{-3} and masses exceeding by millions of times the mass of the Sun are common features in galaxies. Water molecules in them have been detected. Does water ice in the form of comets initiate the birth of stars in these clouds, acting as nuclei of contraction? How does it affect the creation of planets from rotating nebulae? Questions are many, so far unsolved. Radio astronomers have found that clouds of gas in space consist largely of hydrogen molecules and carbon monoxide. Gas that condenses near a star, at the distance of our four gaseous giants, is heated by the star to form low density ices of methane and water, so a constant supply of these substances appears to be assured.

New announcements are made almost daily and the foundations of our knowledge are trembling. Even the Big Bang theory, so secure still, may fall as an aftermath of the recent commissioning of the Hubble Space Telescope. Just recently, for example, astronomers discovered in the Virgo cluster, some 65 million light years from Earth, a giant hydrogen cloud that could be an unborn galaxy and could possibly provide the first evidence that more star systems are being formed. Conventional wisdom used to place the birth of galaxies in some conveniently remote past.

Trying to establish a temporal pattern of occurrence of water in the Universe requires some stretching of the imagination and a fair dose of conjecture. Considering the Big Bang scenario, water did not exist until a first generation of stars exploded, which could happen fairly quickly, in millions of years only after their condensation from primordial hydrogen. Since then, the amount of water has increased steadily to its present (unknown) quantity and is increasing now. This thesis will be probably easier to prove than the stability of the Earth's water resources.

Considering the future of water, it appears quite poor in the closed Universe scenario, when, billions of years from now, matter, space and time will collapse in a Big Crunch and the existing laws of physics will lose any meaning. Mathematicians so far cannot invent a re-emergence of a new, fresh Universe from this unfortunate state. The future looks somewhat better in the open Universe scenario, in which the Universe would expand forever, carrying its cooling and ultimately frozen assets, including water, towards infinity or to concluding proton disintegration, which some scientists believe could happen on a very respectable but little comprehensible time scale of 10^{6000} years.

AFTERWORD

Of all molecules existing in the Universe, water is probably the most important in terms of quantity and influence, with the notable exception of the hydrogen molecule which illuminates the whole scene.

The Earth is immersed in the sphere of influence of the Sun, virtually bathing in the heliosphere (which at this distance exerts a sizeable 2×10^{-9} of the Earth's atmospheric pressure). The vast majority of phenomena which are discussed in hydrology are driven entirely by this star while the remainder have had a solar origin in recent or remote past. It is therefore conceivable that the understanding of astronomical events will add to our comprehension of hydrological phenomena on both global and local scales.

The hydrological perspective has recently received much attention in the works of Klemeš (1983, 1986, 1988), Dooge (1983, 1984, 1987) and Kundzewicz (1986). With the conclusion of the Voyager 2 mission in August 1989 it is possible to introduce for the first time a "water perspective" of the Solar System. The purpose of such an exercise is to provide both some amusement and a moment of reflection perhaps. Hydrogeology of Mars, glaciology of Miranda, oceanography of Neptune and the occurrence, circulation and distribution of waters in distant worlds are bound to become standard disciplines of hydrology much sooner than most of us tend to believe.

REFERENCES

Ahrens, J. T. (1989) Water storage in the mantle. *Nature* **346**, 122-123.

Alvarez, L. W. (1987) Mass extinctions caused by large bolide impacts. *Phys. Today* July, 24-33.

Anderson, D. L. (1989) *Theory of the Earth.* Blackwell Scientific Publications, Oxford, UK.

Anderson, J. D. & Standish, E. M. (1986) Dynamical evidence for Planet X. In: *The Galaxy and the Solar System,* eds R. Smoluchowski, J. Bahcall & M. Matthews, Univ. Arizona, Tucson, Arizona, USA.

Bailey, M. E. (1987) Giant grains around protostars. *Quart. J. Roy. Astronom. Soc.* **28**, 242-247.

Bailey, M. E. (1989) Comet orbits and chaos. *Nature* **345**, 21-22.

Biswas, A. K. (1970) *History of Hydrology.* North Holland Publishing Company, Amsterdam, The Netherlands.

Bullard, F. M. (1976) *Volcanoes of the Earth.* Univ. of Queensland Press, Queensland, Australia.

Carr, M. H. (1987) Water on Mars. *Nature* **326**, 30-35.

Chyba, C. F. (1987) The cometary contribution to the oceans of primitive Earth. *Nature* **330**, 632-635.

Condie, K. C. (1989) Origin of the Earth's crust. *Palaeogeogr. Palaeoclimatol. Palaeoecol. (Global and Planetary Change Section)* **75**, 58-81.

Copernicus, N. (1543) *De Revolutionibus Orbium Coelestium.* Nüremburg, Johannes Petreius, English translation by E. Rosen (1978) *On the Revolutions.* The John Hopkins Univ. Press, Baltimore, Maryland, USA.

Donahue, T. M., Hoffman, J. H., Hodges, R. R. & Watson, A. J. (1982) Venus was wet: a measurement of the ratio of deuterium to oxygen. *Science*, **216**, 630-633.

Dooge, J. C. I. (1983) On the study of water. *J. Hydrol. Sci.* **28**(1), 23-48.

Dooge, J. C. I. (1984) The waters of the Earth. *J. Hydrol. Sci.* **29**(2), 149-175.

Dooge, J. C. I. (1987) Hydrology in perspective. (Presented at Int. Symp. Water for the Future, IAHS and IAHR, Rome) *J. Hydrol. Sci.* **33**, 61-85.

Frank, L. A., Sigwarth, J. B. & Craven, J. D. (1986) On the influx of small comets into the Earth's upper atmosphere. *Geophys. Res. Lett.* **13**, 303-310.

Fyfe, W. S., Price, N. J. & Thompson, A.B. (1978) *Fluids in the Earth's Crust.* Elsevier, Amsterdam, The Netherlands.

Ganapathy, R. & Anders, E. (1974) Bulk composition of the Moon and Earth estimated from meteorites. *Proc. Lunar Sci. Conf.* **5**, 1181-1206.

Greenspoon, D. H. (1987) Was Venus wet? Deuterium reconsidered. *Science* **238**, 1702-1704.

Henbest, N. (1989) Pluto: the planet that came in from the cold. *New Scient.* **1662**, 21-26.

Holland, H. D. (1984a) Degassing of Earth. In: *Patterns of Change in Earth Evolution,* eds H. D. Holland & A. F. Trendall, Springer-Verlag, Berlin, Germany.

Holland, H. D. (1984b) *The Chemical Evolution of the Atmosphere and Oceans.* Wiley, New York,

USA.
Hoyle, F. (1978) *The Cosmogony of the Solar System.* Univ. College Cardiff Press, Wales, UK.
Hoyle, F. (1983) *The Intelligent Universe.* Michael Joseph, London, UK.
Ingmanson, D. E. & Wallace, W. J. (1973) *Oceanology: An Introduction.* Wadsworth Publishing Co. Inc., Belmont, California, USA.
Kalinin, G. P. (1971) *Problemy Globalnoi Gidrologii.* Gidrometeorologicheskoe Izdatelstwo, Leningrad. Translated into English as: *Global Hydrology.* Israel Program for Scientific Translations, Jerusalem.
Kasting, J. F. (1988) Runaway and moist greenhouse atmospheres and the evolution of Earth and Venus. *Icarus* **74**, 472-494.
Kasting, J. F. (1989) Long-term stability of the Earth's climate. *Palaeogeogr. Palaeoclimatol. Palaeoecol. (Global and Planetary Change Section)* **75**, 83-95.
Kerr, R. A. (1989) Comets were a clerical error. *Science* **241**, 352.
Klemeš, V. (1983) Conceptualization and scale in hydrology. *J. Hydrol.* **65**, 1-23.
Klemeš, V. (1986) Dilletantism in hydrology: Transition or destiny? *Wat. Resour. Res.* **22**(9), 177s-187s.
Klemeš, V. (1988) A hydrological perspective. *J. Hydrol.* **100**, 3-28.
Kuenen, P. H. (1950) *Marine Geology.* John Wiley & Sons, New York, USA.
Kulp, J. L. (1951) The origin of the hydrosphere. *Bull. Geol. Soc. Amer.* **62**, 326-330.
Kump. L. R. (1989) Chemical stability of the atmosphere and ocean. *Palaeogeogr. Palaeoclimatol. Palaeoecol. (Global and Planetary Change Section)* **75**, 123-136.
Kundzewicz, Z. W. (1986) The hydrology of tomorrow. *J. Hydrol. Sci.* **31**, 223-235.
Lovelock, J. (1989) *The Ages of Gaia.* Oxford Univ. Press, Oxford, UK.
Lvovich, M. I. (1974) *World Water Resources and Their Future.* (in Russian) Mysl, Moscow, USSR.
Maddox, J. (1989) Neptune's satellites predicted? *Nature* **6236**, 673.
Makarenko, F. A. (1966) Voda pod zemlei. (Underground water) In: *Krugovorot Vody* (Hydrological Cycle), Izdatelstvo Znanie, Moscow, USSR.
Meier, F. M. (1983) Snow and ice in a changing hydrological world. *J. Hydrol. Sci.* **28**, 3-21.
NASA (National Aeronautics and Space Administration) (1989) The Martian surface and atmosphere through time (MSATT). Res. Announcement NRA-89-OSSA-10.
Neher, A. (1975) Vision du tempts et de l'histoire dans la culture juive. In: *Les cultures et de tempts.* Payot, Paris, France, 179.
Oort, J. H. (1950) The structure of the cloud of comets surrounding the Solar System and a hypothesis concerning its origin. *Bull. Astronom. Inst. Netherlands* **11**, 91-110.
Perrault, P. (1674) *De l'Origine des Fontaines.* Pierre Le Petit, Paris, English translation with commentary by A. Larocque (1967): *On the Origin of Springs,* Hafner, New York.
Pinneker, E. V. (1980) *Obschaya gidrologia.* Izdatelstvo Nauka, Moscow. English translation (1983): *General Hydrogeology,* Cambridge Univ. Press, Cambridge, UK.
Poldervaart, A. (1957) The chemistry of the Earth's crust. In: *The Earth's Crust* Moscow, USSR, 130-157.
Press, F. & Siever, R. (1978) *Earth.* W. H. Freeman & Co.
Revelle, R. (1955) On the history of the ocean. *J. Mar. Res.* **14**, 446-461.
Risner. J. K.(1989) Geohydrology of Mars. *Groundwater* **27**(2), 184-192.
Rubey, W. W. (1951) Geologic history of seawater. *Geol. Soc. Amer. Bull.* **62**, 111-1147.
Schopf, J. M. (1980) *Paleoceanography.* Harvard Univ. Press, USA.
Shiklomanov, I. A. & Sokolov, A. A. (1983) Methodological basis of world water balance investigation and computation. In: *New Approaches in Water Balance Computations.* IAHS Publ. no. 148, 77-90.
Shoemaker, E. M. (1984) Large body impacts through geological time. In: *Patterns of Change in Earth's Evolution,* eds H. D. Holland & A. F. Trendall, Springer-Verlag, Berlin, Germany, 15-40.
Staudacher, T. & Allegre, C. J. (1982) Terrestrial xenology. *Earth Planet. Sci. Lett.* **60**, 389-406.
Stern, S. A., Shull, J. M. & Brandt, J. C. (1990) Evolution and detectability of comet clouds during post-main-sequence stellar evolution. *Nature* **345**, 305-308.
Taylor, R. S. (1975) *Lunar Science - A Post Apollo View.* Pergamon Press.
Taylor, R. S. (1982) *Planetary Science - A Lunar Perspective.* Lunar and Planetary Institute, Houston, Texas, USA.
Theokas, A. (1988) The origin of comets. New. Scient. **1599**, 42-45.
Torbett, M. V. (1989) Solar system and galactic influences on the stability of the Earth. *Palaeogeogr. Palaeoclimatol. Palaeoecol. (Global and Planetary Change Section)* **75**, 3-33.
Van Andel, T. H. (1985) *New Views on an Old Planet.* Cambridge University Press, Cambridge, UK.
Vernadski, V. I. (1936) *Istoria Mineralov Ziemnoi Kory.* (History of Earth Crust Minerals) vol. 2 of *Istoria Prirodnikh Vod* (History of Natural Waters), Izdatelstvo AN, Moscow, USSR.
Vinogradow, A. P. (1959) *Chemical Evolution of the Earth.* Izdatelstvo AN SSSR, Moscow, USSR.

Weatherill, G. V. (1980) Formation of the terretrial planets. *Ann. Rev. Astronom. Astrophys.* **18**, 77-113.
Whipple, F. L. (1976) A speculation about comets and the Earth. *Memoires de la Soc. Roy. de Liege,* 6 ser. **9**, 101-111.
Whipple, F. L. (1978) Structure of the cometary nucleus. (Abstract). Summary of the Workshop on Experimental Approaches to Comets, Lunar and Planetary Contribution, 5-9.
Whitmire, D. D. & Matese, J. J. (1985) Periodic comet showers and planet X. *Nature* **313**, 36-38.

Received 2 January 1990; accepted 30 July 1990