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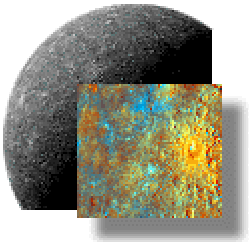
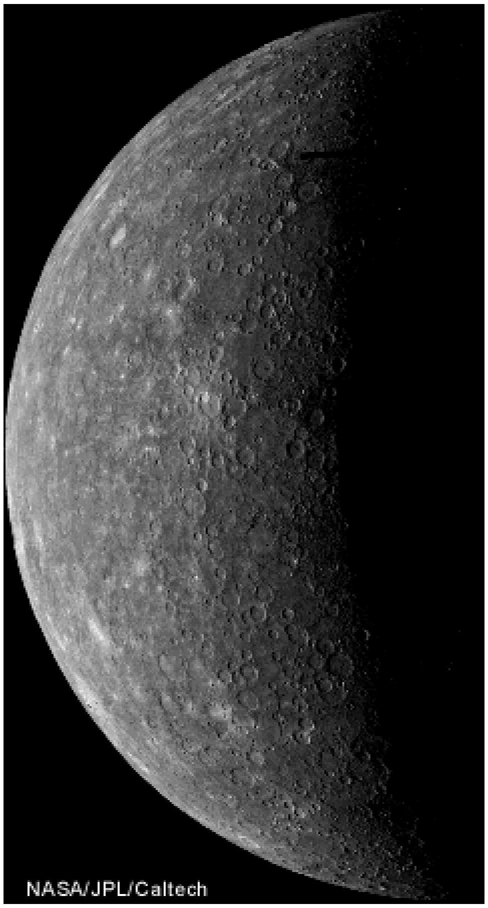


Mercury Unveiled

Written by G. Jeffrey Taylor
Hawai'i Institute of Geophysics and Planetology, University of Hawaii

Mercury, the second smallest planet and the closest one to the Sun, may appear to some as a drab, colorless, heavily-cratered world. Not so. New analysis of data returned by the Mariner 10 mission in 1974 and 1975 reveals a surface with lava flows and deposits from explosive volcanic eruptions, variations in composition across its surface and into its crust, and a different chemical composition from the other inner planets. These discoveries were made by Mark Robinson at the United States Geological Survey in Flagstaff, Arizona (he is now at Northwestern University) and Paul Lucey of the University of Hawai'i. Using improvements in computer and image-processing technologies, and a better understanding of how light reflects off planetary surfaces than was available in the mid-1970s, Robinson and Lucey manipulated the original data and produced a color image of Mercury that depicts compositional differences across its stark surface (Robinson, Mark S. and Lucey, Paul G., 1997, Recalibrated Mariner 10 Color Mosaics: Implications for Mercurian Volcanism, *Science*, vol. 275, p.197-200.)

Mercury: an important little planet



NASA/JPL/Caltech

Mercury is an important part of the Solar System puzzle, yet we know less about it than any other planet, except Pluto. Mercury is the smallest of the inner, rocky planets (Mars, Earth, and Venus) and the closest to the Sun. Its relatively high density (5.4 grams per cubic centimeter) indicates that it has a large metallic core (about 3/4 of the planet's radius) compared to its rocky mantle and crust. The surface is heavily cratered like the highlands of the Moon, but some areas are smooth and less cratered, possibly like the lunar maria (but not as dark). Radar data suggest that Mercury, like the Moon (see PSRD article Ice on a Bone Dry Moon), has deposits of water ice in permanently shadowed areas at the poles. Unlike the Moon, where water is only at the south pole, Mercury has ice at both poles. (The water composing the ice deposits probably came from comets hitting the surface.)

Planet Formation

In one view of how the Solar System formed, Mercury was assembled in the hottest region close to the Sun. This would have led to most of the iron being in the metallic state, rather than oxidized to FeO. If correct, the rocks on Mercury ought to have relatively low contents of oxidized FeO, less than about 3 wt.%. This hypothesis also predicts that Mercury should have higher concentrations of elements that have very high boiling points (called refractory elements), such as calcium and aluminum, and not much of the elements that boil at low temperatures (called volatile elements), such as sodium and potassium.

Another hypothesis tells a much more nomadic and dramatic story of Mercury's birth. This alternative view involves wandering planetesimals that might have come from as far away as Mars or the inner asteroid belt, and a monumental impact that stripped away much of the young planet's rocky mantle. Such a giant impact is considered by most planetary scientists as the most likely hypothesis for the origin of the Moon (see Lesson 1 from the Moon).

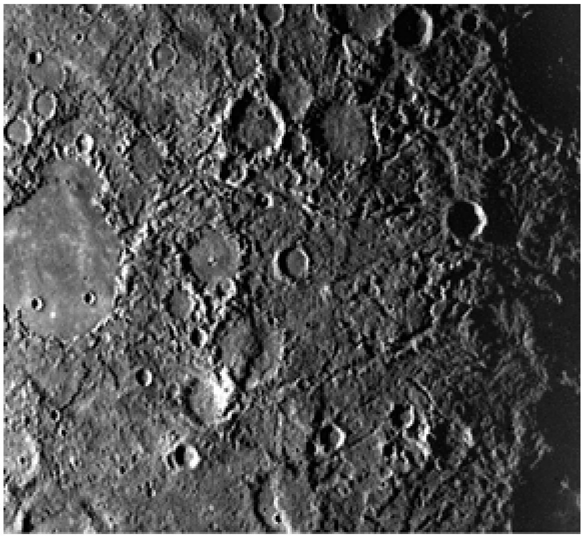
What does the impact hypothesis mean for Mercury? If correct, the composition of the rocky portion of Mercury might not be as depleted in FeO and volatile elements, or enriched in refractory elements, though such characteristics are not ruled out. The event could have stripped away much of the mantle, thereby increasing the amount of metallic core compared to rocky mantle.

Initial Melting of the Planets

Mercury has an important story to tell us about how the process of melting formed the crusts, mantles, and metallic cores of the planets. Size seems to be an important feature of the intensity and duration of the melting processes, and Mercury is intermediate in size between the Moon and Mars. Planetary scientists are pretty certain that the Moon was surrounded by a vast ocean of magma when it formed, in which low-density minerals such as feldspar floated while dense minerals such as olivine sank. Did Mercury have a magma ocean? (See Lesson 2 from the Moon).

Volcanism

Lava flows form vast smooth plains on the Moon, Mars, Venus, and Earth, and large volcanoes on all but the Moon. Did lavas erupt on Mercury? Mariner 10 images show smooth plains in many places, perhaps analogous to the lunar maria.


(NASA photo)

The smooth areas inside the larger craters in this photo of Mercury may be volcanic plains, somewhat like the maria on the Moon. There are many such smooth plains on Mercury. Some scientists have suggested that the plains were formed by rapidly-flowing material ejected from immense impact craters (called basins). However, the plains have smaller numbers of craters on them than do the ejecta blankets of impact basins, indicating a younger age. On some smooth plains, such as those inside the Caloris Basin, sinuous rilles occur, which are thought to be either lava channels or collapsed lava tubes, again suggesting a volcanic origin for the smooth plains.

A key feature of lava flows on many planets is a composition different from the surface the lava sits on, as shown by the maria on the Moon being darker and higher in FeO. Are the smooth plains on Mercury volcanic? (See Lesson 3 from the Moon).

Testing the idea of volcanism requires knowing much more about the chemical composition of Mercury. That is why the work by Robinson and Lucey is so important. It gives us our first good glimpse of the nature of the surface and even the interior of Mercury. The first step in obtaining that glimpse was to calibrate the old data from the Mariner 10 mission.

New ways of looking at old data

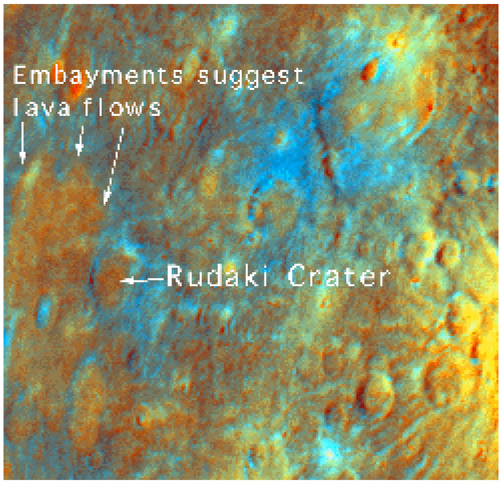
The Mariner 10 data had to be corrected for variations across its pixel array, a response to light levels that was not a simple straight-line calibration, and discrete blemishes. Robinson and Lucey corrected these effects by using special images taken in a lab on Earth before launch, and images taken during the mission of deep space and the relatively featureless cloud tops of Venus. Finally, intense study of lunar samples in laboratories and telescopic measurements of light reflected off the Moon have given scientists a much firmer grasp of how minerals and glasses affect the spectra of reflected light.

Robinson and Lucey used data in two wavelengths to make false-color images of Mercury. On their images, the more red the color, the lower the abundance of dark, opaque minerals. Because ilmenite, $FeTiO_3$, is a common opaque mineral, the more red the color, the lower the concentration of titanium (Ti).

They used green to indicate the combined effects of the FeO concentration and the amount of micrometeorite bombardment (also called "maturity"), so greener portions of the pictures are either lower in FeO or less mature. These two parameters cannot be separated as yet, but use of geological common sense allows us to guess which parameter is most important in a given area. For example, a young impact crater is surrounded by fresh debris excavated during the impact, which is very immature. No matter what the FeO concentration, the value of the iron-maturity parameter will be low, and the image will be distinctly green. However, like the Moon, most of the surface of Mercury is probably quite mature, so in areas between large craters the intensity of the green color is related to the concentration of FeO.

Finally, they used blue to indicate the intensity of the ratio of ultra-violet to visible light. Of course, these **colors then combine** in complicated ways, so the images are composed of more than red, green, and blue areas. In general, the different colors indicate variations in the elements, minerals, or other propeties of the materials present. Robinson and Lucey also used simple black and white images created for each compositional parameter. See How Mark Robinson and Paul Lucey Calibrated Images of Mercury from Mariner 10 for details.

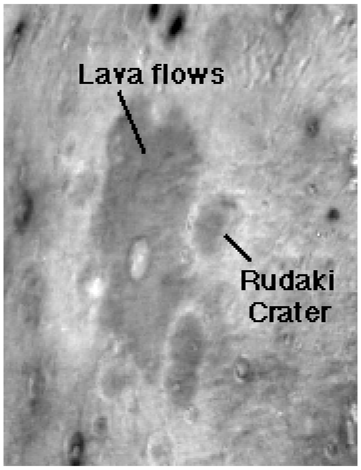
Volcanic Plains on Mercury



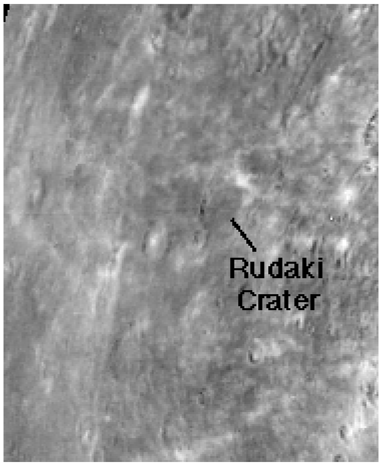
False-color image of Mercury
(Courtesy of Robinson and Lucey.)

The new analysis of Mariner 10 data shows that at least some smooth plains are probably volcanic. A good example is west of the crater Rudaki (see image on the left and images below). Other scientists had pointed out that the boundaries of this unit form embayments (arrows), a feature typical of lava flows. However, they could not conclude that the material was lava because they had no way of determining that it was different in composition from the surroundings. The new analysis shows that the unit is distinct in color from its surroundings, which indicates a different composition, consistent with its origin as one or more lava flows.

The distinctive composition is visible in the black and white images of key parameters seen below. Note that on the opaque mineral image (left image) the lava plains are clearly visible. This is an important compositional difference, probably indicating a lower concentration of Ti in the lava flows. The lava plains are not even visible on the FeO-maturity image (right image), suggesting a similar level of maturity and FeO to the surroundings.



Opaque mineral image of Mercury
(Courtesy of Robinson and Lucey.)



FeO-maturity image of Mercury
(Courtesy of Robinson and Lucey.)

The iron-maturity index alone is not different from the surrounding surface. Assuming that the amount of micrometeorite bombardment is roughly uniform in this region, this suggests that the FeO concentration of the smooth plains lavas is about the same as most of the crust of Mercury. Comparison of Earth-based observations of an entire hemisphere of Mercury with the highlands of the Moon has led some scientists to suggest that on average the mercurian crust contains no more than 6 wt.% FeO. The lava flows near Rudaki, therefore, contain about 6 wt.% (or less) FeO.

Robinson and Lucey do not speculate in their paper on the significance of this observation, but they note in a paper submitted to the 28th Lunar and Planetary Science Conference that the iron content of the surface reflects that of the interior. (The abstract was co-authored by Paul Spudis of the Lunar and Planetary Institute, B. Ray Hawke of the Univ. of Hawai'i, and me.) If lava flows on Mercury formed the way they form on Earth, the FeO concentration in the lava is very similar to (but probably a bit higher than) that of the planet's interior.

So, the mantle of Mercury contains no more than 6 wt.% FeO. This is less than scientists estimate for the mantles of Earth and Venus (8 wt.%), the Moon (11-13 wt%), and much less than estimates (from the compositions of meteorites from Mars) of the martian mantle (18 wt.%). This is consistent with the idea that Mercury is a highly reduced object, but not as reduced as its proximity to the Sun would suggest (0 to 3 wt.%). The planetesimals that accreted to form Mercury probably came from a much wider region than near the present orbit of the planet. However, much more work needs to be done to test such speculations.

Explosive eruptions?

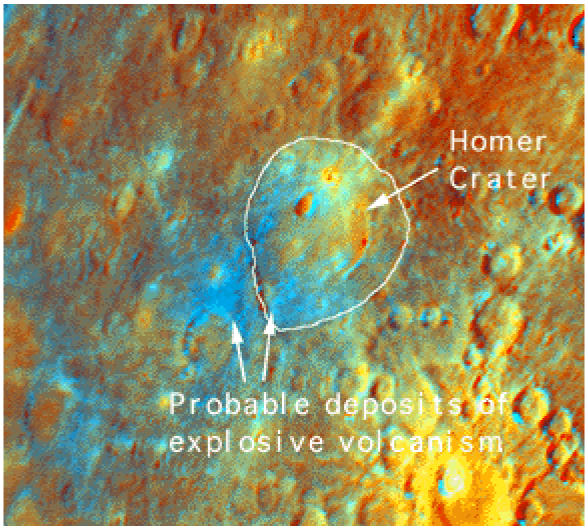
Volcanic eruptions can be explosive, producing high fountains of lava that break into tiny droplets. Many Hawaiian eruptions begin with such fire fountaining, or pyroclastic eruptions. The deposits are composed of rapidly-cooled droplets of lava ranging in size from 1/100 millimeter to about 1 cm.

This 1959 pyroclastic eruption at Kilauea volcano in Hawaii sent lava up to 550 meters into the air.

(Photo courtesy of National Park Service.)

Excellent examples of pryoclastic deposits were seen on the Moon.

On Mercury, an area near the large crater Homer, 320 km in diameter, has a distinctive dark blue color on Robinson and Lucey's new color images. The white line outlines the degraded rim of this old crater.

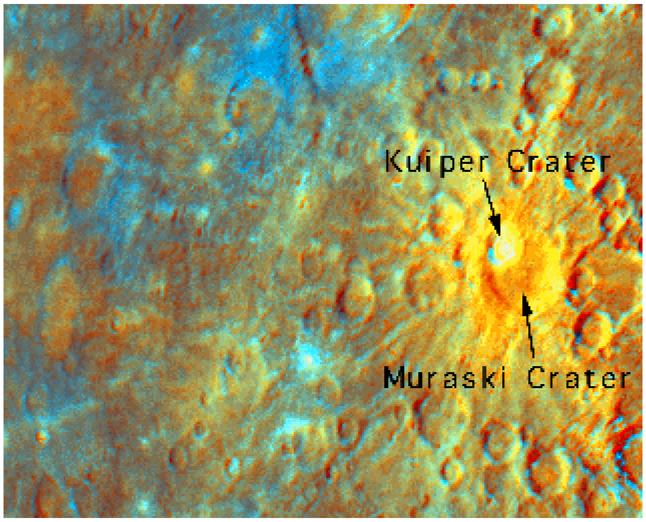


(Courtesy of Mark Robinson and Paul Lucey.)

Most important, the blue area has fuzzy boundaries that seem to grade into the surroundings. This is what one would expect for a pyroclastic deposit. It is also similar to debris from an impact, but there is no crater in the center that would act as a source for the deposited material. In fact, the dark blue materials lie along a straight segment of a border of Homer, similar to some volcanic fissures on the Moon.

If further analysis proves that these are pyroclastic deposits, it has dramatic implications for the amount of volatile elements inside Mercury. Fire fountains are driven by volatiles, usually gases such as CO, CO_2, SO_2, and H_2O. If Mercury formed hot and contains only tiny quantities of such gases, where did they come from? Are they stored in isolated volatile-rich reservoirs? Or is Mercury not really so depleted in volatiles? No answers yet!

Big craters reveal compositional layering



(Courtesy of Mark Robinson and Paul Lucey.)

The area near the craters Kuiper (60 km in diameter) and Muraski (125 km in diameter) gives some clues to compositional layering of the mercurian crust. Craters are quite useful in unraveling the nature of planets because they are natural drill holes. Kuiper crater is superimposed on the rim of the larger Muraski crater, so it is younger. The differences in the color image are mostly due to the difference in age of the two craters. The yellow-orange color of the rock dug up by these and other craters in this region of Mercury signifies that these deposits contain relatively few opaque minerals such as titanium. This indicates that the surface in this region of Mercury is underlain by a chemically distinctive layer at depth.

Answers needed

The original analysis of Mariner 10 images of Mercury cracked the door to understanding this little planet and Mark Robinson and Paul Lucey have opened it a bit more. But many questions remain, especially about the details of composition, the source of volatiles that powered explosive volcanism, the diversity of lava flows, whether Mercury had a magma ocean, and if it formed from planetesimals close to the Sun or from a wider region. The new images provided by Robinson and Lucey will undoubtedly foster additional insights. But to fling the door fully open will require additional missions to the nearest planet to the Sun, including one carrying modern instruments to determine elemental and mineralogical abundances.

Additional Resources

Robinson, Mark S. and Lucey, Paul G., 1997, Recalibrated Mariner 10 Color Mosaics: Implications for Mercurian Volcanism, *Science*, vol. 275, p.197-200.

Strom, Robert, 1987, *Mercury, the Elusive Planet*, Smithsonian Institution Press, Washington, D.C., 197 p.

Chapman, Clark R., 1988, Mercury's heart of iron, *Astronomy*, November, 1988, p. 22-35.

Vilas, F., Chapman, C.R., and Matthews, M.S., eds., 1988, *Mercury*, The University of Arizona Press, Tucson, 794 p.

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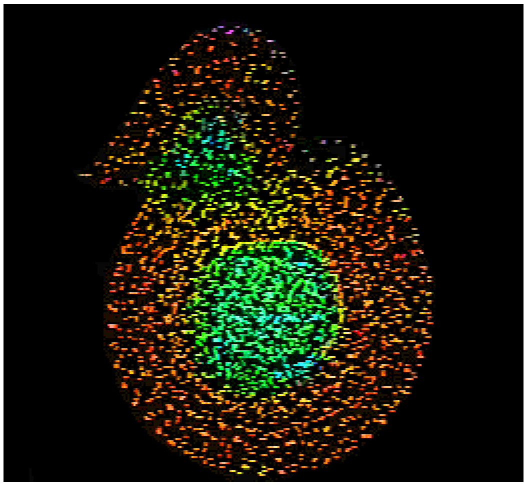
PSR Discoveries

Lesson 1 from the Moon: Formation by Impact



Graphic courtesy of A.G.W. Cameron and W. Benz

This frame from a computer simulation captures a moment in time when a wandering planetesimal the size of Mars struck the young Earth (shown as the large circle of colorful dots) to form the Moon. In this hypothesis, both the planetesimal and Earth already had formed cores (shown in blue-green). Computer simulations of such an impact indicate that the core of the planetesimal is added to Earth's iron core and much of the rocky mantles (orange and gold) of the two bodies melts or vaporizes, and some ends up in orbit around the Earth. This debris then accreted to form the Moon. The formation of Mercury may also have involved a giant impact.

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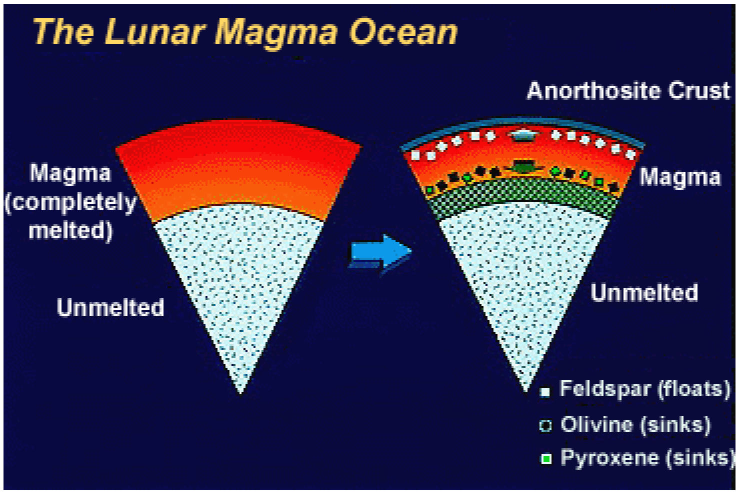
Lesson 2 from the Moon: Initial Melting of the Planets



(PSRD graphic)

When the Moon formed it was enveloped by a layer of molten rock (magma) hundreds of kilometers thick (shown on the left of the blue arrow). As that magma crystallized, the minerals more dense than the magma sank while those less dense (such as feldspar) floated, forming the anorthosite crust. The dense minerals (olivine and pyroxene) sank and later remelted to produce the basalts that compose the maria on the Moon. We do not know if Mercury had a magma ocean.

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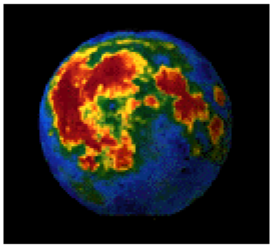
Lesson 3 from the Moon: Volcanism



(Courtesy of Paul Lucey.)

This image shows the FeO concentration of the earth-facing hemisphere of the Moon. Red and white are highest FeO, blue lowest. FeO was measured by a technique developed by Paul Lucey of the University of Hawai'i; it uses the relative intensity of two wavelengths of light reflected off the Moon. The maria (white, red, and orange areas) contain much more FeO than do the surrounding highlands (blue areas).

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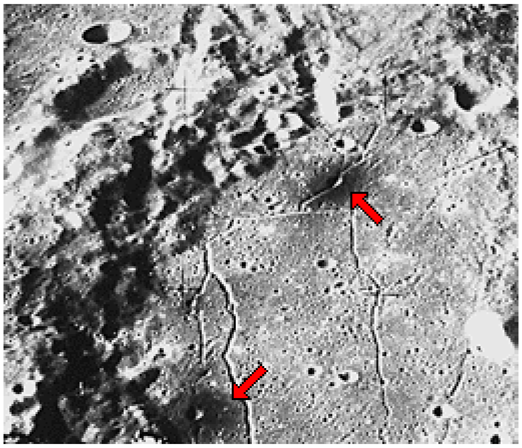
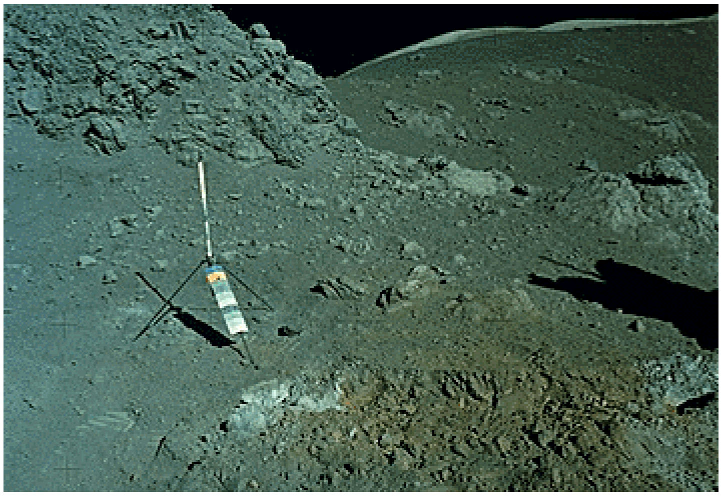
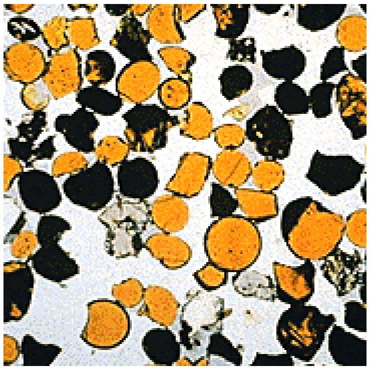
Lesson 4 from the Moon: Explosive Eruptions



Fire fountains happened on the Moon, producing dark, dispersed deposits (red arrows). These are frequently located along cracks in the surface, as here on the floor of the crater Alphonsis. (NASA photo.)



A lunar pyroclastic deposit was sampled at the Apollo 17 landing site. The deposit (seen in the lower right portion of the NASA photograph above) had a distinctive orange color, caused by its high titanium concentration, and was composed of millions of tiny droplets (seen in the photograph below).



Here is a thin slice of some Apollo 17 orange soil as viewed through a microscope. The view is only about one millimeter across. Most of the droplets are composed of glass. The darker ones crystallized only partially and formed the opaque mineral called ilmenite. (Photograph courtesy of Graham Ryder, Lunar and Planetary Institute.)

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PLANETARY SCIENCE RESEARCH
PSRD Discoveries
January 23, 1997

How Mark Robinson and Paul Lucey Calibrated Images of Mercury from Mariner 10

The Mariner 10 spacecraft had two cameras, called vidicons, which detected light on a grid of pixels, each of which digitized the light received into 256 levels of gray. The cameras had eight filters, ranging from the ultraviolet or UV (0.38 micrometers wavelength) to orange (0.58 micrometers). The cameras took excellent photographs in black and white, but various tricky problems prevented their use for color or, more important, for accurately measuring the intensity of the light they detected. Compositional information is revealed by the ratio of reflected light at different wavelengths.

For one thing, the cameras did not respond in a simple, linear way to changes in intensity. So, if the brightness of the surface differed by 10% in one place compared to another, the camera did not indicate a 10% difference. In addition, the response of pixels was not uniform across the detectors. These problems were corrected by carefully analyzing images taken before launch and images taken of deep space (rather than of a planet) during flight.

Calibrating
Mariner 10 Images

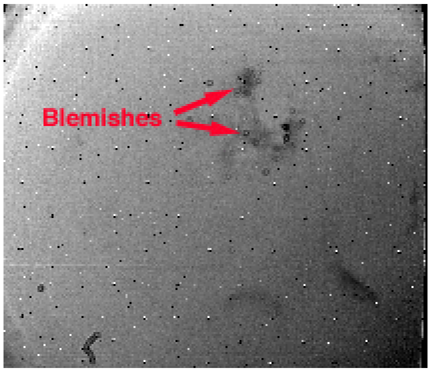
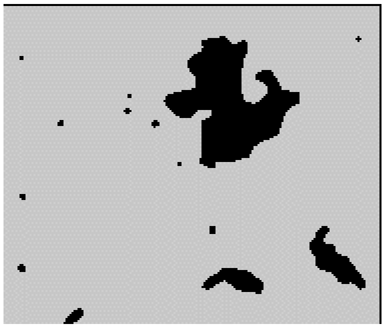


Image of featureless Venus clouds

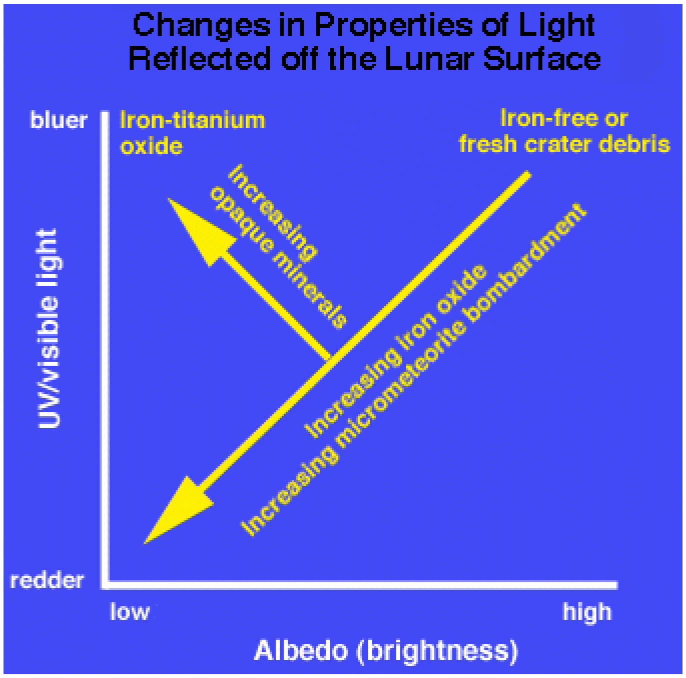


Blemish stencil for camera

(adapted from Robinson and Lucey, 1997, Recalibrated Mariner 10 Color Mosaics: Implications for Mercurian Volcanism, Science, v. 275, p. 197-200.)

Some portions of the pixel grid did not respond at all, producing prominent blemishes on the images. This was correctable because the spacecraft flew past Venus on its way to Mercury and took images of the relatively featureless venusian atmosphere. The blemishes are clearly visible on the photos of Venus cloud tops. This allowed Robinson and Lucey to construct a stencil for each camera. The blemish-producing areas were simply ignored. Of course, this also meant that some of the surface could not be photographed. Fortunately, the spacecraft took so many pictures that any given spot on the hemisphere of Mercury that was photographed appeared outside stenciled areas in at least two images. All of these corrections were implemented using high-powered image-processing computers at the United States Geological Survey, Branch of Astrogeology, in Flagstaff, Arizona.

Since the original analysis of the Mariner 10 data done in the mid-1970s, there have been vast improvements in our knowledge of what compositional features affect the way light is reflected off planetary surfaces. Much of this improved understanding was driven by studies of the Moon from Earth-based telescopes, combined with direct analysis of lunar samples returned by the Apollo missions to the Moon. In fact, many of the key advances were made by Bruce Haptke (University of Pittsburgh), one of the central figures in the original analysis of Mariner 10 data.



(Adapted from Robinson and Lucey, 1997, Recalibrated Mariner 10 Color Mosaics: Implications for Mercurian Volcanism, Science, vol. 275, p 197-200.)

On plots of the ratio of ultraviolet (UV) to visible light (for example, orange) versus the brightness of the reflected light at one of the wavelengths we see some interesting trends.

Rocks with low FeO are bright and have high ratios of UV/orange light (making them sort of blue). As FeO increases, the rocks become darker and the ratio decreases, making the reflected light redder.

A similar effect happens as a fresh surface is reworked by micrometeorite impacts: more reworking darkens and reddens the surface (see graph). So, Lucey developed a technique for determining how far along the line on the graph a surface would fall, and called it the **iron-maturity index** (high maturity means a long duration of reworking by micrometeorite impacts). The first application of this technique was to determine the FeO content of the lunar surface (see Lucey et al., *Science*, vol. 268. p. 1150-1153).

Lunar sample analysis also shows that as the amount of dark, opaque minerals increases, the surface becomes darker. However, instead of becoming redder as it darkens, it becomes bluer (the UV/visible ratio increases). This led Robinson and Lucey to define a second parameter, the opaque mineral index. Since the mineral ilmenite ($FeTiO_3$) is likely to be the darkening agent, this index gives a measure of the titanium content of the surface rocks.

All these trends can be indicated on a color picture by assigning colors to the parameters. Robinson and Lucey made the iron-maturity index green: the more intense the green color, the higher the FeO or the longer the duration of reworking by micrometeorite impacts. They made the intensity of red inversely proportional to the amount of opaque minerals, so the greater the red color, the lower the amount of opaque minerals. Finally, they used the ratio of UV/visible light as another variable, which helps to distinguish rock units from one another. The higher the UV/visible ratio, the bluer the image.

The resulting global image has mostly intermediate colors, of course, because the **three colors combine**. So, a yellow color may represent a combination of high opaque mineral abundance (red) and intermediate iron-maturity index.

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