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Review

Scientific Knowledge of the Moon, 1609 to 1969

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Abstract: Discoveries stemming from the Apollo 11 mission solved many problems that had vexed scientists for hundreds of years. Research and discoveries over the preceding 360 years identified many critical questions and led to a variety of answers: How did the Moon form, how old is its surface, what is the origin of lunar craters, does the Moon have an atmosphere, how did the Moon change over time, is the Moon geologically active today, and did life play any role in lunar evolution? In general, scientists could not convincingly answer most of these questions because they had too little data and too little understanding of astronomy and geology, and were forced to rely on reasoning and speculation, in some cases wasting hundreds of years of effort. Surprisingly, by 1969, most of the questions had been correctly answered, but a paucity of data made it uncertain which answers were correct.

Keywords: lunar origin; lunar crater origin; lunar atmosphere; lunar changes; lunar surface age

1. Introduction

In the 360 years between Galileo's first telescopic look at the Moon and the launch of Apollo 11, the Moon attracted many serious observers who developed questions and possible answers about its origin and conditions. Early interpretations of the Moon, its surface and atmospheric conditions were guided by philosophic beliefs from the ancient Greeks and early Christians. However, Galileo, the first to publish telescopic observations and interpretations derived from them, simply reported what he saw, not fitting his observations into prior assumptions of what should be seen. He set a high standard that was often ignored in following centuries. By 1969 all of the general questions that Apollo set to answer had been identified by telescopic observers, and many correct answers had arisen, along with sometimes wildly improbable ones. This paper reviews major issues that were investigated over three and a half centuries, with results and ensuing controversies. A handful of scientists are identified as real heroes of lunar science, not just because their conclusions were correct, but also because their approaches were innovative, and they best used the limited data available to them.

2. Galileo

Galileo Galilei was the first person to scientifically observe the Moon and publish his discoveries [1]. In late 1609 he discovered that the Moon was not a smooth heavenly sphere but had mountains and valleys, like the Earth. He made the first scientific measurement of lunar topography, determining that one peak was 6 km high. He recognized that the dark areas, which he named 'maria' or seas, were lower and smoother than the brighter regions, and that the lack of clouds indicated that the Moon had little water, so if it had any life it would be different from that on Earth. He also detected the Moon's librations in longitude and in latitude. Galileo was the first selenologist and the first astrobiologist to base his deductions on observations rather than speculations.

3. Maps and Science

The next significant improvement in understanding the Moon came in the mid-1600s from the cartographers Langrenus, Hevelius and Riccioli, who produced the first maps with many recognizable landforms [2]. Maps established the geography (or more accurately, selenography) of the lunar surface, identifying the variety of types of landforms to be explained. Hevelius' maps were published in 1647 in his *Selenographia*, *sive Lunae descriptio*, the first book describing the surface of the Moon, which remained the standard text until the 1830s. Riccioli's map, which was drawn by his student Grimaldi (some things never change), introduced the nomenclature (natural philosophers, scientists, and explorers names for craters) that is the basis for the system still used today. These mapping activities, like most of those that followed, resulted in more complete depictions of the lunar surface but little improvement in understanding the processes that made and modified the Moon.

The German astronomer Johann Hieronymus Schröter spent the last 20 years of the 18th century producing two volumes of *Selenotopographische Fragmente* [3] (pp. 59–73). These were the first extensive studies of individual lunar regions and features. His drawings had more details than previous maps, and he discovered mare ridges, numerous rilles and domes, tall mountains at the South Pole, and he provided the first details of various limb regions. Schröter's careful observations led him to realize that large craters were proportionately more shallow and flat-floored than smaller bowl-shaped ones. Using data from his topographic measurements he built crater models with sand, determining that the volume of the rim equaled that of the crater depression, which he interpreted as evidence that the crater rim formed by volcanic eruptions of ash.

The first modern investigation of the lunar surface appeared as the publication of a detailed map and book, *Der Mond*, by the Germans Wilhelm Beer and Johann Mädler from 1834 to 1837 [3] (pp. 95–118). Mädler, the greatest selenographer of the 19th century, did nearly all of the observing with a 95-mm aperture refractor, and Beer was his wealthy patron who provided the observatory. Based on his meticulous observations, Mädler concluded that the Moon had no atmosphere, and hence no water, and if it had any life it would be much different than life on Earth. He finished by stating that, the Moon was "no copy of Earth", reversing Galileo's conclusion that because the Moon had declivities and mountains it was like Earth. Galileo had shown that the Moon was not heavenly, and Mädler recognized that the Moon, and by extension the planets, did not have to be Earth-like.

The Beer and Mädler book and map were overwhelming improvements to previous work, and it has been said [3] (p. 115) that other observers considered telescopic exploration of the Moon to be complete, and thus they moved to other topics. In many respects this was true. Beer and Mädler's book and maps became the standard reference, even reaching into the literary realm with their maps being carried to lunar orbit in Jules Verne's *From the Earth to the Moon* science fiction book of 1865, and the following *Around the Moon*. Beer and Mädler still had a visual presence nearly a century later when I arrived as a young astronomy student at the Steward Observatory of the University of Arizona in 1960, for their famed one-meter diameter map prominently hung on a wall.

Both before and after Beer and Mädler's work other observers published maps and books about the Moon, with the German Julius Schmidt's being obsessively comprehensive, but in general, little new scientific understanding emerged from the improved mapping. That conclusion continued to hold as photographic atlases began to appear in the 1890s, but the culminating *Photographic Lunar Atlas* of 1960 and supplements by Gerard Kuiper and colleagues had high resolution, large scale, and multiple illumination views that provided data for many new scientific investigations. The most important was a discovery made possible by projecting these telescopic lunar images onto a white globe and then re-photographing the globe directly over limb regions. By doing this, graduate student William K. Hartmann and Kuiper discovered [4] that the small Mare Orientale on the western limb was the center of a large three-ring structure Hartmann named a multi-ring basin. The Orientale mare patch had been independently discovered multiple times since 1903 [5] and there was speculation that the small mare was in a large crater, but the overhead rectified view revealed the bull's eye ring system that became iconic once imaged by the Orbiter IV spacecraft in 1967, and the proto-type for all other basins on the Moon and across the solar system.

Using other images from the *Rectified Lunar Atlas* [6], Hartmann [7] discovered similar multiple rings and radial lineations associated with most other circular maria, leading to the recognition that multi-ring basins were the morphological manifestation of the largest impact craters.

4. Is the Moon Inhabited?

Since ancient Greek times philosophers and scientists had speculated that the Moon, the planets, and even the Sun and stars were inhabited. This was an extravagant extrapolation based on limited sampling. Earth, the only examined celestial body, was inhabited, and all other worlds were assumed to be. Even Kepler wrote a science-fiction style book, *Somnium*, in 1611, combining a fantasy that the Moon was inhabited with scientific descriptions of space travel and the lunar surface.

One of the first scientists to challenge this idea with observational data was the French astronomer Adrien Auzout [8]. In the very first volume of the *Philosophical Transactions of the Royal Society of London* (1665–1666) he discussed changes that lunar inhabitants might witness when observing Earth. They would see moving clouds, winter's whiteness, green colors appearing in the spring as crops grow, and a decrease in dark areas as forests were cut. Lunar observers might also see erupting volcanoes, burning forests, and city lights.

Auzout recognized that such changes had never been observed on the Moon during the 50 years of observations since Galileo. He concluded that these phenomena did not occur on the Moon, and also stated that because there were no seas, clouds nor twilights it was unlikely the Moon had an atmosphere. His remarkably prescient deductions apparently influenced no one, and for hundreds of years observers continued to propose that water, ice, gases, vegetation, active volcanoes, and even people could be found on the Moon.

The German astronomer Schröter observed bright extensions of the lunar terminator at the poles beyond the illuminated areas, interpreting the phenomena as twilight. He also, without any evidence, considered that an area near Marius was a city with Selenite inhabitants, the Hyginus rilles were canals for commerce, and that Mare Imbrium was farmland [3] (p. 80). Schröter's claims of Selenites and their constructions were mercilessly attacked by Mädler, perhaps reflecting his reported dour personality. These fantastical interpretations, along with his poor draughtsmanship, caused later astronomers to criticize all Schröter's work.

But Schröter did inspire a young Bavarian lunar observer, Franz von Paula Gruithuisen, who had proposed that the Great Comet of 1811 was inhabited, and later identified a rectangular pattern of ridges near the lunar crater Bonpland that he interpreted as a city, with transportation networks, agricultural fields (the maria were forests) and possible buried cities for Selenites to escape the Moon's extreme heat and cold—all of these discoveries were made with a tiny 6 cm aperture refractor [3] (p. 82). Gruithuisen also believed that the Moon has a thin atmosphere that sometimes obscured features, accounting for their absence on earlier maps. Like his hero Schröter, his interpretations were grounded in fantasy, what he wanted to see; after a brief period of fame he was dismissed as a crank.

Searches for a lunar atmosphere persisted. One of the greatest mathematicians of the 18th century, Leonhard Euler calculated the Moon's atmosphere density to be 1/200th of Earth's. A few years later in 1748, the Slovene astronomer Roger Boscovich rejected the idea that any atmosphere existed because shadows should be a diffused gray, features near the limb would be blurred, and stars being occulted would dim before disappearing—none of these phenomena were observed.

5. Does the Moon Change?

Because the Moon was assumed to be Earthlike, centuries were taken up looking for changes. Sir William Herschel, discoverer of the planet Uranus, reported in 1787 [9] that he had observed a lunar volcano in eruption, and two others that must have only recently stopped. He had noticed bright spots on the Earth-lit portion of the 3-day old Moon. The bright feature had been named Mt. Porphyry by Hevelius and is now known as Aristarchus, one of the brightest craters on the Moon, and one that glistens in Earthlight. Astronomers of the time cautioned Herschel that the brightness of Aristarchus was a normal appearance. Soon thereafter he stopped observing the Moon and profitably shifted his interests elsewhere.

With volcanism generally accepted as the origin of lunar craters until the 1960s, observers expected to see ongoing volcanic eruptions. But as observations accrued it became clear that large scale changes on the Moon were rare—no large craters were seen to form or change. Thus, astronomers searched for evidence of small changes. This was done by noticing new craters not previously recorded, or by observing obscurations of the surface, or bright spots and flashes or other temporary manifestations interpreted as volcanic degassing or eruptions. Because every generation of lunar observers had larger and optically better telescopes it was common to detect small craters not included on earlier maps. Although an obvious interpretation would be that the earlier cartographers simply had not detected a feature, a common reaction was to claim that a new volcanic crater had formed.

In the most famous purported lunar change of the 19th century, the very experienced lunar mapper Johann Friedrich Julius Schmidt claimed in 1866 that a crater Linné had disappeared. Schmidt was famous for his 1856 book *Der Mond*, which was the first time that lunar features were quantitatively compared with landforms on Earth [10] (p. 20), perhaps the beginning of comparative planetology. Linné was depicted on earlier maps, including the meticulous one by Beer and Mädler, as a crater about eight kilometers wide; Schmidt himself observed it that size in 1843, but in 1866 he found only a small dark spot at the center of a bright nimbus. Because of Schmidt's prestige his claim was taken seriously, and many observers confirmed that the earlier, larger crater no longer existed. This was considered a high confidence observation of change that proved the Moon was still active. However, Mädler himself re-observed Linné in 1867 and stated that it looked the same as when he observed it in 1831. Nonetheless, repeated arguments about Linné and reported changes at other locations persisted for nearly 100 years.

Two famous observations dominate 20th century reports of lunar changes. First was a Soviet report in 1958 of degassing of the central peak of Alphonsus crater [11] (pp. 313–316). Astronomer Nikolai Kozyrev used a 50″ telescope to obtain two photographic spectra centered on the central peak of Alphonsus. On a 30-min exposure when the peak appeared bright he detected faint emission bands that he interpreted as coming from diatomic carbon gas. A subsequent 10-min plate taken when the peak was fainter showed no evidence of the carbon bands. Kozyrev's announcement was international news; people believing that craters were volcanic and that the Moon was still active were ecstatic. Most astronomers doubted that the spectral bands were real, and Kozyrev's reputation declined further when he saw another Alphonsus "eruption" a year later, and three years on detected hydrogen escaping from Aristarchus. No other astronomer could confirm these observations, but for tens of years the observations were debated. Nearly 50 years later when modern spectral observations revealed that the peak of Alphonsus was made of anorthosite, a remnant of the Moon's ancient magma ocean crust, Kozyrev's interpretation could be officially debunked.

The second supposedly reputable report of lunar changes was the observation of three red glows near Aristarchus crater by US Geologic Survey geologists James Greenacre and Edward Barr in 1963 [3]. They used the Lowell Observatory 24″ refractor to observe the Moon when it was only 25° above the horizon. They believed that red glows they observed were volcanic eruptions, but the most likely explanation was that the refractor's known poor corrections of chromatic aberration amplified normal prismatic dispersion of light caused by scintillation of the Earth's atmosphere to produce the sparkly red glows seen on the brightest peaks [3] (pp. 316–318). Later searches of the Lunar Reconnaissance Orbiter Camera's very high-resolution images showed no evidence of recent volcanic deposits [12].

Changes, or Transient Lunar Phenomena (TLP), are still searched for by amateurs and at least one professional astronomer (e.g., [13]), but only one class of TLP has been confirmed as a physical change. Multiple observers at different locations have simultaneously imaged bright flashes caused by meteorite collisions with the Moon. Now even NASA documents such impacts, and the Lunar Reconnaissance Orbiter has imaged hundreds of small new craters formed by impacts [14].

Some other classic TLPs have been reinterpreted following diligently planned re-observation imaging at identical libration and lighting conditions as the original TLP reports. In particular, Lena and Cook [15] confirmed that in at least one case crater floor obscurations do re-occur when grazing sunrise rays pass over low crater rim segments to faintly illuminate a patch of a crater floor before the entire floor brightens as the Sun rises higher. Such re-observations debunk those specific TLP interpretations as gas obscurations, but do confirm that some amateurs did make very careful observations that detected transient illumination conditions, not transient physical changes on the Moon. The 300-year search for changes on the Moon has been one of the most fruitless pursuits in the name of science. Yet we can use these reports to state that no significant internally driven change has been confirmed during this time.

6. How Do Lunar Craters Form?

The origin of the Moon's craters bedeviled observers for hundreds of years. In the 1660s Robert Hooke performed experimental investigations of how craters might have formed [3] (p. 25). He compared possible impact and volcanic origins by dropping balls onto wet clay, and by boiling alabaster; in both experiments circular depressions formed. The impact features looked most like lunar craters, but because Hooke had no evidence that projectiles existed in space, he accepted the volcanic interpretation. While Hooke's experiments were the first attempt to model lunar crater origins, his comparison of depressions a few centimeters wide with craters thousands of times larger was hindered by a complete lack of understanding of the physics of both impact cratering and volcanism. In general, this ignorance continued through the 1950s.

From 1660 to nearly 1960 the origin of the Moon's craters remained contentious. For most of that time various varieties of the volcanic theory completely dominated discussions. But after asteroids were discovered, starting in 1801 and increasingly thereafter, it was apparent that the source of projectiles that Hooke needed had been found. A second discovery in the same time period, that meteorites recently observed to fall in France (L'Aigle, 1803) and Connecticut (Weston, 1807) were from space, not from other places on Earth (i.e., they were not meteorological phenomena), strengthened the belief that cosmic rocks could bombard the Moon just as they did Earth. By 1829, Gruithuisen [3] (pp. 75–89) re-introduced a version of Hooke's impact theory for lunar craters, but because he also speculated wildly about cities on the Moon all of his ideas were generally ignored.

A serious objection was recognized for impact theories—projectiles should impact the Moon at all angles and thus many craters should be elliptical, but almost none are. Without an explanation of why craters were circular, volcanism, a known terrestrial process, remained the only viable origin. But almost everyone (except Gilbert in 1893 [16]) failed to notice that volcanic craters were typically on tops of massive mountains, whereas lunar craters occur on flat terrain. Although the British astronomer John Herschel [17] mentioned that the concentrations of small circular volcanoes near Naples and in the Auvergne region of southern France looked like lunar craters, no one seems to have followed up that observation. It was not until the early 1960s that such maar volcanoes—small, explosively formed, rimmed volcanic craters with sunken floors—that commonly erupt on flat lands, were recognized as possible matches for lunar craters [18] (pp. 291–306). Maars are the best volcanic analogs to lunar craters, but their clustering, small size, lack of central mountains, and common association with volcanic cones and lava flows, fail to match lunar crater occurrences.

The astronomer Richard Proctor advanced the impact theory in his 1873 book (but omitted it in the 1878 edition) [3] (p. 219). In 1893, the American geologist G. K. Gilbert [16] considered impact the most likely crater origin, even suggesting that Mare Imbrium, with its radial sculptures, was the largest impact crater, but the idea gained little ground. To explain why craters were circular rather than elliptical Gilbert suggested that circular craters would be produced if the projectiles were in lunar orbit rather than coming from further away in space. This led Gilbert [16] to propose that the Moon and its craters formed from a ring of projectiles in Earth orbit.

The breakthrough came independently by two scientists whose publications (in Moscow and New Zealand) were unnoticed by the few people of the 1920s interested in the Moon. Until then the concept of impact formation of craters was purely mechanical—the projectile would collide with the lunar surface and gouge out a hole. In 1916, the Estonian scientist Ernst Öpik realized that projectiles in space travel at extreme velocities, making their energy much higher than anyone had considered previously. In 1924, the New Zealand scientist A.C. Gifford [19] independently published results similar to Öpik's. Both scientists realized that given the cosmic velocities of space projectiles, the nearly instantaneously released kinetic energy would cause a mighty point source explosion, creating a circular crater many times larger than the projectile. The Russian language paper of Öpik was totally unknown to Western scientists, and although Gifford's did gain some attention, few people interested in the Moon incorporated his results into their thinking.

A second detriment to the acceptance of the impact origin of lunar craters was that none were known on Earth. Ralph Baldwin [20] recounted the history of impact crater recognition, starting with Barringer's 1906 proof—based on the abundance of nickel-iron meteorites around it—that Coon Butte (Meteor, also known as Barringer) Crater in Arizona was of meteoritic origin. In 1928, the 2nd and 3rd meteorite craters (Odessa, TX, USA and Campo del Cielo, Argentina) were identified, also because of associated iron meteorites. A few more craters were proposed to be of impact origin in the 1930s, but it was not until the 1950s that Carlyle Beals and colleagues [21] used aerial photographs to discover dozens of circular lakes in Canada, many of which turned out to be of impact origin.

In 1938, the geologists J.D. Boon and C.C. Albritton, Jr. [22] realized that older terrestrial meteorite craters would be severely degraded by Earth's dynamic geology, and not bear the clear raised rim and subsided floor morphology of young craters such as Barringer's in Arizona. They proposed that a class of eroded features called cryptovolcanoes were actually ancient meteorite craters—examples are Wells Creek, TN, Kentland, IN, Flynn Creek, TN, in USA and Ries in Germany. Unfortunately, no meteorites were found, but there were no volcanics either, and the most prominent geologists of the day rejected the impact interpretation; later evidence proved them wrong.

In 1946, Robert S. Dietz [23] published one of the most prescient and overlooked papers in lunar science. It was prescient in that most of what he said was correct, and overlooked, like many other important papers, because it was published in a journal that astronomers did not read—the prestigious *Journal of Geology*. Dietz tabulated morphological characteristics of lunar craters, none of which were consistent with known styles of volcanism, so the craters could not be of volcanic origin. He recognized that lunar crater morphology changed with increasing energy of impact (crater diameter), that maria are the largest impact craters, and that although typical terrestrial erosion mechanisms did not exist on the Moon, that subsequent impacts would degrade landforms. He further stated that the generally random distribution of craters was not consistent with volcanism, that crater rays were likely to be pulverized impact ejecta, that pervasive impact events would fracture the upper crust, that the high energy of impact would melt rocks (now called impact melt), and that the small Moon would now be cold and dead. Dietz recognized that the paucity of craters on the maria implied it formed late in lunar history, and he also reasoned that the vast energy released by a cosmic collision would immediately melt the lunar crust, producing the maria. Unlike Baldwin and Shoemaker, Dietz did not have detailed physical evidence for his conclusions but based them on geologic reasoning, which was largely correct. Dietz spent much of the rest of his career discovering *astroblemes*, terrestrial impact craters, and fundamentally contributing to the development of plate tectonics.

The absolute star of the saga of the origin of lunar craters was Ralph Baldwin [24]. Trained as an astrophysicist in the 1930s, he supplemented his faculty salary in the early 1940s by giving public lectures at Chicago's Hayden Planetarium. There he became fascinated by wall-sized enlargements of photos from Mt. Wilson Observatory of the region around Mare Imbrium. He discovered (about 50 years after Gilbert, whose work he was unaware of) linear valleys and lines of small craters nearly radial to the mare. He realized that only a vastly large explosion could transport mountains of rock radially out hundreds of kilometers from Mare Imbrium, gouging out these grooves. Noticing the arcuate Apennine, Alpes and Carpathian mountain chains that bordered the mare he concluded that Mare Imbrium was the Moon's largest impact crater. He immediately considered that the other circular maria—Crisium, Nectaris, Humorum, Serenitatis and Humboldtianum—were as well. He realized that the energies needed to excavate such huge holes and distribute debris for hundreds of kilometers was unheard of in any volcanic eruptions, and concluded that "only the impacts of giant meteorites could supply the requisite energies". If these large features were impact structures probably the smaller craters were too [24].

World War II interfered with Baldwin's investigations of the Moon but also supplied critical data that led to his creation of the most important graph in lunar science history. From the military he received photos and details of craters produced by bombs and shells. Recognizing that these bomb craters as well as putative lunar and terrestrial impact craters were all produced by explosions, he plotted a log-log graph of crater diameter vs crater depth. The result was a continuous curve linking together all of these craters. Baldwin measured dimension of volcanic craters, finding that they display no such a correlation over many orders of magnitude, and he triumphantly concluded: "The case for the explosive origin of the moon's craters is unassailable. The probability is very great that the explosions were caused by the impact and sudden halting of large meteorites." [24] (p. 153).

Baldwin's 1949 book, *The Face of the Moon* [24], immediately convinced many American astronomers of the impact origin of lunar craters. Harold Urey supposedly noticed it at a cocktail party and read it straight through before going home. Gerard Kuiper also immediately accepted the impact theory. But for reasons not clear to me, many European, and especially Soviet, scientists ignored Baldwin and clung to volcanic interpretations. For example, in 1960, the Czech astronomer Zdenek Kopal [25] described an uneasy compromise suggesting that probably both impact and volcanic processes produced lunar craters. He proposed that Copernicus and Tycho formed by impact because their extensive radial rays could only be produced by the vast energy of impact. But he claimed that other craters, such as Plato, Clavius and Archimedes that lack rays, are shallower, often have flat lava-covered floors, and sometimes do not even have central peaks, must be volcanic. Kopal made a mistake common of the times in not recognizing that not all craters are the same age. He, and many others, mistook erosion-caused modification as evidence for different formation mechanisms. We now know that nearly all lunar craters formed by impact, just as did ones on Mercury, Venus, Mars, the asteroids and many satellites of the outer planets. The Earth must have received a similar bombardment, but our planet's continuous geologic turmoil buried or destroyed thousands of beautiful Copernicuses that must have formed, leaving only a few hundred degraded ones for us to find.

Two large organizations founded in 1960 provided many of the next decade's geologic advancements in lunar studies. The greatest success of an organization to transform understanding of the Moon was the development of what became the Astrogeology Branch of the U.S. Geological Survey (USGS) [26]. Eugene Shoemaker, the leader of this group, developed in the late 1950s and early 1960s fundamental understandings of lunar science. First, he studied in detail the mechanics of nuclear craters and Meteor Crater on Earth and applied that knowledge to Copernicus crater on the Moon [27]. This led to the first comprehensive understanding of impact mechanics, and recognition that strings of small craters and bright rays were due to debris ejected by the hypervelocity impact that formed Copernicus; Baldwin had thought the secondaries east of Copernicus must be volcanic.

A second critical discovery from the USGS was that the mineral coesite, a heavily shocked variant of quartz which naturally forms only under the high pressure of an impact, was in the ejecta of Meteor Crater. Edward Chao made this discovery and later, with Shoemaker found coesite in the Ries Kessel of Bavaria, proving it was an impact crater ([26], p. 45).

Meanwhile, Shoemaker and Robert J. Hackmann compiled a geologic map of Copernicus and the southern Mare Imbrium region of the Moon [27]. This established the sequence of events, with the surrounding highlands or terrae being oldest, the Imbrium Basin younger, formation of craters such as Archimedes on the basin floor were next, followed by eruption of the mare lava flows, and finally, impact of Copernicus and smaller post-mare craters. This stratigraphy proved that the maria were not formed as impact melted rocks from the basin-forming collision, but later in time, presumably due to radioactive melting of mantle rocks.

The USGS Astrogeology Branch then started a massive mapping program that ultimately compiled the first geologic map of the lunar nearside and then the farside. These maps established a global stratigraphy demonstrating that the ejecta of impact basins provided widespread stratigraphic markers—each crater could be determined to be older or younger than each basin's ejecta rock units. One disadvantage of constructing geologic maps is that every piece of landscape requires an interpretation, thus USGS mappers evaluated the origin of not just craters, but mountains, rilles, ridges and plains, being forced to make interpretations where evidence was inconclusive. Even in the 1960s volcanism was still regarded as a likely origin for plains deposits that were not dark like the maria. This led to the biggest surprise of the Apollo program when Apollo 16 astronauts landed at the Descartes highlands, a grey plain interpreted as volcanic, but immediately recognized as highly shocked impact debris.

The Astrogeology Branch also trained astronauts to be practical geologists when they were on the Moon, with the only geologist sent to the Moon—Harrison Schmidt—originally a USGS employee. After the Apollo program, geologist Don Wilhelm wrote a personal account, the classic *To a Rocky Moon* [26], chronicling the USGS work in developing lunar science, mission site selection, and astronaut training.

The other organization with a major influence on development of data and ideas about the Moon was the Lunar and Planetary Laboratory founded by Gerard Kuiper at the University of Arizona in 1960 [28]. The main lunar work at LPL was (1) a series of supplements to Kuiper's *Photographic Lunar Atlas*, (2) the *System of Lunar Craters* [29], a comprehensive catalog of nearside lunar craters and nomenclature maps, and (3) a series of papers largely by William K. Hartmann about multi-ring basins, the history of impact bombardment, and the age of the lunar surface. As previously described, the recognition of the Orientale multi-ring impact basin led to a series of papers about concentric and radial structures of nearside basins, culminating with a global survey of impact basins based largely on Lunar Orbiter data by Hartmann and Wood [30]. Using data from the *System of Lunar Craters* catalog, Hartmann [31,32] also determined that there were far more (>200 times) craters per unit area on the terrae than on the maria, implying that the cratering rate in the earliest days of the Moon was much higher than when the maria formed.

7. How Did the Moon Form?

By the 1960s, there were no good models for the origin of the Moon. As Brush [33] and Wood [34] recount, the earliest theory was a second order version of Laplace's nebular hypothesis from the 18th century that the planets formed from the solar nebula, a rotating swarm of dust and gas. In this scenario, the Moon similarly formed from material from a local rotating nebula that ultimately made the Earth. A variant of the Laplace hypothesis proposed that the Earth and Moon formed simultaneously in a cloud of co-accreting gas and particles.

In the 1870s George Darwin, son of the famous evolutionist, proposed that the Moon, which had been discovered to be receding from Earth, had originally spun off an early rapidly rotating Earth; later the Pacific Ocean was said to be the scar from the parting. In 1930 this idea was permanently discounted when the British astronomer Harold Jeffreys calculated that the viscosity within the Earth's mantle would strongly weaken oscillations needed for the Moon to spin away [35] (pp. 141–143).

In 1893, Grove Karl Gilbert [16] proposed that the Moon formed by the accretion of small rocky particles. Gilbert said that the tail end of the accretion would have formed the craters visible on the Moon, an idea 60–70 years ahead of its time. More than 60 years later, the American cosmochemist Harold Urey [36] supported this view, believing that accretion would be a cold process and thus the Moon was made of primitive, 4.5-billion year old cold chondritic material, with no volcanism, just impact cratering and associated melting. Apollo later confirmed what careful observers had recognized for decades—the maria were volcanic lava flows, and the Moon had been hot; Urey was wrong.

Finally, another hypothesis for lunar origin, originated by Urey and popular for a while, was capture of a Moon that had formed elsewhere in the solar system [34] (pp. 30–33).

All of these theories ran afoul of one or more of the three constraints known before analysis of Apollo samples [34]: (1) The Moon is huge in relative size compared to other satellites and their planets; (2) The Earth–Moon system has a very high angular momentum; and (3) The Moon has a very low density (3.3 g/cc) compared to the planets (typically 4 to 5 g/cc). The sad state of understanding the Moon's origin was summed up by John Wood [34] (p. 47) in 1984—at the very conference where a new formation model emerged: "How the Earth's Moon was formed is still not known. Perhaps it will never be."

8. How Old Is the Lunar Surface?

For most of the hundreds of years that the Moon was studied there was no way to determine the age of its surface features. Indeed, it was not until the 1950s that an accurate age of the Earth—4.55 billion years—was determined by radiometric dating.

In the months before Apollo, two of the leading lunar scientists published age estimates for the lunar maria, such as where Apollo 11 was to land; a graduate student had published an age earlier. All three scientists accepted that lunar craters were formed by impact, with more craters per unit area corresponding to an older age than a sparsely cratered surface. The three scientists estimated the surface age by counting the number of impact crater in a maria area, and dividing that number by the rate craters were thought to form—how many craters formed per million years on a million-kilometer size patch of the lunar surface. The crater counting was relatively straight forward but the crater production rate was uncertain, being estimated variously from the rate of fall of meteorites on Earth, the number of meteor craters on ancient Earth terrains, and calculations of the rate that potential crater-forming asteroids came near the Earth/Moon system. Ralph Baldwin and Eugene Shoemaker both came up with estimated ages for lunar maria of a few hundred million years [26] (p. 100). The graduate student, Bill Hartmann [31], derived a lower crater production rate and estimated a mare age of 3.6 billion years, almost exactly the age of the Apollo 11 mare samples the astronauts collected on the Moon.

9. The Early Spacecraft Era

With the 1957 launch of Sputnik the space race officially began. Both the Soviets and Americans had frequent failures but the Soviets launched so often that they dominated spacecraft achievements from 1957 to 1964. In 1959 Luna 1 was the first vehicle to fly near the Moon, detecting no magnetic field. Later in 1959 Luna 2 was the first spacecraft to impact the Moon. Luna 3 (also in 1959) produced high Sun, low resolution images that revealed the farside. After a dozen failed attempts, Luna 9 (1966) made the first successful soft landing, in Oceanus Procellarum, showing a rough surface free of deep dust, and three months later Luna 10 was first to orbit the Moon, confirming its lack of an atmosphere and making the first measurements of soil composition. These Soviet missions were dominantly engineering and public relations successes with limited scientific results.

From 1965 on, the American lunar missions clearly surpassed Soviet attempts, and all the US missions had strong scientific objectives. After an agonizing series of failures, the last three Ranger spacecraft impacted as planned, with cameras taking increasing high resolution images as the spacecraft moved closer to the lunar surface. All of the images showed craters, with the last images displaying craters less than a meter across. There was no way that volcanism could produce similar craters of all sizes, hundreds of kilometers across to meter scale. This was powerful evidence that all lunar craters from the largest to the smallest were of impact origin.

Soon after the triumphant end of the Ranger missions, the US launched five Lunar Orbiters designed to acquire high resolution images of potential Apollo landing sites, views of special craters, rilles and mountains, and 100 m resolution images of much of the entire Moon. The Orbiter images supplanted all previous lunar maps and photo atlases, providing closeup views with 10 to 100 times higher resolution than the best telescopic images. These images allowed selection of relatively safe and interesting landing sites, and were used for detailed lunar geology investigations from the late 1960s until images arrived from Clementine in 1994 and then Lunar Reconnaissance Orbiter in 2009. Based on Lunar Orbiter images, hundreds of papers reflecting new geologic understanding were published covering every category of lunar landform—crater rims, walls, floors, central peaks, basins and their rings, secondary craters, mare lavas, rilles, domes, mountains, swirls and impact melts, for the nearside, the farside and the lunar poles.

The final American spacecraft series before Apollo was the Lunar Surveyors. These soft-landing spacecraft carried cameras and a variety of instruments to determine surface physical properties for landings, and also physical and chemical analyses of lunar soils. The most important discovery resulting from Surveyor data was that chemically the maria were likely basaltic lavas, and the highlands contained significantly less iron, and were a completely different material.

10. What Was Known and Still Unknown about the Moon in Early 1969

- The Moon lacked water, air and life, had hundreds of degrees of monthly temperature variation, and seemed to have been geologically dead for a long time.
- Nearly all evidence was that most lunar craters were of impact origin, but there were skeptics.
- As lunar crater diameters increased their morphology changed systematically from bowl-shaped pits to terraced and central peak craters, to multi-ring basins. Rays and secondary craters were impact crater ejecta.
- Lunar maria were lava flows, but there was no compositional information about the highlands.
- The age of lunar maria was perhaps a few hundred million years or 3.6 billion years, all much more ancient than most of Earth's surface geology.
- If the maria, which were the youngest large scale feature on the Moon, were 3.6 billion years old, most of lunar history occurred in its first billion years.
- The rate of crater formation was very high in earliest times and declined precipitously. Large craters were preferentially formed early in lunar history.
- Nothing was known of lunar geophysics other than it had no current magnetic field, and that mass concentrations—mascons—occurred under most circular maria.
- All theories for the origin of the Moon were unlikely.

11. Committees versus Institutions

At various times committees were established to investigate lunar issues; almost without exception they failed. In 1852 the British Association for the Advancement of Science established a Lunar Committee to make a new map of the Moon showing small features visible in large telescopes, but absent on Mädler's map. The Committee also planned to measure the dimensions of craters, mountains, mare ridges and other landforms. Unfortunately, other than a plan, the Committee accomplished little [3] (pp. 59–73).

Twelve years later the British Association tried again, establishing a Committee for Mapping the Surface of the Moon [37], which proposed to construct a detailed map of the Moon with 225 charts, each identified by a confusing welter of Roman and Greek letters, with individual craters or hills designated by an Arabic number, and Roman numbers indicating latitudinal zones. Craters would be identified by a confusing sequence of alphanumeric digits: Tycho was 3E∑2. The proposed accompanying catalog would contain 1440 pages. A few charts were created before the Committee disappeared from history, perhaps under the weight of an ugly and oppressive nomenclatural system.

A third group, the Committee on Study of the Surface Features of the Moon, was established by the Carnegie Institution of Washington in 1925. It was led by a Carnegie geologist, F.E. Wright, and included prominent physicists, astronomers (including H.N. Russell of Hertzsprung–Russell diagram fame), and geologists. A major goal was to investigate the nature of the materials that the Moon was made of, and the landforms they made. The scientific approach is indicated by the Wright et al. [38] (p. 1) statement that, " … precise data of measurement are needed rather than suggestions regarding possible modes of formation of the different lunar surface features."

Committee goals included producing a large photographic map and a topographic map, neither of which was made. In the 1930s, Wright, who seemed to have done most of the work, innovatively projected telescopic images on spheres coated with photographic emulsions, but failed to discover the Orientale basin or anything else. He also estimated the slopes of 100 craters, and calculated the ballistic range of ejecta with different velocities, but did little with the data. The flagging committee disbanded during WW2 and never accomplished as much as expected based on their distinguished membership.

Why did the committees fail and later institutions succeed? In two of these three efforts, committee members were largely amateurs who worked as volunteers, with many competing interests and no pressing timeline. Based on a lack of publications, essentially none of the luminaries of the Carnegie committee carried out any significant lunar work. By comparison, the USGS Astrogeology Branch and the Lunar and Planetary Laboratory were established as research institutions with professional scientists working in government-funded positions (the Lunar and Planetary Lab was anecdotally called the Dollar and Monetary Lab by university colleagues in more poorly funded endeavors), supporting a critical national goal—getting a man on the Moon within a decade. Leading researchers, Shoemaker and Kuiper, led these institutions, infusing them with dynamic visions and significant understanding of lunar issues, the politics of science, and the funds to hire experts with complimentary skills and knowledge. Researchers were completely focused on their jobs, and were inspired and driven by the race for human exploration of the Moon.

12. Heroes and Careers

Finally, it must be stated that although hundreds of people studied the Moon over the last 400 years only a few significantly advanced understanding of lunar conditions, origin and evolution. Based on this review I propose that these were: Galileo, Hevelius, Auzout, Mädler, Gilbert, Öpik, Gifford, Dietz, Baldwin, Shoemaker and Hartmann; I was privileged to meet five of these heroes. Two of these innovators made almost no impact on lunar studies because their papers were published in journals not read by scientists studying the Moon, and the paper of a third was totally ignored. Additionally, most of these lunar heroes completed their important lunar work in fewer than about five years. Only Baldwin, Shoemaker and Hartmann devoted more than a decade to the Moon. Additionally, these three generated new data, not just theories or observations, to develop and test their ideas. And only since the decade leading to Apollo did lunar (and then planetary) studies develop into a discipline offering graduate education and possibilities of career-long funding (often with hiatuses); Hartmann was among the first of a new generation of young people educated to become lunar and planetary scientists.

One of the fun aspects of learning the history of lunar studies is that craters carry the names of many of the scientists involved. Thus, Boscovich and Euler, who disagreed about the existence of a lunar atmosphere, can both be observed with a backyard telescope. Fittingly, Boscovich crater is bigger than Euler crater.

13. Non-Western Lunar Science?

A reviewer commented that this history, "is a very Western-centric view; was there no lunar observation or thinking occurring in the East or in the Middle-East?" I am unaware of any non-Western discoveries or hypothesizes about the lunar surface, and none that impacted Western science. Wikipedia [39] documents that ancient Chinese observers (like ancient Greeks and others) understood the reasons for eclipses, and that moonlight was reflected sunlight. In China, stars were cataloged, comets and guest stars (novae) recorded, and eclipses predicted, yet the most conspicuous night sky object was ignored. The lack of lunar observations and discoveries even after Westerners brought the first telescopes to Muslim lands, India and China in the early 17th century differs greatly from Europe, where the Moon was one of the first objects to be telescopically investigated. Apparently, the first non-Western study of the Moon was delayed until the end of the 20th century.

I am not a historian, but a journeyman lunar scientist lucky to have met many of the lunar scientists since the 1950s. For this article I have used personal information and understanding, and also heavily relied on two classics of lunar history. W.P. Sheehan and T.A. Dobbins (2001) *Epic Moon* [3] is a magisterial accounting of lunar explorations of the telescopic era. The second mandatory read for any student of the 20th century's lunar history is D.E. Wilhelms' (1993) *To a Rocky Moon* [26]. Other important books focus on single issues: E.A. Whitaker, 1999, *Mapping and Naming the Moon* [2] (does what its title says); S.G. Brush, 1996, *Fruitful Encounters* [35] (origin of the Moon), and E.A. Whitaker (1986) *The University of Arizona's Lunar and Planetary Laboratory; its Founding and Early Years* [28] (institutional history). Finally, the contentious history of debate and evidence for the impact origin of lunar craters was reviewed by Peter Schultz in a little-known publication [40].

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