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Exploring the Solar System by Charles A. Wood

◀ Unlike most other lunar features, crater rays are best seen at or near full Moon.

SEAN WALKER / S&T

Crater Rays — Mysterious No More

Understanding these bright features can add further enjoyment to your lunar observing.

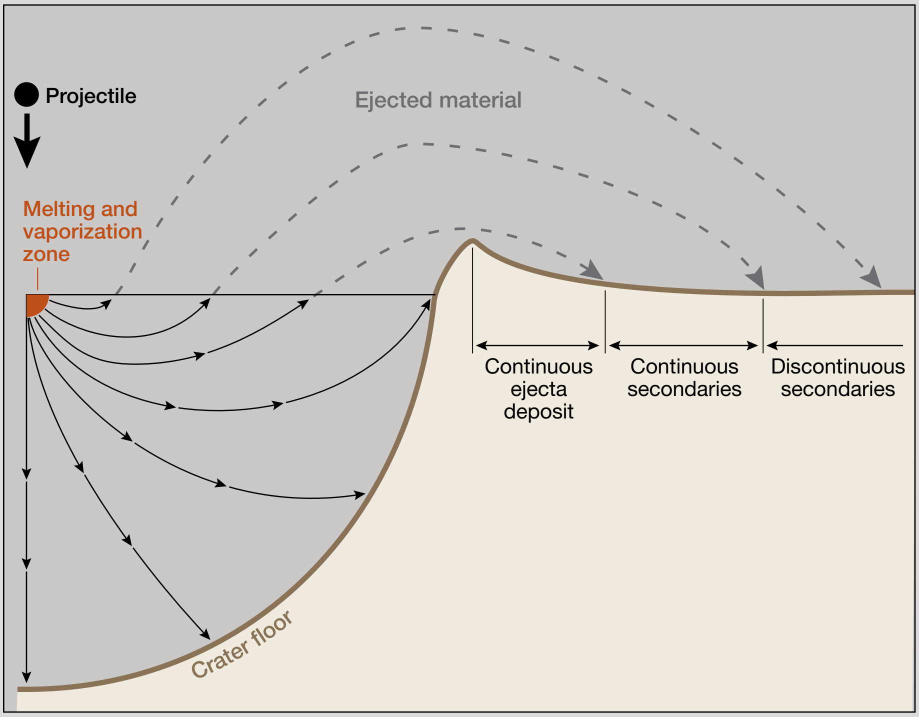
Well into the 20th century, the first sentence of many articles describing lunar rays stated that their origins were enigmatic. This was due to our poor understanding about these bright, filamentary streaks radiating from many young lunar craters. That perception began to change with Ralph Baldwin's transformative 1949 book, *The Face of the Moon*. Baldwin was the first to convincingly make the case for the impact origin of lunar craters by asteroids and comets (rather than volcanic eruptions), with the rays being material ejected during crater formation. A decade later, legendary lunar scientist Eugene Shoemaker published the first ballistic analysis of lunar impacts and the resulting emplacement of ray-forming ejected rocks. Since then, Apollo 12 astronauts collected samples of a ray from Copernicus, and scientists have even studied rays on other worlds. It's safe to say that rays are no longer completely mysterious, though some of their features aren't fully understood.

Both Baldwin and Shoemaker noticed that rays are most conspicuous from craters like **Copernicus** and **Tycho** having youthful characteristics, such as crisp rims and a lack of superposed impact craters. They also recognized that **Eratosthenes** and other craters have fainter rays, while most have no visible rays at all. This implies that rays disappear over time, a fact that Shoemaker and his colleagues at the U.S. Geological Survey used to identify the youngest epoch of lunar history — the Copernican era spanning from about 1.1 billion years ago to the present day. Only craters formed in this period were believed to have visible rays.

The best-known rays are the nearly Moon-girdling ones radiating from Tycho. These are best seen at full Moon, which led some to theorize that rays are flour-like deposits of bright highlands material with no topographic expression. But following Baldwin, Shoemaker recognized that embedded within these bright rays were many small, elongated craters. He interpreted these as secondary craters, created by low-velocity impacts of ejecta from the primary crater and consistent with rays being fragmented and pulverized rocks.

High-resolution images from NASA's Lunar Orbiter and subsequent spacecraft revealed that many secondary craters occur in clusters and chains, indicating that they were formed by clumps of debris, rather than solid boulders. Additionally, the horizontal component of the ejecta's velocity carried smaller particles, creating downrange deposits of dunes and herringbone patterns of fine, bright debris. In most cases these secondaries and other ray deposits are too small to observe telescopically. However, when examining the floor of **Pitatus**, you can see Tycho ejecta as V-shaped white splotches with clusters of secondary craters on their uprange sides.

Careful studies show that material excavated and ejected from the initial impact event changes in thickness and character with increasing distance from the originating crater. The nearest ejecta is thick, contributing to the height of the crater rim itself. It then rapidly decreases farther from the rim, reaching the level of the original terrain at about one crater radius away. This inner annulus is called the *continuous ejecta deposit*. Beyond that is an area of abundant secondary craters in clusters and chains — the zone of *continuous secondaries*. Then, stretching hundreds of kilometers from larger craters is a zone of *discontinuous secondaries*, often isolated craters rather than clusters of secondary impacts. These are formed



▲ The dynamics of crater excavation are illustrated above. At the point of impact, surface rocks are melted and vaporized. Crustal materials are then pushed downward and away, flowing along curved paths where some are ejected when reaching the surface. Boulders and debris near the impact point are ejected first at high velocity and high angles, traveling farthest and forming discontinuous secondaries and dunes. Forces pushing more downward excavate debris from greater depths, ejecting it at lower angles and velocity. That debris is then deposited at the rim and as the continuous ejecta deposit, leaving the deepest rocks at the top of the rim.

by high-velocity blocks of ejecta shot out from near the center of the primary crater. Because these projectiles impact at high angles, the resulting secondaries are nearly circular and difficult to distinguish from small, primary craters.

Major discoveries about rays have come from multispectral imaging. By comparing the spectra of rays at two near-infrared wavelengths, Jennifer Grier and her colleagues at the University of Arizona could identify the *maturity* of a lunar ray. Maturity describes the degree of space weathering that affects the microscopic character of minerals found in the ray. Over millions of years, cosmic rays, solar wind, and micrometeorites darken ray material by creating iron grains and glass-bonded soils on exposed surfaces. Immature rays radiating from young craters haven't been exposed to these effects for long and still appear bright.

Space weathering reduces the brightness, so all rays ultimately disappear. The rate of fading depends on the thickness of the ray. Small secondary craters have shallow ray deposits, which disappear faster than the thicker rays produced by large cratering events.

Multispectral imaging provides a second critical type of information about rays. In 1985, Carle M. Pieters and her colleagues at Brown University imaged lunar rays at near-infrared wavelengths to determine if some are bright because they are immature or because they contain intrinsically bright lunar highland material.

The team discovered that the bright ray from Copernicus that streaks north across **Mare Imbrium** near **Pytheas** contains abundant highlands material, as well as some immature mare material excavated by secondary cratering. Lunar geologist B. Ray Hawke and colleagues at the Pacific Regional Planetary Data Center continued this research, recognizing that some crater rays are made of bright highlands material. Other rays are the pulverized and fractured target material now exposed to space weathering, and some rays are the product of both mechanisms. Thus, there are compositional rays, immaturity rays, and combination rays. But all rays are really produced by secondary craters and their deposits. Some craters previously considered to be Copernican in age have compositional rays and may be considerably older.

The next time the Moon is full (or nearly so), start with Tycho's long streaks that cross **Mare Serenitatis** and **Mare Nectaris** (at **Rosse**). Then jump halfway across the Moon to the familiar triangle of rays from Copernicus (particularly the composition ray near Pytheas), **Kepler**, and **Aristarchus**. More challenging are the faint rays from **Langrenus** near the Moon's eastern limb. Look south for the 32-kilometer-wide **Petavius B**; its oblique-impact origin is indicated by a ray-exclusion zone to the crater's north. As a final challenge, trace the bright ray from **Glushko** at the western limb that passes northeast of **Krafft** and **Seleucus** and continues north of the Aristarchus Plateau — a 1,000-km-long ray!

■ Contributing Editor **CHUCK WOOD** observes the lunar rays every time he turns his telescope on the full Moon.

▶ Apollo 12 astronauts photographed this oblique view showing many secondary craters along the ray near Pytheas (middle) pointing back towards Copernicus (top). South is up.

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