Chapter Four

Science as Storytelling

Making the Moon

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As our closest cosmic companion, the Moon has likely captured our attention since the dawn of human imagination.[1] It is a common feature of ancient cosmological origins stories, often treated as a deity itself or an appointed messenger of the divine. This latter function is comparable to that found in ancient Hebrew cosmology, where the Moon is distinctly described as a *creation*, appointed to serve as the "lesser light" to the rule the night (Genesis 1:16), and to mark signs, seasons, days, and years (Genesis 1:14; Psalm 104:19) as a faithful witness in the skies (Psalm 89:37).[2] The relative motions of the Sun and Moon have thus served as the basis for lunisolar calendars across diverse cultures throughout history, including the ancient Babylonian and Hebrew religious calendars.[3]

However, the Moon's *material* origins have long remained a mystery, and explanations of physical formation processes only appeared after the scientific revolutions of the seventeenth century.[4] *How* was the Moon made? Can something meaningful even be said about events that occurred in an ancient planetary past? How might these creation narratives shape our understanding of the relationship between God and creation? Such questions are commonly raised in the context of Big Bang cosmology or biological evolution. An exploration of planetary cosmogony as an intermediate process may provide new opportunities for scientific and theological dialogue around scientific theory-making and the role of divine action in creation. This chapter will briefly explore how contemporary theories of lunar and planetary formation—and cosmogonies in general—highlight the role of model-making in constructing scientific narratives of origins, as well as the challenges and implications of modeling contingent or stochastic events over planetary time scales. The role of T.F. Torrance's "contingent order"[5] via what Arthur Peacocke describes as the "creative interplay of chance and law"[6] will also be briefly considered as a possible science-religion framework for exploring a creation that reveals a deep and unfolding planetary history.

THE FACE OF THE MOON

A fundamental assumption of this exploration is that creation does indeed *reveal*; that it is both revelatory and intelligible.[7] The concept of creation-as-witness is present from the earliest Christian tradition (built largely upon Psalm 19:1–2 and Romans 1:19–20), in which creation serves as a revelatory expression or icon of God's love and wisdom, and may be approached via a "two-books" metaphor of Scripture and Nature. An explicit articulation of creation-as-text can be found in the Belgic Confession (1561), where the physical universe is described as "before our eyes as a beautiful book."[8] A consequence of a revelatory creation is that every entity in nature, by its very existence, may serve as a witness to its own physical past. As summarized by Kierkegaard, "everything that has come into existence is *eo ipso* [by that very fact] historical."[9] Because the attributes possessed by a physical entity are a product of its history,[10] careful study of these properties might *reveal* something of that history. A confessional assumption of creation-as-witness thus points to the self-disclosure of nature for any who would learn its languages, providing a basis for developing scientific narratives about the history of creation.[11] For the Moon, such historical self-disclosure was first encountered in the appearance of the lunar surface.

Although humans have likely looked at the face of Moon more than any other celestial object, Galileo Galilei was the first to describe the lunar surface with the aid of a telescope.[12] His 1610 landmark *Sidereus Nuncius (Starry Messenger)* described new observations of lunar geography using vivid scenes drawn from the terrestrial imagination: a world of deep valleys and jagged mountains, casting shifting shadows at sunrise and sunset.[13] *Starry Messenger*, along with subsequent works by seventeenth-century selenographers such as Michael van Langren and Johannes Hevelius, would provide the descriptive categories of the lunar surface still in use today: the lower, darker regions as *maria* and the brighter, highland regions as *terrae*.[14]

With the Moon established as a rocky, planetary body akin to the Earth, early studies of selenography and selenology—together with the knowledge of comparable terrestrial processes—sought answers in the appearance and observed properties of the Moon itself. James Nasmyth and James Carpenter, drawing upon a comparison with Darwinian evolution, likewise reflected upon the Moon's witness in the opening to their comprehensive 1874 study of the lunar surface,

> It is almost impossible to conceive that our world with its satellite, and its fellow worlds with their satellites, and also the great centre [Sun] of them all, have always, from the commencement of time, possessed their present form: all our experiences of the working of natural laws rebel against such a supposition. In every phenomenon of nature . . . we see a constant succession of changes going on . . . In the inorganic world we witness the operation of the same principle; but, by reason of their slower rate of progression, the changes there are manifested to us rather by their resulting effects than by their visible course of operation. And when we consider, as we are obliged to do, that the same laws work in the greatest as well as the smallest processes of nature, we are compelled to believe in an antecedent state of existence of the matter that composes the host of heavenly bodies, and amongst them the earth and its attendant moon.[15]

Given a history of change made physically manifest by "resulting effects," how did the Moon come to be as we see it today? What stories are written in the face of the Moon?

A key difference from the Earth was the presence of numerous circular depressions on the lunar surface, described as *maculae* by Galileo and named as *craters* in the eighteenth century. While initially believed to be the result of volcanic eruptions, by the advent of the space age planetary scientists had concluded that nearly all lunar craters were formed via impacts by interplanetary debris striking the surface at random.[16] This cratering reveals a long and uneasy marriage between the geological principles of *uniformitarianism* ("what we observe in nature can best be explained by everyday processes operating over very long periods of time") and *catastrophism* ("what we observe in nature can best be explained by the occurrence of sudden, violent events"). These principles are frequently cited in questions surrounding the characterization of God's role in geological history because they provide convenient boundary questions: to what extent do geologic events in history represent direct divine intervention? To what extent do they represent natural laws allowed to operate independently? Should any such distinction be made? On the lunar surface, each crater testifies to a violent, catastrophic event, repeated millions of times over the history of the Solar System. With no water, winds, or shifting tectonic plates to erase them, these impact features are preserved over eons. The crater population thus provides a new kind of "uniformitarian" method for reconstructing a history of the lunar surface. The longer a surface is exposed to interplanetary debris, the greater the number of impacts it will endure. From this robust assumption, the relative ages of different surfaces can be inferred: older surfaces have more craters than younger surfaces.

The return of *Apollo* lunar samples also allowed for the determination of numerical ages derived from radiometric measurements, pointing to an age of the Moon of nearly 4.5 billion years, roughly similar to that of the Earth.[17] These results provided constraints on the timing of the Moon's formation, along with the large-scale processes that have since shaped its face: darker and smoother lunar maria representing large impact basins filled by ancient volcanic flows, surrounded by even older bright highlands saturated with impact craters.[18] The results also suggested that the Moon's surface has been largely preserved over most of its history, providing a decipherable record of conditions in the early Solar System during the first billion years of Earth's history[19]—a record mostly erased at the Earth's own surface.[20] The face of the Moon has thus served as a faithful witness in the skies throughout the history of the Solar System, even to its own violent origin.

MAKING THE MOON

My own first informal attempt at making the Moon was a mixture of Sunday-school theology (by reading Genesis 1 to suggest that the Earth preceded the Moon) and playground science (through an unarticulated appreciation of angular momentum taught by the merry-go-round). However, the Genesis creation narrative itself offered few additional constraints on either the timing or mechanism of the Moon's creation. A detailed description of the formation process would have to be inferred from available physical clues from the Earth-Moon system itself. I explored my grandparent's Earth globe looking for a place where the Moon could have reasonably split off from a rapidly spinning Earth, choosing a region somewhere in the south Pacific Ocean. This was a crude adaptation of the *fission hypothesis*, first formally developed in 1878 by G.H. Darwin (son of the famous biologist), and generally considered the first modern theory of the Moon's origin.[21] Other proposals would follow, including *co-accretion*[22] wherein the Moon formed as a sibling planetary body in the vicinity of Earth, and *capture*[23] wherein in the Moon formed as a planet elsewhere in the Solar System prior to its capture by the Earth's gravity. The formation events in each of these proposals are visually summarized in Figure 4.1.

Each theory faced significant observational challenges. The co-accretion theory could not account for the very low density of the Moon compared to the Earth, whereas the capture theory—only possible over a very narrow set of circumstances—could not identify where a Moon-like object might have originated. The fission theory, which required a very fast-spinning ancient Earth, retained the most popularity but was difficult to reconcile with the

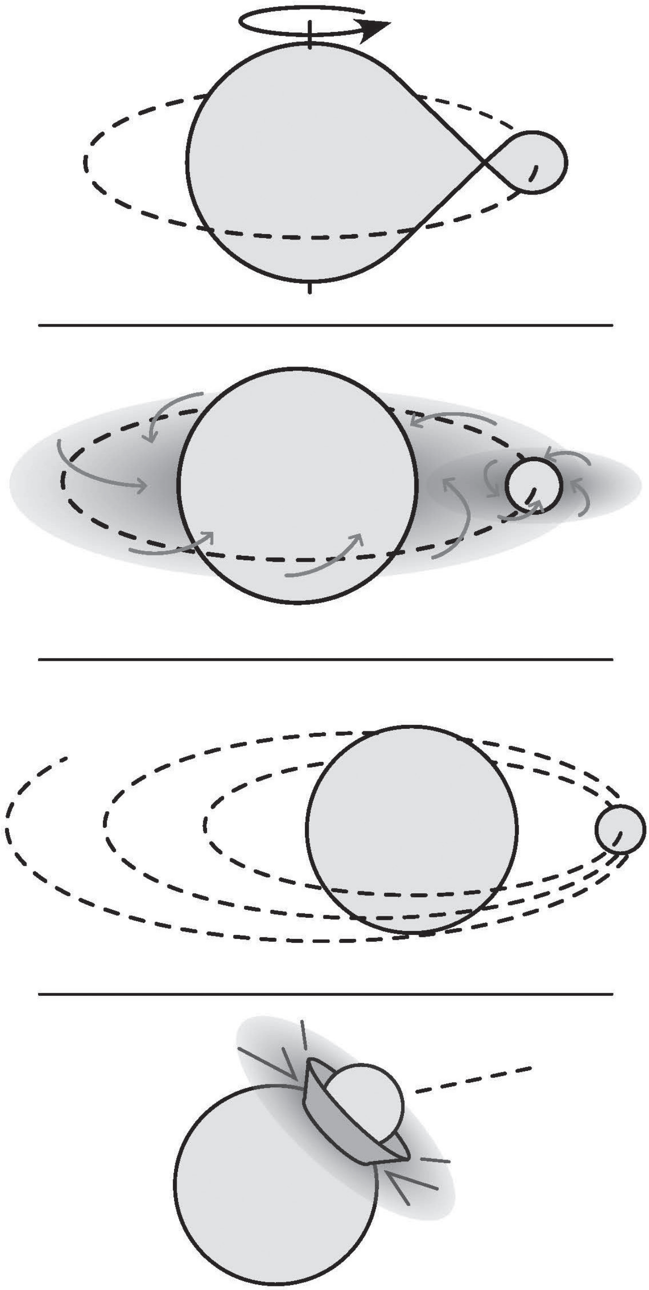

Figure 4.1 A summary of the four main model proposals for the formation of the Moon. From top to bottom: fission, co-accretion, capture, and the giant impact. Figure created by the author.

angular momentum of the Earth-Moon system. As moons and planets go, our Moon is relatively large for a planet the Earth's size, such that the angular momentum of the Earth-Moon system "has been the rock upon which most hypotheses of lunar origin have foundered."[24]

Notably, these early lunar formation theories—fission, capture, and co-accretion—were developed within the broadly uniformitarian paradigm of the eighteenth and nineteenth centuries, following the nebular hypothesis developed by Swedenborg, Kant, and Laplace, and the geological influence of Hutton and Lyell.[25] As noted by science historian Stephen Brush, "within this paradigm, cosmogonic processes had to be deterministic and uniformitarian, even if their net result was the formation of a qualitatively new system" like the Moon.[26] Thus, even where so-called "evolutionary" or "creation-by-natural-law" descriptions of origins were accepted—such as Laplace's nebular hypothesis[27]—there was little room for the type of contingency found in law-abiding yet *stochastic* (i.e., non-deterministic or randomly evolving) processes highly sensitive to variations in initial conditions. Even as a new system, the Moon's origin could only be seen as occurring by processes inherent to "normal" (i.e., non-cataclysmic) planetary accretion and its subsequent motions deterministically provided by Newtonian physics.

It was hoped that new evidence gathered by the *Apollo* missions, including the search for so-called "genesis rocks" (sought-for samples of the Moon's primordial crust) would discriminate among the available hypotheses and reveal the path of lunar formation. However, the new geochemical constraints provided by *Apollo* could not be satisfactorily explained by the existing theories. Without a clear way forward, lunar science reached an impasse of the kind which Thomas Kuhn describes as "crisis": when anomalies or inconsistences cannot be explained by an existing scientific paradigm.[28] Summarizing the situation in 1984, lunar scientist S. Ross Taylor wryly proposed the following,

> Taylor's Axiom: The best models for lunar origin are the testable ones.
>
> Taylor's Corollary: The testable models for lunar origin are wrong.[29]

Applying a Kuhnian framework, the crisis could perhaps "loosen the stereotypes and provide the incremental data necessary for fundamental paradigm shift."[30] Indeed, careful study of the *Apollo* rocks soon revealed that the Earth and the Moon were mostly made of the same stuff, dealing a fatal blow to the capture hypothesis.[31] But there were key chemical differences as well: the Moon is dry compared to the Earth, slightly depleted in elements that are readily vaporized, and slightly enriched in high-temperature elements. The available clues pointed to a different kind of origin.

Taken together, the new evidence led to new proposals describing an energetic, violent birth for the Moon.[32] In these scenarios, the Moon formed in the aftermath of a giant collision between a planet-sized object (now often referred to as "Theia") and the early Earth in the latter stages of the Earth's own formation. The energy of such cataclysm is beyond imagination—large portions of the Earth and all of Theia melted and vaporized, mixed and flung into orbit, forming either a disk or torus of magma and vapor in a broad ring surrounding the Earth. Over the subsequent centuries, this disk of debris cooled and dissipated, with material either falling back onto the Earth or merging to complete the formation of what would become our Moon.[33]

The so-called giant impact hypothesis would emerge as a clear favorite at the Conference on the Origin of the Moon held in Kona, Hawaii in 1984.[34] As noted by planetary scientist David Stevenson, this was mostly "because the hypothesis was given serious and sustained attention for the first time."[35] The story of its widespread adoption by the planetary science community provides a case study of a Kuhn-like paradigm shift in lunar theories of origin.[36] For the past few decades, the giant impact hypothesis has continued to provide the basic framework in which any new data is acquired and considered, and as the starting point for the construction of new models exploring how the Moon was made. Put another way, this paradigm regulates how lunar origin can even be *imagined* in contemporary planetary science. So, for now, it provides the basic story of *how* the Moon was made—at least until a better story comes along.

TELLING CREATION STORIES

In his essay, "Why Buy That Theory?," chemist and Nobel laureate Roald Hoffmann writes, "When things are complex yet understandable, human beings weave stories."[37] This expression reflects the view that science proceeds not merely by the accumulation of facts about the world, but also by the creative development of explanatory frameworks about how different parts of the world behave and interact. This approach appears to be necessary if we are to talk meaningfully about entities or processes that are underdetermined or not presently observable—such as the ancient formation of our own planetary system. Consequently, we see the use of *models* to describe or represent at least certain aspects of complex systems, serving as "symbolic representations, for particular purposes, of aspects of reality which are not directly accessible to us."[38] By this definition, models in scientific inquiry allow for the exploration and articulation of phenomena that would otherwise remain beyond human intuition.

Moreover, even within a prevailing paradigm (such as the giant impact hypothesis), multiple narrative variations can be plausibly constructed from a given set of constraints. This creative practice of theory-making demonstrates the role of science as a human activity subject to its own "cultural contradiction" and change with time.[39] It also highlights a paradox present in any paradigmatic framework: the extent to which scientific inquiry both *discovers* and *produces* scientific knowledge.[40] Scientists seem to have grown accustomed to working within this paradox. As summarized by biochemist and theologian Arthur Peacocke, it is "the implicit, though often not articulated, working philosophy of practising scientists . . . to depict reality" even as they "know only too well their fallibility in doing so."[41] In this view, although scientific

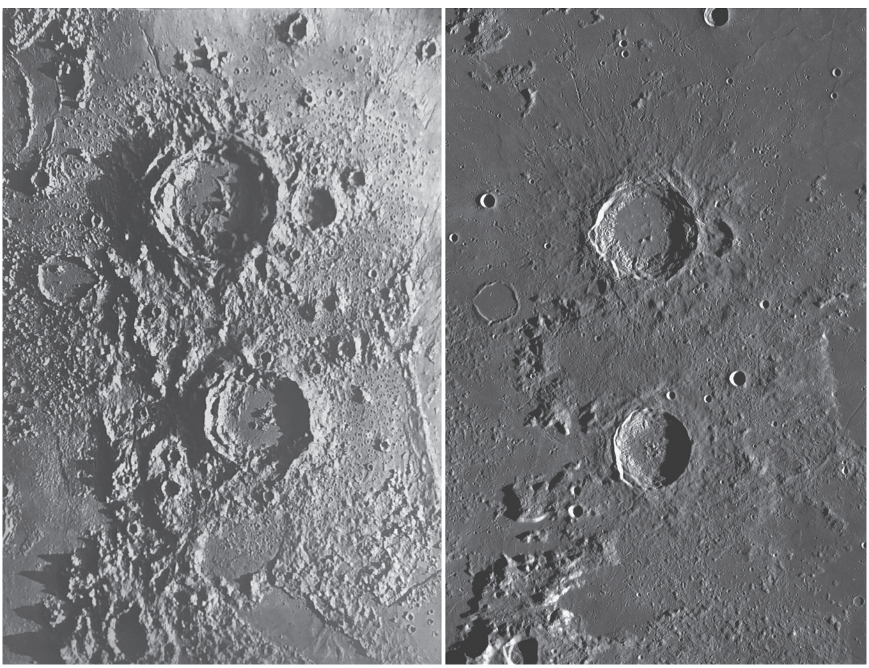

Figure 4.2 Left: A model of the lunar surface, by James Nasmyth and James Carpenter (1874). To produce these images, the authors made detailed plaster models based upon observational notes and sketches of the Moon. The plaster landscapes were then placed in sunlight in such a way that light and shadow would "produce most faithful representations of the original." The image of the craters shown here is from the 1885 edition, on a plate showing Aristotle (top) and Eudoxus (bottom) craters. Aristotle crater is now officially known as Aristoteles. Right: Lunar Reconnaissance Orbiter Camera (LROC) image of Aristoteles (~90 km diameter) and Eudoxus (~70 km diameter); the wide-angle nearside dawn imagery was selected here to give a sunlight angle comparable to that modeled by Nasmyth and Carpenter. Image credit: LROC; NASA/GSFC/Arizona State University.

models represent limited and even provisional human approximations, they are nonetheless tethered to the physical universe, "an objective reality we make it our task to discover."[42] Thus, a simple test of any model is how well it appears to represent reality (for example, see Figure 4.2).

The narratives constructed about the past must therefore stand (even as they are amended by new articulations or modifications) in the face of accumulating evidence—or anomalies—if they are to be accepted as correct in any meaningful way. In science, the stories that endure are those most tenaciously consistent with observations of the physical world as we explore it.[43] Recognizing that even small differences early in the story can lead to dramatically diverging results, the test of any physical theory of lunar origins is likewise provided: does the moon in our formation theories resemble the Moon as we see it today?

CATACLYSM AND CONTINGENCY IN CREATION

Even following its widespread adoption by the scientific community, the extraordinary and cataclysmic character of the giant impact hypothesis has often generated incredulity. Shortly after the 1984 Kona conference now known for the emergence of the giant impact paradigm, planetary scientist Bill Hartmann responded to criticism that the giant impact was *ad hoc* or a "hypothesis of last resort."[44] The critiques appeared to be motivated by the giant impact as a significant stochastic event with an outcome that had "a strong dependence on an element of chance."[45] In a section of his response entitled, *Stochastic ≠ Ad Hoc*, Hartmann provides a helpful distinction between "class-predictable" and "event-predictable" natural events:

> some classes of influential events in solar system history are class-predictable but not event-predictable: i.e., we believe that the class of events occurred, but we cannot determine times and magnitudes of individual events. These events are stochastic, but not *ad hoc*. Giant impacts are class-predictable, in the sense that there are growing grounds to believe that in addition to innumerable [small] collisions, there were a few impacts . . . large enough to alter the nature of the finished planet.[46]

Impact craters on the lunar surface show an exponential relationship between impact size and frequency: smaller impacts occur more frequently than larger impacts, and giant impacts are exceedingly rare. Yet given our understanding of planetary formation and impact histories, it is reasonable to expect some non-zero possibility of giant impacts occurring early in Solar System history. This presents a unique challenge for modeling individual 'influential events' within the broader context of planetary formation and evolution. As noted by geologist Peter Gretener, the rare event introduces an element of uncertainty that is difficult to grasp by a direct approach: we only see the *consequences* of such events.[47] A classic example is the asteroid impact believed to be responsible for the Cretaceous-Tertiary (K-T) mass extinction event 66 million years ago.[48] Observed asteroid and crater statistics suggest that such events should occur every 10–100 million years, but as a class-predictable event, it was difficult to tie specific effects in the geologic record to specific impacts. The discovery of iridium-rich layers at the K-T boundary therefore came as a surprise, with the impact event evident only in hindsight.[49]

Modern theories of planetary formation and evolution are replete with the contingency of class-predictable[50] processes, pointing to the formation of the Earth and Moon via a long sequence of apparently random events. These formation and impact processes can be modeled using *N*-body or SPH (smoothed-particle hydrodynamics) numerical codes, which simulate the motions of thousands or millions of smaller bodies subject to gravitational interaction and classical mechanics.[51] Because these models are stochastic (repeating the simulation can yield a different answer), results are typically reported by performing enough simulations to find the average of expected outcomes for each set of initial conditions. Particular attention is paid to outcomes which most closely approximate the observed planetary architecture of our Solar System or the Earth-Moon system. These results suggest that the appeal to class-predictable statistical outcomes are an inherent property of even well-ordered planetary systems. For example, the eighteenth century polymath Comte de Buffon calculated the odds of an accidently co-planar, co-revolving system of planets in the Solar System at 7,692,624 to 1. These odds suggested either intentional design or some coherent explanatory framework for planet-making, as Laplace would demonstrate.[52] Within the context of the nebular hypothesis, planetary orbits thus provide an example of a contingent, stochastic process that yields—via the cumulative statistical effect of innumerable small objects—a system with an appearance of orderly design.

From observations of other planetary systems, there is growing evidence that giant impacts are a common feature during planetary formation, with collisions playing a key role in shaping a planet's size, stability, composition, and habitability.[53] For example, the proximity and size of a moon produced in the aftermath of a giant impact appears to have played a role in determining the 24-hour rotation period and 23.5-degree obliquity of the Earth. Several studies have also suggested that the Moon also stabilizes the Earth's obliquity by several degrees: without the Moon, the Earth's axial tilt would be chaotic, with large variations ranging as high as 85 degrees.[54] In this way, the Moon may have served to stabilize the Earth's climate to produce a habitable environment suitable for life. This creates unique challenges for formation models, which must be consistent with all of the observed features of the Earth-Moon system. This requirement extends to the "just-so" conditions yielding a potentially habitable Earth as an outcome of otherwise violent and highly stochastic formation models. Looking back on our own history, an application of the anthropic principle is evident: what we can expect to observe about our local part of the universe is restricted by the conditions necessary to produce both our environment and our presence as conscious observers in that environment.[55] In this way, planetary and geologic history shares with evolutionary biology and Big Bang cosmology the phenomenological impact of contingency via a unique history that leads to life in the universe.

As noted above, numerical models of planetary and lunar formation yield a suite of results with a range of outcomes, designed to encompass the observed composition and architecture of our Solar System. In the context of attempts to model planetary history, theological proposals that address contingency in creation may therefore provide a helpful framework for further dialogue. One such approach is found in theologian T.F. Torrance's expansive concept of *contingent order*. This refers to the way in which the universe is contingent upon God's freely creative act, yet conferred with a "created rationality of its own" that is still dependent upon God's "uncreated transcendent rationality."[56] As a consequence, the world is intelligible to scientific inquiry, which "assumes both the contingence and the orderliness of the universe."[57] As Torrance points out, contingency plays a significant enough role in nature such that scientific inquiry can consider it "no longer as a negligible hidden parameter in its theories but as an essential and integral factor"[58] in our understanding of the natural world. This latter claim highlights Torrance's "kataphysical" approach that our knowledge must be developed in accord with reality's nature—that we may even be *compelled* (a term also used by Nasmyth and Carpenter) by reality to do so.[59] The concept of contingent order also extends freedom to the physical world, yet likewise grounded in divine transcendence.[60] Freedom in creation is thus established as a rational yet contingent freedom, a combination "which excludes both arbitrariness and necessity."[61] A similar relation was expressed by Arthur Peacocke, who pointed out that a universe governed by rigid law alone would be repetitive and uncreative, whereas one governed by chance alone would never develop persistent entities open to rational scientific inquiry.[62]

Within the context of understanding our lunar and planetary history, why are intrinsically contingent models necessary? How do our sometimes cataclysmic origin stories reflect both the rationality and the freedom of a divinely created contingent order? Given the aim of scientific theory-making to depict reality, these stories are compelled to reflect the behavior of creation itself.[63] Stochastic models are needed to tell the story of a contingent planetary history. They point to a universe of unfolding creational development, expressing a beautiful and creative "interplay of chance and natural law"[64] that allows for new things to happen.[65] This interplay gives rise to "a free play of randomness which generates the new emergent entities of the cosmos and enables all its potentialities to be explored."[66] Such creative playfulness evokes Proverbs 8:30–31 where God and wisdom together rejoice (*śāḥaq*)—a word more often translated as "play" or "laugh"[67]—in the creation of the Earth in a testimony to God's transcendent faithfulness. Thus, even as our own planetary stories may shift and change, we are witness to an ordered but free, dynamic yet faithful, intelligible yet unfathomable world, made freely as a creative act of love.

NOTES

1. This contribution is an expanded essay based upon an earlier article by the author, published as Channon Visscher, "Lunar Stories: The Violence of Creation," *Reformed Journal* (May/June 2016), used with permission.

2. While the Moon is referred to in Genesis 1 as a "lesser light," the word most often translated as "moon" (*yareah*) does not appear until Joseph's dreams in Genesis 37. This term appears to derive from name of the Ancient Near Eastern moon god *Yarikh* for which the city of Jericho (*Yereho*) served as a place of worship. As noted by commentator John Goldingay, the designation of the Moon as an appointed creation may represent a polemic against neighboring nations that worshipped the Moon as divine. See John Goldingay, *Baker Commentary on the Old Testament Wisdom and Psalms*, Vol. 2 (Psalms 42–89) (Grand Rapids, Michigan: Baker Academic Press, 2007).

3. For a comprehensive treatment of the ancient Hebrew calendar and the lunisolar basis of Jewish holidays, see Michael LeFebvre, *The Liturgy of Creation: Understanding Calendars in the Old Testament Context* (Downers Grove, Illinois: InterVarsity Press, 2019). For example, the initial appearance of a new (waxing) crescent moon marks the beginning of each lunar month and allows for the proclamation of a new moon feast day. The lunisolar calendar is also used to set the dates of significant holidays such as Jewish Passover, which begins on first full moon of the first month (*Nisan*) of spring (itself begun by the first spring new moon) and of moveable feasts such as Christian Easter, which in the implementation of the Gregorian calendar lands on the Sunday following the first full moon after the spring equinox.

4. For a review of the history of proposals about lunar origins up to the twentieth century, see Stephen G. Brush,"Early History of Selenogony," in *Origin of the Moon (Papers presented at the Conference on the Origin of the Moon, Kona Hawaii, October 1984)*, ed. W.K. Hartmann, R.J. Phillips, G.J. Taylor (Houston: Lunar and Planetary Institute, 1986), 3–16.

5. Thomas F. Torrance, *Divine and Contingent Order* (Oxford: Oxford University Press, 1981). For a shorter summary see Thomas F. Torrance, "Divine and Contingent

Order," in *The Sciences and Theology in the Twentieth Century*, ed. A.R. Peacocke (Notre Dame: University of Notre Dame Press, 1981).

6. Arthur R. Peacocke, *Creation and the World of Science: The Reshaping of Belief* (Oxford: Oxford University Press, 2004), 246.

7. Cf. Psalm 19:1–2; Alvin Plantinga notes, "there is an *adaquatio intellects ad rem* (an adequation of the intellect to reality)" Alvin Plantinga, *Where the Conflict Really Lies: Science, Religion, and Naturalism* (Oxford: Oxford University Press, 2011); for further discussion of Christian understanding of "creation as text," see Lydia Jaeger, *What the Heavens Declare: Science in the Light of Creation,* trans. Denis Vaughan (Eugene, OR: Cascade Books, 2012).

8. Faith Alive Resources, trans. *The Belgic Confession, Article 2: The Means by Which We Know God*, approved by Synod 2011 of the Christian Reformed Church in North America and General Synod 2011 of the Reformed Church in America. See https://www.crcna.org/welcome/beliefs/confessions/belgic-confession.

9. "everything that has come into existence is *eo ipso* historical . . . it accepts the one decisive historical predicate: it has come into existence . . . nature has a history," Soren Kierkegaard, *Philosophical Fragments; Johannes Climacus*, ed. Howard V. Hong, Edna H. Hong (Princeton: Princeton University Press, 1985), 76ff.

10. "the very possession of its attributes by a natural thing takes time," R. G. Collingwood, "Human Nature and Human History," in *The Idea of History* (Oxford: Oxford University Press, 1946), 157–174.

11. Cf. Lydia Jaeger, "The Contingency of Creation and Modern Science" *Theology and Science*, 16:1 (2018): 62–78.

12. James Lawrence Powell, *Four Revolutions in the Earth Sciences: From Heresy to Truth* (New York: Columbia University Press, 2015).

13. Galileo Galilei, *Sidereus Nuncius* (*Starry Messenger*), 2nd ed, trans. Albert van Helden (Chicago and London: University of Chicago Press, 1610); see also Scott L. Montgomery, *The Moon & the Western Imagination* (Tucson: University of Arizona Press, 1999).

14. Perhaps most famous is Mare Tranquillitatis, site of the *Apollo 11* landing in July 1969.

15. James Nasmyth, and James Carpenter, *The moon, Considered as a Planet, a World, and a Satellite* (London: James Murray, 1874).

16. For a more comprehensive narrative about the mid-twentieth century debate between the volcanic and impact origin hypotheses for lunar craters, see James L. Powell, 2015.

17. Radiometric methods had already supported the paradigm of an ancient Solar System with the most reliable measurement to date (based upon measurements of meteorite samples) yielding an age of over 4.5 billion years; see Claire Patterson, "Age of the meteorites and the earth," *Geochmica et Cosmochimica Acta* 10, no. 4 (1956): 230–237; see also Charles K. Shearer, et al., "Thermal and Magmatic Evolution of the Moon," and Dieter Stoffleret al. "Cratering History and Lunar Chronology," in *Reviews in Mineralogy & Geochemistry Volume 60: New Views of the Moon*, ed. Bradley L. Jolliff, Mark A. Wieczorek, Charles K. Shearer, and Clive R. Neal (Chantilly, Virginia: Mineralogical Society of America, 2006), 365–595.

18. In *Starry Messenger*, Galileo likewise noted that maculae (craters) are found scattered across the whole surface of the Moon, "but especially the brighter portion of it." Crater *saturation* is a scale-dependent term describing a surface where the crater density is so high that a new crater cannot form without covering a previous crater.

19. More specifically, the lunar impact record is taken to be representative of the inner Solar System for heliocentric (i.e., Sun-orbiting) impactor populations. The lunar surface also serves as a recorder of the astrophysical environment more generally, e.g., see. Ian A. Crawford, Katherine H. Joy, Jan H. Pasckert, and Harald Hiesinger, "The lunar surface as recorder of astrophysical processes," *Philosophical Transactions of the Royal Society A* 379 (2020): 2188.

20. Ironically, one of the Earth's oldest measured rock fragments may have been found on the Moon, arriving after being blasted of the Earth by a terrestrial impact nearly 4 billion years ago, and returned to Earth with an Apollo 14 sample; see Juni J. Bellucci, et al., "Terrestrial-like zircon in a clast from an Apollo 14 breccia," *Earth and Planetary Science Letters* 510, (2019):173–185.

21. For a comprehensive review of the history of proposals about lunar origins, see Brush "Early History of Selenogony." A broader review of cosmogonic history and its relation to paradigms is found in Stephen G. Brush "Theories of the Origin of the Solar System 1956–1985," *Reviews of Modern Physics*, 62, no.1 (1990): 43. An early description of Darwin's hypothesis can be found in G. H. Darwin, "On the Precession of a Viscous Spheroid, and on the Remote History of the Earth," *Philosophic Transactions of the Royal Society of London* 170 (1878): 447–538. The departure of the Moon from the Pacific basin was modification added to the hypothesis by Osmond Fischer in 1882, prior to the discovery of plate tectonics.

22. The co-accretion hypothesis was first proposed in 1883 by Edouard Roche.

23. The capture hypothesis was first proposed in 1909 by T.J.J. See and revived in the 1950s by Harold Urey and Horst Gerstenkorn.

24. S. Ross Taylor, Carle M. Peters, and Glenn J. MacPherson, "Earth-Moon System, Planetary Science, and Lessons Learned," in Reviews in Mineralogy & Geochemistry *Volume 60: New Views of the Moon,* ed. Bradley L. Jolliff, Mark A. Wieczorek, Charles K. Shearer, and Clive R. Neal (Chantilly, Virginia: Mineralogical Society of America, 2006).

25. James Hutton (1726–1797; often referred to as "The Father of Geology") and Charles Lyell (1797–1875) developed what would become known as the Principle of Uniformitarianism.

26. Brush, "Theories of the origin," 43–114.

27. Ronald Numbers, *Creation by Natural Law: Laplace's Nebular Hypothesis in American Thought* (Seattle: University of Washington Press, 1977); Numbers demonstrates that the nebular hypothesis was generally embraced by American Christians in the early nineteenth century.

28. Thomas S. Kuhn, *The Structure of Scientific Revolutions*, 3rd ed. (Chicago: University of Chicago Press, 1996).

29. Paraphrased by planetary scientist Sean Solomon and printed as an epigraph to *Origin of the Moon (Papers presented at the Conference on the Origin of the Moon,*

Kona Hawaii, October 1984), ed. W.K. Hartmann, R.J. Phillips, G.J. Taylor (Houston: Lunar and Planetary Institute).

30. Kuhn, *The Structure of Scientific Revolutions*, 89.

31. This conclusion that the Moon and Earth are derived from the same material is primarily supported by the near identical agreement in oxygen isotope abundances between lunar and terrestrial samples. In the 1970s, cosmochemist Robert Clayton demonstrated that oxygen isotopes could provide a fingerprint to distinguish among source regions in the Solar System.

32. Hartmann and Davis (1975) and Cameron and Ward (1976) independently proposed an impact-assisted mechanism an alternative way to make the Moon, similar to an earlier and largely overlooked proposal by Reginald Daly in 1946; see William K. Hartmann, and Donald R. Davis, "Satellite-Sized Planetesimals and Lunar Origin," *Icarus* 24 (1975): 504–514; Alistair G.W. Cameron, and William R. Ward, "The Origin of the Moon," *Abstracts of the Lunar and Planetary Science Conference* 7, no. 120 (1976); Reginald A. Daly, "Origin of the Moon and Its Topography," *Proceedings of the American Philosophical Society* 90, (1946): 104–119; see also Ralph B. Baldwin, and Don E. Wilhelms, "Historical Review of a Long-Overlooked Paper by R.A. Daly Concerning the Origin and Early History of the Moon," *Journal of Geophysical Research* 97 (1992): 3837–3843.

33. This process could plausibly explain the pre-*Apollo* constraints of relatively low bulk density for the Moon, the high angular momentum of the Earth-Moon system, and newer geochemical and isotopic constraints provided by lunar samples. For examples of recent models see C. Visscher, and B. Fegley, "Chemistry of Impact-Generated Silicate Melt-Vapor Debris Disks," *Astrophysical Journal Letters* 767 (2013): L12; R. M. Canup, C. Visscher, J. Salmon, B. Fegley, "Depletion of Volatile Elements in the Moon Due to Incomplete Accretion within an Impact-Generated Disk," *Nature Geoscience* 8 (2015): 918–921; S. J. Lock, S. T. Stewart, M. I. Petaev, Z. Leinhardt, M. T. Mace, S. B. Jacobsen, M. Ćuk, "The Origin of the Moon within a Terrestrial Synestia," *Journal of Geophysical Research: Planets* 123, no.4 (2018): 910–951.

34. The papers presented at this conference (several of which explored the idea of a giant impact origin) can be found in Hartmann, et al., eds, *Origin of the Moon*.

35. David J. Stevenson, "Origin of the Moon-The Collision Hypothesis," *Annual Reviews in Earth and Planetary Science* 15, no. 271 (1987).

36. Brush, "Theories of the origin," 43–114; cf. Kuhn, *The Structure of Scientific Revolutions*.

37. Roald Hoffmann, "Why Buy That Theory?" in *Roald Hoffmann on the Philosophy, Art, and Science of Chemistry*, ed. Joeffrey Kovac and Michael Weisberg (Oxford: Oxford University Press, 2012), 15–20.

38. Ian G. Barbour, *Myths, Models, and Paradigms: A Comparative Study in Science and Religion* (New York: Harper & Row, 1974). Cf. Alister E. McGrath, *Science & Religion: A New Introduction*, 2nd ed. (Oxford: Wiley-Blackwell, 2010), 102; and Barry B. Powell, "The Big Bang Is Hard Science. It Is Also a Creation Story," *Nautilus* (September 2014). Barbour further notes that models in religion can

serve a comparable function: to help humans attempt to comprehend the otherwise incomprehensible.

39. D. Lorraine, "When Science Went Modern," *The Hedgehog Review* 18, no. 3 (2016).

40. For an exploration of humans as "co-creators" of scientific truth, see Philip Hefner, *The Human Factor: Evolution, Culture, and Religion* (Chicago: Trinity Press International, 1993); see also Bruno Latour, *Science in Action: How to Follow Scientists and Engineers Through Society* (Cambridge, MA: Harvard University Press, 1987); Ava Kofman, "Bruno Latour, the Post-Truth Philosopher, Mounts a Defense of Science," *The New York Times Magazine*, Oct 25, 2018.

41. Arthur Peacocke, *Theology for a Scientific Age: Being and Becoming-Natural, Divine, and Human* (Minneapolis, MN: Fortress Press, 1993).

42. Karl Popper, *Realism and the Aim of Science* (London: Routledge, 2013).

43. This "tethered" or "constrained" mode of storytelling also informs arguments of selective scientific realism, i.e., that the "success-generating" theoretical components of older hypotheses might be retained by successor hypotheses. For example, in both the now-discarded fission hypothesis and the giant impact hypothesis the relatively low density of the Moon and the high degree of Earth-Moon isotopic similarity are attributed to terrestrial material being ejected and incorporated into what would become the Moon. Thus, a "success-generating" component that provided some success in the failed theory has survived as part of the successor theory. See Amanda J. Nichols and Myron A. Penner, "Selective Scientific Realism and Truth-Transfer in Theories of Molecular Structure," in *Contemporary Scientific Realism*, ed. Timothy D. Lyons and Peter Vickers (Oxford University Press, 2021), 130–158.

44. William K. Hartmann, "Moon Origin: The Impact-Trigger Hypothesis," in *Origin of the Moon (Papers presented at the Conference on the Origin of the Moon, Kona Hawaii, October 1984),* ed. W.K. Hartmann, R.J. Phillips, G.J. Taylor (Houston: Lunar and Planetary Institute, 1986).

45. Hartmann, "Moon Origin," 586.

46. Hartmann, "Moon Origin," 586.

47. P.E. Gretener, "Significance of the Rare Event in Geology," *Amer Assoc Petr Geol Bull* 51, no. 11 (1967): 2197–2206.

48. An impact event as the cause for extinction was proposed by L.W. Alvarez, W. Alvarez, F. Asaro, H. V. Michel, "Extraterrestrial cause for the Cretaceous–Tertiary extinction," *Science* 208 (1980): 1095–1108; after these authors had discovered anomalously high levels of iridium (common in meteorites but rare on Earth's surface) in the K-T sedimentary layers. The Chicxulub crater, now buried by sediments on the Yucatan Peninsula, is considered the site of this impact.

49. Hartmann, "Moon Origin," 587.

50. That is (following Hartmann's description), events that are likely to have occured, even if the timing and magnitude of specific events cannot be determined.

51. For recent examples in planetary formation research, see Kevin J. Walsh, "A Low Mass for Mars from Jupiter's Early Gas-driven Migration" *Nature* 475, no. 7355 (2011): 206–209; R. Canup, "Simulations of a Late Lunar-Forming Impact," *Icarus* 168, no. 2 (2004): 433–456; Craig B. Agnor, Robin M. Canup, and Harold F. Levison,

"On the Character and Consequences of Large Impacts in the Late Stages of Terrestrial Planet Formation," *Icarus* 142, no. 1 (1999): 219–237; R. Gomes, H. F. Levison, K. Tsiganis,and A. Morbidelli, "Origin of the Cataclysmic Late Heavy Bombardment Period of the Terrestrial Planets," *Nature* 435, no. 7041 (2005): 466–469.

52. Numbers, *Creation by Natural Law*.

53. For recent examples, see H. Y. A. Meng, et al., "Large Impacts around a Solar-Analog Star in the Era of Terrestrial Planet Formation," *Science* 345, no. 6196 (2014): 1032–1035; A. S. Bonomo, "A Giant Impact as the Likely Origin of Different Twins in the Kepler-107 Exoplanet System," *Nature Astronomy* 3, no. 5 (2019): 416–423; M. A. Thompson, et al., "Studying the Evolution of Warm Dust Encircling BD +20 30 7 Using SOFIA," *The Astrophysical Journal* 875, no. 1 (2019): 45; Miki Nakajima, et al., "Large Planets May Not Form Fractionally Large Moons," *Nature Communications* 13, no. 1 (2022): 568; Elisa V. Quintana, et al., "The Frequency of Giant Impacts on Earth-Like Worlds," *The Astrophysical Journal* 821, no. 2 (2016): 126; J.A. Kegerreis, et al., "Atmospheric Erosion by Giant Impacts onto Terrestrial Planets," *The Astrophysical Journal* 897, no. 2 (2020): 161.

54. J. Laskar, and P. Robutel, "The Chaotic Obliquity of the Planets," *Nature* 36 (1993): 608–612; D. M. Williams, and D. Pollard, "Earth-Moon Interactions: Implications for Terrestrial Climate and Life," in *Origin of the Earth and Moon*, ed. R. M. Canup and K. Righter (Tucson: University of Arizona Press, 2000); J.J. Lissauer, et al., "Obliquity Variations of a Moonless Earth," *Icarus* 217 (2012): 77–87; K. Atobe, and S. Ida "Obliquity Variations of Terrestrial Planets in Habitable Zones," *Icarus* 188, no. 1 (2007): 1–17.

55. Brandon Carter, "Large Number Coincidences and the Anthropic Principle," in *Confrontation of Cosmological Theories with Observational Data; Proceedings of the Symposium*, *Krakow, Poland, September 10–12, 1973*, ed. Malcolm S. Longair (Dordrecht, Holland: D. Reidel Publishing Co., 1974), 291–298; John D. Barrow, "Chance, Uncertainty, and Unknowability in the Universe and Beyond," in *Abraham's Dice: Chance and Providence in the Monotheistic Traditions*, ed. Karl Giberson (Oxford University Press, 2016), 36–58.

56. Torrance, "Divine and Contingent Order."

57. Torrance, "Divine and Contingent Order," 85.

58. Torrance, "Divine and Contingent Order."

59. See Kevin J. Vanhoozer, "T.F. Torrance (1913–2007) Christ the Key to Creation and Theological Science," in *Science and the Doctrine of Creation: The Approaches of Ten Modern Theologians*, ed. Geoffrey H. Fulkerson and Joel Thomas Chopp (Downer's Grove, Illinois: InterVarsity Press, 2021).

60. Cf. Jaeger, "The Contingency of Creation and Modern Science."

61. Torrance, "Divine and Contingent Order," 88.

62. Peacocke, *Theology for a Scientific Age*, 65.

63. "Reality Compels Us to Know it According to Its Nature" Tapio Luoma, *Incarnation and Physics: Natural Science in the Theology of Thomas F. Torrance* (AAR Academy Series, Oxford: Oxford University Press, 2001); cf. Cf. Jaeger, "The Contingency of Creation and Modern Science," 11.

64. Torrance, "Divine and Contingent Order," 85.

65. Cf. Isaiah 43:19.
66. Peacocke, *Creation and the World of Science*, 246.
67. Dylan Demarsico, "In the Beginning Was Laughter," *The Behemoth* 5 (2014).

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