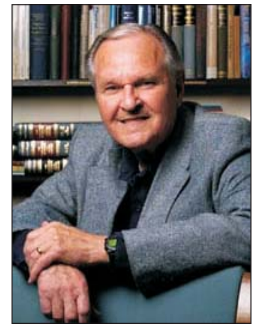

Joseph L. Spradley

Ten Lunar Legacies: Importance of the Moon for Life on Earth*

Joseph L. Spradley

The origin, size, and location of our Moon play a unique and essential role for the existence of life on Earth. Earth's Moon is the largest moon in the solar system in relation to its host planet and appears to have formed in a unique way, compared to all other known moons, by a giant glancing collision. Computer simulations of this giant-impact theory have led to a new recognition of the importance of the Moon for life on Earth. Ten apparently life-sustaining results from a glancing collision and large Moon are summarized, along with their implications for the uniqueness of life on Earth.

It has long been assumed that many earthlike planets exist around the billions of stars in our galaxy, and that life is therefore widespread in the universe.[1] Recent considerations have shown that the conditions for a habitable planet are quite strict and that life on Earth may be a highly unusual result of many unique features of our planet.[2] Many of these life-sustaining features can now be traced to the formation of our Moon, an event that itself is highly random and rare, but appears to be an essential requirement for producing a habitable planet.[3] Such an event is the result of probabilistic natural processes, but can also be viewed as a providential legacy.

Our Moon has several unusual features that have long confounded attempts to explain its origin. It is about fifty times larger than any other moon in the solar system relative to the mass of its host planet. It has the largest angular momentum relative to the mass of the planet about which it revolves. It has a much lower density and much less iron than that of Earth and the other terrestrial planets. The Apollo missions of the early 1970s revealed other unusual features, including a lack of volatiles and evidence that a deep ocean of magma once existed on the Moon.[4]

None of the historical theories for the origin of the Moon could account for all of these unusual features. The coaccretion (sister) theory that the Moon was formed together with Earth out of the proto-planetary disc was suggested by Immanuel Kant in 1755 and developed by Edouard Roche in 1873.[5] However, it could not account for the differences in chemistry and density between the two bodies. In 1898, George Darwin, son of Charles Darwin, introduced the fission (daughter) theory that the Moon was spun off from Earth. Although this theory failed because fission would require a much faster rotation of Earth (about two hours), it did reveal that tidal friction is slowing Earth's rotation and that the Moon was once much closer when

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the day was only about five hours long.[6] In 1909, Thomas Jefferson See proposed the capture (spouse) theory that Earth's gravity captured the Moon as it passed nearby.[7] This theory failed despite efforts by Harold Urey in the 1950s, since there was no accepted way to slow the Moon enough for capture.[8]

The giant-impact theory combines features of all the previous theories and resolves most of their problems. It was first suggested in a 1946 paper by Canadian geologist Reginald Daly at Harvard, but was largely overlooked.[9] After the Apollo program, William Hartmann and Donald Davis began to apply computer programs to the problem of planetesimal formation in the early solar system, and confirmed the power law for the size distribution of planetesimals consistent with crater sizes on the Moon's surface: for roughly every thousand 1-km craters, there are one hundred 10-km craters, ten 100-km craters, and one 1000-km basin. Their work showed that planetesimal accretion by collisions, leading to the formation of Earth, could produce bodies in its accretion zone as large as the Moon. It then occurred to Hartmann that such an object in Earth's orbit could have impacted Earth in a glancing collision to form the Moon. Such a collision would provide vast energy, explaining the Moon's magma ocean, lack of volatiles (evaporated in the collision), and lack of an iron core (sunk into Earth). In 1975, he and Davis published their giant-impact theory.[10]

When Hartmann first presented these ideas in 1974, he learned that Alastair Cameron, another Canadian at Harvard, was working on the same theory with a postdoctoral student, William Ward. An abstract of their work was published in 1976.[11] Using computer simulations of a glancing collision, they could account for the formation of the Moon if the impactor was a Mars-sized object about ten times larger than the Moon. About half of the debris blasted into space by the collision would remain in orbit around Earth and in a few weeks would coalesce to form the Moon, at that time about fifteen times closer than today. The collision would increase the daily rotation period of Earth to about five hours, increase its mass by about 10 percent, and produce a Moon lacking volatiles and an iron core.

Little attention was given to the giant-impact theory until, nearly a decade later, a post-Apollo conference was held in 1984 at Kona, Hawaii, on the origin of the Moon. Several papers were presented on the giant-impact model, leading to an unprecedented agreement among many of the conferees on the advantages of the model.[12] This Kona consensus led to more and improved computer simulations, notably by Cameron, now retired to Arizona, and by Robin Canup at the Southwest Research Institute in Boulder, Colorado.[13] They began using the "smooth particle hydrodynamics" (SPH) method, which had been developed for modeling bomb explosions. These new simulations differentiated between rock and iron "particles" (several thousand of each) and now showed the melted iron core of the impactor falling back and sinking into Earth's core. Accretion models suggest that the giant impact occurred about 40 million years after the formation of the solar system at about 4.57 billion years ago as determined from the oldest meteorites, giving the date for the birth of the Moon at about 4.53 billion years ago. (See Figure 1.)

Several benefits of our Moon have long been recognized, such as illumination of the night sky, the phases of the Moon for keeping time, and the lunar tides for helping to cleanse and oxygenate the oceans. With the growing consensus in support of the giant-impact theory, there has been an increasing recognition that the formation of the Moon was critical in providing the conditions needed for life on Earth.[14] Several authors have suggested this lunar legacy over the last two decades: In his 1993 book *What if the Moon Didn't Exist?* Neil Comins lists three or four of these necessities for life, depending on how they are counted; Peter Ward and Donald Brownlee list about four or five in their 2000 book *Rare Earth*; Guillermo Gonzalez and Jay Richards list about five or six in their 2004 book *Privileged Planet*; and Hugh Ross lists about six or seven in his 2009 book *More Than a Theory*.[15] Summaries of ten such factors essential for life on Earth, which now appear to be related to the formation of a large Moon, are discussed below under the assumption that complex life requires liquid water. The first five of these factors relate to the giant impact itself, and the last five relate to the subsequent influence of the Moon on Earth. Many of these factors are debatable, but they provide a framework for further discussion and research. Arguably, the absence of any one of these lunar legacies might have prevented the existence of life on Earth.

Lunar Legacies for a Habitable Earth

1. Faster rotation rate for Earth. The glancing collision that formed the Moon appears to have given Earth its initial 5-hour rotation rate, much faster than any other planet in the solar system.[16] This rotation rate was sufficiently rapid so that over the time for life to develop, the rate could be slowed by the Moon's tidal action on Earth's oceans to our current 24-hour day, which moderates daily temperature variations and makes photosynthesis a viable possibility. Wide temperature variations occur on Mercury with its rotation rate of fifty-nine days produced by the Sun's tidal action, causing its long 100K nights and 700K days to vary far beyond the freezing and boiling points of water.

Recent computer simulations suggest that Mars also sustained a giant impact, causing the hemispheric dichotomy of southern highlands and northern lowlands.[17] These simulations required an oblique collision at between 30° and 60° to account for the unusual surface of Mars, which apparently gave it a rotation rate similar to that of Earth's current rate, but without enough energy to produce a large moon to slow its rotation. The slow retrograde rotation of Venus (-243 days) suggests a large collision of some kind, reversing its rotation but not forming a moon.[18] Although giant impacts of a random nature appear to have had a variety of effects on terrestrial planets,[19] only Earth gained a large Moon with its favorable results that allow for life.

2. Favorable axial tilt of Earth. The glancing collision that formed the Moon would almost certainly have changed Earth's axial tilt (obliquity), leading sooner or later to its favorable axial tilt of about 23° relative to a perpendicular to Earth's orbital plane (ecliptic) and thus its relatively mild seasonal variations.[20] In the giant-impact model, the debris cloud that formed

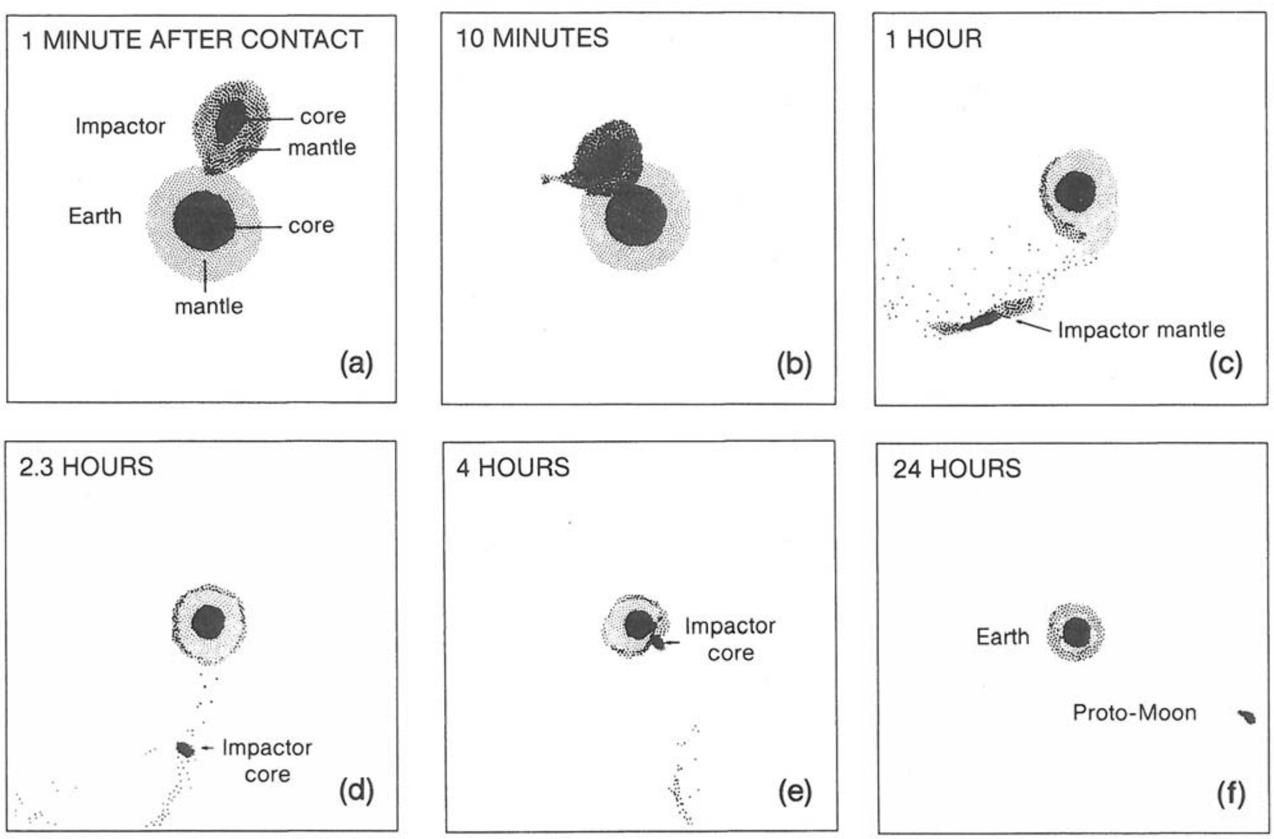

Figure 1. Giant-impact computer simulation for oblique collision of a 0.14-Earth-mass body at a velocity of 5 km/s. It encourages a new appreciation for the special gift of life and an environment suitable for its survival. It echoes the words of Psalm 8:3–4, "When I look at your heavens, the work of your fingers, the moon and the stars, which you have set in place, what is man that you are mindful of him, and the son of man that you care for him?" Figure courtesy of A. G. W. Cameron and W. Benz, Smithsonian Astrophysics Institute, from S. R. Taylor, *Solar System Evolution* (Cambridge, Cambridge University Press, 1992), 159.

the Moon would likely be in the equatorial plane of Earth's rotation, but the Sun's gravity would tend to pull it toward the ecliptic plane. The small (5°) inclination of the Moon's orbit relative to the ecliptic plane remains unexplained, but probably arises from tidal interactions with the Sun and Earth. A large axial tilt beyond 60° would make life difficult due to frozen oceans extending to the equator, and a small tilt would allow little or no seasonal variations to help stimulate evolutionary processes.[21] By comparison, the larger gravity from the Sun on Mercury has resulted in no tilt, which allows for no seasonal variations.

For several years, evidence has suggested that Earth experienced widespread glaciation, reaching nearly to the equator between 800 and 600 million years ago, the melting of which might have triggered the Cambrian evolutionary explosion.[22] The usual explanation for this "snowball Earth" effect is the fact that the early Sun was dimmer and the oceans had absorbed most greenhouse gases such as carbon dioxide. A radical suggestion in 1993 claimed that the axial tilt of Earth was greater than 54° during most of its history, making equatorial regions the coldest part of the planet, and that core-mantle dissipation reduced it to 23° about 600 million years ago.[23] But this does not explain why such viscous dissipation occurred over only a short period of Earth's history. Another suggestion is a process called climate friction (oblateness-obliquity feedback), in which axial tilt shifts from redistribution of glacial ice masses.[24] Recent analysis has shown that such a mechanism can only account for a shift of 3° or 4° over the last 800 million years.[25] Evidence from the growth patterns of an 850-million-year-old stromatolite, assuming growth toward the noontime Sun (heliotropism), suggests a 26.5° axial tilt at that time.[26]

3. Greenhouse gases removed. Several investigators have suggested that a giant-impact formation of the Moon would have stripped Earth of much of its primordial atmosphere.[27] Venus, our nearest planet in both distance and mass, has an atmospheric pressure about 90 times that of today's Earth. The thick atmosphere on Venus consists mostly of carbon dioxide, which traps solar radiation by the greenhouse effect, causing a surface temperature of about 700K that boils away all surface water.[28] Surface water on Earth helps to absorb excess carbon dioxide, but may not have been able to remove quantities like that on Venus without a giant impact.

With Earth's surface in a molten state after the collision, a new atmosphere would form from outgassing and comet collisions. A few million years after the giant impact, Earth's surface would be cool enough to form a crust and for water vapor to condense and form the oceans, which then would begin to absorb carbon dioxide.[29] The reformulated atmosphere on Earth after the collision and water condensation was thin enough to prevent a runaway greenhouse effect and sufficiently transparent to eventually allow photosynthesis to occur with its associated production of oxygen.

4. Strong magnetic field formed. Computer simulations of the giant-impact theory show the molten iron core of the impactor sinking into Earth's iron core (see Figure 1e).[30] Enlargement of Earth's liquid-iron core together with a much faster rotation rate from the giant impact increased Earth's magnetic field to about 100 times larger than any other rocky planet. The dynamo theory of Earth's magnetic field is analogous to the magnetic field from a current-carrying coil of wire (electromagnet), but involves the more complex rotation, convection, and electrical conduction of Earth's liquid-iron core.[31] Such a strong magnetic field deflects the high-energy charged particles in the solar wind, which would otherwise strip much of Earth's atmosphere and threaten any emerging life.[32]

A small magnetic field on Mars indicates a limited iron core as suggested by its low density; in addition the slow rotation rates of Mercury (59 days) and Venus (243 days) produce little or no magnetism to deflect the solar wind. This was confirmed in 2008 when the European Space Agency's Mars Express and Venus Express spacecrafts detected significant atmospheric depletion on both planets due to the solar wind. Apparently the atmosphere on Venus is sustained by large-scale volcanic activity, but Venus Express detected hydrogen and oxygen atoms escaping from the atmosphere of Venus during solar storms, leaving little water vapor in its atmosphere.[33]

5. Stronger gravity holds water vapor. In the giant-impact simulations, most of the mass of the Mars-size impactor is accreted to Earth, increasing its mass by about 10 percent. This increased mass is especially critical in providing sufficient gravity to hold enough of Earth's water vapor in its atmosphere for a long period before condensing to form the oceans.[34] Too much mass might have held even more water vapor, which could have inundated all land and produced a "waterworld" that would support only sea life. The loss of planetary atmospheres is a complex process involving several thermal and nonthermal mechanisms with no single threshold, but the most important factors are temperature and gravity. High upper-atmosphere temperatures produce high molecular speeds, and larger mass and its gravity increase the escape velocity.[35]

The escape velocity for molecules in Earth's atmosphere is more than twice that of Mercury and Mars, which have lost most of their atmospheres even though Mars is much further from the Sun. The escape velocity on Venus is only about 10 percent less than that on Earth, but insufficient to prevent the loss of water vapor by thermal processes and by the solar wind.[36] Some estimates indicate that Venus could have lost an ocean's worth of water in a few tens of millions of years.[37] Water vapor is especially vulnerable to leakage since its molecular weight is among the smallest of atmospheric gases, and dissociation of water molecules by collisions or ultraviolet radiation nearly inevitably leads to loss of hydrogen.

6. Plate tectonics supported by giant impact. Several features of a giant impact appear to have contributed to the unique tectonic activity on Earth, occurring on no other known planet. These features include a removal of up to 70 percent of Earth's silicate crust to form the Moon, a large increase in core and mantle heat, and an increase in radioactive isotopes to sustain this heat. A similar giant impact on Mars appears to be the cause of crustal thinning of the northern hemisphere lowlands of Mars, but not energetic enough to support plate tectonics.[38] As a thinner crust re-formed on Earth after the collision, it was more susceptible to cracking and the driving forces of heat convection.[39] The giant impact added to the internal heat of Earth both from the collision energy and from an increase in radioactive isotopes. Plate tectonics built the mountains and continents of Earth, without which it would be mostly covered by water with little chance for developing land-based life. For example, if water covered the thicker crust on Venus to an average depth of only 3 kilometers, it would cover more than 90 percent of its surface, and any remaining land would eventually erode.

Tectonic activity also recycles the crust, bringing minerals to the surface and controlling long-term climate by the carbon cycle that balances atmospheric carbon dioxide.[40] When volcanic carbon dioxide traps heat and temperatures increase, more evaporation occurs and increased rainfall washes the carbon dioxide into the oceans, causing the water and air temperatures to drop. This carbon dioxide eventually forms limestone on the ocean bottom, which is then recycled by plate tectonic activity (subduction) and returns to the atmosphere again by associated volcanic activity. Without this cycle Earth would have undergone either a runaway greenhouse effect with too much carbon dioxide, or a runaway snowball effect without enough carbon dioxide in the atmosphere to trap heat.

7. Huge tides enrich oceans with minerals. In the giant-impact model, many minerals needed for life probably sank with iron into the mantle and core of the molten Earth, but turbulent convection probably retained some minerals near the outer mantle boundary. Some of the impact debris was vaporized into a silicate disk around Earth, about half of which formed the Moon.[41] After the impact, the surface cooled by radiation and the crust began to form within about one thousand years.[42] Condensation of the disk followed, and some metals condensed from the giant-impact debris and fell back into Earth's re-forming crust to form a veneer of life-essential minerals, some of which were later brought to the surface by tectonic activity.

Another possibility is that these minerals might have also been enriched in Earth's crust by a late heavy bombardment of asteroids and comets that occurred about 4 billion years ago, as shown by the crater record on the Moon, although there is little evidence of these minerals on the Moon's surface. Recent evidence has identified zircons in Earth's crust dating before this bombardment at 4.4 billion years ago.[43] When the Moon was about ten times closer than it is now and the day had slowed to perhaps ten hours, the tidal forces would be one thousand times larger, since they increase as the inverse-cube of the distance, and tides would be hundreds of times higher than today. Huge tides from the early Moon would erode minerals from far inland about every five hours, enriching the oceans with the minerals needed for life.[44]

8. Lunar tides slow Earth's rotation. As shown by George Darwin, the tidal forces between Moon and Earth slowed Earth from its initial 5-hour rotation to its present 24-hour rotation, and the Moon moved outward from at least 3 Earth-radii, the so-called Roche limit for forming a satellite, to its current 60 Earth-radii. Early recession of the Moon in the first few hundred million years would be rapid due to much stronger crustal and ocean tidal action, and Earth's rotation would also decrease rapidly.[45] Early rapid rotation would produce super hurricane-force winds, similar to those observed on Jupiter with its rapid ten-hour rotation, which would pose severe threats to most life forms.

After the initial rapid decrease in rotation of Earth and the formation of its oceans, ocean tides would continue the slowing process. A slower rotation rate optimizes wind circulation and surface temperatures for life. Geological evidence for slowing of Earth's rotation comes from measurements of tidal rhythmites, alternating layers of silt and sand offshore from tidal estuaries, showing that Earth's rotation had slowed to about eighteen hours by about 900 million years ago, and to about twenty-two hours by 600 million years ago.[46]

9. Tides produce tidal pools for emerging life. In addition to the role of lunar tides in helping to cleanse and oxygenate the oceans, tidal pools have long been recognized as good locations for concentrating nutrients, by evaporation, for emerging life forms. Rapid tidal cycling occurred when the day was shorter and the Moon was closer, so that the tides would have been larger and tidal pools would cover larger areas. It has been suggested that cycles of wetting and evaporation along the shorelines of the early oceans might have provided the kind of environment in which protonucleic acid fragments could begin to associate and assemble molecular strands leading to the origin of life.[47]

Since the early Moon receded much more rapidly due to strong crustal and ocean tides, it may not have been much closer to Earth when life was emerging than it is now.[48] As the Moon recedes, its force on Earth weakens, eventually reaching about twice the force of the Sun and producing lunar cycles of spring and neap tides, which allow for longer periods of evaporation and concentration of nutrients for early life forms to develop in intertidal pools. Since organic reactions proceed slowly, these longer cycles increase the possibility of long sequences of chemical reactions favorable to emerging life forms. Incidentally, this condition of similar forces by the Sun and Moon happens to correspond to each having nearly the same angular size, which allows for dramatic eclipses.[49]

10. The Moon stabilizes the tilt of Earth's axis. As mentioned above (legacy 2), there have been suggestions that Earth's axial tilt might have been much larger during much of Earth's history, even though the tendency of the Sun's gravity is to minimize axial tilt on the closer planets. If Earth did have a larger axial tilt, the early Moon's strong tidal effects might have had a role in reducing this tilt since its orbit is closer to the ecliptic plane. However, a larger tilt could also have resulted in chaotic changes in Earth's axial tilt with disastrous results on climate and life. Since the early 1990s, it has been known that the axial tilts of both Earth and Mars are subject to the possibility of chaotic variations due to gravitational forces from the outer giant planets.[50]

Fortunately, the large size of our Moon produces sufficient gravitational force to keep the axis of Earth inclined in a narrow range between about 22^o and 25^o, stabilizing annual climate variations in a favorable range for living organisms and producing the regular seasons that occur on Earth.[51] In this respect, the Moon acts as a kind of regulator for climate on Earth. It prevents the kind of large and chaotic changes in tilt that have been shown to occur over a few million years on Mars, which has two very small moons but no large moon to stabilize its axial tilt.[52]

Conclusion

All of the above legacies are potential contributions to making life on Earth possible, and it appears that the lack of any one of them might have prevented the development of complex life forms, if not life itself as we know it. Not only is it remarkable that Earth has all these life-sustaining features, but that they all appear to be the legacy of our Moon. Beyond these features, Earth has many other properties that are needed for life, such as the right size Sun, a favorable location in the galaxy, the right location in the solar system, the ozone layer to protect from ultraviolet radiation, and many others. These conditions greatly restrict the possibilities of life elsewhere in the universe when factored into the 1961 Drake equation for estimating how many other planets might support extraterrestrial life, which led to the oft-quoted estimate of one million.[53] In spite of these restrictions, Frank Drake, as late as 1992, still insisted that there should be about 10,000 planets with intelligent life in our galaxy.[54] He made no attempt to take into account the importance of a large moon for life.

Computer studies have shown that any accreting planet has some chance of being hit by a planetesimal object one-tenth its size in the same accreting zone, and that the giant-impact theory of the Moon fits within this probabilistic framework. However, it is also evident that the right kind of glancing collision is not inevitable and, in fact, has very low probability. One estimate of this probability takes into account five independent parameters, each with its own estimated probability (in parenthesis): the right size impactor (0.001), the right time for the impact to occur (0.1), the right direction for an effective glancing collision (0.03), the right point of impact on the proto-earth (0.2), and the right speed to place enough debris in orbit (0.01). The product of these factors gives an estimated probability of about 10^{-8} for this event.[55] Although these probability factors are somewhat arbitrary, the final estimate is consistent with the fact that no other planet is known to have had a similar glancing collision that produced a large moon. It is also consistent with recent data from an infrared survey of more than four hundred young stars (about 30 million years old, and thus past their planet-forming age), carried out by NASA's Spitzer telescope, revealing only one dust cloud signature large enough to be a possible moon-forming collision.[56]

Applying the above probability for a large moon from a glancing collision to the very optimistic Drake estimate in 1992 of 10,000 intelligent civilizations in our galaxy, suggests a very low probability ($10^{-8} \times 10{,}000 = 0.0001$) for any other planets in our galaxy with intelligent life. This probability is much lower if other factors ignored by Drake for a habitable planet are taken into account, such as proto-planet size and composition prior to a glancing collision, size and location of its parent star, and many other critical factors.[57] Although such low probabilities do not prove divine intervention, they do suggest the possibility of a plan and purpose behind natural events. The random or stochastic nature of such events can be viewed in a Christian framework, where "random" could be translated as "non-predictable" within a generalized doctrine of divine providence.[58] In such a view, God can work through a preordained plan or a continuous supervision of his creation, perhaps through quantum uncertainties consistent with the causal order of creation.[59] This is reflected in Charles Darwin's prefatory quote of Anglican priest and historian of science William Whewell in the first edition of *On the Origin of Species*:

> But with regard to the material world, we can at least go so far as this—we can perceive that events are brought about not by insulated interpositions of Divine power, exerted in each particular case, but by the establishment of general laws.[60]

The special nature of our Moon and its Earth-shaping role reveal the unusual legacy that makes life possible. The apparently unique nature of our Earth-Moon system violates the contemporary materialistic faith that life is commonplace in the universe. For Christians, it supports the belief that God can work through natural and seemingly random processes to achieve his purposes in creation.[61] It encourages a new appreciation for the special gift of life and an environment suitable for its survival. It echoes the words of Psalm 8:3–4, "When I look at your heavens, the work of your fingers, the moon and the stars, which you have set in place, what is man that you are mindful of him, and the son of man that you care for him?" ✯

Notes

*An abbreviated version of this paper was presented at the ASA Annual Meeting at Baylor University, Waco, TX, in August 2009.

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