360 YEARS OF LUNAR SCIENCE: FROM GALILEO TO APOLLO 10. C. A. Wood, Planetary Science Institute, 1700 East Fort Lowell, Suite 106, Tucson, AZ 85719-2395; cwood@psi.edu

Introduction: In 1609 Galileo became the first scientist to investigate the Moon. He discovered depressions and smooth dark plains that he called maria, and concluded that the Moon, like the Earth, is a variegated world, not a perfect heavenly sphere. He saw no sign of oceans and realized that any life on the Moon would be different from than that on Earth.

Over the next 360 years a few hundred others reported observations and speculated beyond their data or knowledge about the alien landscapes they saw. A series of questions developed about the origins of the Moon, its features and conditions. The Apollo program sought to answer many of those questions.

Is the Moon Inhabited? Long before the telescope's invention philosophers postulated that other bodies in the sky were inhabited. Once Galileo revealed the Moon to be a place, the speculations increased, with nearly everyone agreeing that it was inhabited. But as early as 1666 the Frenchman Auzout commented that during the 50 years since Galileo, lunar observers had not reported weather, seasonal changes or civilization; Auzout concluded that those phenomena did not occur on the Moon. He was ignored and many observers through the mid-1800s assumed that putative changes resulted from agriculture and city building. This led to searches for ever smaller objects, while large features such as impact basins were overlooked. Few observers suggested that changes compared to earlier maps might be due to improved telescopes or differences in sketching abilities.

Does the Moon Change? By the mid-1800s it was generally accepted that the Moon's atmosphere was very tenuous if it existed at all, and thus advanced life was unlikely. From then until today (TLPs – transient lunar phenomena) reported changes were thought to be due to geological activities such as volcanism creating small craters, and degassing periodically concealing them. In the 1830s Mädler, a careful lunar mapper using only a 95 mm aperture refractor, discounted claims of change. However, in 1866 the professional astronomer Schmidt reported the disappearance of the crater Linné, and other more minor changes continued to be reported, including some in the 1960s being ascribed to insects and vegetation. As recently as 2015 a galactic astronomer tried and failed to discover and document changes. No reported change interpreted as a geologic event has ever been confirmed, including red spots near Aristarchus and gases escaping Alphonsus. Since 2000 A.D. newly formed craters have been imaged by LROC and amateur observers have detected flashes from formation of meter-scale craters-real changes!

How Did Craters Form? The origin of craters was a lunar question that most people through the 1950s considered to be solved: Craters were volcanoes. Volcanism was a familiar process on Earth and presumably occurred on the Moon. Some observers from Robert Hooke on had proposed that cosmic collisions could create craters, but there were three strong arguments against that. First, no projectiles in space were known to collide with the Moon. Second, if that did occur, impacts would occur at all angles and thus many craters would be elongated, but all were circular. Third, no impact craters were known on Earth.

In 1893, the American geologist G. K. Gilbert 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 him to propose that the Moon and its craters formed from a ring of projectiles in Earth orbit.

The discoveries in the early 1800s that meteorites did come from space, and of asteroids, weakened the lack of projectiles argument. But craters were still round. In 1916, the Estonian astronomer Öpik calculated that at the extreme velocity of space projectiles, craters would not be formed by mechanical gouging but from tremendous explosions as kinetic energy was absorbed by collision. Eight years later the New Zealand astronomer Gifford, independently came to the same conclusion. Unfortunately, both Öpik and Gifford published in journals not read by astronomers, and it wasn't until the 1940s that the energy of collision was accepted as the reason for circular craters.

In 1906, Earth's first identified impact crater was confirmed by iron meteorites surrounding it; this recognition was commemorated by the name change from Coon Butte to Meteor Crater. Associated meteorites also identified the next two discovered impact craters (Odessa and Campo del Cielo) in 1928. In the 1930s, geologically older structures called cryptovolcanoes were proposed to be of impact origin, as were various circular lakes in Canada in 1950s and 60s. All of these interpretations of ancient structures as impact craters (astroblemes) were highly disputed until the 1960 discovery in Meteor Crater glass of coesite, an unusual mineral formed only during an impact.

The three arguments against impact cratering were overwhelmed by new discoveries, but it wasn't until Ralph Baldwin's *The Face of the Moon* in 1949 that a coherent scientific argument emerged for the impact origin of lunar craters. Baldwin rediscovered Gilbert's Imbrium Sculpture and realized that extraordinary energy would be required to propel mountains of rock hundreds of kilometers beyond Imbrium's rim. He introduced major evidence, a graph showing that explosion crater depths were proportional to their diameters from meter scale bomb craters of WW2, to the few known terrestrial impact craters, to 100 km wide lunar craters. This evidence immediately convinced Gerard Kuiper and Harold Urey, leading planetary scientists of the time, and soon most of the developing lunar science community accepted the impact origin. Strangely, many European and especially Soviet scientists clung to volcanic interpretations for another decade – why?

Baldwin, Kuiper and Urey overlooked an earlier paper that assembled a surprisingly modern understanding of the Moon. The geologist Robert Dietz showed that lunar craters were morphologically unlike volcanic craters. He accepted Gifford's argument for hypervelocity formation of craters, recognized that lunar crater morphology changed with increasing energy (crater diameter), that maria are within the largest impact craters, and that subsequent impacts would degrade landforms. He further stated that the 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 (megaregolith), that the high energy of impact would melt rocks (impact melt), and that the small Moon would now be cold and dead. Dietz recognized that the maria formed later in lunar history, and the vast energy released by a cosmic collision would imelt the lunar crust, producing the maria. Everything he deduced, except that last statement, was true and decades ahead of others. Dietz' work was overlooked for it published in a journal astronomers didn't read, the prestigious *Journal of Geology*.

In the late 1950s and early 1960s Eugene Shoemaker developed fundamental understandings of lunar science. He studied the mechanics of nuclear explosion craters and Meteor Crater on Earth and applied that knowledge to Copernicus on the Moon. This led to the first comprehensive understanding of impact mechanics, including that strings of small craters and bright rays were due to debris ejected by the hypervelocity impact that formed craters. Shoemaker and Robert J. Hackmann compiled a geologic map of Copernicus and the southern Mare Imbrium region of the Moon that established the sequence of events or stratigraphy that proved maria were not formed as impact melted rocks from the basin-forming collision, but later, presumably due to radioactive melting of mantle rocks.

The final major discovery in the early 1960s was Bill Hartmann and Kuiper's recognition that Mare Orientale was at the center of a bull's eye pattern of concentric mountains; Hartmann documented similar concentric and radial structure at every circular mare.

How Old is the Lunar Surface? In the months before Apollo 11, Shoemaker and Baldwin published age estimates for lunar maria; Hartmann, a graduate student had published an age earlier. All three accepted that lunar craters formed by impact, with more craters per unit area corresponding to an older age. Baldwin and Shoemaker estimated that maria were only a few hundred million years old. Hartmann determined an age of 3.6 billion years, exactly the age of Apollo 11 mare samples.

How Did the Moon Form? Before Apollo there were no good models for the origin of the Moon. The earliest theory was a version of Laplace's nebular hypothesis that the Moon accreted from a local rotating nebula forming the Earth. In the 1870s George Darwin proposed that the Moon, which had been discovered to be receding from Earth, had originally spun off an early rapidly rotating Earth, with the Pacific Ocean being the scar. In 1930 Harold Jeffreys calculated that was geophysically impossible.

In 1893 Gilbert proposed that the Moon formed by accretion of small rocky particles in Earth orbit. During the tail end of accretion the craters visible on the Moon formed. More than 60 years later Urey supported this view, believing that accretion would be a cold process and the Moon was made of primitive, 4.5-billion year old chondritic material, with no volcanism, just impact cratering and associated melting. Apollo later confirmed that the maria were volcanic lava flows, and the Moon had been hot. Urey originated another unlikely hypothesis that the Moon formed elsewhere and was captured by Earth.

All the theories ran afoul of one or more of three severe constraints known before Apollo: the Moon is large, of low density, and the Earth–Moon system has a high angular momentum. The sad state of understanding the Moon's origin was summarized by John Wood in 1984 at the very conference where a new formation model emerged: "How the Earth's Moon formed is still not known. Perhaps it will never be."

Lunar Heroes: The scientists who made the most important contributions to understanding the Moon before Apollo 11 were Galileo, Hevelius, Auzout, Mädler, Gilbert, Öpik, Gifford, Dietz, Baldwin, Shoemaker and Hartmann. The last four attended LPSCs!

References: See *Scientific Knowledge of the Moon, 1609-1969*:
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