18

Debriefing

1973–1984

SHUTDOWN

In December 1972 humans took their last steps on the Moon for the foreseeable future. Compressed within 17 years of 18 successful Soviet lunar spaceflights were 8 1/2 years of 23 American ones including 300 fleeting hours of human presence on the Moon. Then, to the puzzlement of our competitors in space, we decided we had done the job and could quit.

Apollo was a triumph of know-how, teamwork, economic vitality, and typically American big science and big technology that hip writer Norman Mailer, calling himself Aquarius, admiringly admitted was a "triumph of the squares."[1] The other side of the square American coin was expressed by Supreme Court Chief Justice Earl Warren when he said that Apollo was an "expedition of the mind, not of the heart." Americans traditionally have believed that everything must serve some practical purpose, and engineer-dominated NASA did not allow Apollo to stand on its own merits. They talked of spin-offs like the famous Teflon frying pans, electronic miniaturization, and military capability that could grow from the space program, but seldom of a bold and exhilarating adventure on a new frontier or of a scientific probe into the unknown. Except for a few highlights like Apollos 8, 11, and 13, NASA and the news media succeeded in the seemingly impossible task of making a flight to the Moon seem boring; this despite the spectacular scenery and color television during the J missions.

Americans have notoriously short memories and attention spans. Engineers similarly say, "If it works, it's obsolete." NASA built the greatest rockets and spacecraft in history and then scrapped them. NASA could not get Americans to the Moon today or five years from today. It gathered immense amounts of data and then literally threw them in the dumpster.[2] Lyndon Johnson was among those who knew that his countrymen are better at breaking new ground than in

caring for the ground they have already broken. In 1967 the Apollo 7 astronauts heard him say, "It's too bad, but the way the American people are, now that they have all this capability, instead of taking advantage of it, they'll probably just piss it all away."[3]

Ironically and tragically, it was Johnson more than any other individual who allowed this to happen. It had been he who pressed President Kennedy to adopt a manned lunar landing as a major national program, he who convinced James Webb to take the helm of Apollo, and he who kept the funds flowing in the early 1960s. But, right or wrong, he is also the person most closely identified with the seemingly endless and divisive Vietnam War which increasingly diverted his and his country's attention from space. Johnson gave both birth and death to Apollo. He died on 22 January 1973, broken in body and spirit. A month later, on 17 February 1973, the Manned Spacecraft Center was renamed Johnson Space Center (JSC). To save a little money, post-Apollo and post-Vietnam America ceded the once-in-a-lifetime opportunity to rendezvous with Halley's comet in 1986 to the USSR, the European Space Agency, and Japan. The space shuttle needed the money.

By these morose comments I am mourning for the ignominious end of our grand visions of cosmic exploration, but I do not mean to imply that I think Apollo itself should have been greatly extended. Based on what we know about the Moon, I think the originally proposed cutoff after Apollo 20 was justified; nine or ten landings would have skimmed the scientific cream in a cost-effective way. But by the same token the cutoff at Apollo 17 was not justified: a relatively small additional cost and short extension of the polished operational and hardware support would have paid off scientifically. The way site selection was heading, Apollos 18, 19, and 20 would probably have landed at Gassendi, Copernicus, Marius Hills, or, if the operational constraints were relaxed, Tycho. Today I would add a definitive point on the Nectaris basin to the list. Gassendi would have been a good choice for Apollo 17 or 18. We could have sampled the subsurface at Gassendi, Copernicus, or Tycho and could have dated the craters themselves, the rocks they penetrate, and nearby features. Although its age was probably learned at the distant Apollo 17 site, Tycho would have been an especially valuable geological, geochemical, and geophysical target because it lies so far from any other landing site. I am less sure that the Marius Hills would have been as valuable as many people thought in the late 1960s and early 1970s; the domes and cones are flooded by intermediate-age mare units, so they are not particularly young, and the compositional differences that created their relief may be minor. But we will probably never know. When 39 scientists, including Hal Masursky, complained in September 1970 about the cutoff of two Apollos to George P. Miller, the supportive chairman of the House Committee on Sci-

ence and Astronautics, who had been a key figure in starting Apollo on its way to the Moon, Miller replied, "Had your views on the Apollo program been as forcefully expressed to NASA and the Congress a year or more ago, this situation might have been prevented."[4] Few other scientists bothered to complain officially at all.

So the glass is half empty. But it is also half full. I do not fully agree with the many criticisms of Apollo as a scientific instrument. The astronauts got more Moon trips than they might have, and the geologists got far, far more science than they might have if the sky scientists or an earlier funding cutoff had ended Apollo before the J missions started, as was very nearly the case. And there would have been no science at all from Apollo if the Apollo systems had not worked.

We can see the scientific value of Apollo and its predecessors if we compare the state of ignorance recorded in chapter 1 with what has been learned since September 1959, when Luna 2 hit the Moon 115 km north of what later became the Apollo 15 landing site. After firing Luna 21 (Lunokhod 2) and two or three other post-Apollo Lunas at the Moon (appendix 1), the Soviets also rang down the curtain when Luna 24 touched down in Mare Crisium in August 1976 long enough to extract a 1.6-m core of regolith and bring it back to Earth.[5] There has not been a manned or unmanned scientific mission to the Moon since. Nevertheless, throughout the 1970s and 1980s the laboratory and photograph data banks have continued to give up their many secrets.[6]

THE VANISHING MYSTERIES

Pioneers like Ralph Baldwin, Gerard Kuiper, and Eugene Shoemaker were convinced that the maria were created by volcanic eruptions and the craters by the shock of impacts, but others like Harold Urey and most of his contemporaries in the 1950s and earliest 1960s ascribed either internal or impact origins to all lunar features. The all-important distinction between the volcanic maria and their containing impact basins did not become clear until photographs yielded evidence of a substantial time gap to the eyes of Baldwin, Kuiper, Hackman, Mason, Shoemaker, and Hartmann. The gap was finally proved conclusively even to nonbelievers when geochronologists found half-aeon differences between the mare rocks returned by Apollos 11 and 12 and between the mare basalts and Imbrium basin breccias returned by Apollo 15. Surveyors 5 and 6 in 1967 had already supported the majority opinion that the maria consist of basalt, and every sampling mission discovered variations in the basalts' composition. So the maria did not form all at once, and no mare filled its basin immediately after the basin was blasted out of the Moon's crust by a great impact. Obviously the Moon is not a primordial object but an evolved one.

The 83% of the Moon occupied by terrae was less accessible than the maria to the scrutiny of the individual researcher or simple space missions. Extensive sampling and teams of laboratory analysts were required to learn their age and composition. Basin ejecta has proved to be an important constituent (I think almost the only constituent) of the terrae. As Gene Shoemaker predicted in the early 1960s, the eagerly sought primitive lunar crust was not sampled in outcrop but only as small "pristine" fragments in the breccias, which have been recycled repeatedly from earlier ejecta blankets. The compositions known at the few terra sampling points (Apollos 14–17 and Luna 20) can be roughly extrapolated to the 10% of the surface covered by the X-ray spectrometers and the 22% covered by the gamma-ray spectrometers that were carried in orbit by Apollos 15 and 16. The laboratory and orbital data indicate a terra crust rich in plagioclase that floated to the top of a global magma ocean hundreds of kilometers deep early in the Moon's history. This primitive crust was subsequently intruded by mare-type basalts and by a magnesian suite of terra rocks found most abundantly in the Taurus-Littrow massifs. Rocks generally similar to the Moon's are known on Earth, but only a few small lunar fragments approach earthlike granites in composition. The mobile plates that create so many terrestrial rock types are unknown on the Moon.

Clamoring through the entire history of lunar investigations is the debate about how hot the Moon is and was. Most of the peculiar rilles, chain craters, domes, cones, pits, ridges, and other eye-catching objects I have been calling special features have proved to be either optical illusions or parts of impact basins and craters. The ones that do exist and that were formed by internal heat or stresses are in the maria. Sinuous rilles were formed by flowing lava, and low mare domes and Marius-type cones are true accumulations of volcanic rock. Otherwise, most mare special features are the products of passive processes, and not volcanism. As Ralph Baldwin long believed, arcuate rilles and the more numerous wrinkle ridges were formed when the slabs of maria sank a bit into their basins below their original level, stretching at the edges to form the rilles and squeezing elsewhere as folds and thrust faults. Tracking of Lunar Orbiters in 1967 showed us that the maria sink because, once lavas solidify, they form mascons denser than the terra rock.

The many features of craters long thought to be internally generated succumbed one by one during and after the age of lunar exploration. We know from terrestrial craters and experiments that the central peaks that characterize craters about 20–150 km across were formed by violent rebounds in response to the shock of impact. That secondary impacts, and not gas eruptions, created the bright crater rays was realized by the best telescopic observers, confirmed by Ranger 7 in 1964, and documented in precise detail by Lunar Orbiter photos

and laboratory simulations. The twin raised-floor craters Sabine and Ritter were thought to be calderas even by impact advocates until mapping and theory showed that all craters inside basins suffer enhanced isostatic uplift,[7] and spaceflights showed that impacts of twin projectiles have been common on all planets. Small rille-related dark-halo craters like those in Alphonsus are still believed to be maarlike volcanoes, but detailed photos show that most dark halos around circular craters consist of basaltic debris quarried by impacts from beneath a light-colored surficial layer. There may be a few calderas on the Moon, but they are very few and relatively small, and the old hybrid idea has been discarded except in the sense that the mare fillings of impact craters are volcanic. Impact specialist Dick Pike suggested that even the craters of the conspicuous Hyginus Rille chain formed by collapse unaccompanied by any eruptions.[8]

The "hybrid" feature of craters that had the longest life, surviving Apollo by a few years, was the smooth pools superposed on the floors and rims of craters. Tycho and Copernicus are notable examples, but even small craters have them. Gene Shoemaker had thought the pools were impact melts even at the time of Surveyor 7 in January 1968, and in the 1970s the smooth-working Menlo Park team of Keith Howard and Howard Wilshire (a team we called H^2, Howard squared) thoroughly analyzed the geologic relations of the pools in Tycho, Copernicus, the far-side 77-km crater King, and other craters viewed by Lunar Orbiter and Apollo. Their verdict, which to me seems unassailable, is that the pools consist of rock made liquid by the impacts that formed the craters themselves.[9] So ends, I believe, the old debate about the great variety of landforms that the old selenologists classified into fine categories.

The hot-cold controversy was attacked directly by the Apollo 15 and 17 heat-flow probes, which, after earlier higher estimates, suggested a moderate amount of internal heat. The minuscule internal moonquakes, whose annual energy would not be noticed on Earth even if all released in one instant, also indicate the near absence of internal activity today. However, the Moon was probably completely molten when it formed, continued for perhaps 150 to 250 million years to support the magma ocean, and remained locally hot enough and internally active enough to generate the visible maria for at least three more aeons.

But the basalts of the maria constitute less than 1% of the volume of the Moon's crust, which itself constitutes about 10 to 14% of the Moon's volume. (The rest is either a crudely layered mantle or a mantle plus a small core.)[10] Mare-type basalt clasts not derived from the present maria are also found in terra impact breccias, indicating the past existence of now-disintegrated maria or basalt intrusions.[11] For example, John Shervais, who as a student worked the night shift in Astrogeology at Menlo Park and is now on the faculty of the Univer-

sity of South Carolina, has found fragments of 4.3-aeon-old mare basalt in the largest sample from Cone crater (14321); it was probably once part of the Fra Mauro Formation. A few grains collected by Apollo 15 from the Apennine Bench Formation may also be volcanic. Otherwise, the volcanic terrae were almost completely put to rest by Apollo 16 in April 1972 except in the minds of some geochemists who still believe certain samples represent a "highland basalt." No terra landforms of volcanic origin are known. This major controversy almost surely would still be raging if Apollo 16 had not landed at the Descartes Highlands. Even if some light-toned plains someday prove to be volcanic, volcanism can never assume the major role in formation of the Moon's features that many investigators once thought it had. Cosmic impact rules the Moon.

The minor volcanism explained the paradox that bothered Harold Urey: How can volcanic maria exist on a Moon cold enough to support mountains and mascons? The maria are conspicuous only because their small volume is spread out in thin sheets in preexisting depressions, namely, the terra impact basins. So the Moon is cold or cool and was never very hot except early in its history. Whatever the real or psychological cause of transient phenomena, it is not volcanism.

The laser altimeters carried by Apollos 15 and 16 have shown that the earthward bulge that seemed to emerge from the astronomers' careful measurements is probably not a bulge in the shape of the Moon, as it was conceived in the 1950s and 1960s, but rather is an offset toward Earth of the center of mass away from the center of figure; that is, the geometric bulge is actually on the far side. Current interpretations, which are dependent on many assumptions, place the average lunar crustal thickness at between 60 and 86 km, with below-average thicknesses in the Imbrium-Procellarum region and above-average thicknesses at the Apollo 16 landing site and on the far side. The thinner near-side crust is the reason the maria are more extensive there. I think the major near-side–far-side differences, including the concentration of the maria on the near side, are caused by the indentation of the near side by the giant basin that Peter Cadogan called Gargantuan and Ewen Whitaker and I call Procellarum. The Imbrium impact pierced this already weakened part of the crust, something that did not chance to happen within the giant 2,500-km South Pole–Aitken basin on the far side. The additive penetration is the cause of the concentration of the deep-seated material KREEP in the Imbrium-Procellarum region. The lavas in the old Procellarum basin are also probably the source of John Shervais's basalt fragments, because that is where the Imbrium projectile that created the Fra Mauro Formation hit.

Dating of the samples has established the ages of enough key stratigraphic units to outline the main episodes of lunar and Solar System history (see appen-

dix 4). The oldest dated impact basin is Nectaris, tentatively 3.92 aeons, followed by Serenitatis at about 3.87 aeons and Imbrium basin at about 3.84 aeons. Better but also overlapping mare ages of 3.84–3.57 aeons were obtained for Mare Tranquillitatis at the Apollo 11 landing site, 3.72 aeons for the edge of Mare Serenitatis at the Apollo 17 site, and 3.64 aeons for the dark Apollo 17 blanket. The Soviets added 3.40 aeons for Mare Fecunditatis at the Luna 16 landing site and 3.30 aeons for Mare Crisium at Luna 24. Basalts and pyroclastics at the Apollo 15 landing site in Palus Putredinis were formed 3.30–3.26 aeons ago, and basalts in Mare Insularum under Surveyor 3 and Apollo 12's LM cap the record at 3.16 aeons. Then there is an unfortunate gap of 2.3 aeons until the tentatively dated Copernicus ray at 0.8 aeon (Earth's Precambrian), and the well-dated (I believe) Tycho ray at 0.11 aeon, or 109 million years. Extrapolating these absolute ages by means of crater counts and crater morphologies, we have learned that maria continued to form on the Moon until almost the time of the Copernicus impact. Missing is knowledge of how much mare basalt formed between about 3.2 aeons and 1 aeon. And badly lacking is knowledge of the ages, and therefore rates, of pre-Imbrian basin impacts and volcanism. But we can say in general that the Moon was severely, though possibly episodically, struck until about 3.8 aeons ago, then settled down for a quiet retirement while the Earth was undergoing constant turmoil. Most of the lunar face that we see today is profoundly old.

The strange optical properties of the lunar surface and the full moon have been pretty well explained. Albedo depends mainly on the quantity and composition of glass-bound *agglutinates* that are created by incessant small impacts in regoliths. The agglutinates get their darkness and color from the iron and titanium in the rock from which they formed.[12] For the maria, therefore, the dark = young equation proposed in the 1960s is wrong; or, rather, it is wrong that half of the time when the older mare units happen to be rich in iron and titanium, as they are along the southern border of Mare Serenitatis. The terrae are relatively bright mainly because they contain less iron and titanium than the maria, but also because fresh nonglassy material tends to be exposed on their slopes. Rays and steep slopes of young craters are especially bright because they expose so much of this fresh material. So the bright = young equation for craters and the terrae is still valid if all else is equal. The porous "fairy castle" structure that makes the limbs of the full moon as bright as the center is not obvious on the lunar surface, but Gold's closeup stereoscopic camera suggested that it is a loose packing of very fine soil particles that is destroyed by sampling.

The sharp albedo and color boundaries in the maria that Shaler noted a century ago have been preserved since the visible maria formed because the impact rate has been too low to distribute large amounts of material laterally, as

Gerard Kuiper realized in the Ranger epoch. In fact, topographic detail formed anywhere on the Moon after the Orientale impact 3.8 aeons ago has retained most of its original sharpness as seen at coarse scales. Erosion has occurred, however, and small amounts of material have been distributed laterally at every point on the Moon. The impact rate before maria began to be preserved 3.8 aeons ago was too great for distinct color or albedo boundaries or topographic sharpness to be preserved in the terrae.

Although I believe that small secondary craters were well understood after the end of the Lunar Orbiter missions in 1967, large clusters of larger craters were not. At the Santa Cruz conference in 1967, for example, a densely cratered area in the southern hemisphere near the craters Maurolycus and Barocius was proposed as a landing site because of its supposedly volcanic craters and pre-Imbrian "pitted" volcanic plains. After the secondary-impact origin of the large clusters and these "pits" was recognized in the 1970s, the distributional patterns of the large circumbasin crater clusters and chains made sense, and they could be geologically mapped at small scales. Because they contact so many other features, they enable the relative ages of lunar features to be determined over vast expanses. If we had only known how dominant basins are in lunar geology, we could have constructed fewer, smaller-scale, and simpler maps than we thought necessary at the special feature–ridden beginning of the lunar Space Age. Large-scale, detailed maps were needed only for surface exploration by the astronauts. We learned this lesson after we exploited the rich record of the Orientale basin provided by the indispensable Lunar Orbiter 4.

The physicists who study magnetism have been good customers of geology because the puzzling lunar magnetism seems to have something to do with impacts. Kinsey Anderson of the University of California's Space Sciences Laboratory and Lonnie Hood of UCLA and LPL have correlated readings from the Apollo 15 and 16 subsatellites with basins and, interestingly, their antipodes.[13] My mapping of basins was also picked up by Keith Runcorn of the University of Newcastle-upon-Tyne, whose research on paleomagnetism led him to propose in the 1950s that Earth's poles had "wandered" relative to the continents. He has detected a similar change in the orientation of the Moon's rotational axis from the concentration of basins of different ages along different great circles. Although the Moon has no mobile plates, Runcorn tenaciously insists that it has been knocked into new orientations by the basin-scale impacts.

Some remaining puzzles about craters and ringed basins have been cleared up by continued study of lunar photographs, in the laboratory, in the field, by the nuclear explosions at the Nevada Test Site, and by the large chemical explosions at Suffield, Alberta, and elsewhere. In September 1976 Dave Roddy convened a productive conference in Flagstaff that united the Moon-impact and

"bomb" communities for an exchange of views that resulted in a thick volume we call the Blue Bible.[14]

The origin of basin rings at the large end of the impact series, however, is still unclear. To cut a very long story short, I will mention only my favorite model, based on one by Ralph Baldwin and developed in parallel by John Murray.[15] I think a basin-size impact liquefies the lunar crust and sets it in motion like toothpaste or water, causing it to oscillate while material is being ejected. Ejection is lateral at first, then more nearly vertical. The excavated zone freezes from the outside in on a time scale of minutes. A ring is left at each stillstand. The processes explain both the regularities and the irregularities in basin interior structure. Basin ring formation and ejection are far more complex than the analogous processes in craters.

I think that to a first approximation we can summarize the geologic style of the Moon very simply. Primary and secondary impacts, helped by a little lava and minor faulting, have created almost the entire range of lunar landforms. The cosmic impact catastrophes have alternated with gentle volcanic extrusions and an occasional fire fountain originating deep in the Moon's interior. Horizontal plate motions like those of Earth are unknown on the Moon. Vertical motions are more important, but only in the settling of the mare mascons and in the rise of crater floors that are not loaded with mare basalt. The Moon's face has been molded by the rise of basaltic magmas into receptacles dug in plagioclase-rich terra material by impacts. The Moon is neither cosmic exotica nor a little Earth.

THE EXPLORATION STRATEGY

I think this summary shows that we have learned much about the Moon that we wanted to know. Evidently the strategy with which NASA explored it worked. Nevertheless, criticisms of that strategy have not ceased, particularly with regard to the value of manned versus unmanned missions. I add my assessment with the benefit of hindsight and with a look toward future exploration of the Moon and Mars.

The progression from telescopic study to Rangers and then to overlapping Surveyors and Lunar Orbiters was appropriate, even though the successful Rangers and Surveyors came along later than had been hoped and planned. The control exercised by the Apollo program over the unmanned projects actually worked in the favor of geologists (though not of physicists) because it favored photography over instrumental measurements. I think the strategy for selecting the early Apollo landing sites first from telescopic terrain studies and then from Orbiter 1, 2, and 3 photos also worked well except for details like the expenditure of too many Orbiter frames on Sinus Medii and the choice of the Apollo 12

site. The decisions to lower the orbit of Lunar Orbiter 1 and not to fly the sixth Lunar Orbiter were painful from our viewpoint but were made by reasonable and competent people for reasons they considered good. Similarly, a point landing at the time of Apollo 12 was also necessary for NASA because of the overshoot by Apollo 11, although Apollo 12 could have landed at the Surveyor 1 site if the backup requirement had been discarded a little sooner. But if a few of the NASA scientific personnel wore black hats, the engineers who planned and executed the missions definitely were white-hatted all the way in my opinion. They were magnificent.

The success of the Surveyor television experiment, alpha-scatterer, and soil instruments suggests that the original plan for Surveyors as complete scientific exploration tools would have returned some of the information that Apollo ended up getting. However, the return to Earth of physical samples, including some rocks, was imperative. Absolute ages can be measured only in a well-equipped and ultraclean laboratory. Dating a history-rich breccia sample is difficult enough at best, for its "age" may mean anything from the time its elements assembled from the original Solar System cloud, through the time it crystallized from magmas, to the times it was shocked by any number of impacts—including the ones that put it where the astronauts found it. Even in the maria, samples large enough to contain more than one mineral formed in a magma at the same time are necessary in dating to avoid dependency on assumptions about original isotopic ratios; if we had only the Apollo 11 soil, the geochemists might still think Mare Tranquillitatis is as old as the Moon.[16] Although very valuable in light of the Apollo experience, the regolith core samples returned by the Soviet Lunas might well have been similarly misinterpreted if the astronauts had not brought back rock-sized samples from a known geologic context.

Inevitably, Apollo was limited in its range as well as weight and lunar stay time. A higher percentage of pristine, or at least very old, samples would presumably have been acquired if Apollo and Luna could have landed outside the belt of Imbrian and Nectarian basins that happen to fill their near-equatorial zones of accessibility. Future missions to the far southern highlands or the far side are needed.

So, was Apollo worth its cost of a little more than $25 billion in 1960s money (about $80 billion in 1990 money), and were human crews needed to explore the Moon scientifically? I think my opinion has become clear: hell yes, it was worth it, and to pass up the opportunity to land people on the Moon when the once-in-a-lifetime opportunity arose would have been unconscionable. Those who say the money would have been better spent on social problems are unrealistic. Either it would not have been spent at all or it would gone to "defense" or to the pork barrel. The Vietnam War cost about seven times more than Apollo.[17]

Were the scientific data we obtained worth $25 billion? Not that much, no, but they were worth plenty, and anyway, science was not the primary reason for undertaking the grand human adventure. I have no patience with those who say it all could have been done more cheaply by robotic means. Some of it could have, some not, but so what?

The adventure was grand from the geologists' viewpoint, too. The astronauts, especially the crews of Apollo 11 and the J missions, performed superbly as field geologists. The geology support teams reconstructed the fieldwork beautifully. Planning during the 1960s was also right on the mark, and one can only regret the deletion of the automatic range finder in light of the unfortunate experience of Apollo 14 and also later missions. The Apollo 14 MET suggested by Shepard and Mitchell did not work well, but the J missions' LRV worked very well indeed. The orbital experiments were useful though limited by the narrow ground tracks into which they were forced. The seismic experiments, at least, were vital inclusions on the ALSEP. But here NASA's latter-day parsimony and shortsightedness intrudes. To save some $200,000 a year, reception from the five still-functioning ALSEPs was terminated on 30 September 1977,[18] the end of the fiscal year, even though we still know the thickness of the lunar crust in only a few regions. Large meteorites undoubtedly have struck the Moon since then and gone undetected and unexploited.

TIME'S FLIGHT

Ralph Baldwin did not participate in any spaceflight mission and appeared physically at few scientific meetings during the lunar Space Age. I did not meet him until 1984, but since then we have kept in touch. At the end of February 1991 he finally resigned from the family business in Michigan, and he spends the winters in Florida. He is renewing his acquaintance with the golf course but is as intensely devoted to science as ever, and continues to write papers about such longtime interests as the cratering rate and the isostatic response of the lunar crust. Wearing his industrial hat, he has also written numerous articles complaining about the ambulance-chasing lawyers who bring capricious product-liability suits against American manufacturers and thereby weaken our international competitiveness.

Carolyn Shoemaker has given up trying to get her husband to do anything except science and is now his active partner in discovering asteroids and comets at Mount Palomar and mapping craters in the Australian outback, both interests stemming from the late 1950s. Gene concluded in the 1960s that these and the postmare craters of the Moon were formed, and still can form, by impacts of objects that intrude on the Earth-Moon system. He told me that the resumption

of this work was inspired by losing a bet to Gerry Wasserburg about the age of the Apollo 11 mare. Like Baldwin, he agrees enthusiastically with the late physicist Luis Alvarez and his geologist son, Walter, that one or more of these intruders hit the Earth 65 million years ago and threw up such a cloud of dust and smoke that photosynthesis dropped precipitously and the dinosaurs died—a beautiful example of an important scientific spin-off from lunar investigations.[19] The danger of another strike is very real; Gene enlisted Henry Holt in the search at Mount Palomar, and in March 1989 Henry found an object called 1989 FC that missed the Earth by only twice the distance to the Moon. Gene has been well recognized for his contributions[20] and has now reached the enviable position of living where he wants (in a beautiful house in the woods near Flagstaff) and doing what he wants, when he wants, with only himself as boss. He deserves it. The science of lunar geology and I personally owe everything to this giant in the history of modern science.

Dai Arthur had a falling out with Kuiper in 1967 and transferred to the USGS in Flagstaff, where he continued selenographic and also "aerographic" (Mars) work until his retirement in February 1982. He now lives in central Arizona. Ewen Whitaker retired in 1989 and still lives in Tucson. Bob Strom is still at the Lunar and Planetary Laboratory and has specialized in the moonlike planet Mercury ever since his participation on the Mariner 10 imaging team along with Mert Davies, Don Gault, Newell Trask, and team leader Bruce Murray, to mention only the geoscientists. Kuiper was on the team, too, but he died in Mexico City on Christmas Eve 1973, shortly after his sixty-eighth birthday, while Mariner 10 was on its way to Venus. He had not been active in lunar studies for several years and was searching for new observatory sites when he died.

Harold Urey lived well past the age of lunar exploration that he did so much to initiate. He died in January 1981 at the age of 87. He saw his concept of the Moon confirmed in part (impact is indeed the major lunar process) and refuted in part (the Moon formed hot and was volcanically active for at least three aeons). He accepted both outcomes with equal grace, a "simple country boy from Indiana" who was one of the great gentlemen in the Moon business. Let us remember him with particular fondness and admiration.

Four Surveyor and six Apollo landings established the strength, thickness, block content, impact origin, and paucity of meteoritic material in the Moon's regolith. There is fine pulverized soil, but it is weak only for a few centimeters of its thickness. Yet Thomas Gold is still fighting the battle. Still believing radar more than geological sampling and evidently unaware of Apollo 15's sampling at Station 9A, he wrote in 1977 that "there has been no suggestion that any lava flow has been sampled"; and "the [radar] evidence does not fit the lava flows, but most investigators will not believe the large-scale migration of powder. This

is the impasse at which we are at the end of the Apollo programme."[21] Nevertheless, he has told some of his astronomer colleagues that he never said there would be deep dust.[22]

Gold is not the only tireless pursuer of the exotic. For example, readers may be more familiar with the "face" and the "pyramids" of Mars than with any real features of that fascinating planet. I do not want to put Jack Hartung in the category of Gold or the perpetrators of the "face" fraud, but Hartung's fanciful yarn that monks sitting in front of Canterbury Cathedral on a fine June night in 1178 A.D. witnessed the formation of the crater Giordano Bruno has received far more publicity than its immediate, firm, and definitive debunking. The late Harvey Nininger and a colleague showed that what the monks saw was the trail of a fireball in Earth's atmosphere.[23]

In 1972 Ray Batson and the USGS took over ACIC's function of constructing lunar and planetary maps and also retained the services of Pat Bridges and her colleague Jay Inge. They and others they have taught are still creating maps of the finest quality for whatever new planet or satellite comes within range of spacecraft cameras.[24] Made with the old-fashioned qualitative methods of visual observations and airbrushing, these maps are better than any that could have been made by photographic or automated means alone. Ray's team has produced some 600 maps of 22 planets and satellites. However, in the onrushing age of high technology and low individual skills, the successors of these airbrush artists will have to be machines.[25]

Don Gault, Ed Chao, and John O'Keefe still believe tektites come from the Moon. Don retired from Ames in October 1976 to found and constitute the Murphys Center of Planetology near the California gold country town of Murphys. After 17 years at Astrogeology and 18 months at NASA, Chao transferred in October 1977 to coal studies. O'Keefe, who is still at Goddard, realizes that tektites do not come from the Moon's surface — the Surveyor, Apollo, and Luna data disproved that origin — so he calls instead on the pre-Nininger idea that volcanoes ejected them from the Moon's interior.[26] Almost everybody else, however, has accepted terrestrial origins. To my satisfaction, the aerodynamic shapes that characterize tektites have been shown to be caused by reentry into Earth's atmosphere after being thrown to great altitudes by impacts on Earth. For example, the Ries impact created the Czech tektites called moldavites that were known and dated long before their connection to the Ries was known.

Jack Green has been teaching at California State University, Long Beach, since 1970 and still believes that over 95% of lunar surface features are volcanic.[27] In 1975 O'Keefe established a working group to revive and redebate the impact-volcanism controversy for crater origins, intending to present their discussion to the 1976 IAU meeting. Responses varied from wild enthusiasm

(Green) to annoyance that the issue was even being raised (Baldwin and most of the rest of the lunar community).

Creative but slow-producing Dick Eggleton eventually annoyed Branch Chief Mike Carr and our NASA contract monitors to the point of getting himself transferred to a nonastrogeologic position in Denver in 1975, from which he retired in August 1986. For years after he left the Survey, Chuck Marshall would periodically appear in Menlo Park asking if we had a job for him, hoping desperately that we did not. He now lives in a suburb east of San Francisco Bay.

Tom Young's competence has not gone unnoticed. During the Lunar Orbiter missions that he helped run so well, he had the same lowly civil service rating as the rest of us did. After Orbiter he moved over to the Viking Mars project, ending as mission director. Then he became director of lunar and planetary programs at NASA Headquarters (1976–1979), deputy director of the NASA Ames Research Center (1979–1980), and director of the Goddard Space Flight Center (1980–1982). He would have made a good NASA Administrator, but in 1982 he went over to private industry; namely, the Martin Marietta Corporation, the prime contractor for the Viking lander. Tom characteristically ascended Martin's ladder to become its president and chief operating officer.

After Bellcomm shut down in April 1972, Farouk El-Baz went on to found, organize, and direct the Center for Earth and Planetary Studies in the National Air and Space Museum of the Smithsonian Institution (1973–1982), then to become vice president of Itek Corporation in Lexington, Massachusetts (1982–1985). A serious heart attack in 1985 made him seek a less stressful job, and he is now "only" director of the Center for Remote Sensing at Boston University.

Noel Hinners climbed steadily up the NASA ladder after leaving Bellcomm in 1972, starting as deputy director and chief scientist of lunar programs and then becoming associate administrator for space science (1974–1979). He next directed the Smithsonian's Air and Space Museum (1979–1982), then, when Tom Young moved on, the Goddard Space Flight Center (1982–1987). In 1987 Noel took on NASA Headquarters' third-highest position, Homer Newell's old job of associate deputy administrator and chief scientist. He retired from NASA in May 1989 and is now a Martin Marietta vice president.

The SPE Branch was dissolved officially in November 1973 after a lifetime of six years and a lingering death, having outlived its function of supporting astronaut training and mission operations. The branches recombined under the 1967 name Branch of Astrogeologic Studies and not the original Astrogeology because too much paperwork would be needed to make the name change on everyone's records. Al Chidester retired in January 1985 after 42 years in the USGS and died in August of the same year from complications following heart surgery, as did his old nemesis, Arnold Brokaw, in August 1990.

The Reaper has spared the geology field team members, except Dale Jackson and Bob Sutton, though an aneurysm in 1974 almost took Gordon Swann's life. Outwardly, Gordon recovered fully, but he never again showed the high level of energy that served the Apollo fieldwork so well. In December 1975 he married Jody Loman, who had been secretary to Gene Shoemaker in Flagstaff and to the geology team in Houston. Gordon has retired, but Jody Swann now runs the Lunar and Planetary Data Facility in Flagstaff. Bill Muehlberger is still teaching at the University of Texas. Lee Silver is energetically pursuing his laboratory work and teaching at Caltech, but is cutting back on the number of doctoral students he supervises with the aim of future retirement (we shall see).

After leaving Astrogeology in 1975 and Flagstaff in 1984, George Ulrich literally immersed himself in geology. While studying active lava flows in Hawaii in June 1985 he broke through a solid crust and sank into molten lava above his knees. Although the experience was not pleasant, he recovered, and moved first back to Flagstaff and then to the USGS headquarters in Reston, Virginia. George retired in December 1990, but Ed Chao, Robin Brett, Dan Milton, Terry Offield, Howard Pohn, Larry Rowan, Jack Salisbury, and Newell Trask were still in Reston as of that date, in a building with a floorplan so delightfully confusing as to lose the most experienced field or mining geologist. Tim Hait is a consulting geologist in Arizona. Ed Wolfe had a distinguished career at the Hawaiian Volcanic Observatory that included preparation of a new geologic map of Hawaii. Since April 1989 he has been scientist in charge of the Cascades Volcanic Observatory that keeps watch over Mount St. Helens and other potential eruption sites.

A stalwart group of five branch chiefs led Astrogeology and Astrogeologic Studies during the heyday of lunar and planetary exploration: Gene Shoemaker (1961–1966), Hal Masursky (1967–1970), Jack McCauley (1970–1974), Mike Carr (1974–1979), and Larry Soderblom (1979–1983). Each had a different approach and each was right for his time, though each eventually burned out and passed the baton to his successor. Gerry Schaber, the last surviving geologist of the SPE Branch still on duty in Astrogeology in Flagstaff, took over from Larry in early 1983, and in late 1986 gave way to the versatile geoscientist and instrumentalist Hugh Kieffer. In October 1990 the relentless procession of the generations brought Phil Davis, part of about the fourth or fifth wave of hires, to the chief's office as he turned 40. Older astrogeologists Baerbel Lucchitta, Dave Roddy, and Dave Scott are also still plying their trade in Flagstaff.

Until August 1990 Paul Spudis was among them, but he left for a nine-month stint at NASA Headquarters, followed by a move to the Lunar and Planetary Institute. LPI, recently moved to new quarters, has found plenty of missions to justify its existence. It serves as a repository and clearinghouse for lunar and

planetary information. It organizes scientific conferences in its own buildings and elsewhere, and publishes the results and also other works. It hosts and does the grunt work for NASA panels that review proposals for research and sample analysis.

In 1976 Chief Geologist Dick Sheldon and Environmental Geology Office Chief Jack Reed commissioned a USGS professional paper (actually a large book) summarizing lunar geology from the Survey's slant, earmarking for the task the only large sum of money the USGS ever gave Astrogeology. Howard Wilshire was to be the editor, and the rest of us were to contribute sections appropriate to our competence. But Howie, who was among the many astrogeologists who performed their lunar duties with a longing eye cast toward the outdoors of Earth, became passionately involved in a fight against off-road vehicles. I took over more and more of the job and eventually ended up as the sole author except for sections by Jack McCauley and Newell Trask.[28] The book is built around my main contribution to lunar science, the Moon's stratigraphy. Like Kuiper, I devoted much attention to artistic matters like appearance and layout of figures. Jack McCauley and I took early retirement from the USGS in August 1986, the same month as Dick Eggleton, Gordon Swann, and Henry Holt, to gain our freedom from regular office hours and writing proposals to beg NASA for money. Maybe these restrictions are necessary, but to hell with them.

Mike Carr is still furiously plunging into new scientific and mission-planning challenges in Astrogeology's recently (January 1989) relocated and shrunken office in Menlo Park, which he shares with only two other survivors of the once-flourishing Astrogeology presence, old Henry Moore and young Gary Clow. Dick Pike is in a nearby office on the same floor, but he left Astrogeology in 1986 to concentrate on his old interest, terrain studies. I spent much postretirement time between January and July 1989 disbursing the formerly enormous collection of lunar photographs, maps, and data to other repositories, mainly the Flagstaff office of Astrogeology, Brown University, the University of Hawaii, the University of Western Ontario, and Chabot Observatory in Oakland. There is little I regret more than the disposal of resources assembled at such great cost and effort. But this is an American and NASA specialty.

For several years Hal Masursky suffered a series of strokes and mental setbacks, and he retired from the USGS in February 1990. He was diabetic, and the disease finally caught up with him on 24 August 1990 at age 67. Throughout his long tenure in Astrogeology, his colleagues were of two minds about Hal. We loved his great personal warmth and enthusiasm and his successful advancement of our cause with NASA, the news media, and the public. On the other hand, he seldom wrote more than a memorandum of a few lines, yet year after year he pretended to his colleagues, proposal reviewers, the press, and himself

that next week, next month, or next year he would engage in some major research project. He often represented other peoples' work as his own, called himself by the nonexistent title chief scientist of astrogeology in Flagstaff, and acquired an impressive office that dwarfed those of Gene Shoemaker and the branch chief. But those who ghost-wrote for him are among his mourners.

In 1976 Jack Schmitt was elected Republican senator from New Mexico, and he served until he was defeated for reelection in 1982.[29] In July 1985 he visited his old buddies in Menlo Park for dinner and reminiscences that all of us remember with the greatest warmth. Jack had mellowed. In his days at Flagstaff and Houston — and, I am told, in the Senate — he sometimes was insensitive to the more delicate feelings of his associates. But at that dinner he was in serene command of himself and his friends. Jack held back from any personal revelations, as usual. Later we found out that he was already engaged. Gordon Swann served as his best man, and Jack and Teresa were married in Santa Fe, New Mexico, in November 1985, a few days after Gordon had also stood up for Jack Sevier in Santa Fe, Texas.

DID THE QUEST END AT KONA?

Harold Urey used to say that science had proved that the Moon does not exist.[30] None of the proposed origins explained both the composition and the celestial mechanics of the Earth-Moon system. Earth and Moon more nearly constitute a double planet than any other planet-satellite pair except the much smaller Pluto and Charon. However, the Moon's mean density (3.3 g/cm^3) is less than that of Earth (5.5 g/cm^3) or any other terrestrial (inner) planet. The system has an unusually large angular momentum thanks to the big Moon's orbital motion. The returned lunar samples showed that even though Earth's core has most of the system's metallic iron, the Moon has more iron in the ferrous form (FeO) than does Earth's upper mantle. The compositions of the two bodies have other differences — notably the Moon's far lower abundance of volatile substances like water, sodium, and lead — but also many similarities.

The general compositions and densities can be explained by a primordial molten Earth forming a core and spinning off the Moon from its lighter mantle as a "daughter," as Charles Darwin's son George, Don Wise, and John O'Keefe believed.[31] But the necessary rapid spin and subsequent braking are unlikely, and the Moon's orbit is inclined more than 18° out of the equatorial plane into which such a fission would have put it. Coaccretion or binary accretion as Earth's "sister" during the original condensation of the Solar System, as Kuiper and Russian cosmogenists Schmidt and Ruskol suggested, is hard to reconcile with the Moon's large angular momentum, orbital inclination, and uneven distri-

bution of iron. Intact capture as Earth's "spouse" from somewhere else in the Solar System, as Urey hoped, is essentially eliminated by the unlikely coincidence of close approach trajectory and low relative velocity it would require. A fourth idea combining elements of the "sister" and "spouse" models and calling for accretion from a Saturn-like ring of broken-up captured objects, as suggested in different forms by G. K. Gilbert and Ernst Öpik, fails the dynamic tests and the riddle of why only Earth has such a large satellite. In fact, this question of why any of these mechanisms should have operated only once is especially perplexing. Lunar exploration showed what happened to the Moon after it formed, but how it formed was almost as uncertain after the end of the Apollo flights as it had been in 1949 or 1969.

I saved time for my other duties and interests by ignoring the seemingly intractable subject of origin altogether. But other lunar scientists kept thinking. Bill Hartmann, Jeff Taylor, and geophysicist Roger Phillips, then director of the Lunar and Planetary Institute, thought that October 1984 might be the right time to hash over the matter again and that the Kona (west) coast of Hawaii might be the place to do it. For some reason I sensed big doings and paid my own way to Kona, having no good excuse, as a stratigrapher dealing with the already formed Moon, to attend officially. The conference was incredible. Outside the hotel's conference room were the beaches and soft climate that most people find appealing. But nobody stirred. In anticipation of the usual inconclusive hypothesizing, the organizers had entitled two conference sections "My Model of Lunar Origin I" and "My Model of Lunar Origin II." But to everyone's surprise, "our model" emerged from the presentations of one speaker after another.[32]

With great relief most of the conferees discarded the traditional theories in their original forms. In their place reappeared an idea that is still undergoing testing but appears to present no insurmountable obstacles. Bill Hartmann and astrophysicist A. G. W. Cameron are usually given credit as the principal devisers of the idea,[33] but a remarkably similar suggestion appears in the 1946 paper by Reginald Daly (1871–1957) that I mentioned in chapter 1.[34] The only one among the modern revivers of the idea who I am sure knew of the Daly suggestion is astronomer Fred Whipple, who, Daly says, also "encouraged the idea that one more geologist might be encouraged to guess about the moon."

Our satellite is a daughter of not one but two parents. Not long after the Earth accreted and concentrated most of its iron into a core, it was struck a tangential blow by an object about the size of Mars that also contained an iron core. The enormous energy of the collision vaporized and ejected part of Earth's mantle. Most of the impactor's core reimpacted Earth, but much of its mantle material joined that of Earth in orbit, whereupon the disk of mixed substances accreted

to form the Moon. As in biological genetics, this dual parentage explains both the earthlike and the unique geochemistries revealed by the Apollo and Luna samples. The heat of the collision drove off the water and volatile elements that are conspicuous by their absence or rarity on the Moon. The angular momentum of the system and the orbital inclination of the Moon are natural results of the encounter. The Earth-Moon double planet is unusual because it originated in an unusual event. And so, as Reginald Daly and Ross Taylor said, the Gordian knot was cut.

WHAT NOW?

After Kona I *think* we can say that the questions we asked about the Moon at the beginning of the Space Age have been pretty well answered. But we always knew there was a second level of more difficult problems that had to be addressed by the futuristic dual launches, long stays, and long rover traverses. Those plans will have to be dusted off (or, more likely, reinvented) if the Moon is to be probed in true geologic detail. What is the stratigraphy of the ancient basin ejecta and mare basalts within the lunar mountains? How much mare basalt or other volcanic rock remains hidden, and when did it form? When *did* the Moon's volcanic heat engine finally shut down? When did the first visible basins form, and how many now-invisible ones formed before that? For that matter, do we really know the ages of the basins and craters that have been sampled? How thick is the lunar crust beyond the few spots where it has been measured? Much remains to be learned about the composition and origin of the crust, not to mention the mantle. Where and from what material did the mare units of different compositions originate, and why did they pour out in certain spots? What kind of volatiles expelled the glass droplets that compose the dark blankets, and from where in the mantle, and are they still there? Not only the nature but even the existence of the core is unknown. And do we really understand the Moon's origin?

Carl Sagan is well known in the lunar science community for his opinion that the Moon is boring. Well, it is not icy like Mars, deformed like Venus, or active like the incredible Io or Triton, but it is conveniently nearby. It can still serve as a Rosetta Stone to the primitive Solar System — a "pitted and dusty window into the Earth's own origins and evolution," as Jack Schmitt put it.[35] Most, if not all, planets and satellites had a geologic style roughly like the Moon's during the time of the heavy impact bombardment and before internal geologic processes took over. Mercury, Callisto, and some small satellites still do. We can go to the Moon and learn more about these inaccessible times and objects. The more recent impact rate, if better specified, could also show us the extent of the danger now facing Earth from comets and asteroids. The lunar regolith still

holds a vast unread historical record of solar and galactic radiation.[36] Continuing Apollo for three more landings would have been cost-effective, but it is too late for that now. Now is the time for a cheap global orbiter and some well-directed robotic geophysical stations and sample returners of the Luna type. They could provide at least partial answers to many of the remaining questions if they were sent to the right spots and returned whole rocks.[37] Later the time may come to fulfill the decades-old visions of a full-out lunar base and long explorations by roving vehicles if a societal or political need for them is felt.

Some remaining questions might still be answered from the existing sample collection. The first era of lunar exploration is not really over. Each March, lunar and planetary investigators still troop down to Houston (more precisely, Clear Lake) to show and tell how wisely they have spent their grant money during the previous year and to exchange real information in the coffee room. Although few people study lunar photographs anymore (Paul Spudis is an exception), some sample studies are still performed. Almost 382 kg of rock, soil, and core samples—38% of a metric tonne and 42% of an English short ton—were returned from the Moon, given 2,196 sample numbers, and cut up (so far) into 80,000 pieces.[38] Gordon Cooper once told Dale Jackson that he would bring some samples back in his cuff for Dale's personal use, but few if any samples seem to have been "lost," as is sometimes claimed. The samples reside at JSC in the Lunar Sample Building (31-A) of the Planetary Materials Laboratory, born as the Lunar Receiving Laboratory in another building during the Apollo era. Now the laboratory handles not only Moon rocks brought back by Apollo but also several collected as meteorites from the Antarctic ice. Elbert King resigned as curator in 1969 to teach at the University of Houston, which he is still doing. John Dietrich has been the curator since July 1988. One vault contains the samples that have been studied and returned. Another contains the 279 kg, or 73% of the original total, that have never been out of the curator's custody and are carefully protected from oxygen, safecrackers, hurricanes, and disorganized people. To avoid total loss if JSC should be destroyed, another 14% of the lunar samples are in a vault at Brooks Air Force Base in San Antonio. Even the cataloging job is not finished and will not be until examination of the samples is finished; ever so often those of us on the mailing list receive a new catalog prepared by Graham Ryder of the Lunar and Planetary Institute. The early studies were devoted to characterizing each type of rock identified during the preliminary sample examination. Now, those who propose to study a lunar study need to be looking for something specific.

Possibly the most important spin-off from Apollo is the concept of Spaceship Earth. Apollo may have been a first step into the cosmos, but further steps have not yet followed as we thought they would. Apollo taught that we *cannot* colonize

space except on a very small scale. The astronauts had to bring absolutely everything with them to sustain their lives, and at the present rate the Earth will be worn out long before the knowledge to live cost-effectively on the Moon or another planet is developed. Earth is our home.

A QUIET NIGHT

Let us take a flight of fancy through time. Imagine yourself propped up comfortably on a lawn chair watching the Moon with a pair of binoculars for three quarters of an hour some quiet night. Never mind that the planet you are resting on just got smashed by something the size of Mars and has been in frantic turmoil every time-compressed second ever since. Each minute you watch corresponds to 100 million years of history, each second to 1,670,000 years.

As you are settling down, a ring of droplets is gathering together to form a sphere. If the majority of petrologists and geochemists are right, patches of the sphere glow warmly for about the next three minutes from the heat inherited from the vaporized material in the ring. Pinpricks are constantly appearing on the sphere as new objects strike from space, and every few seconds something bigger splashes on it and briefly opens a red-hot wound.

After the third minute the sphere cools and darkens except where sudden blows splash bright rays over its surface; each ray splash fades after a few of your minutes. The half of the sphere you can see is rapped more sharply about once every two and a half seconds, and great clouds of matter race out from the great impact centers, swamping all nearby objects and scouring others over most of the scene. Each of these paroxysms takes only a few minutes or hours of the Moon's time, too fast for you to glimpse in one of your seconds. Six and half minutes after you settled down — a time known since February and July 1971 — a particularly violent paroxysm of this type involves the entire visible hemisphere. The Imbrium basin has formed. Half a minute later another almost as violent blasts the left-hand limb of the lunar disk (Orientale) and makes itself felt on much of the rest. Then, only seven minutes after you started watching, there are no more paroxysms.

Starting at minute 7 you see something you had not noticed before (maybe you overlooked it in the turmoil): dark pools of lava start to spread out in the basins and in the troughs between the circular mountains. Maybe you can glimpse clouds of dark or fiery spray spurting up in the same places (think of the orange and black glass scooped up in December 1972). The dark pools — the maria — keep spreading out gradually for a while, but you will not notice much change after about the twelfth or fifteenth minute of your vigil. The rays keep

splashing too, but much less frequently now; perhaps you will notice a new splash about every 30 seconds.

The scene during the last half hour does not change much. Eight and a half minutes before you stop watching, a large sunburst of rays radiates out from the arcuate mountain range bordering southern Mare Imbrium, accentuating the division between an "eye" and the "nose" of the Moon's face; Copernicus has formed. A few of the new rays are partly covered by small, new dark pools, and the rest gradually fade. Another sunburst that will not fade splashes out from the crater Tycho in the southern part of the disk one minute before you quit watching—another time that has been known since December 1972.

You blink and barely see Man appear on the scene. Now all is quiet again.