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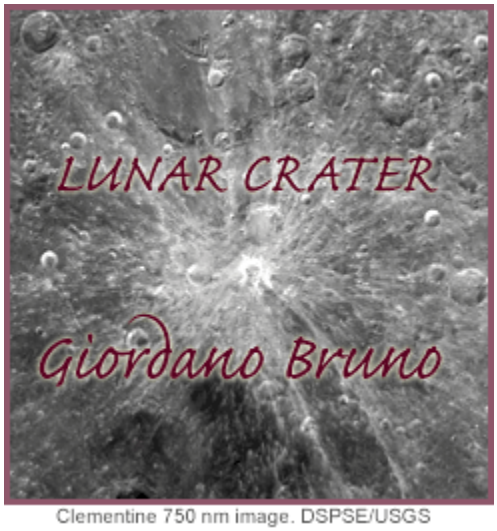
How Young is the Lunar Crater Giordano Bruno?



Clementine 750 nm image. DSPSE/USGS

--- High-resolution images are used to determine how recently this crater formed, a mere 832 years ago or over a million years ago.

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High-resolution images acquired in 2008 by the Terrain Camera on board the Japanese lunar orbiting spacecraft SELENE (Kaguya) show numerous small craters on the ejecta blanket of the farside crater Giordano Bruno. The 10 meters/pixel spatial resolution of the images, more than 10 times higher resolution than previous image data of this area, allows unprecedented study of surface details. A team of 12 scientists from the Institute of Space and Astronautical Science at the Japan Aerospace Exploration Agency (JAXA), and other research centers in Japan used Terrain Camera data to determine the formation age of Giordano Bruno by the time-honored method of counting the craters on its continuous ejecta. Morota and coauthors estimate that Giordano Bruno is between one to 10 million years old, which argues against the crater's possible formation in medieval time. The SELENE (Kaguya) data has sparked additional interest in the age of this and other young craters determined by the crater-counting method.

Reference:

- Morota, T., Haruyama, J., Miyamoto, H., Honda, C., Ohtake, M., Yokota, Y., Matsunaga, T., Hirata, N., Demura, H., Takeda, H., Ogawa, Y., and Kimura, J. (2009) Formation Age of the Lunar Crater Giordano Bruno. *Meteoritics and Planetary Science*, v. 44(80), p. 1115-1120.

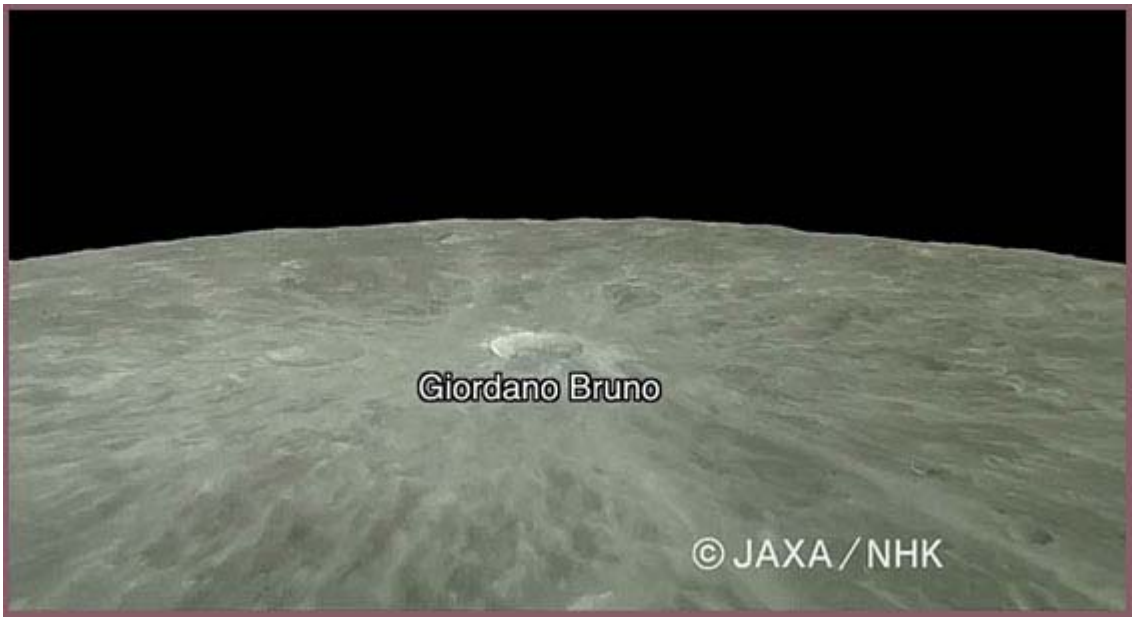
PSRDpresents: How Young is the Lunar Crater Giordano Bruno? --Short Slide Summary (with accompanying notes).

Five Monks from Canterbury...

Sitting on the Moon at 36 ^{o}N, 103 ^{o}E, the bright-rayed, 22-kilometer-diameter crater, Giordano Bruno, is just out of sight from Earth but visible in images acquired from orbit (see title image, above). What separates this particular crater from the untold multitude of craters and basins on the Moon is an idea, proposed by Jack Hartung some 30 years ago, that people in medieval England saw the impact that formed it. Hartung's idea is based on eyewitness accounts described in the medieval chronicle of an English monk and historian named Gervase of Canterbury. In the year 1178, on the evening of June 18, five monks from Canterbury saw (an English translation from Latin):

> "Now there was a bright new moon, and as usual in that phase its horns were tilted toward the east and suddenly the upper horn split in two. From the midpoint of this division a flaming torch sprang up, spewing out, over a considerable distance, fire, hot coals, and sparks. Meanwhile the body of the moon, which was below, writhed ...[and] throbbed like a wounded snake."

Though intriguing, Hartung's hypothesis is not universally accepted. Morota and coauthors summarize some of the counter arguments, which also began to surface 30 years ago. They include the 1977 argument by H. H. Nininger and Glenn Huss (American Meteorite Lab) that what the monks actually saw was a meteor blazing through Earth's atmosphere that passed in front of their view of the Moon. They also include the 2001 work by Paul Withers (then at the University of Arizona, now at Boston University) showing the complete lack of any historical record of a huge meteor storm that would have occurred in Earth's atmosphere after the formation of Giordano Bruno crater.



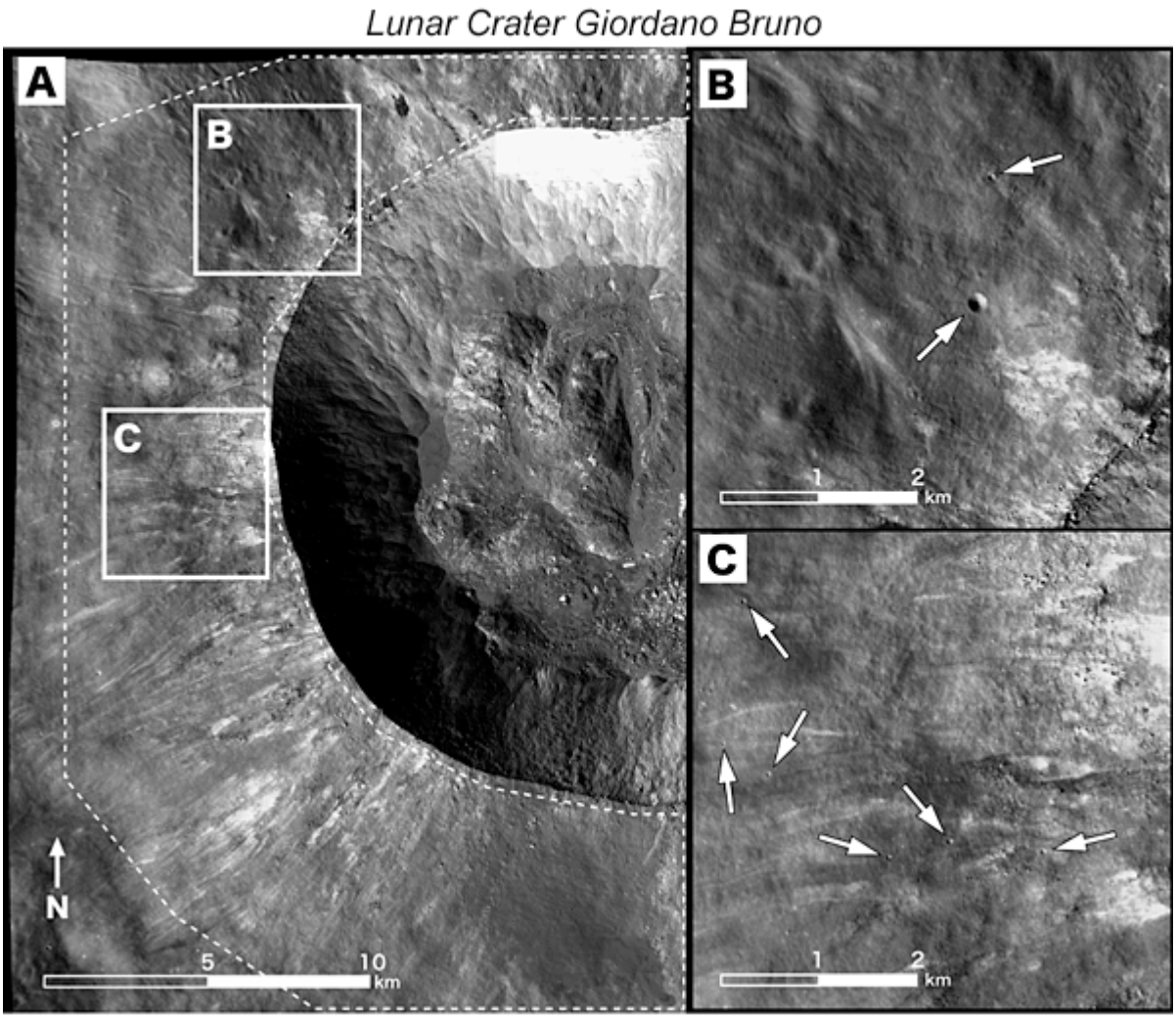
This image of Giordano Bruno crater and ray system was obtained by the HDTV onboard SELENE (Kaguya) in May, 2008 from an altitude of 100 kilometers. Watch the movie -->Giordano Bruno crater flyby -- SELENE (Kaguya) HDTV, © JAXA/NHK shown on YouTube. [Link opens in a new window.]

With the SELENE (Kaguya) data, Morota and colleagues sought to finally determine the formation age of Giordano Bruno by counting craters on its ejecta blanket to test the medieval formation hypothesis. This was all made possible because of the beautifully detailed views captured by the Terrain Camera of the extremely fresh features of Giordano Bruno including its pristine rim, smooth internal melt ponds, the large number of boulders inside and outside the crater, its cratered ejecta blanket, and bright rays.

Count Quite a Lot of Craters

Determining the age of a planetary surface by counting craters is based on the simple idea that a newly developed surface has no impact craters and older surfaces have accumulated more craters with time. (For a short explanation of the crater counting technique visit the Planetary Science Institute web page.) Morota and colleagues counted craters in a 294 km^2 area (surrounded by the white, dashed line in image A, below) on the continuous ejecta from the crater's rim out to a distance of one crater radius. Crater size-frequency measurements are sensitive to any contamination by secondary craters, but Morota and colleagues determined the craters (40 to 200 meters in diameter) in this study area are primary craters formed after

Giordano Bruno and not secondary craters produced by fallback of high-velocity ejecta blocks from other recently-formed large craters. This point will be revisited in the last section of this article.

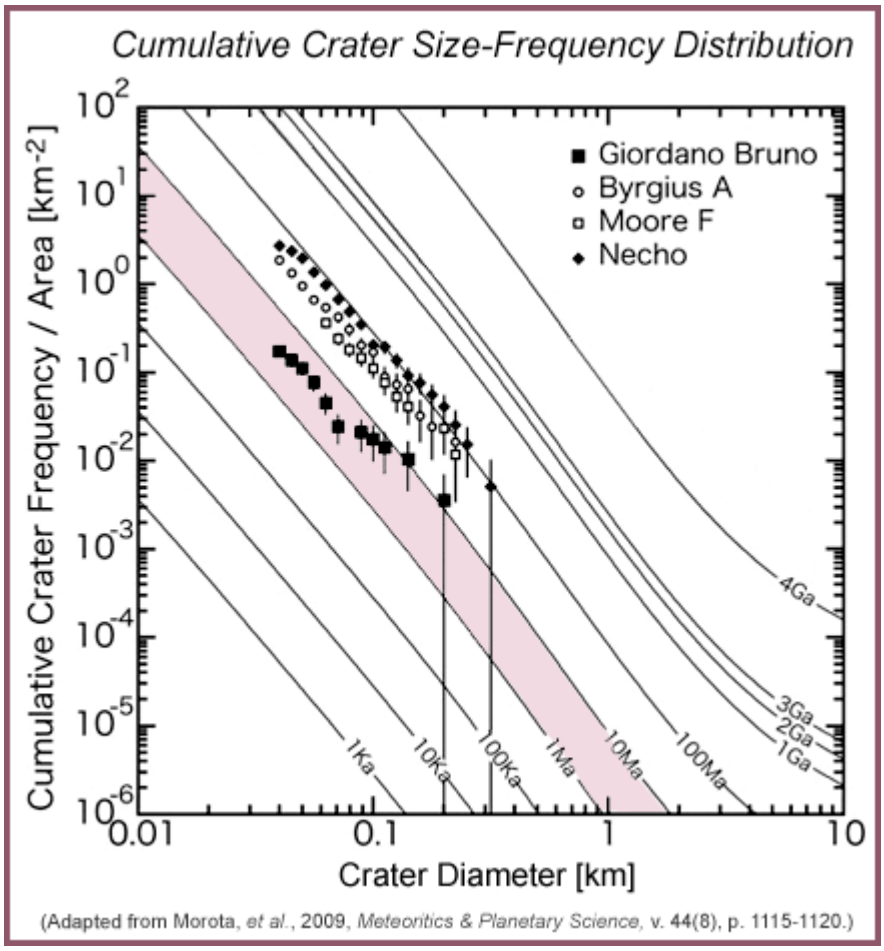


(From Morota, *et al.*, 2009, *Meteoritics & Planetary Science*, v. 44(8), p. 1115-1120.)

Acquired by the Terrain Camera on SELENE (Kaguya), these images are among the four terabytes of TC data released so far by JAXA. Spatial resolution is 10 meters/pixel. Morota and coauthors measured the size-frequency distribution of craters in the area bordered by the white, dashed line. Images B and C are close-ups of regions of interest with arrows pointing to craters larger than 40-meters in diameter.

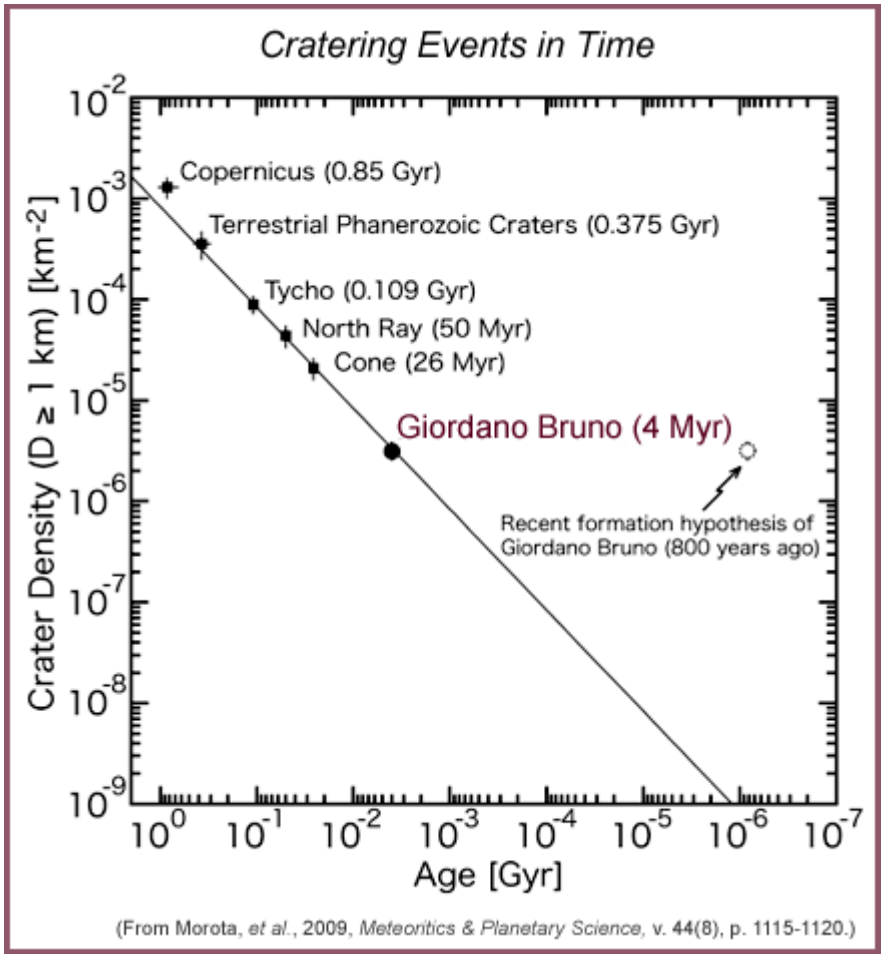
Size-frequency distributions, plotted on log-log plots, show the number and sizes of craters in a given area. The 49 craters, counted by Morota and colleagues, on the Giordano Bruno ejecta blanket are shown as black squares in the plot below. Crater counting from three other lunar craters, Byrgius A, Moore F, and Necho, are shown for comparison. These three craters also have intensive, bright-ray systems and have been classified previously into the youngest (Copernican-age) group of craters along with Giordano Bruno (all younger than Tycho crater, which is 109 million years old).

Fortunately, crater frequencies on lunar surfaces can be converted to very good estimates of absolute ages because we know the absolute ages of the rocks brought back by the U. S. Apollo and Soviet unpiloted Luna missions (determined in the laboratory using (radiometric dating techniques). In fact, crater-counting studies show that Earth's Moon preserves a record of almost four billion years of Solar System impact history. So when did Giordano Bruno crater form? The graph below shows the isochrons, lines of equal age, for the Moon determined by the cratering chronology model developed by Gerhard Neukum (Freie Universität, Berlin, Germany) and colleagues. Based on the crater counting of Morota and colleagues, Giordano Bruno formed between 1 to 10 million years ago (data points plot in the shaded zone).



Cumulative size-frequency distributions of craters on the continuous ejecta of Giordano Bruno and three other young craters for comparison. Frequencies of craters per unit area are plotted against crater diameters and used with chronology models to derive the age of the surface. If a medieval formation hypothesis were correct, then the crater-size distribution for Giordano Bruno would plot on an isochron (line of equal age) of 1 Ka (one thousand years). Instead, we see that the crater-size distribution points plot between 1 to 10 million years.

Assuming a constant impact flux rate for the last 100 million years, depicted by the straight line in the graph below, Morota and coauthors argue that Giordano Bruno formed 4 million years ago, and that it would be extremely unlikely for a surface 832 years old to exhibit the crater density of a surface four million years old.



This graph shows the lunar cratering chronology for the last 100 million years. Absolute ages for Copernicus, Tycho, North Ray, and Cone craters were determined by cosmochemists from analyses of lunar samples. Giordano Bruno crater plots on this diagram with an absolute age of 4 million years compared with the other lunar and terrestrial craters. The open-circle point shows where Giordano Bruno would plot based on the medieval-age formation hypothesis.

Young and Immature

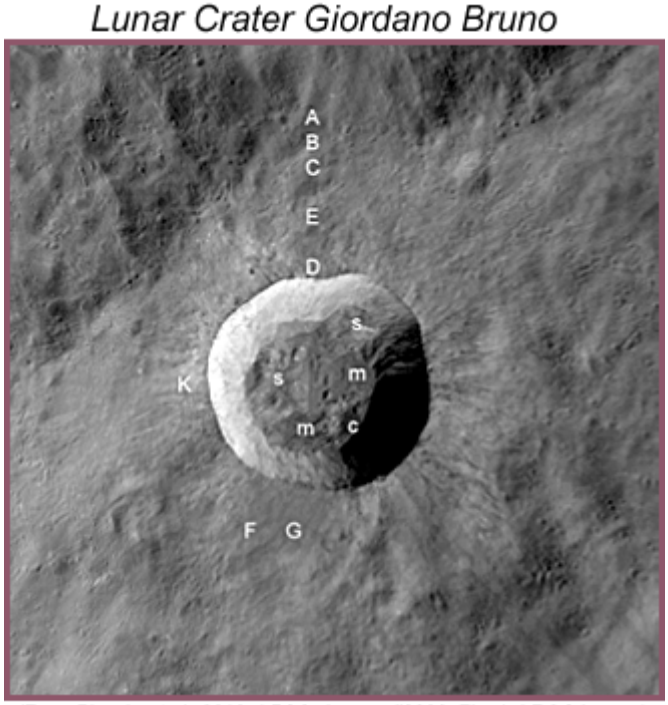
The high-resolution images from the Terrain Camera on SELENE (Kaguya) show numerous small craters superposed on the ejecta blanket of Giordano Bruno. The size-frequency distribution of these small craters led Morota and colleagues to establish an age of 4 million years for Giordano Bruno. Anything Copernican in age, or less than a billion years old, is considered young in lunar parlance. The age correlates well with other indicators of crater youth determined by other methods. In previous studies, researchers cited the ratio of large ray length to crater diameter as evidence of the crater's young age. More importantly, the extensive ray system of Giordano Bruno has been interpreted previously as spectrally immature. By maturity we mean how long a surface has been exposed to (and displays effects of) space weathering; hence, an immature surface has been exposed for a shorter time than a mature surface.

Significant work has gone into using orbital multispectral data correlated with lunar sample geochemistry to determine the maturity levels of lunar surfaces. The techniques developed by Paul Lucey (University of Hawai‘i) and colleagues use a comparison of Clementine 950 nm/750 nm ratio to reflectance at 750 nm to calculate the optical maturity parameter (OMAT) of surface materials. Based on work by Jennifer Grier (Planetary Science Institute, Arizona) and colleagues, young ray ejecta have higher OMAT values (~0.28 to 0.22 near the rim to lower values farther away from the rim) compared with lower OMAT values (< ~0.15 to 0.14) for older ray ejecta. The OMAT value for Giordano Bruno ray material is ~0.27, which makes Giordano

Bruno the most immature of any large farside crater. (For other examples and discussion of OMAT see **PSRD** articles: Lunar Crater Rays Point to a New Lunar Time Scale and Recent Gas Escape from the Moon.) Considering the 4-million-year-old age estimate and the apparent lack of large craters in the area younger than Giordano Bruno, Morota and coauthors resolved that no crater on the Moon is related to the transient spectacle witnessed in 1178.

Primary versus Secondary Craters

After carefully considering the visible freshness of the ejecta blanket, Morota and colleagues concluded that the small craters they counted on it are primary craters formed by meteorite impacts after the formation of Giordano Bruno and are not secondary craters produced by fallback of high-velocity ejecta from other recently-formed large craters. Yet, current preliminary work by researchers using Lunar Reconnaissance Orbiter Camera (LROC- narrow angle camera) images from the Lunar Reconnaissance Orbiter mission aims to determine whether secondary craters may, in fact, be affecting the crater counts. These images have 0.5 meter/pixel spatial resolution compared to 10 meters/pixel resolution of SELENE (Kaguya). Jeffrey Plescia (Johns Hopkins University, Applied Physics Lab) and colleagues report that LROC images show the Giordano Bruno ejecta blanket is not uniformly cratered, that these pockmarks do not have fresh crater geometries (including sharp raised rims) expected for young primary craters, and that many are partly buried by continuous and blocky ejecta. Based on their observations, Plescia and colleagues suggest the craters might be secondary craters formed from the Giordano Bruno event itself. In other words, they contend that some blocks of material were ejected so high during the Giordano Bruno impact event that they fell back after the ejecta blanket was laid down. Plescia and colleagues suggest the formation age of Giordano Bruno could be substantially younger if a good portion of the craters are indeed secondaries. How much younger? If half the craters were secondaries, then the age of Giordano Bruno would be about half of the reported age, or about 2 million years. What if all the craters are secondaries that formed from the Giordano Bruno impact event? Then perhaps Giordano Bruno may be young enough that someone saw it happen.



(From Plescia *et al.*, 2010, *LPSC* abstract #2038, Fig. 1, LROC image.)

Lunar Reconnaissance Orbiter Camera (LROC) image from Plescia and colleagues. Capital letters indicate locations where they counted craters; lower case letters indicate units they described in the floor deposits (s: slump material, m: melt, c: chaotic debris). Giordano Bruno crater has a diameter of 22 kilometers.

The work on Giordano Bruno crater and other young, fresh lunar craters will continue as high-precision data help to generate more dependable estimates of absolute age. Making comparisons of these ages derived by the crater-counting method with spectral maturity OMAT parameters will also give us a more complete understanding of recent weathering rates on the Moon. Morota and coauthors speculate it will be possible to measure directly the present-day impact flux rate by searching for and dating the small, fresh primary craters in the new lunar data sets. Most importantly, to be completely confident in the ages of young craters, we need to collect samples from at least a few of them and determine their ages in laboratories here on Earth. The big picture, of course, looks beyond the Moon itself. Accurately defining the ages of young lunar craters, such as Giordano Bruno, is vitally important for understanding the impact flux rate over the past few million years *throughout* the inner Solar System, including on Earth.

Additional Resources

LINKS OPEN IN A NEW WINDOW.

- **PSRDpresents:** How Young is the Lunar Crater Giordano Bruno? --Short Slide Summary (with accompanying notes).

- Giordano Bruno crater -- SELENE (Kaguya) movie by HDTV, © JAXA/NHK shown on YouTube.
- Grier, J.A., McEwen, A.S., Lucey, P.G., Milazzo, M., and Strom, R.G. (2001) Optical Maturity of Ejecta from Large Rayed Lunar Craters. *Journal of Geophys. Res.*, v. 106, p. 32847-32862.
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- Nininger, H. H. and Huss, G. I. (1977) Was the Formation of Lunar Crater Giordano Bruno Witnessed in 1178? Look Again. *Meteoritics*, v. 12(1), p. 21-25.
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- SELENE (Kaguya) mission web site from the Japan Aerospace Exploration Agency (JAXA).
- Taylor, G. J. (2006) Recent Gas Escape from the Moon. *Planetary Science Research Discoveries.* http://www.psrd.hawaii.edu/Nov06/MoonGas.html.
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