Chapter 2

Lunar Impact Features

The Moon is an airless body, devoid of the atmosphere that Earth has to protect it from the impacts of meteoroids. In the case of the Earth, the atmosphere shields the ground from all but the larger (and much rarer) meteoroid collisions. We see the collision between the meteoroid and the atmosphere as a "falling" or "shooting" star, sometimes leaving a brief luminous trail of ions in the atmosphere. On the Moon, where there is no air, any meteoroids collide directly with the lunar surface, without being slowed by air. Over the age of the Solar System, meteoroids and asteroids of all sizes impacted the Moon and other celestial bodies, producing the pockmarks that we know as craters. It was not until the middle of the twentieth century that craters on the Moon were found to be a result of the impact. Also, it was not until the advent of spacecraft exploration that craters were found on other worlds, such as Mars and Mercury.

I will give a brief overview of lunar impact features (craters) in the following sections. I look at how the number of craters changes with region (Maria versus Highland Craters), how the appearance of craters on the Moon change with age (Young versus Old Craters), how the appearance of the crater changes as it gets bigger (Appearance versus Size), and how one can recognize different types of features.

Maria vs. Highland Craters

A casual look at the first quarter or waxing gibbous Moon through a low-power telescope reveals two tones of gray: the darker gray regions seem smooth and largely devoid of craters while the brighter regions are rough and heavily cratered. In fact, many areas of the highlands appear saturated with craters of all sizes. The reasons behind the dichotomy are asteroid impacts and past volcanic activity of the Moon. During the tail end of the era of heavy bombardment, the Moon was impacted by asteroid-sized objects, whose craters were later filled with molten rock. The molten rock appeared during a time when the Moon underwent a period of high volcanic activity, where molten rock seeped through cracks in the surface and filled the low-lying basin areas. Since this happened after most of the big impacts of the heavy bombardment, we observe the lack of craters in the Maria versus the brighter, older highlands. Impacts after Maria solidified are few and far between.

Figure 2.1, courtesy Don Pearce of Houston, Texas, was taken on 27 July 2008 and shows the Moon two days after the Last Quarter. Major impact features, as well as

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Fig. 2.1. Waning crescent moon showing differences in cratering density between maria (darker gray) and the highlands (gray-white). Image taken on 27 July 2008 through a 6-inch refractor with a Nikon D50 camera by Don Pearce of Houston, TX

the Earth-facing Maria (mostly Oceanus Procellarum) are seen in this image. Looking closely at this image, the Maria appears as smooth region with few craters and darker shades of gray, while the highlands show up brighter and rougher, with many impact craters. It appears that the main difference between Maria and highland cratering is the number of craters per unit area. The appearance of a crater of a given size on the Maria (example: Copernicus) is largely similar to the one on the highlands (example: Tycho, but this one is much younger than Copernicus).

One can get an estimate of how old an airless surface is by counting the number of craters per unit area, which gives the crater density, usually expressed as the number of craters per million square kilometers. The older the surface, the more the craters, hence, higher the density of craters per unit area (the technique of counting craters is introduced briefly in the next section and discussed in detail in Chapter 6). Not only does counting craters help us understand the geologic evolution of a surface, but it also enables the identification of surface and subsurface processes in that world.

Young vs. Old Craters

For individual craters, due to exposure to radiation and micrometeoroids, appearance changes over time. Fresh material is usually brighter and bluer; "weathered" material darker and redder. An example of a fresh crater is shown arrowed in

Fig. 3.2, next chapter. Professional planetary geologists sometimes use a parameter called "Optical Maturity" or OMAT to gauge the age of a feature or part of feature.[2] One method used to determine the OMAT parameter of a feature is with multi-spectral images, images sensitive to the iron oxide and titanium oxide content of the lunar surface, as well as other spectral bandpasses. This uses an approach similar to color studies of the Moon by LTP observers: by comparing the intensity of a feature in one wavelength with the intensity in another, a ratio is determined, which leads to the OMAT parameter. OMAT changes across the face of a large feature, and the way this change occurs determines the age of the feature. For example, young craters have high OMAT values near the rim, but the values drop off steeply away from the rim. Older craters have very low OMAT values near the rim, and the change of value is flat, moving away from the rim. The ejecta patterns show up best at full Moon: younger craters have ejecta blankets and rays that have a high contrast with the surroundings, but older craters have blankets that blend well with the background, making them harder to see. An example of a young crater is Tycho, about 100-million-years old, with an OMAT profile as described above. An example of a mature (older) crater is Copernicus, 810-million-years old. Other examples of older craters include Eudoxus, Aristillus, and Lichtenberg. Age estimates for some of the craters in the "Top 100" List of Impact Features to observe are provided along with a few other physical parameters.

In addition to changes in brightness and contrast of ejecta blankets with age, the outline and sharpness of the central crater changes over time as well. Besides the crater counting mentioned above, the age of the crater can also be determined by context: if the surface is heavily cratered and the crater itself appears to have been disturbed by others, it is true that the crater of interest is older. On the other hand, if the crater stands almost alone in a flat Maria plane, or if it appears well-defined and undisturbed amidst a background of more degraded craters, then this is probably a younger crater. These lines of reasoning come from the geologic principle known as the "law of superposition" where the younger features appear to be "on top" of an older feature, since the younger feature will likely be "placed" at a later time in history.

A good example of a mix of craters of various ages is visible in the image of the Clavius crater (Fig. 2.2): the large crater Clavius shows a flat floor as a result of flooding by molten rock; but many small craters are found on the floor. Also, notice the craters on the rim of the large crater (at least four, including one with a central peak are evident) and compare the sharpness of the large Clavius crater with that of the superimposed central peak crater along the top (north) edge. Look closely at the image to find craters of various sizes and degrees of sharpness, including some which show advanced stages of being erased or obliterated by younger craters.

Crater counting provides a method of determining the approximate age of a region. On the Moon, the greater the number of craters in a given region, the older the surface: the Maria has fewer craters and hence, is younger while the highlands have more craters and are older. Counting craters gives an excellent estimate of age, and the estimate can be rather accurate as long as some guidelines are followed. Craters of volcanic origin, such as the volcanic pits along Hyginus Rille, do not get counted. Secondary craters, sometime hard to distinguish against the background mix of pre-existing craters, do not get counted. Counts are made in areas that formed at the same time in geologic history, and over areas of similar sizes.

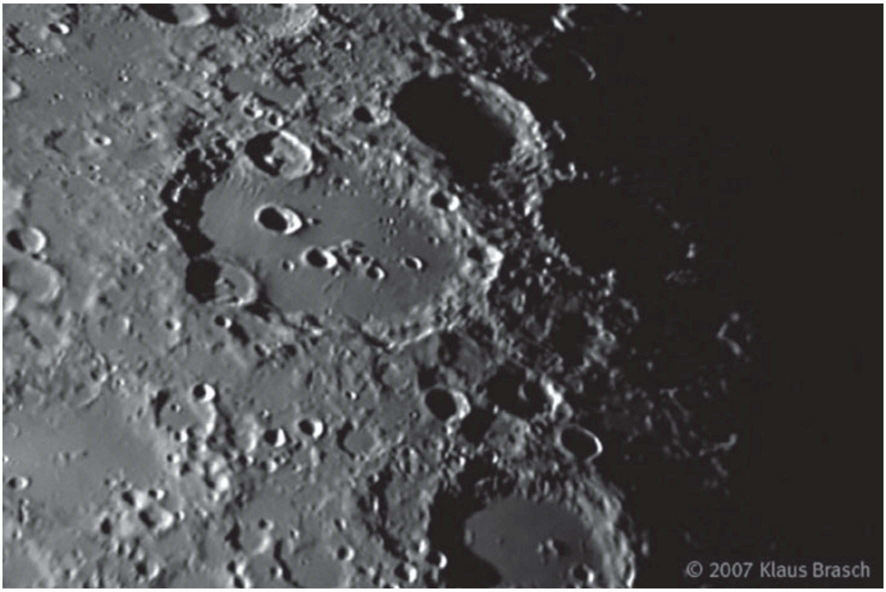

Fig. 2.2. Clavius and its environs. Image courtesy of Klaus Brasch

After carefully counting the craters, an observer can compile a sequence of relative ages, from youngest to oldest. The ages can be confirmed with samples from these regions, which can yield absolute ages in millions and billions of years. Apollo samples provide starting points for the absolute calibration of crater counts, but ideally we would want samples from both the absolute oldest and youngest parts of the Moon's surface. All the lunar Maria and large basins are represented by samples which have made it possible to assign estimates of absolute ages to these features.

Craters on an airless surface are modified or destroyed by a handful of processes. These processes are considered to have been active at one point in the Moon's history or are still active today and include later impacts (great and small, including a constant "shower" of micrometeoroid impacts) or flooding by lava flows. The rate of obliteration of lunar craters is greatest for the smallest craters and increases with increasing crater size.

Impacts break up bedrock, produce regolith and redistribute surface material and are the most important processes that affect the surface. Apollo seismographs recorded the seismic signatures of 70–150 impacts per year in the 100 g to 1,000 kg range. More common are the micrometeoroid bombardment which includes erosion, ionization, vaporization, and lateral transport of material over short distances. The erosion rate of the lunar surface is about 1 mm per 1 million years. The seismic shocks of impacts introduce vibrations that cause a down slope movement of material on craters and other topographic features. One particular Apollo image shows a boulder that had rolled down a hill, leaving a trail on the hillside.

To summarize, young craters show bright ejecta rays, sharp rims, prominent ejecta blankets, secondary craters, and a fresh, bright appearance overall. Aging craters, on the contrary, show a darker, more degraded appearance: the rays disappear, secondary craters become subdued and disappear, the rough-textured ejecta blanket takes on a smoother texture, the rim sharpness decreases, and any terraces are modified by radial channels. Simple craters are partially filled by ejecta from later impacts as they age, and their profiles change over time. Young simple craters have round, bowl-shaped profiles with raised rims while older simple craters have flat floors and rounded rims. Complex craters also get shallower over time and get filled by lava or impact ejecta. Sometimes the central peak is partially covered, at other times it is completely buried. Not only can crater counts provide a chronology for a region but also the changes in crater morphology can give an indication of the age of a particular feature.

Appearance vs. Size

Craters on the Moon (and on Moon samples) range in size from 0.1 μm to 1,600 km (4.0×10^{-9} in. to 1,000 mi), with those <1 cm called "microcraters" or "zap pits". We do not see any microcraters on Earth because of the atmosphere shielding the surface. Craters with diameters larger than 300 km (186 mi) are called basins. Earth does not show any basins because geologic and weathering activity erases them over time. Figures 2.2 and 2.3 show areas on the Moon that display a wide range of craters of different sizes. Many of the characteristics that are described in

Fig. 2.3. The region of Sabine & Ritter, showing craters of various types and sizes. Maria and highland terrain can be seen in the image, which is courtesy of Richard Hill and Jim Loudon Observatory.

the following sections are visible in these images. I encourage the reader to look at these images as the following sections are read.

Factors that influence the appearance and size of craters on the Moon include the impactor velocity, density, and size. Lunar regolith also plays a role in the appearance of the crater. Those less than a few meters in size show up as shallow depressions without raised rims. An impactor of average density traveling with an average velocity of around 20 km/s (12 mi/s) will produce a crater between 10 and 20 times the diameter of the impactor. The simplest craters, larger than tens of meters but less than about 15 km (9 mi) in diameter, are bowl-shaped, with a smooth, slightly concave floors; sharp, well-defined rims; and steep inner walls; no central peak; and a small debris field with blocks up to 1 m across. Craters larger than 20 km (12 mi) in diameter become more complex: those ranging in diameter from 20 to 175 km (12–105 mi) tend to have central uplift features that take the form of a central mountain peak or group of peaks. They usually have relatively flat floors and more complex walls, with some slumping (collapsing or caving in) of material forming terraces on the inner wall of the crater. Larger craters (those bigger than about 175 km or 105 mi across) tend to have complex, ring-shaped central peak clusters. Larger still, those with diameters greater than 300 km (190 mi), are no longer called craters, but are called impact basins, of which there are about 40 on the Moon.

There are many examples of each type of crater on the Moon. An excellent example of the simple bowl-shaped crater is the Moltke Crater (Fig. 2.4). This crater is about 7 km (4 mi) in diameter and shows a modest debris or ejecta field.

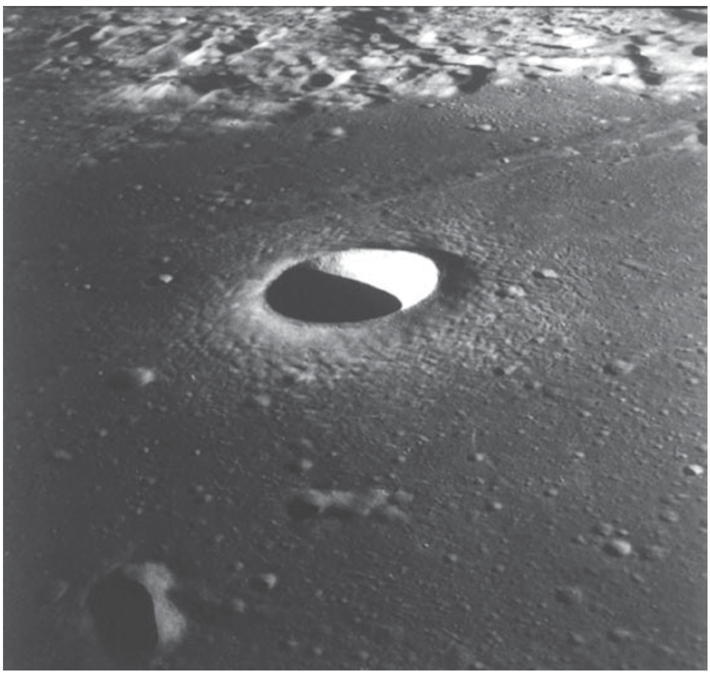

Fig. 2.4. Moltke coutersy of NASA/Apollo 10 photograph AS10-29-4324

Craters of a given size range show common features: as size changes, the features change, to an extent that scientists have generated a crater main sequence, similar to the stellar main sequence. As one goes from smaller crater sizes to larger sizes, there appears to be some form of continuity of development, like the stars encountered as one moves up the stellar main sequence. Crater morphologies depend primarily on the energy of the impact (just as stellar spectral type depends primarily on the star's mass) and the crater's state of preservation. Other factors that determine crater morphology include the gravitational strength of the target, the presence or lack of atmosphere, and the target surface (and subsurface) composition.

Simple craters (<15 km or < 10 mi) show a circular outline, a bright inner wall, and a parabolic shadow reflecting a bowl-shaped profile. One example is the 13 km (8 mi) wide feature Mösting A, which is up to 2.7 km (1.7 mi) deep. Another is Bessel Crater (Fig. 2.5) which is 2 km (1.2 mi) deep.

Larger craters (15–50 km/9–31 mi) are more complex with slumping material. The outline is polygonal in shape instead of circular, and surrounding a floor littered with mounds of material that slid down walls. In some cases, the walls are terraced and the floors flat, with one or more central peaks. The rims are raised and the surrounding terrain shows a radial pattern of rays with secondary impacts up to several kilometers across. Triesnecker is an example of a crater in this size range; it measures 26 km (16 mi) across and is up to 2.7 km (1.7 mi) deep. Euler is another such example (Fig. 2.6).

Craters larger than 150 km (90 mi) diameter have rings of peaks instead of the central peak(s). Many of these are classified as basins (large craters with distinct central rings), especially if they are 200–300 km (125–190 mi) across or more. Ringed basins such as the Orientale basin display concentric mountain basins and depressions. Rings can extend to 500 km (310 mi) from the center and mountains that form the rings can peak as high as 500 m. Basins are thought to have formed from the impact of asteroid-sized bodies or comets and their impacts cover most of the lunar surface with their debris and ejecta. There are some 43 basins catalogued on the Moon that have diameters greater than 220 km (140 mi). There are

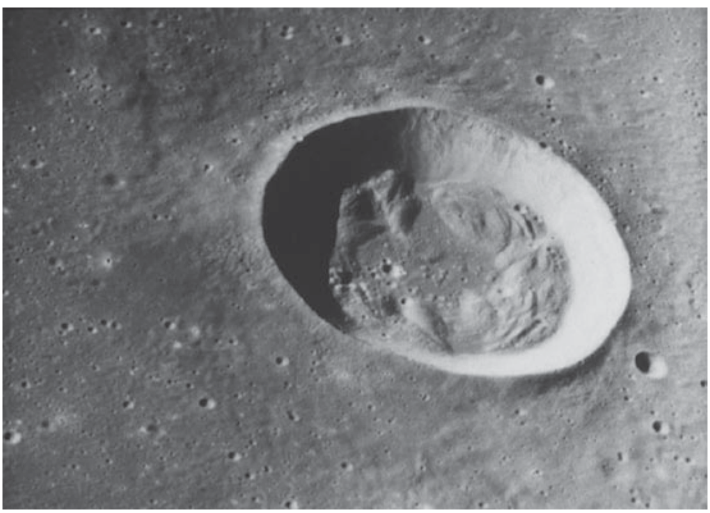

Fig. 2.5. Bessel crater; courtesy of NASA/Part of Apollo 15 Panoramic photograph AS15-9328.

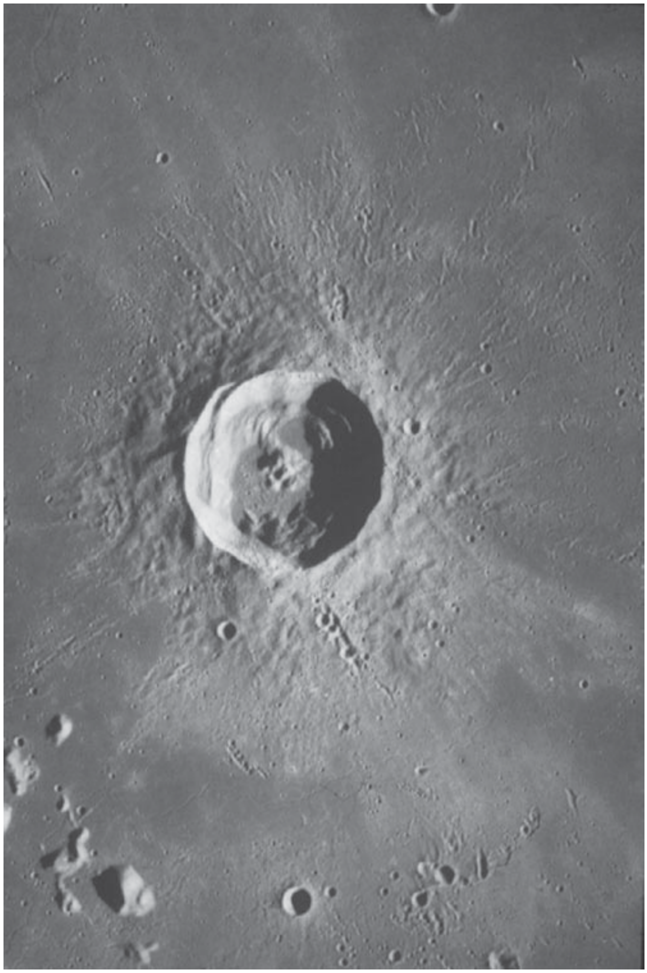

Fig. 2.6. Euler crater, courtesy of NASA / Part of Apollo 17 Metric photograph AS17-2923.

about equal numbers of basins on the near side and far side; those on the near side are generally flooded with lava basalt to form the familiar Maria.

How to Recognize Different Types of Features

One of the best times to observe craters is between 3 days after New to 2 days prior to Full, and again from 2 days after Full to 3 days prior to New. This will vary with ecliptic angle, elongation, and so forth, but the thing in common is the low sun angle which casts shadows that make identifying the physical character of a feature much easier; it adds 3-D relief to the scene. The full phase (or within one day of Full) is best for observing ray structures and bright spots on the lunar surface.

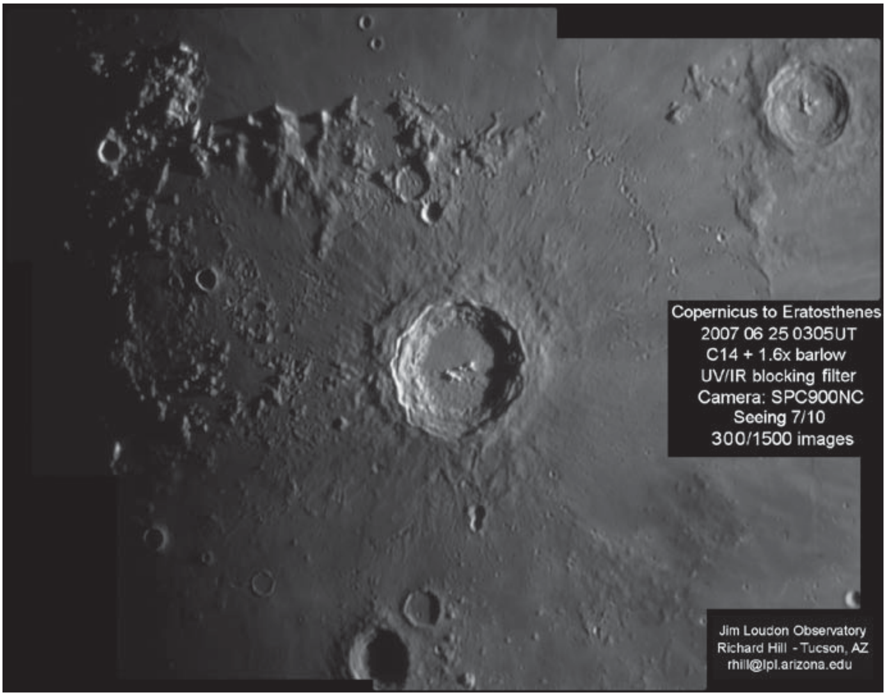

Fig. 2.7. The region of the moon from Copernicus to Eratosthenes, showing craters of various types and sizes. Maria and highland terrain can be seen in the image, which is courtesy of Richard Hill and Jim Loudon Observatory.

A reliable approach to recognizing different types of features is by studying the morphology of the feature (Craters of various sizes and morphologies are depicted in Figure 2.7). Features to look for include the presence or absence of a central peak or complex of peaks. The appearance of this central part of the crater formation will help you get an idea of the size range of the crater itself. Also look at the structure of the walls of the crater. Is the structure intact or is it broken, and if broken, by how much? Are there secondary craters on the floor of the main crater or among the ejecta blankets of the main crater? What does the ejecta blanket look like: is it well-developed or quite faded? How does its appearance change with sun angle? How do all of the impact features change with changing sunlight? Fig. 2.8 provides another useful example with which you can have practice at identifying different types of features.

Where does the crater occur, in the Maria or highland regions? Does it appear to have disturbed its neighboring craters or does it stand out seemingly untouched. Does it interact with any other craters in the region? The "top 100" list of lunar impact structures to observe (provided in Chapter 6), along with the list for the Astronomical League's two Lunar Clubs, will allow picking and identifying various types of craters. It is also worth noting that you will get more out of your observing session if you draw the features you are interested in and include your responses to the above questions. Any good book on observing and drawing the Moon will be helpful if you are starting from scratch. By drawing the features and making notes, you will have a permanent record of what you saw, and it will enable you to take your notes and make an estimate of the age of the feature, and compare the estimate with published values. Some of the craters in the "top 100" list have published ages that you can use to see how well you estimated their ages on your own.

Fig. 2.8. Image PIA02321: “Single Still Image Full Resolution”; image courtesy of NASA/JPL/Cassini Imaging Team/University of Arizona). Use this image (and Figure 2-7) to try your hand at recognizing different kinds of features. NASA/JPL/Space Science Institute

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