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A New Look at the Moon

by Albert R. Hibbs

Galileo did not invent the telescope.

This may come as no surprise to you, dear reader, but it did to me. In gathering information for this article, I was checking the date on which Galileo (I thought) invented the telescope. I discovered he did not invent it at all. Instead, someone in Beligum or someone in Holland (the records are not very conclusive) was the first to discover that, if you held one lens in front of another and then looked through them both, distant objects would appear closer.

This happened in the very early 1600's. In the year 1609, Galileo, visiting Venice, heard of this discovery. On his return home he tried it for himself.

Galileo then developed his Galilean telescope and used it to observe the planets. He discovered that the planet Venus, when viewed from the earth, changes phase in a manner that could only be understood if the sun were the center of the solar system.

Twenty years later, on the basis of the observations he had made with the telescope, as well as arguments similar to those first presented by Copernicus, Galileo wrote his "Dialogues Concerning the Two Chief World Systems." The two systems discussed in this dialogue were the Copernican and the Ptolemaic systems, the first of which had the sun as the center of the solar system and the second of which put the earth in this special position.

For writing this dialogue, Galileo was sentenced to prison for the rest of his life. His arguments ran contrary to the metaphysical doctrines of the Church.

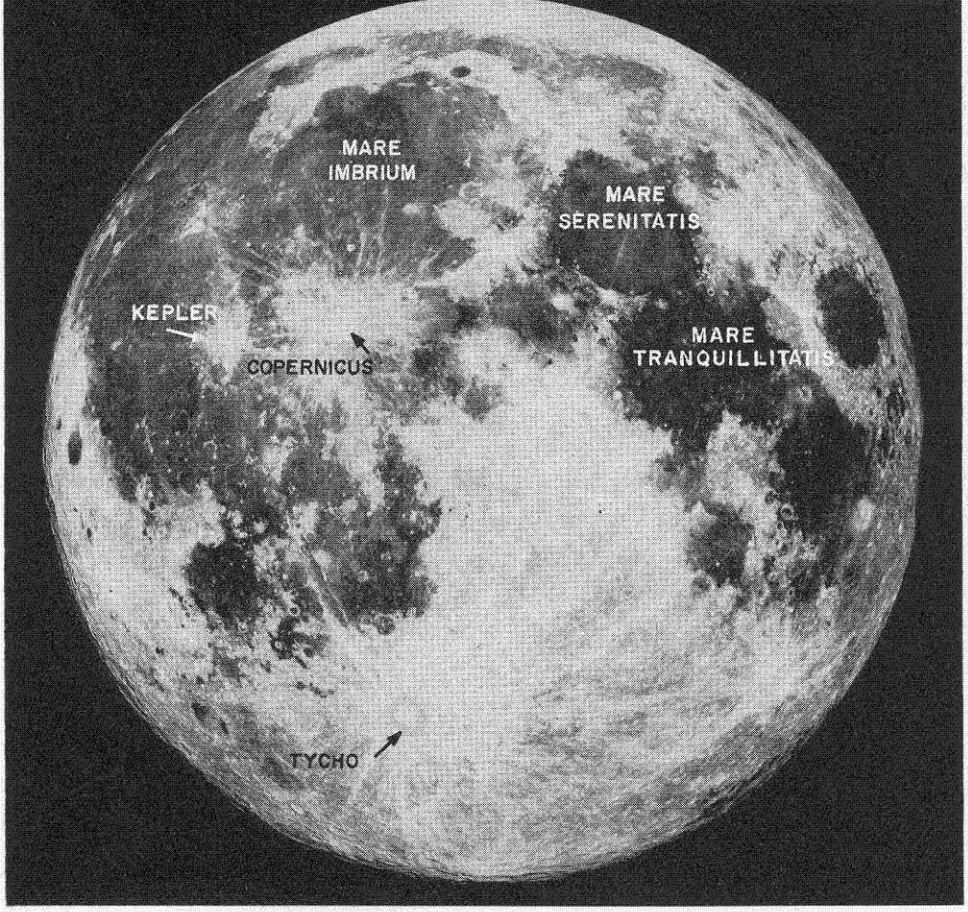
In the translation of this dialogue by Stillman Drake, Galileo described his observations of the moon as follows:

> "The prominences there are mainly very similar to our most rugged and steepest mountains, and some of them are seen to be drawn out in long tracts of hundreds of miles. Others are in more compact groups, and there are also many detached and solitary rocks, precipitous and craggy. But what occur most frequently there are certain ridges (I shall use this word because no more descriptive one occurs to me), somewhat raised, which surround and enclose plains of different sizes and various shapes but for the most part circular. In the middle of many of these there is a mountain in sharp relief and some few are filled with a rather dark substance similar to that of the large spots that are seen with the naked eye; these are the largest ones, and there are a very great number of smaller ones, almost all of them circular."

A little more than 300 years later, the 14th edition of the *Encyclopaedia Britannica* describes the surface of the moon as follows:

> "The most striking formations on the moon are the craters, which are of all sizes up to a hundred miles or more in diameter and are scattered over the surface with a great profusion, frequently overlapping. These craters in appearance closely resemble the volcanic craters on earth, and it is possible that they may have a similar origin. They have, however, often so large a diameter compared with height that the analogy may not be so close as it first appears. A typical crater has a surrounding ring rising to anything up to 20,000 feet above the general level. The floor of the crater may be higher or lower than the outside level. Often, there may be a central peak or peaks within the crater. The darker areas which are not so much covered by craters have been considered to be seas of lava which have spread over the moon's surface at a later date than that of the formation of most of the craters."

As you can see, there is very little difference in the



The full moon. The craters (Tycho, Copernicus and Kepler) are surrounded by rays, probably resulting from explosive impacts of meteorites.

two descriptions, which is not surprising, since neither the moon nor our observational techniques have changed much during the intervening 300 years. We are still as far away from the moon as Galileo was. The one outstanding difference in the two descriptions is that the *Encylopaedia Britannica* indulges in a little speculation, whereas Galileo restricted himself to the things he could see.

In between Galileo and the 14th edition of the *Encylopaedia Britannica*, the geologist, G. K. Gilbert, delivered an outstanding paper at an 1893 meeting of the Philosophical Society of Washington, D.C. On the basis of excellent arguments, Gilbert concluded that the features of the surface of the moon have resulted principally from collisions of objects with the surface. Even the maria, he reasoned, are the result of such collisions, and, in fact, Gilbert believed that there were no volcanoes at all on the moon.

Gilbert based his conclusions not only on his extensive experience as a geologist but also on a lengthy series of observations of the moon at the Naval Observatory in Washington which he undertook a year before his paper was presented.

He was in Washington on a mission that is familiar to many of us. Gilbert at this time was Chief Geologist of the National Survey. During 1892, Congress was cutting back funds of the Survey, and Gilbert was supposedly lobbying for more money. (In the annals of the Survey, this time period is recorded as "The Disaster," when half of the personnel was laid off.) Nevertheless, Gilbert found time to spend many nights at the Observatory, looking at the moon.

Gilbert wrote to a friend on this occasion, "I am a little daft on the subject of the Moon, being troubled by a new idea as to its craters, and I have haunted the Observatory for three evenings in which I have netted but one hour of observation. Clouds and congressmen are about equally obstructive."

The congressmen, on their part, were not silent. During debate in the House of Representatives, one of them said, "So useless has the Survey become that one of its most distinguished members has no better way to employ his time than to sit up all night gaping at the moon."

From Gilbert's "gaping" came what remains to this day one of the most impressive discussions of the lunar surface features and their origins. Gilbert's idea that almost all of the craters are due to meteor impacts is now generally accepted, although the mechanism he suggested for this process does not appear to be equally valid. He suggested that the earth was surrounded by a ring of moonlets, just as Saturn is surrounded by a ring of rocks. These moonlets were supposed to have crashed into the moon one by one as variations in their orbits brought them near the moon. This would have resulted in a preponderance of craters near the lunar equator, which of course is not the case.

Gilbert felt that the moonlet theory was necessary to explain the fact that most craters appeared circular. He reasoned that meteorites striking the moon from random directions — not necessarily vertically — would often leave oval-shaped craters. Thus, he suggested moonlets in orbits around the earth, which would approach the moon at relatively slow speeds and then be drawn to the moon's surface by the moon's gravity, striking it nearly vertically.

Nowadays we do not feel that Gilbert needed to have gone to all of this trouble. A body impacting at high speed does not scoop out a trench, but simply explodes. The resulting depression will be a circular crater centered at the point of impact, regardless of the angle of flight of the impacting body.

After Gilbert's paper appeared in print, it was remarked that the majority of astronomers explained the craters of the moon by volcanic eruption – that is, by an essentially geological process; whereas a considerable number of geologists are inclined to explain them as an impact of falling bodies upon the moon – that is, by an essentially astronomical process.

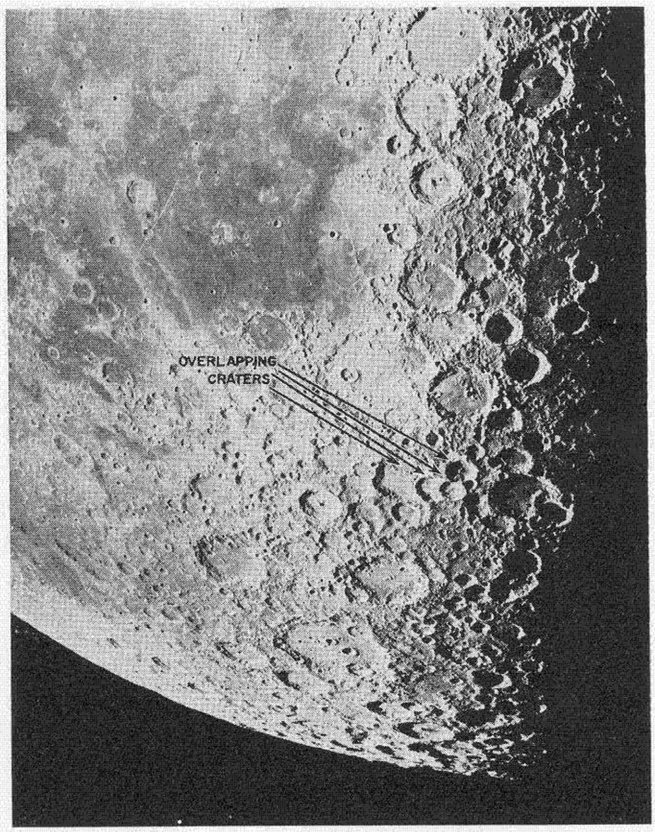
The full moon (opposite page) displays some of the signs which led Gilbert to conclude that the craters were the results of impacts. Although the topography is not apparent in the flat lighting of the full moon, the rays around many of the craters stand out quite sharply. For example, the long rays of Tycho (the crater in the southern hemisphere which looks like the navel on a navel orange) radiate out from it to a great distance, apparently going all the way to the invisible hemisphere. Perhaps when we get a *good* picture of the back side of the moon we will see the rays of Tycho stretching across it. Looking at the crater Copernicus, north of the equator, toward the west, you can almost hear the "splat" of the crashing meteorite.

The craters are named after astronomers and philosophers of the Renaissance and before – Tycho, Copernicus, Kepler, Eratosthenes, Aristotle, Ptolemy, and so on. The large dark areas are called "seas" or "oceans," and some of them are called "bays." Latin names are used, such as Mare Serenitatis, Mare Tranquillitatis, Mare Imbrium.

The rumor that the watery nomenclature of the moon's surface was introduced by an ambitious admiral anxious to establish a roles-and-mission position for the U.S. Navy's space program is absolutely untrue. These names were given hundreds of years ago, when early astronomers thought that perhaps the moon might actually have water on its surface.

Today, on the basis of careful observations (for example, when the moon passes in front of a star, we measure how rapidly the starlight is dimmed by any lunar "atmosphere") we have determined that not only does the moon possess no water but that it has no appreciable atmosphere. In fact, the atmosphere of the moon is a better vacuum than any we can produce in most of our laboratories.

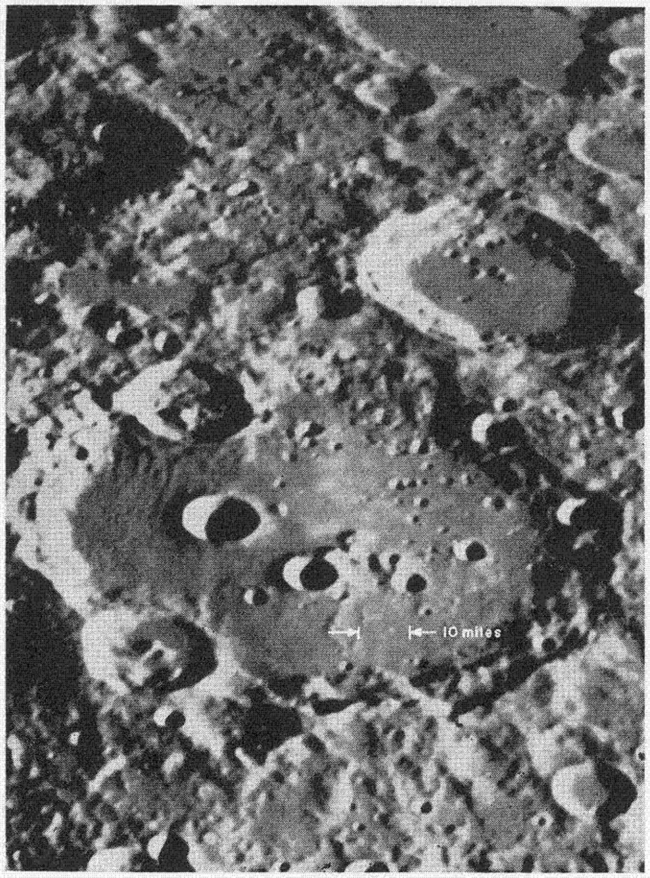
The absence of a lunar atmosphere is important in determining the objectives of lunar exploration. The formation process of the solar system must have ended billions of years ago. The planets and all their satellites, including the earth's satellite, the moon, were probably built up by the accumulation of smaller hunks of rock. Today, very few of these original hunks of rock are left. But still, a meteorite occasionally comes into the atmosphere – and on even rarer occasions a meteorite comes in that is big enough to reach the surface of the earth and to be picked up. Very infrequently – maybe once every hundred thousand years – a meteorite hits the earth that is big enough to make a crater almost a mile across, such as the one near Winslow, Arizona. But most of the bombardment was over billions of years ago.



The southern portion of the moon during the last quarter. The rugged appearance of the craters is accentuated by the shadow detail near the sunset line – or terminator. Many series of overlapping craters can be picked out. The relative overlap is a measure of relative age.

After the formative bombardment ceased, the mountain-building processes on the earth, aided and encouraged by the erosion due to the earth's watery atmosphere, has so continuously changed the appearance of the earth's surface that no record of its early formation persists. But on the moon the record remains. It is very likely that the surface of the moon will show us the history of the solar system's formation.

In the photograph above we get a closer look at the southern portion of the moon. Sunset is approaching along the right-hand edge, and near the shadow line (the "terminator") the topography of the moon stands out clearly. Numerous craters are visible in the southern region. In fact, close inspection shows that the surface is covered with them, one on top of the other. This region is called the "highlands" to



The crater Clavius, whose walls have apparently been eroded from their original rugged shape and whose central section is filled with the debris from this erosion process. This central plain is marked with the impacts of later meteorites.

differentiate it from the smoother, dark plains called the "seas."

A little more than halfway down the terminator you can see a series of four overlapping craters extending from the terminator off to the west. The overlap indicates the relative ages of the various craters. The newer crater cuts into the walls of the older crater. At least, this seems a sensible way to distinguish relative ages of craters. Fortunately, nowhere on the moon do we find a ring of craters with each one overlapping the one in front of it, like a ring of elephants each holding onto the other's tail. Such a situation would defeat the logic of the relative age idea.

A close look at these craters reveals one interesting detail. The older craters appear to have the least rugged walls. Ruggedness seems to be a characteristic of young craters. Other examples can be found in this area and other areas of the moon, showing this same relationship. Some craters can be found whose walls are almost nonexistent, as if they had been worn away to almost nothing. These worn-down craters are in most cases filled with some sort of smooth material in their central section, whereas the newer rugged craters are often found to have an extremely rugged central section with a central peak.

Certainly, there is a very strong suggestion that some sort of erosion process has been operating on the moon, gradually changing the appearance of the surface markings. This process must be quite different from the erosion we are familiar with on the earth.

Professor Thomas Gold, now at Cornell University, has suggested one possibility for such an erosion process. He points out that several processes are available for the creation of dust and the wearing away of the rock's surface, such as the impact of meteorites and dust particles (micrometeorites), high-energy solar radiation (which never reaches the surface of the earth, since it is absorbed in the earth's atmosphere), and violent temperature changes between the lunar night and day. What is required is a process to move the dust from the peaks and sides of the crater rims to the flat areas at lower altitudes.

Professor Gold suggests that high-energy solar radiation can electrostatically charge small areas of the lunar surface. In particular, particles of dust will acquire charge and be electrostatically repelled from the surface. They will hop about with a greater tendency to hop downhill than uphill. This process may seem slow compared with the processes of wind or water erosion on the earth. Surely, a hopping dust particle would take a long time to travel 100 or 200 kilometers from a crater in the highlands to one of the maria. However, these particles on the moon have had five billion years to hop. So they could have travelled quite a distance.

Professor Gold has reported that some preliminary experiments carried out in a vacuum chamber with dust particles illuminated by ultraviolet light have shown that such a process actually does occur.

On the basis of these arguments, he suggests that the maria, as well as the centers of many of the old craters, are not filled with lava, but rather with dust. He computes the thickness of the layer of dust which must have formed in the maria by estimating the total amount of rock which has been removed from all of the old worn-down crater walls in the highlands. On this basis, he reaches a number of one kilometer for the maximum dust depth – that is, a little over one-half mile.

It should be pointed out that, although this material may have been dust at some time in its past history as it was moving from a higher spot to a lower spot, once it has settled in its final resting place it probably does not behave very much like the dust we are familiar with on earth. After all, our intuitive experience with dust is gained in an environment where the dust is mixed with air. "Dustiness" is more a property of the air lubrication between particles than it is of the particles themselves. In a vacuum, dust tends to become hard packed. Thus, we can imagine that any deep dust layer on the moon would have the physical properties resembling pumice more than the pile of dust we are familiar with on earth.

Unfortunately, it is not possible to resolve the controversies on the nature of the lunar surface — the controversies between volcanoes and impacts or between lava and dust — by looking through our largest telescopes. The photograph on the opposite page was taken with the 200-inch telescope at Palomar at high magnification. The smallest detail that can be seen in this picture (one of the small crater pits inside the large crater Clavius) is almost a mile across. Details smaller than that are simply unresolved.

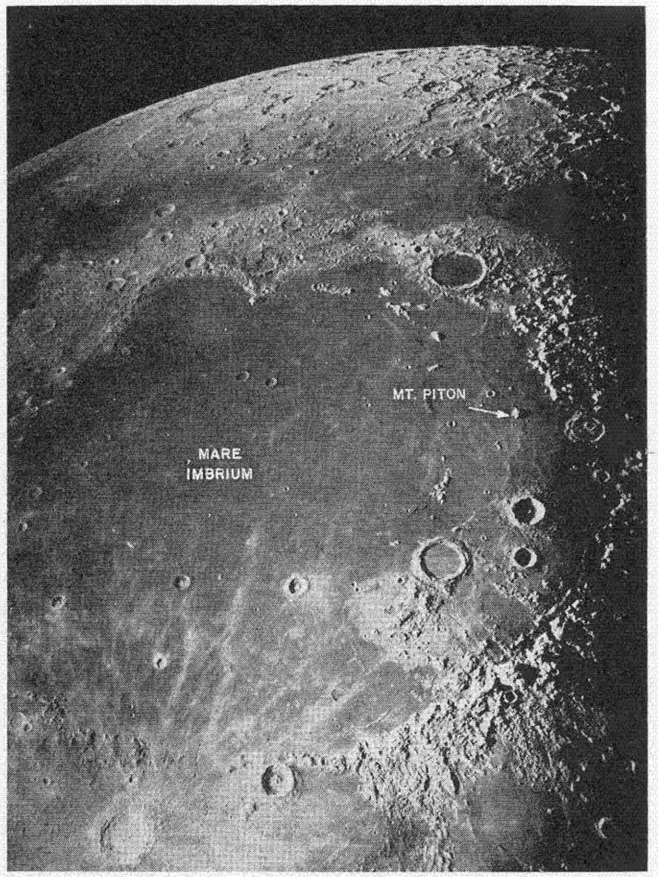
The material filling the crater Clavius might be as smooth as it appears, or it might be composed of rocks 100 or so feet in diameter. Looking out from under our blanket of atmosphere here on the surface of earth, we cannot tell the difference. The turbulence of the atmosphere through which we look — the turbulence that makes the stars twinkle so beautifully — unfortunately makes the details of the moon twinkle also. In this twinkling, the resolution is lost.

As a matter of fact, better pictures can often be obtained with a telescope of much smaller diameter. A telescope of 30- to 40-inches diameter is often considered better for lunar photography than one of 100 inches or more. The diameter of a telescope does not affect its power to magnify, but rather its power to gather light, its power to see farther out into the universe to the far-distant, faint objects. On an astronomical scale, the moon is neither far nor faint.

The photograph at the right shows the Mare Imbrium — the right eye of the face of the Man in the Moon — as the sun is beginning to set on its eastern edge. This is one of the level plains which Gold supposes is filled up with dust. Standing out of the plain near the shadow line is a peak that appears as jagged as a hound's tooth — Mt. Piton. This is one of the prominences which Galileo described as "very similar to our most rugged and steepest mountains." Literally, how rugged and how steep is Mt. Piton? It is possible to measure heights on the moon with surprising accuracy. Relative heights of 50 to 100 feet can be determined with a technique known to the ancient Egyptians — the measuring of shadow lengths. When an object stands out against a flat surface, the length of the shadow it casts is proportional to its height. If we know the angle of the sun to the surface, we can determine height.

For a peak such as Mt. Piton standing out of a nearly level plain, this technique is well applicable.

Over the last few months, Professor Zdenek Kopal, at Manchester, England, working in cooperation with astronomers at Pic du Midi in France, has applied this method systematically to many craters and mountains on the moon's surface. In particular, he made a rough contour map which shows how Mt. Piton would look to a moon explorer standing on the surface a few miles from its base. It is a high but gentle hill rising to about 7000 feet, and stretching out more than 70,000 feet (about 13 miles). The top is so nearly level that it would be difficult to choose the highest point. Certainly, from this point of view it looks quite different from the rugged mountain it appears to be in the photograph above.

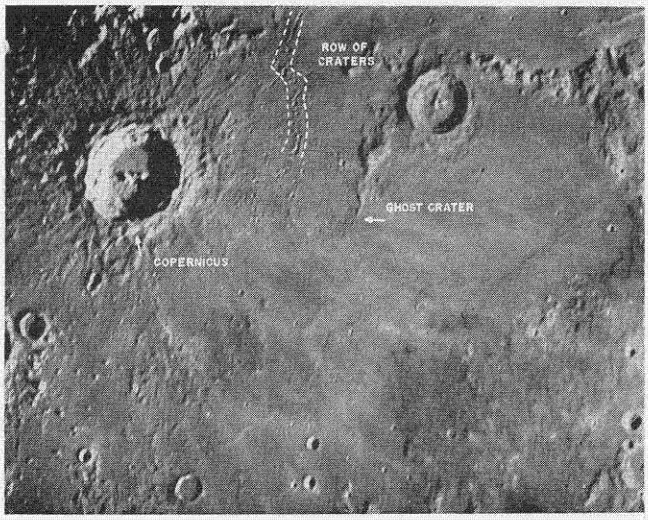


The Mare Imbrium, with sunset on its eastern edge. Near the sunset line, Mt. Piton stands out as a jagged peak, casting a long shadow to the east.

Although the moon appears to be bright when we look at it in the dark, star-studded sky, it is actually made of rather dark rock. It reflects less than one-tenth of the light which it receives from the sun. The earth, on the other hand, with its clouds and oceans, reflects almost four-tenths of the light it receives. Thus, a space traveler flying away from the earth-moon system and looking back at them out of his porthole would see the earth as a much more brilliant object than the moon.

The dark color is almost the only thing we know about the surface rock of the moon. We know the average density of the moon, since we can measure both its diameter and its mass (the mass measurement comes from a measurement of the effect of the moon's gravity on the motion of the earth). The average density of the moon is less than that of the earth and is similar to the density of the crustal rock of the earth. Thus, we might guess that the moon lacks the comparatively large fraction of iron which we believe makes up the core of the earth and accounts for its greater density.

Unfortunately, we cannot make any unambiguous deductions about the lunar material from the density



The crater Copernicus and its smaller neighbor Aristosthenes, taken with the 200-inch telescope. To the right of Copernicus lies a group of small craters running almost in a straight line.

measurement alone. Not only are granite and basalt on the earth's crust similar in density to that of the moon, but the stony meteorites also have this same general density. One of the most important measurements which we can make in the early stages of lunar exploration will be a measurement to determine the chemical nature of the crustal rock.

We know even less about the interior of the moon than we do about the surface. Of course, this fact is true of the earth also, so it comes as no surprise. However, there are some features of the surface which allow us to make a few deductions about the nature of its interior. For example, there are no "strike-slip faults" visible on the moon. These are the faults of earthquakes where the slippage of the earth is horizontal rather than vertical. The San Andreas fault – responsible for the great San Francisco earthquake and for numerous shocks since – is such a fault on earth. Over many millions of years, the horizontal displacement can build up to several miles, perhaps hundreds of miles.

On the surface of the moon there are so many linear and circular features that we should easily see evidence of such a fault, and yet no such evidence exists on any portion of the visible face of the moon.

Although horizontal motion has apparently not occurred, some geologists feel that vertical faults are present on the moon. Along the eastern edge of Mare Imbrium, for example, a chain of mountains cut by several valleys radiates outwards generally from the center of the Mare. These valleys may be the result of vertical sliding.

A close-up (above) of the crater Copernicus, taken with the 200-inch telescope, shows another feature commonly held up as evidence for faulting and perhaps even volcanism sometime in the moon's past. To the right and above the crater there is a curved line of several small crater pits in a row. It is hard to imagine that these craters could have been the results of random impacts of meteorites striking the surface. Random impacts just would not line up so neatly. Instead, it is suggested that a crack was opened here on the moon's surface (perhaps by the impact which caused the crater Copernicus) and volcanic gases trapped beneath the surface bubbled out through this crack. The crater pits remaining are the result of these bubbling gas streams.

Another peculiar feature shows up in this photograph. Just below the row of craters is a faint circular mark – a "ghost" crater. Gold, in his study of lunar surface erosion has pointed out several examples of such ghost craters which he believes have been covered up to the brim with the dusty debris from higher regions on the moon's surface.

The question of faulting on the moon's surface – either vertical or horizontal – is closely related to the question of the moon's temperature history. If the moon was at one time quite hot and has since cooled then we would expect that the interior is shrinking and the crustal surface must wrinkle to accommodate the shrinking interior. This would result in the strike-slip faults which are remarkable by their absence. This appears to imply that the moon has not undergone any significant cooling since the formation of its surface.

If, on the other hand, the moon is steadily heating up, then the interior is expanding and the surface is stretching to accommodate it. This would result in vertical faults as chunks of the surface fall into the cracks left by the stretching skin. Perhaps this is what has happened. But, if so, then we can argue towards another conclusion. If large pools of lava were available below the surface at some time in the past – available for release by the impact of large meteorites, as is suggested by the lava school of thought – then these pools of lava must be available today, because the moon has not been cooling. Here, again, we are led to an important measurement for the early lunar exploration program – the temperature gradient of the moon's surface.

Coming up – a really new look

Today, our new look at the moon has little more visual evidence than that which was available to Galileo 350 years ago. Perhaps our increased knowledge of geophysics has made some of this visual evidence more understandable to us, but for many of the controversies and uncertainties we must wait until our instruments land on the surface for a *really* new look at the moon.

Now we can hope that the wait will be a short one. We can hope that in less than one percent of the time between Galileo and now we will have solved many of these ancient mysteries – and very likely will open up twice as many new ones.