EIR Science & Technology

The Moon: Where it came from, how we will colonize it

Dr. Alan Binder discusses the continuing puzzle of where the Moon came from, and the discoveries that will make it more easily habitable. He was interviewed by Marsha Freeman on Nov. 2.

Dr. Alan Binder was the originator and motive force behind the Lunar Prospector mission currently in progress. Lunar Prospector was launched on Jan. 6, 1998, and it is in a lunar polar orbit at an altitude of about 60 miles. Less than two months after launch, Dr. Binder and the scientific team announced stunning new discoveries about the Moon, including their estimates of the amount ice at the Moon's poles. After its primary mission is completed at the beginning of 1999, Lunar Prospector's orbit will be lowered to less than 15 miles, on average, above the surface of the Moon, for a closer look.

Dr. Binder, the Principal Investigator for the Lunar Prospector mission, earned a bachelor's degree in physics in 1961 from Northern Illinois University, and a doctorate in geology and lunar and planetary science in 1967 from the University of Arizona's Lunar and Planetary Laboratory. Dr. Binder was a Principal Investigator on the 1976 Viking Mars Lander Camera Team. For ten years, he taught and conducted lunar research in Germany, and was an adviser to the European Space Agency. Before his recent founding of the Lunar Research Institute in Tucson, Arizona, Dr. Binder worked for Lockheed. He has authored 70 scientific papers, mainly in the areas of lunar and Martian geology, geochemistry, petrology, and geophysics.

During a wide-ranging discussion with *21st Century Science & Technology* Associate Editor Marsha Freeman, Binder reviewed the theories of how the Moon was formed and where it came from—questions still far from being answered. He described the results from his lunar spacecraft and contending theories on whether there is water ice at the poles.

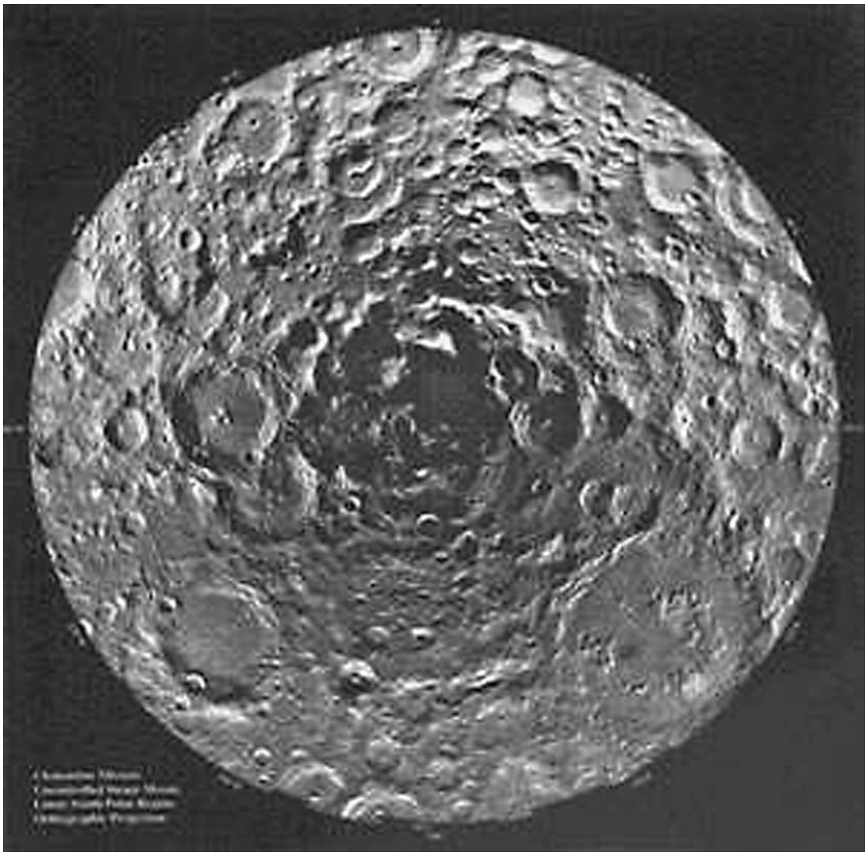
Dr. Binder believes that Lunar Prospector has opened the door for the colonization of the Moon, because it has verified that there is water ice available, and because it has demonstrated that inexpensive spacecraft, using available technology, can be marshalled by the private sector to take the next steps in lunar exploration. For NASA to lead the effort for a manned lunar base in the future, Dr. Binder believes that the agency would have to return to the mission-orientation it had during the Apollo program.

Interview: Dr. Alan Binder

Q: Many people believe that when we completed the manned Apollo missions in the early 1970s, we understood most of what we would need to know about the Moon. What did we learn from the Apollo missions?

Binder: Most people erroneously think that the Moon is a small place, and that once you've been there and brought a couple of rocks back, you've understood it. Part of the problem is that when the Apollo program was started, NASA gave a "motherhood and apple pie" objective, which we all have, which is to understand the origin and evolution of the Moon and the planets. Those clearly are our overall goals. But science doesn't work in that magical way, where you get one piece of information and all of a sudden, Eureka! you understand everything. It's a slow process of accumulating enormous amounts of data and sorting it out, and slowly but surely getting an understanding of whatever you're trying to understand.

Geologists have been studying the Earth for about 300 years, and there have been literally hundreds of thousands of geologists, or certainly on that order of magnitude, who have



This image taken by the Clementine spacecraft shows the Aitkin basin (center) at the south pole of the Moon. These permanently shadowed regions at the poles are where scientists expected to find water ice.

studied the Earth and who continue to do so, and we are still learning about the Earth. The Earth is fairly complex, obviously, but it's not easy to understand how any planet forms and evolves, and where the resources are. The Moon has a diameter about one-quarter of that of the Earth's, but the surface area is equal to North and South America combined. That's a big place. Think how little we would know about even just the United States, if there were six crews who spent a grand total of three working days exploring six sites in the United States. You would know virtually nothing about it. That's where we were with the Moon, after the Apollo program.

To be sure, the Moon is smaller than the Earth. Its active evolution quit pretty much within the first billion years of its existence. Most of the history that we see written in the rocks and on the surface is the first half a billion years. The time from the Cambrian, the time of visible life on Earth, to the current time, is also half a billion years, and that's what geologists have been spending these last 300 years trying to decipher. So, the magnitude of effort needed to understand the Moon, at the time when it was active, is about the same as that needed to understand the Earth. On the Earth, most rocks are younger than this half a billion years. You pick up very few rocks that are much older than that, because they've been destroyed by plate tectonics, by weathering, erosion, and so on.

We've got a lot to learn about the Moon. It's a very complex place, certainly not as complex as the Earth, but nonetheless very complex, and we have just scratched the surface.

My background is basically astronomy. I was going to be an astronomer and study the planets, and when spacecraft came along, instead of telescopes (which I still enjoy), I used spacecraft to study the planets, and specifically, the Moon. We had a very poor understanding of the Moon before Apollo, as you might expect, from just remote observations. Even though we had the Lunar Orbiters and Surveyors, that was just the barest beginnings. The Apollo samples, and the Apollo experiments that were put down on the surface, such as the seismic network and the heat flow measurements, made a giant leap forward.

When we ended Apollo, we had some very basic knowledge about the lunar rocks, petrology, the timescale of lunar events, and the internal structure of the Moon. We did not know if it had a core, which is an important question. We did not know what the real sequence of events was, prior to the Imbrium impact, since debris from that impact has covered a large part of the Moon, and most of the Apollo sites were near the Imbrium event, so we really had only started to decipher this history for the first billion years of the Moon's history.

[During Apollo] we sampled Mare Tranquilitatis, Serenitatis, and Imbrium, and a little of Oceanus Procellarum, in terms of mare units. We sampled four or five volcanic units in the mare, and yet there are many times that [number], that have been actually identified in terms of remote sensing. So, we've hardly even scratched the surface of looking at the mare basalt units, let alone the highland units. We had only one true highland sample site—that was on Apollo 16—and the highlands make up 80% or more of the Moon's surface. We've seen nothing from the far side, nothing from the poles. Basically, we've just gotten started.

Q: Wasn't it the case that because the Apollo missions were manned, the landing sites had to be near the equator, and on the near side that faces the Earth?

Binder: Yes. The Apollo landing sites were dictated by the fact that there would be people on the surface. This meant that they had to be on the near side, to enable communications with Earth; they had to be near the equator, and all those things restricted our accessibility to the Moon. We've totally undersampled the Moon.

One of the things that I want to do is use unmanned vehicles to bring back samples from the Moon. There is a report called "Lunar Science from a Lunar Base," in which we called out about 100 different sampling sites, just to begin to understand the Moon. So, you can see the magnitude of what we're talking about. We've only had samples from the six Apollo sites, plus the three [Soviet] Luna sample sites. Nature has been kind to us and we have a half-dozen or more meteorites from the Moon, but the trouble is, we don't know where they're from. We have to do global sampling.

Q: What were some of the things we did learn about the Moon during Apollo?

Binder: During the Apollo era, we set up a seismic network of four stations, all very close together—about 1,000 kilometers apart—on the near side on the Moon.

We detected two basic types of moonquakes. One was the impacts from meteors, but we also found that there were very, very small moonquakes deep in the interior, between 1,000 and 1,400 km deep, which are caused by the tidal interactions between the Earth and the Moon. These are very weak. Their magnitude is zero to one-half on the Richter scale. You and I wouldn't even feel them, but they are there.

However, there are also true tectonic quakes which are occurring in the upper mantle and in the crust. The strongest one measured was on the order of 3 or 4 on the Richter scale. That's not too severe. These quakes are occurring now, and we see evidence from the high-resolution pan imagery of Apollo that there are fault scarps caused by these moonquakes.

One of the problems is that we only have seismic data from the Moon over about six years. In California, for example, there are a lot of earthquakes, but most of them are magnitude 3 or 4. Those which are destructive, magnitude 6 and 7, you get only every 30 or 40 years. We were not on the Moon long enough to know if there are significant seismic events.

On the Earth, the maximum magnitude that you can have is about 8.5 on the Richter scale, because the rocks simply will not stand more stress. They break at that magnitude. That's true when you're dealing with the quakes that occur around the edges of the tectonic plates, where the rocks are already fractured and relatively weak.

But the earthquake that occurred at the beginning of the last century in the Mississippi Valley was an interplate quake, and it is the biggest quake that has ever been measured. Of course, we didn't have seismic networks in those days, but seismologists can tell by the effects of the quake that it was much larger than the San Francisco quake. It was probably a 9 or so. When you're in the stable centers of tectonic plates, the rocks are stronger and it takes a lot more force to break them. These are interplate quakes, which do occur very infrequently, but are very disastrous.

The quakes we see on the Moon are similar in characteristic to the interplate quake. It is conceivable that you have enormous quakes on the Moon, not very frequently, but when they occur they are a very large magnitude. There are a lot of little ones for every big one. One other factor: Rocks on the Moon are a factor or two stronger than Earth rocks, because there is no water or air to weaken them. We could have very big quakes on the Moon. My guess is that you could have quakes that are easily magnitude 9 on the Moon, but that's wild extrapolation.

Moonquakes also last a good hour. Unlike an earthquake, which lasts a few minutes, because there's no air or water in the rocks which could dampen the energy quickly and dissipate it, the seismic vibrations on the Moon go on, and on, and on. You could imagine if these quakes do occur on the Moon, how devastating it would be if we had a base or colony on the Moon. Yet we do not know that seismic risk factor.

There's a lot to do on the Moon. Because of a lack of weathering and plate tectonics, we do have the earliest history of the Moon preserved in these rocks. This equivalent early history of the Earth has been totally wiped out.

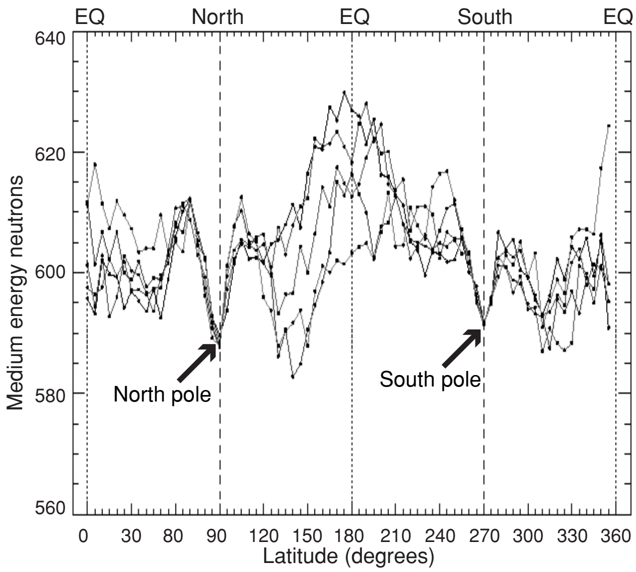
On Apollo missions 15, 16, and 17, science instruments were carried in the Service Module and we mapped the Moon through the gamma rays and X-rays and magnetometry—the same types of things that Lunar Prospector is doing. All these landing sites were in the near equatorial region, with the orbits of the Service and Command Modules in low-inclination orbits, so, at best, we mapped about 20% of the surface. But we need the global coverage, to begin to understand the global picture. Prospector began doing that. I picked five different mapping techniques and we've pretty much completed the mapping using those five techniques. There are still about seven orbital mapping techniques that I would like to do to get the complete picture, but Prospector started that.

Q: The one result from Lunar Prospector that has, without doubt, received the most attention, is that there is ice at both the North and South poles of the Moon, and that there is much more of it than previously believed. Why do you believe so strongly that there is ice at the poles, even though Prospector can only detect hydrogen and not water? Hasn't this extrapolation been questioned by others in the scientific community?

Binder: When we reported our first results from Lunar Prospector last spring, and announced that we had found excess hydrogen at the poles that we said was water ice, I was asked by reporters how sure we were, and how sure I was, that this is water ice. I said, "We're quite sure." The reporter asked, "Would you bet your house on it?" And I said, "Yes, I would." And I stand by that.

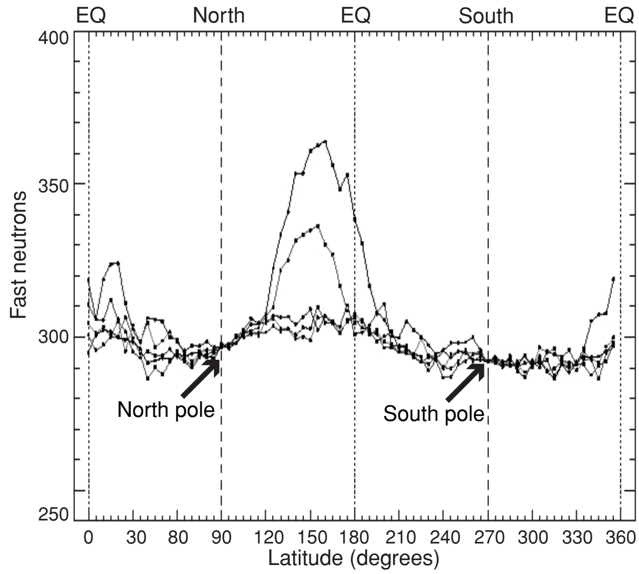
We are quite convinced that this is water ice. But there is

FIGURE 1
Water ice signature
(medium energy neutrons)



This graph of medium energy, or epithermal, neutrons, measured by Lunar Prospector's Neutron Spectrometer, clearly show two dips at the North and South Poles. Lunar soil with ice is better at moderating or slowing down these epithermal neutrons, which leads to these lower measurements. From this data, scientists estimate that there is 1-10 billion metric tons of ice in the lunar polar soil.

FIGURE 2
Ice below the lunar surface
(fast neutrons)



As can be seen from this graph, Lunar Prospector did not measure any dips in the incidence of high energy or fast neutrons at the Moon's poles. The Lunar Prospector team proposes that the ice is below the Moon's surface.

a difference between a scientific fact and a personal opinion. We don't have scientific fact right now; we have an extrapolation of our data, and even though we think we have very good arguments for it, it's simply not a fact.

The question has been raised by [geologist and Apollo astronaut] Harrison Schmitt, and others, "Is it something else?" Is the hydrogen that Lunar Prospector measures, solar-wind-implanted hydrogen?

What did we really find? Lunar Prospector maps hydrogen, not water. We know that there's an excess of hydrogen in the polar region, because we have sufficient resolution to observe it. The maximum amount of hydrogen is in the areas [at the poles] where there are permanently shadowed craters, so we are dealing with an area where the water is supposed to be.

We do know that the solar wind has deposited hydrogen in the regolith, or soil, of the Moon. If you take a typical sample brought back from the Apollo missions, you find on the order of 50 to 100 parts per million of hydrogen in the regolith. Our measurements are so sensitive that when we are done with this mission, we will be able to map the distribution of hydrogen in the regolith over the entire Moon at the 50-100 parts per million level.

What Harrison Schmitt is arguing is that the equilibrium value of 50-100 ppm, which is in equilibrium, because the solar wind continues to put more hydrogen in the soil but some of it is lost, would change at the poles; that the colder it is, the higher that level of equilibrium should be [so you would expect to find more hydrogen, but not necessarily ice]. Frankly, I've had people who are chemists, tell me that that's simply not the case, but that's not been in the literature and I can't verify it.

Bill Feldman [at Los Alamos Laboratory] and I have found that our data in the intermediate energy range, or the epithermal energy range, of the neutrons [measured by Lunar Prospector], clearly show that there's excess hydrogen there. But we should see the same dip in the fast neutron, or high-energy neutron flux [in the presence of hydrogen], and we do not [**Figures 1 and 2**]. The only way you can explain this is if the hydrogen we are seeing is buried under about 30-40 centimeters of soil. The fast neutrons only come from the outer 30-40 cm, so, if there were hydrogen of any abundance there, you would see a dip in the fast neutron flux when you went over the poles. The epithermal neutrons that we're seeing come from as deep as a meter. There is no significant enhancement of the hydrogen in the outer foot or so of the regolith. We see it at deeper levels.

Interestingly enough, scientists see the same thing in the radar observations of Mercury, which indicate that the water there is buried by about a foot or so of Mercury's soil. [But] we didn't know that, because that little fact is in one of the authors' Ph.D. thesis, and was never published. It also turns out that you can make radar observations, from the Earth, into the permanently shadowed polar regions of the Moon because of the libration. That is, the Moon tips back and forth, with respect to the Earth, by about plus or minus six degrees. Even though the Sun doesn't shine down in these craters, we can see partly into them from the Earth with radar. [But] those radar observations show no evidence of water. How do we explain that?

The difference between Mercury's soil and lunar soil is that Mercury's soil is very deficient in iron oxide, whereas the lunar soils are relatively rich. It turns out that radar doesn't penetrate very well in iron oxide-rich soil, so you're not looking very deeply into the lunar soils at radar wavelength, but you do look quite deeply into Mercury's soils with radar observations.

These three sets of observations—the Mercury observations, that indicate the ice is buried underneath a foot or so of soil; our observations, which say the neutron data indicate ice is buried a foot or so beneath the soil; and the fact that the Earth radar observations can't penetrate deeply enough in this relatively iron-rich lunar soil to get below this foot—indicate we're looking at ice deposits underneath the soil.

The solar wind that Harrison Schmitt is trying to use to explain the excess hydrogen that we're seeing, would be deposited in the upper part of the regolith. It would not be buried below the soil. So we're saying, if he were correct, then you should see the dip in the fast neutron flux the same way we see a dip in the epithermal neutron flux, and we don't. So we're quite convinced that we're dealing with water ice.

Q: Then you see the data from Lunar Prospector affirming the announcement made four years ago by the Clementine spacecraft team, of water ice at the poles?

Binder: Caution is required in evaluating the data from the Clementine spacecraft, which that team claimed was ice at the south pole. I don't want to be disparaging about their results, but I have to say what the rest of the scientific community thinks about those results. First of all, they made four different measurements attempting to look for water, two in the north and two in the south, and only once did they see a signal which they claimed was water. Ever since they put their results out, most of the scientific community has not given any credence to what they have reported. Stanford radio astronomers have taken those data that Clementine produced and did an independent analysis of it. They say flatly that what they are seeing is a typical noise pattern. In fact, they see the same noise pattern elsewhere [on the Moon], and I would tend to believe the professionals, rather than the Clementine guys.

Also, the Arecibo radar astronomy people have mapped the Moon with similar techniques, and they see anomalous results in the polar regions just about where the Clementine people see it, but they also see the same type of anomalous signals elsewhere on the Moon at lower latitudes, where there could be no water. Even if the Clementine results were real and not just noise that they interpret as a real signal, you see that same type of signal elsewhere on the Moon, where there could be no water, because it's far too hot. My personal opinion, not trying to belittle their work, is that I don't believe it. They were pushing very hard to make a very interesting observation. I think they deserve a lot of credit for that, but I don't think they have really done anything except create a lot of interest, which is good. I just don't put any credence in the Clementine results. I'd like to, because then I could say, "We see water, and Clementine did, too," but I don't think their results are reliable enough to say that we've confirmed what they say, or vice versa.

Q: But you are very confident about your results?

Binder: When discussing Lunar Prospector's results, we always make a statement of caution, which is that, clearly, remote sensing observations never completely, 100%, prove anything. They are strongly indicative of something, but you've got to go down to the surface and measure it. That's the next step: to go with a rover or other lander and make measurements by drilling down into the regolith a meter or so, getting samples, and seeing if this is truly water. While I may believe strongly that this is water, the proof is in the pudding, when we actually get *in situ* measurements. But we're still dealing with water as far as we're concerned. I still will bet my house on it.

Q: What more do you expect to learn when the spacecraft's orbit of the Moon is moved to a lower altitude?

Binder: After the primary mission for Lunar Prospector is completed in early 1999, we plan to lower its orbit to 25 km above the surface, on average. We will then be able to refine our data concerning the presence of lunar ice.

First of all, right now the footprint of the neutron spectrometer is 200 miles across. That is how much of the Moon is visible below that instrument while we're flying over an area. But our data show trapezoid-shaped areas with about 60 km resolution, so we are already able to pull out information at one-third the resolution that the data hypothetically should be showing us. When we go down to 25 km, we're going to be seeing detail on the 10-15 km scale. That will allow us to very carefully show where these hydrogen deposits are, and help us determine whether they are in the permanently shadowed regions or not.

Second, when we get closer to the surface of the Moon, we are going to have more sensitivity, and there are things we should begin to see if there is any hydrogen in the outer 40 cm. We should start to see a dip in the fast neutron flux. That will be key, because we'll have greater sensitivity to see whether or not we're seeing anything in the upper foot or so of the lunar regolith. If not, if we only see it in the epithermal flux, then that strengthens our case that this is really ice, and not solar-wind-deposited hydrogen. Even if we do see a little bit of a dip in the fast neutron flux, it should tell us that most of it is buried at a foot or so depth.

Q: One of the most puzzling questions that mankind has asked is: Where did the Moon come from? What do scientists think today? It seems that the "great impact" theory is now fashionable.

Binder: Over centuries, there have been many different theories about how the Moon formed, and where it came from. Like many other things, even in science, these theories have gone in and out of fashion. Science is like anything else. We're human beings; we believe certain things because we are convinced of them, and things are fashionable.

If you look at the history of the theories of the origin of the Moon, there have been times during various epochs of studying the Moon when it was thought that it was a captured body [from elsewhere in the Solar System], and everyone believed that because the evidence seemed to point that way. Earlier, it was the fission concept [that the Earth flung off material that became the Moon], because that seemed reasonable, so things do go in and out of fashion.

It is fashionable right now for everybody to believe in the giant impact model. I'll tell you where the impact theory came from. The Apollo data clearly showed that the material from which the Moon was made was genetically related to the mantle of the Earth, because the composition of Earth's mantle and the bulk composition of the Moon are almost identical. The isotopic ratios of things like oxygen and sulfur and silica are exactly the same for the lunar rocks as the rocks that come from the Earth's mantle. Those isotopic ratios are very definitive. If you look at the meteorites we have from Mars, the asteroids, and materials from comets, every kind of body has a distinctive isotopic ratio for these elements, and they're very, very different.

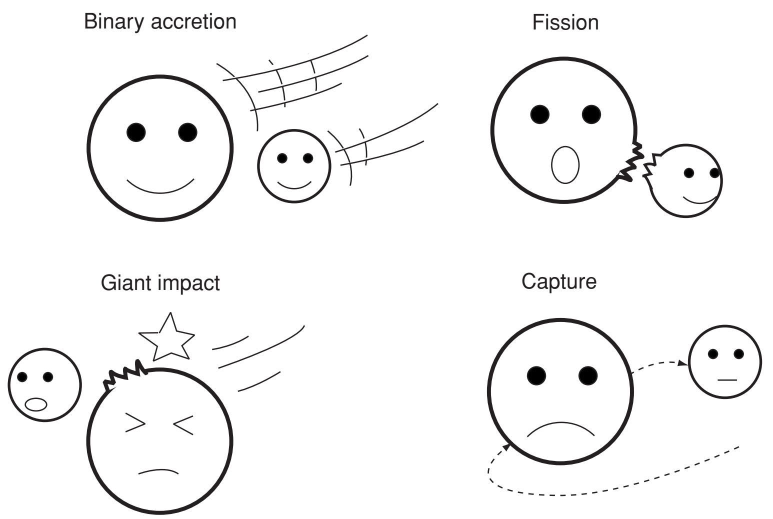
The big issue, in terms of trying to understand where the Moon came from, is the fact that the Earth has a giant core. Thirty percent of the Earth's mass is tied up in the iron core. On the Moon, the core is, at most, only a percent or two. So here you have two bodies with identical compositions in terms of their silicates, the mantle material, and yet the one has 30% iron and the other has, at best, a couple of percent iron. How do you explain that?

The compositional similarity tells us that the material that the Moon is made of came off the Earth, in one way or another. Proposing that the Moon formed after the core of the Earth had formed, is the simplest way to explain why the iron content and two cores are so different.

Way back in Charles Darwin's days, it was postulated that the Earth spun very rapidly [during its formation] and the Moon was flung off. Unfortunately, that process seems to be dynamically impossible. So colleagues of mine, started by Bill Hartman and Don David at the Lunar and Planetary Institute in Tucson, suggested that a Mars-sized body smacked into the Earth and splashed off the material the Moon was made from. The more that people have worked on that impact theory, though, the more improbable the dynamics become.

At first, it was a Mars-sized body that you required, and I find it difficult to believe that there were Mars-sized bodies careening around the Solar System in early history. But more to the point, [for the impact the-

Theories of where the Moon came from



This cartoon illustrates the theories that scientists have considered as to the origin of the Moon. The binary accretion theory proposes that the Earth and Moon formed from the same proto-planetary disc, at the same time. The giant impact theory holds that a large body crashed into the Earth, splashing out material that became the Moon. The fission theory is based on the idea that the Earth was spinning very quickly during its formation, and flung out material that formed the Moon. The capture theory proposes that the Moon was a small body from somewhere else in the Solar System, that was captured by the Earth's gravity.

ory to work], that body has now gotten twice as big as Mars: Every time they work through the dynamics, they find it has to be a bigger and bigger body.

Also, one of the arguments against the fission concept of the formation of the Moon from Darwin's time, was the fact that nobody could figure out, dynamically, how that could happen, that the Earth threw off what became the Moon. If you take the angular momentum of the Earth-Moon system today, it's far too small for the Earth and Moon to have spun up that fast. Angular momentum is conserved in a system, and if you take what the Earth-Moon system has today, it's only about 40% the angular momentum the Earth would have had if the Moon were flung off. But now, it turns out that if you had had this huge body crashing into the Earth, the same problem with angular momentum exists. You cannot explain the current angular momentum [and what] the system would have had at that time, with the big impact theory.

When you have a new model which seems to answer some of the questions, as you dig deeper and deeper, you unfortunately seem to find more inconsistencies. I, frankly, have no idea how the Moon was formed. I know that the material came from Earth, but how it got off the Earth, I don't know.

Lunar Prospector under construction, prepatory for launch at the NASA Ames Research Center in California.

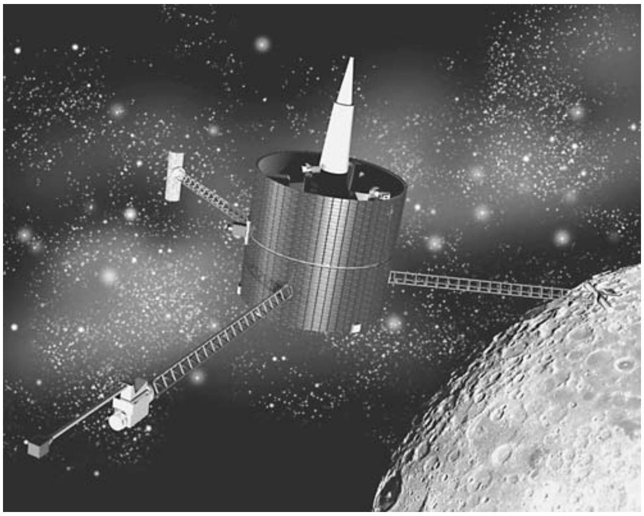
Q: Does the fact that Lunar Prospector has identified a small core in the Moon, narrow down the theories that could explain where the Moon came from?

Binder: Yes. One key to the origin and history of the Moon is this question of the core. There has been an argument made that if the Moon does have a core, then it did not come from the Earth's mantle [as the giant impact theory would require]. That argument is based on the following: There are elements which we call siderophile elements, which means iron-loving elements, like chromium, platinum, gold, and others, which like to go where iron goes. Wherever there are big chunks of iron, that's where you find the rest of these elements. You do find, when you pick up a piece of Earth rock, whether it's on the surface or a piece of the mantle, there is always a small amount of these siderophile elements in there. They are at the parts-per-billion level—tiny amounts. But they have very distinct distribution patterns, that is, the ratio of platinum to gold to chromium to iron is a very set pattern.

When the Earth's core formed, it took these siderophile elements out of the mantle, to a large degree, and concentrated them in the core, and left behind a very distinct pattern, in the parts-per-billion level. If the Moon formed from the Earth's mantle after the core had been formed [which would seem to be the case, since the Moon's core is so much smaller], then you would expect that the siderophile pattern in lunar rocks would be identical to terrestrial rocks; but, that's not the case.

We find that there was an apparent second differentiation of iron-loving elements in the Moon. That might be expected, because clearly the Moon formed when the Solar System was still being formed and things were evolving. And even if the Moon were flung off or was splashed off from the Earth, the formation of the Earth's core was probably not complete, and you would have a slightly different pattern in the terrestrial rocks than you would in the lunar rocks. When I say slightly different, we have measured that, and we know the differences between the two, and it says, you could only have 0.5% or 1% more iron collecting in the lunar core to cause these differences between the Earth and the Moon's siderophile patterns. If it turns out that our Lunar Prospector measurements, and the seismic measurements that will hopefully follow, show that the mass of the lunar core is 2 or 3%, then you'd get a very distinctly different pattern.

All that's fine and good, but it does depend upon many of your assumptions. It depends upon whether you assume that the little iron droplets were spread uniformly through the Moon and then collected in a core, or whether they were formed by the reduction of iron oxide. There are a lot of ifs, ands, and buts in all this. This is why things go in and out of



An artist's drawing of the Lunar Prospector in orbit about 60 miles above the surface of the Moon.

being popular. I'll guarantee you this right now: If it turns out that the lunar core is 2 or 3%, people will go back to their modelling and decide what parameters are sensitive and can change these results. You can work out theoretical models which would explain what we see in terms of the actual data.

Let me tell you a little story. Before it was recognized that these so-called SNC meteorites—meaning shergottites, nakhlites, and chassignites (named after the places where they fell on Earth)—were from Mars, the dynamicists, the people who study impact phenomena, had sworn that you could not blast meteors from the Moon or from Mars. They said that it was just dynamically impossible. So, when the SNC meteorites were first discussed as possibly being from Mars, the dynamicists said, "No, no, no, that's just impossible." A good friend and colleague of mine is one of those people, and he said, "You know, Alan, I just finished these calculations and there's one little bitty area in this diagram of pressure and force where you could possibly get the meteorites to come off Mars. But, I'm sure that I'll be able to show that that's really not the case, and that that one little possibility will go away."

About a month later, it was shown conclusively that the isotopic ratios in the noble gases that were trapped in the SNC meteorites were identical to the atmospheric measurements taken during the Viking Mars missions. The scientific community said, "My God. These things came from Mars." All of a sudden, that little bitty area on that one diagram that this theoretician was trying to get rid of, in order to show you couldn't get the meteorites off Mars, expanded. It became really easy to get these things off the planet.

In all of these calculations, you are bound by what you already know, and you are unbound by the things that you don't know. When we have more data, we will have to readdress these issues, and I'm sure that the size of the core, in terms of how big it could have been, had the Moon come from the Earth's material, will change as we work through these models. That's the history of science. I am always amused by scientists—and I poke fun at myself in this—that we tend to believe things so fervently with the data we have, that when new data come in, we say, "We were still right. Now we just have to adjust the model parameters!"

Q: It has been said that old scientific theories die only when old scientists die.

Binder: But, I have also found that some of the old theories, which were intuitive to the natural philosophers from 150 or 200 years ago when they didn't have a lot of data, those intuitive guesses are quite frequently right. They get unpopular because our understanding gets better, they get laughed off, but frequently, the basic concept was right, but not the details. So, I tend to look at the old ideas a little more carefully than I think most people do, because some things are kind of obvious.

Take the Moon as an example. The concept that the Moon came from the Earth was, as I said, started by Darwin a century and a half ago, and was quite popular because it explained the fact that there was no core, or significant core in the Moon, and it said that the density of the Earth's mantle was about the same as the Moon. That was nice, and everybody kind of believed it.

Then, this fell out of favor, and one of the ideas was that the Moon was captured. This was a nice way of explaining a lot of things about the Moon, so that was very popular. In fact, [planetary scientist] Harold Urey was pushing that idea very hard just before the Apollo era. One of the reasons this could be popular, was because we had no idea of the composition of the Moon, because we had no basis for making a measurement.

After we got the Apollo rocks (actually, it took us quite some time to decipher the information and understand it), all of a sudden, here was a Moon that had the same composition as the Earth's mantle. That just completely annihilated the capture model, because if the Moon had been formed elsewhere in the Solar System and captured by the Earth, its composition would be very different from that of the Earth, and here it was, almost identical. So, we went off capture models and core accretion models, and now we're right back with the general concept that the material came from the Earth somehow.

On the other hand, even though the capture model for the Moon had been repudiated by the Apollo results, we're very convinced that Phobos and Deimos at Mars were captured. When I was a student, the idea of bodies being captured was considered impossible. There was nobody who could explain the dynamics, so it was assumed the moons had to be formed when the planet was forming. Now everybody just believes, without question, that they were captured asteroids. Again, there are a lot of popular concepts. It's amusing to me how quickly scientists go from one to the other.

An example: During the early part of the Apollo program, the accepted concept was that the Moon had formed by accretion in one way or another and that only the outer couple of hundred kilometers were melted, and that this explains some of the early observations from the Apollo rocks. These observations actually were not correct but, nevertheless, this model was very deeply ingrained in lunar thinking by most of the community, so most people, if you ask them, will say, "The Moon was only molten on the outer few hundred kilometers." There are a few of us who have argued that that's not the case, that the Moon was totally molten in the very beginning. I believe there is solid evidence for that. Those of us who said the Moon was totally molten were shouted down.

One consequence of the adoption of the idea that the Moon was formed by a giant impact is that initially the Moon would have had to have been totally molten. Everybody now just accepts that without even thinking about all the reasons they thought it was not totally molten before. They don't even question it anymore. If, all of a sudden, somebody says this is what fashion is, there is a strong tendency to follow that.

Q: How can what we learn about the Moon help us understand the other bodies in the Solar System?

Binder: When we go to the Moon, we can study what the Earth was like in the earliest stages of development. Similarly, we will understand Mars and the other terrestrial planets better by understanding the Moon.

Each one of these missions adds a couple of pieces to the puzzle. I would wager that, 50 years from now, when I hope we've had a lot of exploration and have a colony up there, we'll probably find that most of the things we thought we knew from the Apollo era are probably not very accurate.

If you take the terrestrial planets, which include the Moon, which we consider a planet in this context, the Earth, Mercury, Venus, and Mars, and even the asteroids, each of these bodies, because each is a different size, has undergone a different degree of evolution. The Moon was frozen in its evolutionary track about 1 billion years ago. The asteroids were frozen even earlier, because they were smaller. Mercury was somewhat larger and probably has a little longer history of development. Mars is one-half covered with ancient craters and the other half is fairly highly evolved with volcanic plains and the big volcanoes. The Earth and Venus are very large planets and are still actively evolving.

Before we started exploring the planets, you had data on one planet, and it's a weird planet that we live on. It has a thick atmosphere, not as thick as Venus's, but nonetheless an important, thick atmosphere, which is modified *dramatically* by biological activity. We have a lot of water, which has made a big difference in the evolution of the Earth, and we have plate tectonics. You find none of these things on the rest of the planets. So, the Earth is a very atypical planet, and yet this is where we had to start from when we started exploring the Solar System. Every bit of knowledge that we gain about Mars, Mercury, the Moon, the asteroids, tells us more about how planets as a whole evolved.

Q: How does the Lunar Prospector mission move us closer to living on the Moon?

Binder: I believe very firmly that it is our destiny to go into space as a civilization, and that we will colonize the Moon, we will colonize Mars, and perhaps the planets, and that eventually we may even reach the stars. The research that I and others are doing is really opening up the Moon for human utilization. That's what I think is important.

You'll notice that we called this "Lunar Prospector." We did not call it "Lunar Explorer," or anything like that, because we wanted to make sure that the public knew that we were actually looking for resources, for things that can be useful to mankind. That is the significance of Prospector.

Everything we do on the Moon will be made easier if there is water there. When I was in Houston at the Johnson Space Center, working for Lockheed, I was involved, as I have been in a large part of my career, in doing planning on manned missions to Mars and the Moon. In those days, of course, ten years ago, we assumed that there was no water, because we had no reason to believe that there was water ice on the Moon. We knew how to build a lunar colony and a lunar base. It was very expensive without the water, but you could do it using the resources that are there.

Having water ice on the Moon makes it easier to do it, by a factor of 100. The water is an enabling fact. You've got water there for life support, you've got water there that you can make hydrogen and oxygen fuel out of, so it just makes it much easier and more feasible to do. It opens the door to lunar exploration and colonization and opens the door to the exploration and colonization of the rest of the Solar System, because the Moon becomes a fueling depot. Finding ice on the Moon is a tremendous operational discovery. It doesn't teach us much about the Moon, because the water that we're finding has been brought there mainly by comets. We may learn something about the history of cometary impacts, but the real thing is that this opens the door to have humanity live and work on the Moon.

I think that in the future, lunar exploration should be done commercially. I would say that Lunar Prospector is a total success from the standpoint of showing that this would be feasible. Yes, it's true we did not do it privately, but the purpose of Lunar Prospector was a demonstration. We didn't set out only to collect science data about the Moon, although that was our obvious objective.

Prospector was started by a large group of volunteers to show that you could do such a mission inexpensively, without a giant bureaucracy; that you could get good data at a very low cost; that it could be done commercially; and to create interest in lunar science again, and hopefully create interest in getting man to the Moon.

By "commercially," I mean that the spacecraft and instruments would be privately financed and then the data would be sold to the government, universities, the European Space Agency, or whoever wants to buy it. NASA's Discovery program is a "data buy" program. NASA pre-pays for the data, so it is still a NASA-supported program in that sense.

Those of us who want to do commercial lunar exploration are quite happy that NASA is not interested in the Moon, because it makes it easier for us to go ahead and do it commercially. The fact that they weren't interested meant that I could do this. We worked very hard for a number of years, as you're aware, to do this, but the fact that we got the job done, even though it was supported by NASA, allowed us to demonstrate you could do it cheaply with a private effort, using available technology. Now the world is really aware that there is a commercial viability to such missions.

There are a number of groups and individuals trying to do commercial lunar missions, including me and my institute. The public is now aware that you can do lunar missions so inexpensively that you could make a profit doing it. That was the real goal of Lunar Prospector. The Congress is passing legislation to encourage this. There are tax breaks for companies doing commercial space activities.

We are planning a workshop in March to verify the business plan that we are devising right now for a commercial lunar base. My institute, and a colleague of mine who works at Sandia National Laboratory, have been working on a document which we have in the second draft form, called "Design Concept of a Commercially Viable Lunar Base Architecture." I firmly believe that we will open the door commercially to a lunar base and the further exploration of the Moon, unmanned as well as manned, and that that will be the beginning of a lunar colony.

In the interim, we will continue to do unmanned exploratory missions, because we clearly need more information. We need to verify that there is water ice, because you do not want to set up a lunar base *assuming* that's water ice; you've got to *know* it's water ice. There is a lot to be done. Prospector was meant to show it *could* be done, and even though we had to get Federal funding, still, all the objectives that we had, we've reached.

NASA is very interested in Mars and, of course, Pathfinder and Sojourner got tremendous coverage. But NASA has done relatively little to promote Lunar Prospector, because they really don't care that much about what is going on, on the Moon. That's what I want to change with my institute.

As a scientist, I enjoy very much working on the origin and evolution of the Moon. But the real thing is, that the data we're getting are going to help us define how we build a lunar civilization.