PLANETARY SCIENCE RESEARCH
PSRD Discoveries

Hot Idea

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Did Martian Meteorites Come From These Sources?

--- Researchers find large rayed craters on Mars and consider the reasons why they may be launching sites of Martian meteorites.

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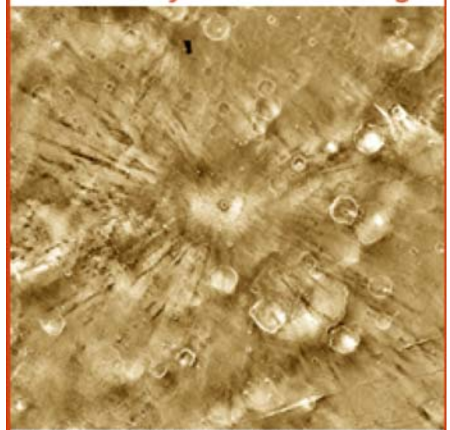
Gratteri Rayed Crater at Night



THEMIS infrared: NASA/JPL/Arizona State Univ.
[CLICK for additional information.]

Large rayed craters on Mars, not immediately obvious in visible light, have been identified in thermal infrared data obtained from the Thermal Emission Imaging System (THEMIS) onboard Mars Odyssey. Livio Tornabene (previously at the University of Tennessee, Knoxville and now at the University of Arizona, Tucson) and colleagues have mapped rayed craters primarily within young (Amazonian) volcanic plains in or near Elysium Planitia. They found that rays consist of numerous chains of secondary craters, their overlapping ejecta, and possibly primary ejecta from the source crater. Their work also suggests rayed craters may have formed preferentially in volatile-rich targets by oblique impacts. The physical details of the rayed craters and the target surfaces combined with current models of Martian meteorite delivery and cosmochemical analyses of Martian meteorites lead Tornabene and coauthors to conclude that these large rayed craters are plausible source regions for Martian meteorites.

Reference:

- Tornabene, L. L., J. E. Moersch, H. Y. McSween Jr., A. S. McEwen, J. L. Piatek, K. A. Milam, and P. R. Christensen (2006) Identification of large (2-10 km) rayed craters on Mars in THEMIS thermal infrared images: Implications for possible Martian meteorite source regions. *Journal of Geophysical Res.*, v. 111, doi: 10.1029/2005JE002600).

Finding What They're Looking For

There are currently 34 Martian meteorites identified out of the 24,000+ that have been cataloged. The numbers are growing as a result of ongoing searches primarily in the world's deserts (for example see **PSRD** article: Searching Antarctic Ice for Meteorites). Cosmochemists have determined that these rocks came from basaltic igneous sources with young (by planetary standards) crystallization ages no more than 1.3 billion years (with the one exception: ALH84001 with an age of 4.5 billion years) and were ejected from Mars by impact cratering events between 600,000 and 20 million years ago. While these rocks provide invaluable direct 'ground truth' that scientists are using to help piece together the chemical and geological history of Mars, the question remains where exactly did these rocks come from? Knowing their provenance will add significant details to our understanding of how the planet formed, differentiated, and evolved geologically.

One approach to answering the question has been to search orbital multispectral datasets to find volcanic terrains on Mars that match the mineralogy and spectral properties of Martian meteorites. These locales must be sufficiently dust-free to allow spectral analysis of the surface compositions and must also have at least one impact crater of appropriate size and age that could have ejected rocks at greater than Mars' escape velocity of ~ 5 kilometers per second. Previous work by Vicky Hamilton (University of Hawaii) using data from the Mars Global Surveyor Thermal Emission Spectrometer (TES) pointed to Eos Chasma, a branch of the Valles Marineris canyon system, as a possible source for unique Martian meteorite ALH84001. Hamilton's work with Ralph Harvey (Case Western Reserve University) identified Syrtis Major as a possible source region of nakhlite/chassignite meteorites. This is exciting on-going work to find meteorite source regions.

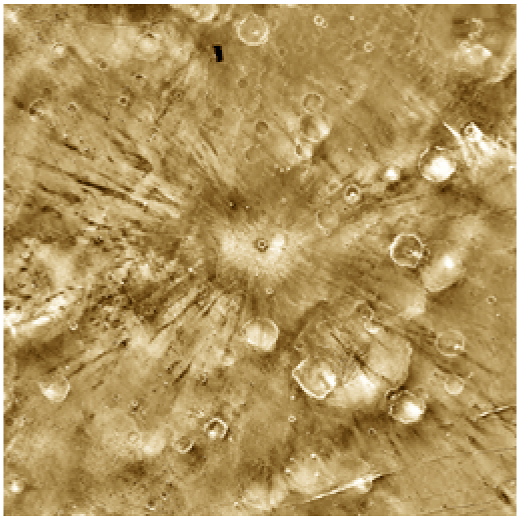
Alternatively, an answer to Martian meteorite sources may well come from studies of some uncommon Martian craters that, until just a few years ago, had gone unnoticed. In 2003, using new Mars Odyssey Thermal Emission Imaging System (THEMIS) thermal infrared data, Alfred McEwen (University of Arizona) and colleagues reported the first discovery of a rayed crater, Zunil, in the southern Elysium region of Mars. More recently, Livio Tornabene and colleagues have identified an additional four large rayed craters and three more they deem probable. Their detailed observations of the craters combined with the known geochemistry of the meteorites and models of how meteorites are ejected off the planet add up to a compelling story that these rayed craters could have supplied Martian meteorites.

Rayed Craters Defined and Located

Tornabene and coauthors define a crater ray as filamentous (thread-like) elements in radial to subradial lineaments that spread out from a source crater like spokes from the center of a wheel. A ray contrasts with the surrounding, underlying surface. We are used to seeing crater rays on the Moon in visible-light images where this contrast is recognized as albedo. Lunar rays are brighter than the underlying surface. On Mars crater rays are not distinctive in visible light but are apparent in the thermal infrared because of a thermophysical (temperature-related) contrast with the surroundings. Martian rays appear brighter or darker than the underlying surface depending on the relative thermal properties of the materials when (day or night) the images were taken (see images below).

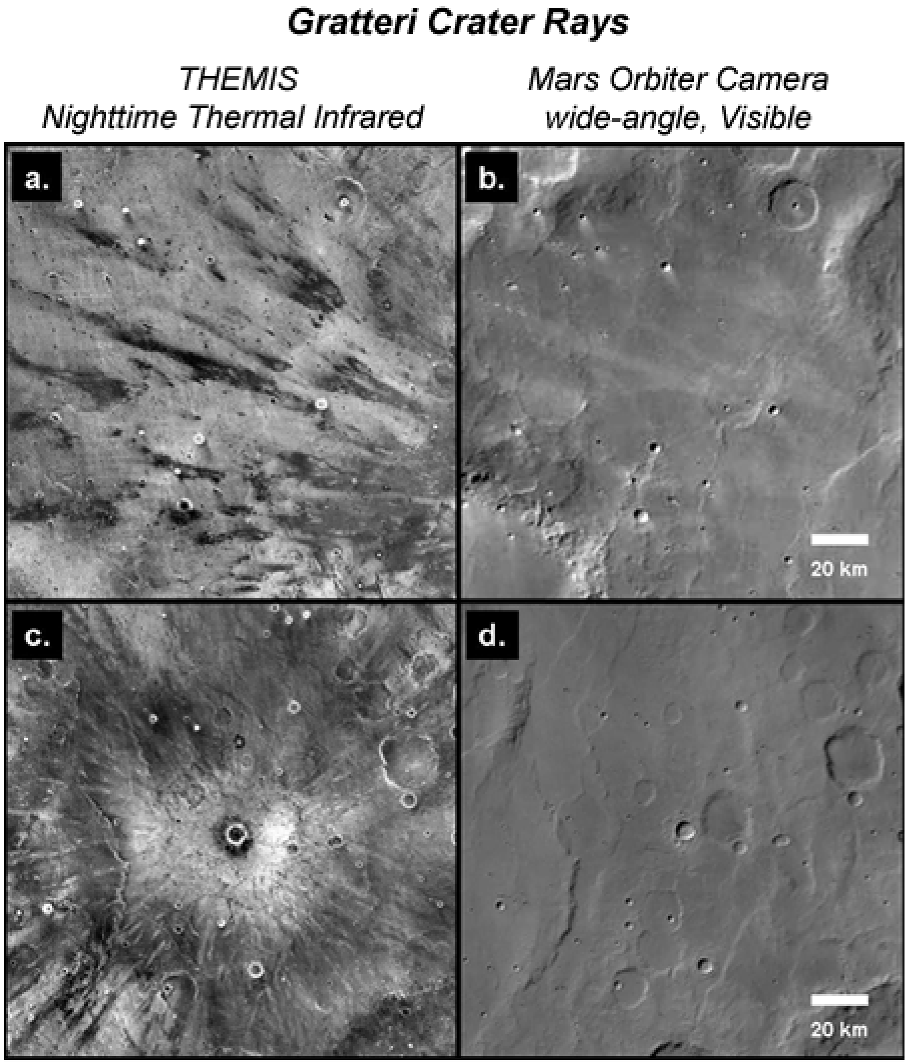
Moon ***Mars***

(NASA PIA00302 / USGS / Clementine 750nm)



(NASA/JPL/ASU / THEMIS nighttime IR, 12.57 µm)

LEFT: Clementine images show albedo (reflectivity) variations on the nearside of Earth's Moon. Extensive bright ray systems surround craters Copernicus (upper left center) and Tycho (near bottom). Click the image for more information in a new window. Bright crater rays have also been observed on Mercury and the icy Galilean moons. RIGHT: Crater rays on Mars show up in the thermal infrared and can be dark or bright. This is a nighttime thermal infrared image of Gratteri crater and its dark rays. Rocky areas are brighter because they retained daytime warmth into the night. In contrast, the dark rays and patches show where finer-grain materials cooled after local sunset. Click the image for more information in a new window.

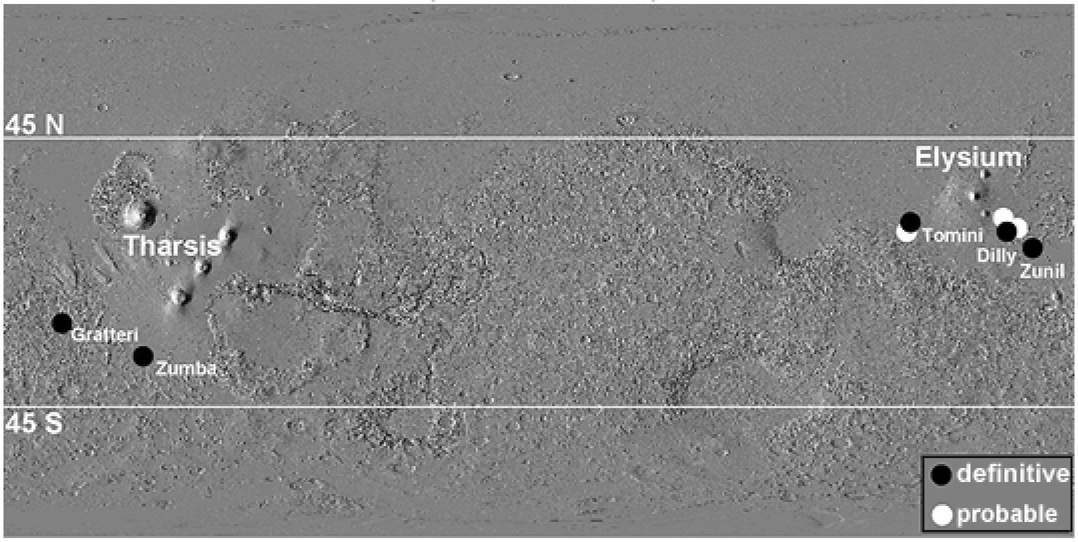


(From Tornabene *et al.*, 2006, *JGR*, v. 111, doi: 10.1029/2005JE002600, Fig. 8.)

Pairs of images illustrate how Martian crater rays appear in different wavelengths of light. The left hand images are THEMIS nighttime thermal infrared images. TOP LEFT (a): Gratteri crater rays are revealed as dark streaks (see figure caption above for more explanation). BOTTOM LEFT (c): Warmer (brighter) Gratteri ejecta around the crater and colder (darker) rays are revealed. The right hand images are contrast-stretched MOC visible images of the same area. RIGHT (b and d): Crater rays are not easily seen. There is very little albedo difference between rays and the surrounding plains.

In their global survey for rayed craters, Tornabene and colleagues studied both THEMIS nighttime and daytime thermal infrared (TIR) brightness temperature images derived from band 9 (wavelength of 12.57 micrometers). This wavelength is used because it has the highest signal to noise value and is relatively transparent to atmospheric dust. Image resolutions ranged from 32 to 256 pixels per degree. They found that daytime TIR images are not as useful as nighttime TIR images for identifying rays. The effects of albedo, surface slope, and time of day all affect daytime surface temperatures more than at night. Moreover, the survey focused on latitudes specifically between 45 ^{o}N and 45 ^{o}S (see map below) because surface radiance and diurnal (a single daily cycle) thermal contrast generally decrease poleward of the equator. They note that lower surface radiance translates as lower signal to noise detected at the spacecraft's instrument, which generates poor quality images (especially at night when temperatures are much colder) making it more difficult to recognize rays with certainty at the higher latitudes. Their survey resulted in an additional four, and another three probable, rayed craters.

Location map of Martian Rayed Craters

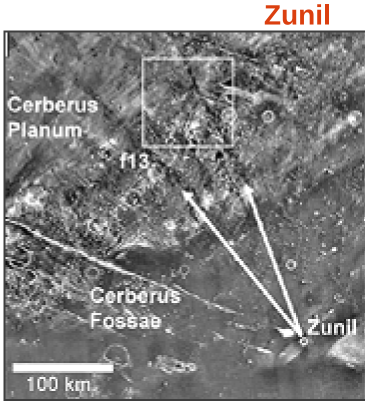
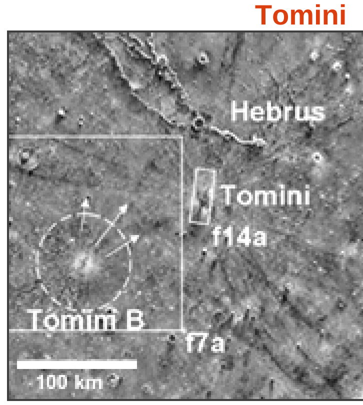


(From Tornabene *et al.*, 2006, *JGR*, v. 111, doi: 10.1029/2005JE002600, Fig. 2.)

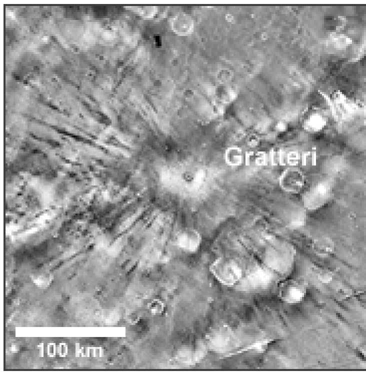
The five known rayed craters (black circles with white name lables) and three probable rayed craters (white circles) are located on this MOLA shaded relief map of Mars. The rayed craters cluster in two groups; two craters are located south of Tharsis (the largest volcanic region on the planet) and the other six, including the probables, are in or near Elysium Planitia (the second largest volcanic region).

Characteristics of Martian Rayed Craters

Tornabene and colleagues found that the eight identified rayed craters all lie within lava plains or adjacent to the two major volcanic regions (Tharsis and Elysium Planitia, see map above). The table below (and continuing on the next page) summarizes what is known about Martian rayed craters. Each is shown in THEMIS nighttime infrared images, with North to the top. Crater locations are listed in latitude, longitude. Crater diameters and the longest ray length measured for each crater are listed in kilometers.

Martian rayed crater characteristics	
Zunil	**Tomini**
 (From Tornabene *et al.*, 2006, *Journal of Geophysical Research*, v. 111, E10006, doi: 10.1029/2005JE002600.) *THEMIS data from:* NASA / JPL / ASU.	 (From Tornabene *et al.*, 2006, *Journal of Geophysical Research*, v. 111, E10006, doi: 10.1029/2005JE002600.) *THEMIS data from:* NASA / JPL / ASU.
Crater Location: 7.7 ^{O}N, 166 ^{O}E southeast of Cerberus Planum within Elysium Planitia in Amazonian-aged lava plains **Crater diameter:** 10.1 km **Ray Length:** 927 km Rays are not symmetrically arranged around the crater. White arrows point to two distinct dark rays to the northwest of Zunil crater.	**Crater Location:** 16.27 ^{O}N, 125.9 ^{O}E southwest of Elysium Mons in Hesperian-aged ridged volcanic plains **Crater diameter:** 7.4 km **Ray Length:** 668 km Curved dark rays are prominent to the west and southeast. A long, straight ray trends north-northeast opposite the forbidden zone (a wedge-shaped zone where crater ejecta was never deposited).

Gratteri



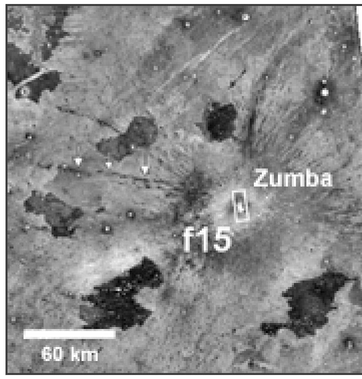
(From Tornabene *et al.*, 2006, *Journal of Geophysical Research*, v. 111, E10006, doi: 10.1029/2005JE002600.)

THEMIS data from: NASA / JPL / ASU.

Crater Location 17.7 ^{O}S, 199.9 ^{O}E
near Memnonia Fossae southwest of Tharsis
in Noachian-aged volcanic plateau
Crater diameter: 6.9 km

Ray Length: 595 km
More than 30 rays, more than double the number found with any other rayed crater. Longest rays occur to the northwest and southeast. Region north of the crater is very dusty, so if rays exist in this region they lack a therophysical contrast to the dust.

Zumba



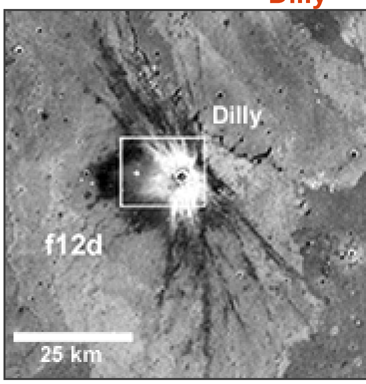
(From Tornabene *et al.*, 2006, *Journal of Geophysical Research*, v. 111, E10006, doi: 10.1029/2005JE002600.)

THEMIS data from: NASA / JPL / ASU.

Crater Location 28.65 ^{O}S, 226.9 ^{O}E
Daedalia Planum
in Hesperian-aged lava flows
Crater diameter: 3.3 km

Ray Length: 240 km
One of its longest rays trends to the east while another of the longest rays trends west. Zumba rays are unique because they are also distinct in daytime TIR images.

Dilly



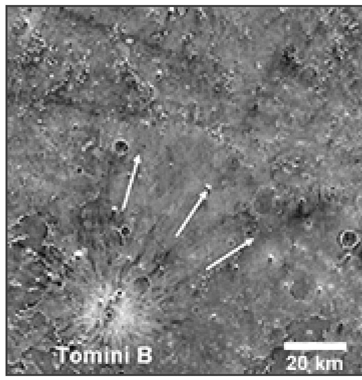
(From Tornabene *et al.*, 2006, *Journal of Geophysical Research*, v. 111, E10006, doi: 10.1029/2005JE002600.)

THEMIS data from: NASA / JPL / ASU.

Crater Location 13.27 ^{O}N, 157.23 ^{O}E
Cerberus Planum within Elysium Planitia
in Amazonian-aged volcanic terrain
Crater diameter: 2.0 km with an elliptical shape

Ray Length: 50 km
Dark rays appear to the northwest and southeast in distinctive "butterfly wing" pattern.

Tomini B



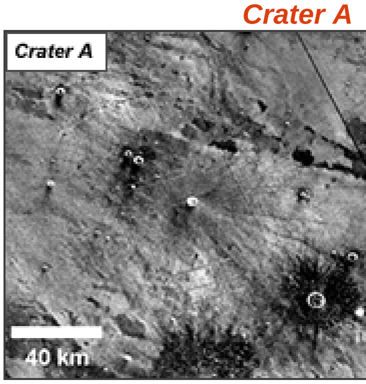
(From Tornabene *et al.*, 2006, *Journal of Geophysical Research*, v. 111, E10006, doi: 10.1029/2005JE002600.)

THEMIS data from: NASA / JPL / ASU.

Crater Location 14.9 ^{O}N, 123.25 ^{O}E
near Tomini crater
in Hesperian-aged volcanic plains
Crater diameter: 4.2 km

Ray Length: 220 km
Three discernable, but faint rays.

Crater A



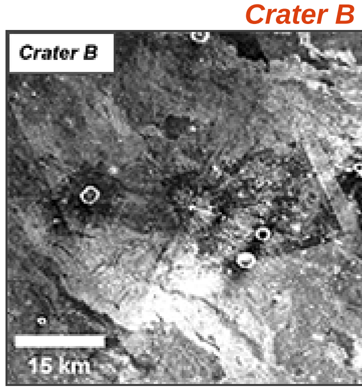
(From Tornabene *et al.*, 2006, *Journal of Geophysical Research*, v. 111, E10006, doi: 10.1029/2005JE002600.)

THEMIS data from: NASA / JPL / ASU.

Crater Location 18.1 ^{O}N, 155.5 ^{O}E
near Zunil and Dilly craters
in Amazonian-aged volcanic terrain
Crater diameter: 5.7 km

Ray Length: 86 km; Faint rays.

Crater B



(From Tornabene *et al.*, 2006, *Journal of Geophysical Research*, v. 111, E10006, doi: 10.1029/2005JE002600.)

THEMIS data from: NASA / JPL / ASU.

Crater Location 15.5 ^{O}N, 159.2 ^{O}E
near Zunil and Dilly craters
in Amazonian-aged volcanic terrain
Crater diameter:1.5 km

Ray Length: 42 km; Faint rays.

Table Notes: The four new rayed craters have International Astronomical Union approved names of Gratteri, Tomini, Zumba, and Dilly named after small towns or villages in Italy, Indonesia, Ecuador, and Mali, respectively. The three crater names in italics are probable rayed craters. Probable rays were identified by Tornabene and coauthors after they used digital image processing to stretch the contrast on the nighttime thermal infrared images. The technique of contrast stretching reveals the subtle tonal differences in the images that represent faint temperature signatures of the rays. The white boxes in some of the images refer to close-up images in Tornabene and coauthor's published research article.

The researchers found that Martian rays, like their lunar counterparts, are comprised of densely concentrated and clustered chains of small secondary impact craters (tens to hundreds of meters in diameter), ejecta, and surge deposits from the primary and secondary craters. Their detailed work shows that the rays have two characteristic thermal signatures: colder areas and warmer small spots. The different signatures are attributed to different particle sizes and induration (or hardness) of the materials. The colder areas (darker streaks in the THEMIS nighttime thermal infrared images shown in the table) are interpreted to be fine-grained, loosely-packed debris. This material cools quickly after sunset. On the other hand, the warmer (brighter) spots are interpreted to be fresh secondary craters (formed from ejecta blocks originating from the source crater), which excavated courser, rocky materials upon re-impacting the surface. Rocks or indurated sediments cool more slowly and consequently appear warmer (brighter) than their surroundings at night. A variety of other Mars data sets (such as THEMIS visual, Mars Orbiter Camera (MOC) narrow-angle images, TES-dervied thermal inertia, albedo, and dust cover maps) were compared to the THEMIS thermal infrared data to corroborate the interpretations made by Tornabene and his colleagues.

The research team identified rayed craters in volcanic plains that are specifically characterized by intermediate values of albedo, thermal inertia, and dust cover index (previously defined as "thermophysical Unit C" by Michael Mellon, University of Colorado, Boulder, and colleagues). Only about 20% of the Martian surface appears to have this optimal combination of thermophysical properties needed to recognize crater rays. This suggests that other rayed craters may be present on Mars, but cannot be readily detected by means of THEMIS thermal infrared images. For example, if ray debris lies on top of surfaces that have dark nighttime TIR signatures, such as dust-mantled surfaces, then the rays are not discernable because there is no thermal contrast. Hence, a surface covered with a thick dust mantle obstructs our view of crater rays. Conversely, regions with little to no dust cover would not be able to produce the cold ray material that we so readily observe in THEMIS nighttime thermal infrared images. As a consequence, other (more rigorous and difficult) means may be necessary to detect additional rayed crater systems on Mars such as linking far-field secondary crater populations to a single source crater. High-resolution visible images from cameras like HiRISE (High Resolution Imaging Science Experiment) or CTX (Context Camera) on NASA's Mars Reconnaissance Orbiter may be very useful in future ray surveys.

Ray Patterns and Oblique Impacts

Rays are evidence of high-velocity ejecta. The fact that Martian rayed craters are among the freshest craters of their size and are found in young volcanic plains makes some people wonder if some of the ejecta from these impacts could have escaped from Mars to become Martian meteorites on Earth. The Mars rock would have to reach the escape velocity of 5 km/sec. During an impact event the kinetic energy of the incoming projectile causes shock deformation, heating, melting, and vaporization, as well as excavation of the crater and ejecta material. However, Martian meteorites show low to only moderate degrees of shock. To address this question Tornabene and coauthors examined the ray patterns to better understand the formation process.

Elliptical crater shapes, forbidden zones (wedge-shaped zones lacking crater ejecta), and "butterfly wing" ray patterns in four definitive rayed craters (the exception is Zunil) and all three probables are cited as evidence that the Martian rayed craters formed by moderately oblique impact events. During oblique impacts it is possible that some of the ejecta is released at high velocities but low shock pressures. This is a process known as spallation and it is likely responsible for creating some of the ray-forming secondaries. Spallation is also currently the favored mechanism for ejecting relatively low-shocked rocks off Mars. Models also show increases in spallation volumes when oblique impacts strike volatile-rich subsurfaces. This is significant because Tornabene and colleagues observed fluidized ejecta blankets around the primary craters or around nearby larger craters--commonly recognized as evidence for subsurface volatiles (water ice). They concluded the ray formation process is consistent with spallation models of Martian meteorite delivery.

Launch Sites for Meteorites from Mars

Cosmochemical analyses show that Martian meteorites came from basaltic igneous sources (by crystallization from cooling magma) with young (<1.3 billion year) crystallization ages (with the one exception of 4.5 billion year old ALH84001) and were blasted off Mars by impact cratering events 600,000 to 20 million years ago. Taking into account the uncertainties in ages derived by crater counting for Martian terrains (e.g. see review by William Hartmann, Planetary Science Institute, Tuscon), Tornabene and coauthors have suggested matches between certain rayed craters (based on surface ages) and the crystallization age groupings of the Martian meteorites. Based on their studies, Tornabene and colleagues suggest rayed craters within Elysium are possible sources for the shergottites and the two rayed craters outside of Elysium (Zumba and Gratteri) are possible sources for nakhlites, chassignite, and ALH 84001. Specifically, Zumba is in late Hesperian-age volcanic terrain and could be a source crater for the nakhlites and chassignites, which are about 1.3 billion years old. Gratteri, which is in older volcanic terrain (Noachian-age), is suggested as a possible source for the oldest Martian meteorite known, ALH 84001.

As the research by Tornabene and coauthors shows, observations of the rayed craters and target surfaces combined with current models of Martian meteorite delivery and cosmochemical analyses of Martian meteorites suggest these large rayed craters are plausible source regions for Martian meteorites. Finding meteorite source regions will continue to pique our interest as researchers look further into the spectral signatures of the surfaces where rayed craters have been identified to help define and compare the compositions to the only field samples we have.

Additional Resources

LINKS OPEN IN A NEW WINDOW.

- Christensen, P. R., N. S. Gorelick, G. L. Mehall, and K. C. Murray, *THEMIS Public Data Releases*, Planetary Data System node, Arizona State University. http://themis-data.asu.edu.
- Hamilton, V. E. (2004) Detailed investigation of a globally unique, orthopyroxene-rich deposit in Eos Chasma, Mars, *Eos Trans. AGU,* 85, Fall Meet. Suppl., Abstract P11A-0959.
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- Mars Meteorites, comprehensive site from Ron Baalke, Jet Propulsion Lab.http://www2.jpl.nasa.gov/snc/.
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- Taylor, G. J. (2005) Martian meteorites record surface temperatures on Mars. *Planetary Science Research Discoveries.* http://www.psrd.hawaii.edu/July05/Mars_paleotemp.html.
- THEMIS Feature Image: Gratteri Crater's Far-Flung Rays.

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