PLANETARY SCIENCE RESEARCH
PSRD Discoveries

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Lunar Crater Rays Point to a New Lunar Time Scale

(NASA PIA00302 / USGS / Clementine 750nm)

--- Optical maturity maps of rays, derived from Clementine multispectral data and calibrated with lunar sample analyses, provide a new way to define the two youngest time stratigraphic units on the Moon.

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The Lunar Time Scale should be reevaluated -- suggest remote sensing studies of lunar crater rays by B. Ray Hawke (University of Hawai'i) and colleagues at the University of Hawai'i, NovaSol, Cornell University, National Air and Space Museum, and Northwestern University. These scientists have found that the mere presence of crater rays is not a reliable indicator that the crater is young, as once thought, and that the working definition of the Copernican/Eratosthenian (C/E) boundary should be reconsidered. The team used Earth-based spectral and radar data with FeO, TiO_2, and optical maturity maps derived from Clementine UVVIS images to determine the origin and composition of selected lunar ray segments. They conclude that the optical maturity parameter, which uses chemical analyses of lunar samples as its foundation, should be used to redefine the C/E boundary. Under this classification, the Copernican System would be defined as the time required for an immature surface to reach full optical maturity.

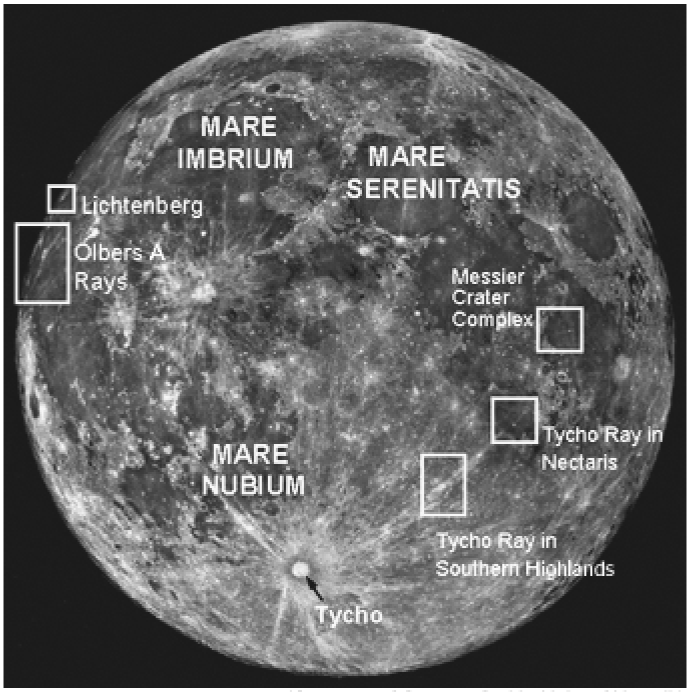
Reference:

Hawke, B.R., Blewett, D.T., Lucey, P.G., Smith, G.A., Bell III, J.F., Campbell, B.A., and Robinson, M.S. (2004) The origin of lunar crater rays. *Icarus,* v. 170, p. 1-16.

Investigating Lunar Crater Rays

Lunar crater rays are those obvious bright streaks of material that we can see extending radially away from many impact craters. Historically, they were once regarded as salt deposits from evaporated water (early 1900s) and volcanic ash or dust streaks (late 1940s). Beginning in the 1960s, with the pioneering work of Eugene Shoemaker, rays were recognized as fragmental material ejected from primary and secondary craters during impact events. Their formation was an important mechanism for moving rocks around the lunar surface and rays were considered when planning the Apollo landing sites. A ray from Copernicus crater crosses the Apollo 12 site in Oceanus Procellarum. Rays of North Ray and South Ray craters cross near the Apollo 16 site in the Descartes Highlands and a ray from Tycho crater can be traced across the Apollo 17 site in the Taurus-Littrow Valley on the eastern edge of Mare Serenitatis. There is still much debate over how much ejecta comes from the primary impact site or by secondary craters that mix local bedrock into ray material.

To sort out the nature of rays, Hawke and his colleagues focused their study on rays associated with four craters: Tycho, the Messier crater complex, Lichtenberg, and Olbers A (see photograph below). They combined Earth-based observations with Clementine-derived maps to investigate ray compositions, maturities, and modes of origin, and to assess the consequence of their findings on the lunar time scale.



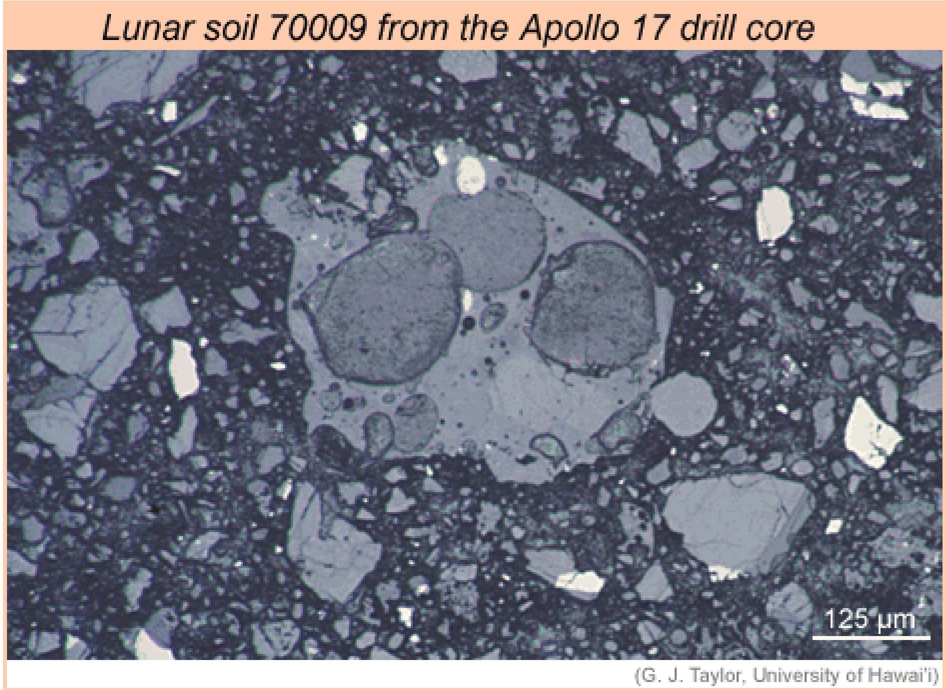
(Courtesy of Gregory Smith, Univ. of Hawaii.)

The white boxes on this photograph show the locations of the crater rays in the investigation, clockwise from the left: Olbers A ray system, Lichtenberg crater rays, Messier Crater Complex, Tycho ray in Mare Nectaris, and Tycho ray in the southern highlands. Prominent maria and Tycho crater are also labeled.

The Role of Cosmochemistry

Chemical analyses of lunar samples provide "ground truth" to understand the geologic processes on the Moon. Specifically, the discoveries by cosmochemists of nanophase-iron grain coatings, Fe-Si phases, and other space weathering products in lunar rocks and meteorites have enabled us to better understand the physical, chemical, and optical changes that occur over time as the lunar surface is exposed to the space environment and matures. Older surfaces in which these changes have reached a steady state are said to be fully mature. Younger surfaces are called immature.

Space weathering products in the lunar material, which can only be discovered by sample analysis, affect the spectral signatures of the Moon's surface. Detailed studies of the variation of spectra with extent of space weathering have recently been made by Larry Taylor (University of Tennessee, Knoxville), Carlé Pieters (Brown University) and their colleagues. Using scanning electron microscopy, they've measured, for example, the abundance of agglutinate glass and major minerals in grain-size separates of lunar regolith (see photographs below).



This is a photograph in reflected light of a polished thin section of regolith from the Apollo 17 drill core. The big particle with round bubbles in it, in the center of the photograph, is an agglutinate (impact glass bonded with rock, mineral, and glass fragments). Many small agglutinates are also visible. The abundance of these glassy particles increases with the amount of space weathering, or maturity. And average grain size decreases as the regolith matures.

Larry Taylor and his colleagues used a scanning electron microscope like the one pictured above to analyze lunar soils in exquisite detail.

Putting It Together With Remote Sensing Data

Three types of data were compiled and analyzed by the research team to study the lunar rays.

- Maps of FeO, TiO_2, and optical maturity derived from Clementine UVVIS images (415-1000 nanometers) and sample analyses, using the methods developed by Paul Lucey (University of Hawai'i) and co-workers. Spatial resolution was ~100 meters/pixel.
- Near-IR reflectance spectra between 0.6-2.5 µm (600-2500 nanometers) collected at the University of Hawai'i

2.24-meter telescope at Maunakea Observatory. Spacial resolutions (called spot sizes) were ~1.5 km and 4.5 km in diameter. Spectral curves showed absorption bands near 1 μm characteristic of iron-bearing silicate minerals. They used the shape and position of this band to determine the composition and relative abundance of pyroxene and olivine minerals, which helped them distinguish rock types.

- Radar data at three wavelengths: 3.0 cm, 3.8 cm, and 70 cm transmitted and received by radar antennae at Haystack Observatory (Massachusetts) and Arecibo Observatory (Puerto Rico). Surface and subsurface scattering properties of the Moon were analyzed using these radar backscatter images. The 3.0 cm and 3.8 cm radar data are sensitive to roughness on the scales of 1 to 50 cm within the upper meter of the regolith. The 70 cm data show roughness on scales from 50 cm to 10 m within 5 to 10 meters depth. Rough (blocky) ray deposits are bright in radar images. As these young rays are exposed to space weathering, they mature and become smoother so they appear darker in the radar images.

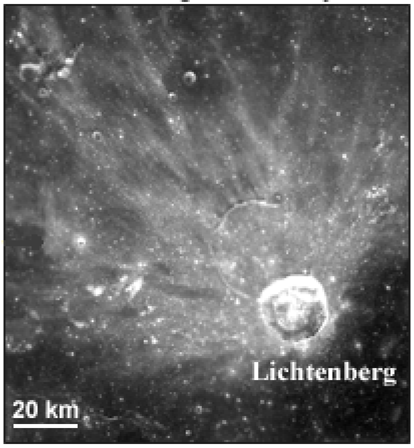
Making Sense of It

Take a look below at the Clementine albedo images and derived maps of FeO, TiO_2, and optical maturity parameter (OMAT) for each ray segment studied by Hawke and colleagues. Toggle between maps by moving your cursor over the three rectangular buttons [FeO, TiO_2, and OMAT] below the images.

General point to consider: Bright areas in the albedo images are either due to the presence of low FeO material or an immature surface. The dark lunar maria are lava plains composed of an Fe-rich rock called basalt. The brighter highlands are made of rocks much lower in FeO.

Following the images, we will discuss the results of the integration of Clementine data with the Earth-based near-IR and radar data for the crater rays.

Lichtenberg Crater Rays

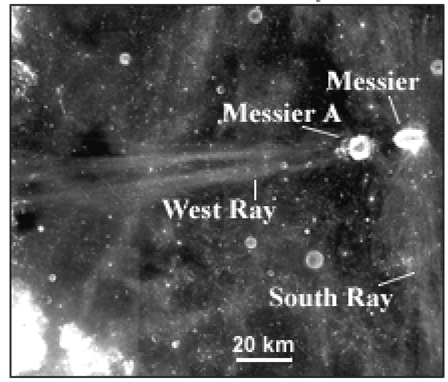


Clementine 750 nm image (albedo)

LUNAR CRATER RAYS

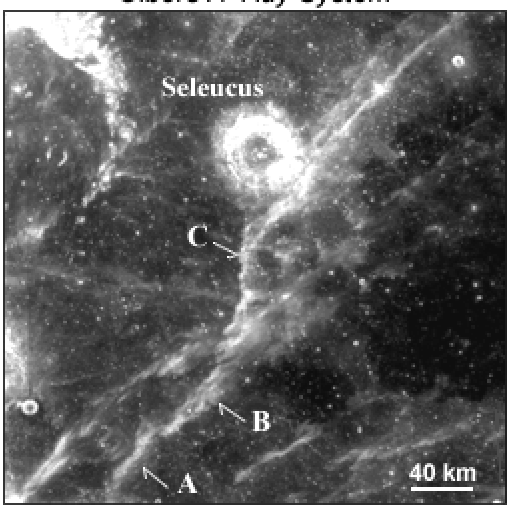
The Clementine 750 nm images of each ray segment studied by Hawke and colleagues are shown here. Move your cursor over the three buttons located below the images to view the crater ray data. FeO maps, TiO2 maps, or Optical Maturity parameter images will appear at the same time for each ray.

Messier Crater Complex



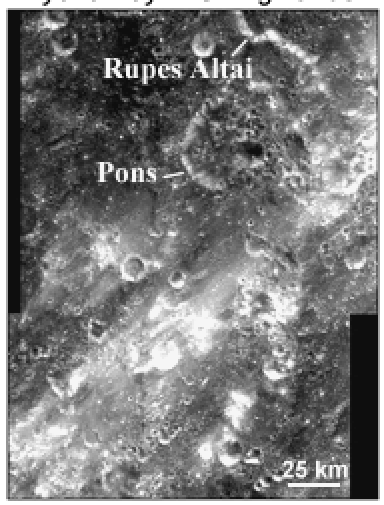
Clementine 750 nm image (albedo)

Olbers A Ray System



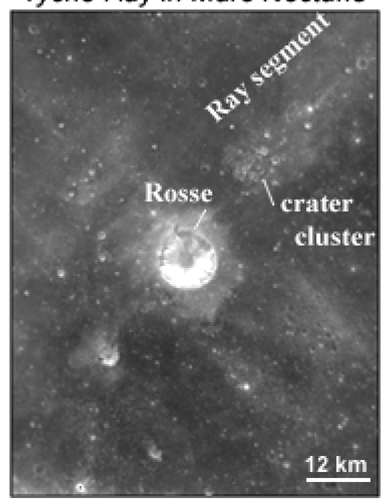
Clementine 750 nm image (albedo)

Tycho Ray in S. Highlands



Clementine 750 nm image (albedo)

Tycho Ray in Mare Nectaris



Clementine 750 nm image (albedo)

FeO maps	TiO_2 maps	Optical maturity maps
FeO wt.% dark is lower and bright is higher	TiO_2 wt.% dark is lower and bright is higher	OMAT Parameter dark is mature and bright is immature

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Messier Crater Complex. Near-IR spectra as well as the FeO, TiO_2, and maturity maps indicate that the south and west rays of the Messier complex are composed of debris from immature mare basalts. They appear bright in radar images. Highlands material is not present in these rays, hence they are bright because they are immature.

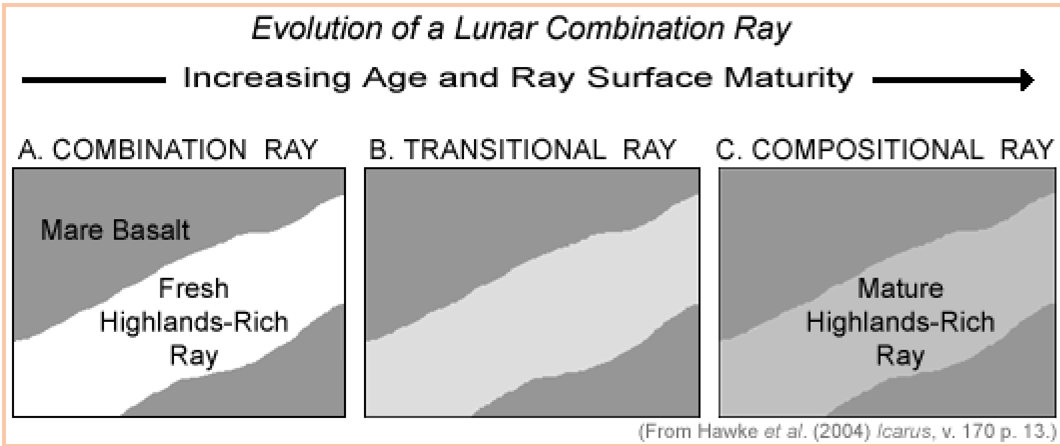
Tycho Ray in Mare Nectaris. The portion of Tycho ray in Mare Nectaris is composed largely of immature mare basalt with little to no detectable Tycho ejecta material. The ray is dominated by fresh local material excavated and emplaced by the secondary craters as well as fresh material that is constantly exposed on the crater walls due to landslides. This ray segment is bright because it is immature.

Tycho Ray in Southern Highlands. This ray segment is composed of relatively immature highland debris. But it is not possible to determine how much of the material is local and how much is projectile material blasted in from Tycho Crater. This ray segment is bright because it is immature.

Lichtenberg Crater Rays. FeO and TiO_2 abundances for these rays are consistent with highland rocks. The optical maturity map demonstrates that these highlands-rich ejecta deposits and rays are fully mature. Hence, these rays are bright because of their composition.

Olbers A Ray. This high-albedo ray, which was deposited on a mare surface, has reduced FeO and TiO_2 abundances, consistent with the presence of a large non-mare component. Much of the ray is not distinct in the optical maturity map but some areas are bright in the OMAT (see arrows A, B, and C) suggesting that these areas are not as mature as the adjacent terrain. This ray has a significant amount of highlands ejecta debris and is bright because of composition and immaturity, and is a good example of a "combination" ray.

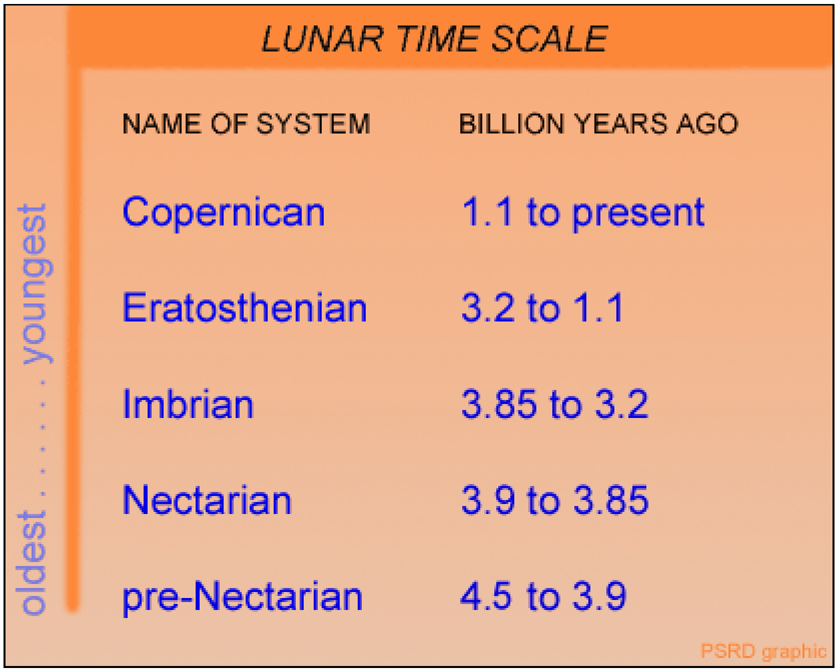
The work by Hawke and others shows that the brightness of rays is due to immaturity and/or compositional differences.



This cartoon shows the evolution of a lunar combination ray. In panel A the ray brightness is due to the presence of immature, high-albedo highlands material and immature mare debris excavated by secondary craters. Panel B shows a ray in transition. The ray is less bright because of increased maturity. In panel C the ray has reached complete optical maturity and its brightness is only due to the fact that highlands-rich ray material is brighter than the darker material of the mare surface below.

Redefining the C/E boundary

The working definition of Copernican age craters (larger than a few kilometers in diameter) is that they have sharp features and bright rays. Craters with slightly subdued form and have no rays have been traditionally given an Eratosthenian age. It is generally accepted that the boundary between Copernican and Eratosthenian is 1.1 billion years ago (see chart below) though different people have defined different durations for the systems. Copernicus crater itself (about 0.8 billion years old, based on dates obtained from Apollo 12 samples) is considered a good early Copernican marker, but it does not mark the base of the system.

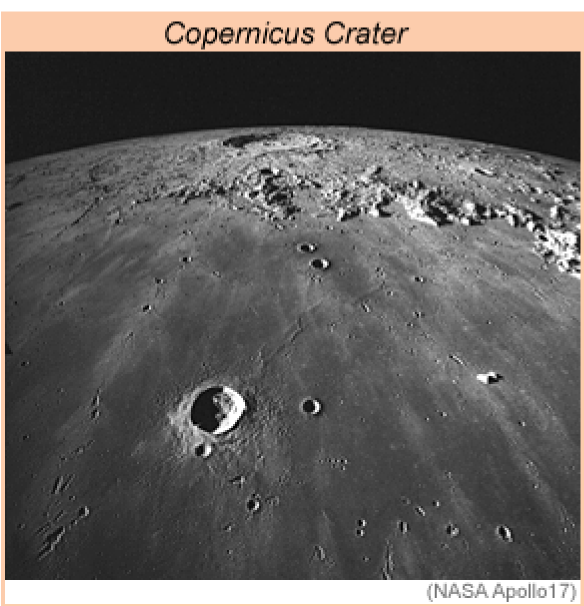

LUNAR TIME SCALE

NAME OF SYSTEM	BILLION YEARS AGO
Copernican	1.1 to present
Eratosthenian	3.2 to 1.1
Imbrian	3.85 to 3.2
Nectarian	3.9 to 3.85
pre-Nectarian	4.5 to 3.9

There are craters with compositional rays whose ages are significantly greater than 1.1 billion years. Lichtenberg is a prime example. This 20-km-diameter crater is embayed on the southeast by mare basalt flows. Harry Hiesinger (Brown University) and his coworkers have estimated the age of these flows on the basis of the number of craters formed on them. They report an age of 1.6-2 billion years, distinctly older than the nominal C/E boundary age of 1.1 billion years. It follows that the mere presence of rays is not a reliable indicator of crater age. And it is no longer valid to assign a Copernican age to craters based only on the presence of rays.

Hawke and others conclude that a new method using the optical maturity parameter is required to distinguish Copernican from Eratosthenian craters. They acknowledge a problem of not knowing the time required for a surface to reach full optical maturity; no such age has been firmly established.

A possible solution was proposed by Jennifer Grier (formerly at the University of Arizona and now at the Harvard-Smithsonian Center for Astrophysics) and Al McEwen (University of Arizona) and colleagues. Their work showed that if the ejecta of Copernicus crater were slightly more mature, it would be impossible to tell apart from the optically mature bedrock. Since the commonly accepted age of Copernicus is about 0.8 billion years, then perhaps full optical maturity occurs at about 0.8 billion years. More work is necessary and future studies will look more closely at optical maturity maps of the Copernicus crater region to better define the C/E boundary in the lunar time scale.



This oblique photograph was taken by the Apollo 17 crew in 1972 with a view looking south across Mare Imbrium. Copernicus crater, 93 kilometers in diameter, is seen in the distance. Hummocky ejecta, rays, and several chains of small secondary craters from Copernicus are visible in the foreground, as well as the crater Pytheas, 20 kilometers in diameter.

One particularly useful way to pin down the ages of specific craters is to determine their absolute ages by isotopically dating samples returned from them. Cosmochemists could date either samples of impact melt from the floors of the craters or samples of mare basalts that embay ejecta from the craters, as at Lichtenberg.


(NASA painting by Pat Rawlings.)

Future automated sample-return missions to the Moon could allow cosmochemists to date specific impact craters or lava flows that embay craters. Such targeted sample return missions also allow us to address many other important problems in lunar science, such as the age of the youngest lava flows on the Moon.

Additional Resources

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