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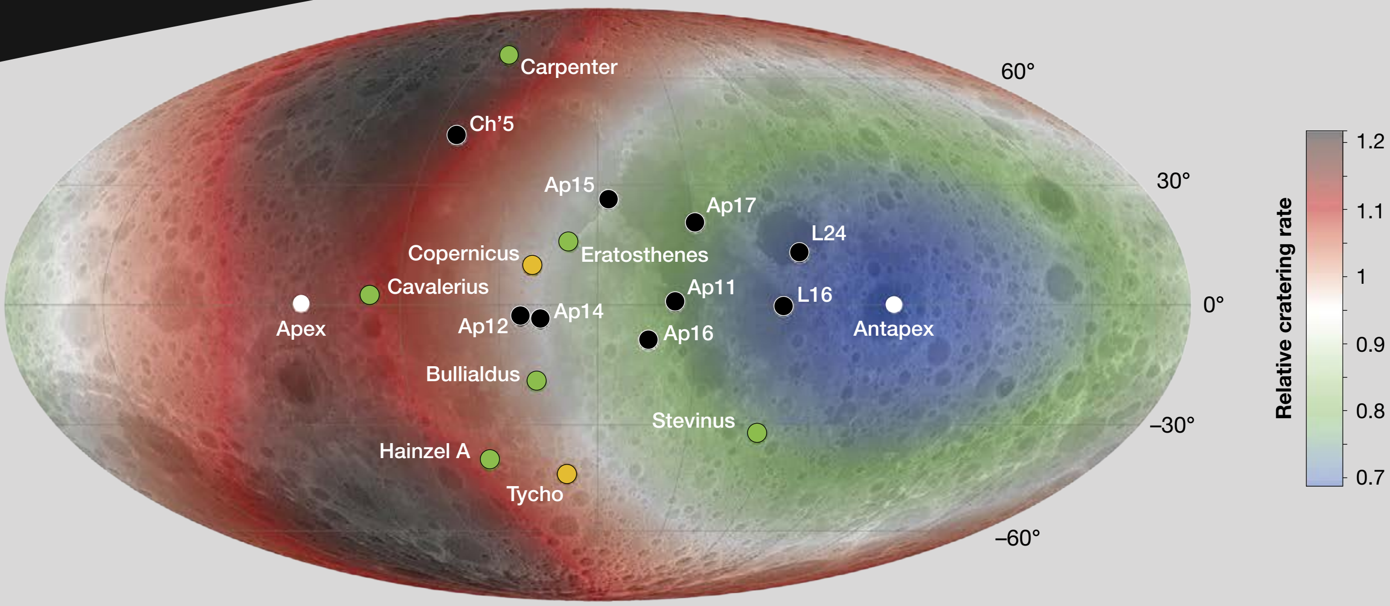
Exploring the Solar System by Charles A. Wood



▲ This map illustrates the asymmetry of lunar cratering rates, with red colors showing higher-than-average rates and blues for lower-than-average ones. The two white circles mark the *apex* or leading edge (left) and *antapex* or trailing face (right) of lunar motion. Black and yellow circles indicate 11 age-dated samples used for chronology calibration; green circles are craters listed in the table below.

ANTHONY LAGAIN

Craters Younger Than We Thought

New crater counts help to revise our understanding of lunar chronology.

Among the most critical data required to understand lunar history are the approximate times that major lunar features formed. The most accurate ages come from radiometric analyses of lunar samples. Unfortunately, samples from only 11 sites have been returned to Earth by the lunar programs of the U.S., the Soviet Union, and China.

For the rest of the Moon, the standard method used to estimate crater ages and other formations is to count the number of impact craters in an area of interest. This technique assumes that craters form all the time, and therefore older surfaces have more craters and younger regions have fewer. Impact craters have formed throughout the last 4.5 billion years, though not at a constant rate.

To determine how the crater production rate (CPR) changed over time, scientists count the number of impact craters with diameters larger than 1 kilometer that are present per square km. This is called the N(1) value. For the areas where lunar samples were returned to Earth, their absolute ages were measured in laboratories. A graph of N(1) and age data shows how the CPR decreased over lunar history, with a very high cratering rate about 4 billion years ago and a much lower, near-constant rate for roughly the last 3 billion years.

Astronomers establish an estimated age (called the *model age*) for any feature lacking radiometrically dated samples by counting craters to derive their N(1) values, then plotting them on a graph. Having done so, scientists determined hundreds of model ages for features. For instance, the east side of **Sinus Iridum** is about 3.35 billion years old, while the west side is 350 million years younger. Both values match that of adjacent **Mare Imbrium** lavas, which flowed downhill into Iridum.

Revised Crater Ages (billions of years)

Crater	Neukum age	Lagain age
Carpenter	3.1	2.4
Cavalerius	3.1	2.5
Hainzel A	3	2.5
Bullialdus	3.7	3.6
Eratosthenes	3.3	3.3
Stevinus	0.9	1.0

As marvelous as the ability to ascertain a model age is, there are uncertainties that sometimes lead to disparate estimates. For example, researchers often count different numbers of craters in the same area. This can be due to the difficulties in deciding if a feature is a crater, a degraded crater, or random topography. They also sometimes disagree if a crater is a primary impact or a secondary crater that formed from the fallback of materials ejected from a primary impact and thus should be ignored. Another variable arises when researchers develop different mathematical fits to N(1) values and absolute-age data. In extreme cases, this can result in a billion years of difference in the model age! The late Gerhard Neukum (Free University of Berlin) and colleagues established a standardized fit in 2001 that has been widely used since.

But now, Anthony Lagain (Aix-Marseille University in France) and a team of colleagues have reevaluated orbital and projectile factors that affect the diameter and number of impact craters that formed in different lunar regions. In their paper (**https://is.gd/cratercounts**) they found that a given N(1) value yields different model ages depending on the location. Simply put, any chart that plots N(1) versus age is only correct for places on the Moon with the same cratering rate. Complex equations must be solved to estimate model ages for each feature.

Here are three major corrective factors proposed by Lagain and his team:

1: More impacts occur close to the lunar poles than near the equator.

2: The approach angle of impactors varies across lunar latitudes.

3: The number of impacts and their velocities vary according to the distance from the Moon's apex of movement around Earth (the point on our tidally locked Moon that always faces the direction of its orbit).

Both factors 1 and 2 are due to the orbital characteristics of near-Earth objects (NEOs) that are the main contributors to inner-solar-system cratering over the last 3.5 billion years. NEOs are typically collisional fragments of main-belt asteroids with orbits that bring them into the inner solar system. Although many NEOs have low-inclination orbits that favor collisions near the lunar equator, the dynamics of high-inclination NEOs lead to cratering at the poles being 1.13× greater than near the equator. And steeper impact angles increase the polar cratering rate to 1.26× the equatorial rate.

With regards to factor 3, the near match between the periods of the Moon's orbit and its axial rotation causes one side of the lunar surface to constantly lead as the satellite orbits Earth. As a consequence, the leading face (or *apex*) collides with more NEOs, and at higher velocity, than the trailing side. The lunar apex of motion at 0°N, 90°W (just north of **Mare Orientale**) receives 28% more impacts and produces slightly larger craters than the antapex side (0°N, 90°E, at **Mare Smythii** on the eastern limb).

Combining all three factors shifts the location of the maximum cratering intensity to ±60°N, 90°W, with the minimum cratering rate at the eastern equatorial limb. Overall, the cratering rate at maximum-intensity locations is 1.77× greater than at the area with the minimum rate.

◀ Carpenter crater (left) is 700 million years younger than previously thought. Stevinus (lower left) turns out to be 100 million years older because it formed in terrain with a lower-than-average cratering rate.

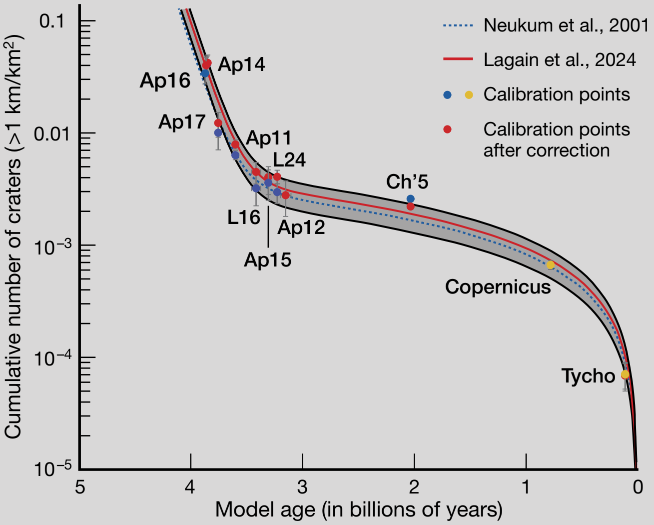
Adjusting for these three factors leads to corrections of N(1) and thus model ages for craters at different locations on the Moon. The table on the facing page lists the model ages in billions of years of several familiar nearside features using the 2001 Neukum cratering curve and the new relation by Lagain and colleagues.

A few notable differences arise with this new approach. Craters such as **Carpenter**, **Cavalerius**, and **Hainzel A** are in a zone where the impact rate is predicted to be higher than normal, yielding corrected Lagain ages that are 500 to 600 million years younger than the Neukum-derived ages.

The ages for **Bullialdus** and **Eratosthenes** are essentially unchanged, because these craters are in the annular zone where the corrected cratering rate is the same as the old rate.

Stevinus is in a zone where the cratering rate is lower than average, and its corrected age is 1 billion years old, slightly older than the previous Neukum value of 0.9 billion years.

The new Lagain model will soon be tested with samples from never-before-visited lunar regions. The upcoming Artemis landing near the Moon's South Pole is in an area predicted to have high impact rates, and thus samples should be younger than expected from the traditional N(1)-age relationship. I bet they will be.



▶ This graph updates the absolute lunar chronology, plotting the ages of measured lunar samples (blue circles) on the *x*-axis against the cumulative number of craters larger than 1-km diameter per square kilometer of lunar surface along the *y*-axis. The gray area shows extremes of corrected fits for high-cratering-rate areas (top black line) and low-cratering-rate areas (bottom black line). Gray bars represent the margin of error.

GRAPH: ANTHONY LAGAIN; CRATERS: NASA / GSFC / ARIZONA STATE UNIVERSITY

■ Contributing Editor **CHUCK WOOD**'s lunar columns have appeared in *Sky & Telescope* for 25 years.