Planetary Environments Part 2: The Moon

by Garry Toth and Don Hillger (Un-manned Satellite Philately)

This is the second article in the *Astrofax* series on planetary environments. The first article appeared in the Summer 2023 *Astrofax* (Vol 31, issue 2). Parts of this article will also serve as background material for later ones in the series. The Moon is very close to Earth in astronomical terms. People have watched it with the naked eye for millennia and it has become a cultural icon. For example, in Chinese mythology, Chang'e is the lovely goddess of the Moon, celebrated in art and literature and lunar festivals. In paintings she is often shown floating toward the Moon (Fig 1). China's recent lunar missions have been given the name *Chang'e.* Western cultures have "the Man in the Moon" and "the Cow that Jumped over the Moon" (Fig 2).

Figure 1. China PR, Sc2113, 1987. goddess Chang'e floating up to the Moon

Figure 2. FDC, Great Britain, Sc1368

Who can forget the iconic image of the Man in the Moon with a space vehicle stuck in one eye (Fig 3)? It comes from the 1902 short movie *Le Voyage dans la Lune* by the pioneering French filmmaker Georges Méliès, which was loosely based on lunar flights of fancy in novels by Jules Verne and H. G. Wells. This article will, however, concentrate on lunar science rather than the Moon's cultural impact.

Figure 3. Monaco, Sc2267, 2002

The story begins with Thomas Harriot, an Englishman who observed the Moon with an early telescope and produced the first known drawings of the lunar surface in July 1609 (Fig 4). Galileo built his own telescope and began using it at the end of 1609. He observed the Moon, Venus, Jupiter and its principal moons, sunspots, and various stars, and so is generally credited as being the "father" of modern astronomy. He published some of his results in 1610 in a report titled *Sidereus Nuncius (Starry Messenger)*. In it, he included some of his drawings of the lunar surface, which he found to be rugged rather than flat. One of his drawings, from page 16, is reproduced in the stamp in Fig 5. In it, the dark and light halves are separated by a terminator which crosses a large crater (possibly Tycho?) in the lower center of the image. Of particular interest are the darker patches in the sunlit area at the upper right of the image. Galileo describes them on pages

Figure 4. Guinea, Mi6519A, 2009. Thomas Harriot and part of his lunar map

Figure 5. Guinea-Bissau, Mi4445A, 2009

19-20 of *Sidereus Nuncius*: *"Now the great spots of the Moon"* are seen to be *"even and uniform … so that if anyone wishes to revive the old opinion of the Pythagoreans, that the Moon is another Earth, so to say, the brighter portion may very fitly represent the surface of the land, and the darker the expanse of water."* In other words, Galileo evokes the possibility of water in those areas. His observations also caused him to wonder (page 26) if *"there is round the body of the Moon, just as round the Earth, an envelope of some substance denser than the rest of the ether, which is sufficient to receive and reflect the Sun's rays, although it does not possess so much opaqueness as to be able to prevent our seeing through it."* This was his speculation on the possibility of a lunar atmosphere.

Figure 6. Ajman, Mi604, 1970

A lunar map published in 1645 by the Dutch astronomer Michael van Langren referred to the dark areas on the Moon as *maria* ("seas", the plural of the Latin noun *mare*), and in one case as an *oceanus*. He was probably familiar with *Sidereus Nuncius*, so his use of those Latin terms might have been inspired by Galileo's speculation about lunar water. Maps of the Moon were also presented by Johannes Hevelius (*Selenographia*, 1647), and Giovanni Riccioli (*Almagestum Novum*, 1651). They too used the *mare* nomenclature, which is still with us today (as is *oceanus*, in *Oceanus Procellarum*). We now know that the *maria* are large, dark basaltic lunar plains. A stamp with a modern photograph of the Moon (Fig 6) shows the stark contrast between the dark and light areas that so impressed Galileo.

A century later, the Croatian Jesuit scientist Rudjer Bošković (Fig 7) argued in *De Lunae Atmosphaera* (1753) that the Moon has, at most, an extremely thin atmosphere nothing at all like that of Earth. This means that the lunar surface pressure must be near zero (pressure is the weight of the atmosphere above any given point). In 1892, American astronomer William Pickering calculated that the Moon's surface must have less than 1/4000 (2.5×10^{-4}) of Earth's surface pressure (current estimates are *much* smaller, with values around 3×10^{-15}). This led him to conclude that water ice, a "volatile" substance (one that vaporizes easily), could not exist on the Moon because it would quickly sublime (transform directly to vapor) in the near vacuum. That was the consensus for a long time. However, in a paper published in 1961, the American physicist Kenneth Watson showed that ice on the Moon would be far more stable than various possible atmospheric constituents. He proposed that, though it would "boil away" when exposed to the Sun, lunar ice could exist in permanently shadowed craters ("cold traps"). As we shall see, this idea was eventually proven correct.

Figure 7. Vatican, Sc1482, 2011

For practical, engineering purposes (such as landing a LEM), the lunar atmosphere can be treated as a vacuum. That does not mean, though, that it is not worthy of fundamental scientific study.

Figure 8. Cuba, Sc962, 1965

Earth has a dense atmosphere, a fluid in which collisions among its atoms and molecules constantly occur. It has several layers, symbolically depicted in Fig 8. The stamp features a weather balloon/research balloon in the lowest two layers (the troposphere and the stratosphere, shown together as the lower white layer), and a research rocket moving through the lowest layers and the mesosphere (blue) and into the thermosphere (purple). The outermost layer, the exosphere, is the upper white layer. Its base varies from around 500 to 1000 km, depending on solar activity, and it merges with outer space. In the exosphere, the atmospheric density is so low that its atoms and molecules can be considered to move without collisions. The atmospheres of some planetary bodies, such as the Moon and Mercury, are surface-bound exospheres. They are too tenuous to absorb measurable quantities of radiation, lack the circulations found in dense atmospheres, and lose component gases to space at a significant rate (and so must be constantly replenished in some fashion).

The temperature of an object can be related to the energy of motion of its molecules. Heat flows from areas of faster motions ("warmer") to areas of slower motions ("colder"). That transfer is done through conduction (direct contact, as in an oral thermometer), convection (due to fluid motions, as in an air temperature thermometer with air flowing over it) or radiation (energy carried by electromagnetic waves). A thermometer that comes into a balance with those heat flows provides a temperature value. An air temperature thermometer must be shaded – if it absorbed solar radiation, it would provide a false reading.

Things are different in space. The temperature of the void can be defined as 2.73 kelvins (-270.42 °C), the temperature of the cosmic microwave background radiation as measured by spacecraft such as COBE (Cosmic Background Explorer). However, we usually want the temperature of an *object* in space. Since there is no fluid, no energy can be transferred by convection, and it is impractical if not impossible to insert a traditional thermometer into direct contact with the object to get a temperature through conduction. We are left with the fact that every object spontaneously and continuously emits electromagnetic radiation. In 1900, the physicist Max Planck (Fig 9) developed a relationship between that radiation and the object's temperature. That temperature can therefore be calculated if the radiation is measured (using an instrument known as a radiometer), but the details are complex. In this approach, the temperature is "remotely sensed". In one well-known example, instruments aboard Earth-orbiting satellites can measure, within limits, the temperatures of the cloud tops, or of the surface if there are no clouds. Many other types of physical variables can also be measured through remote sensing techniques.

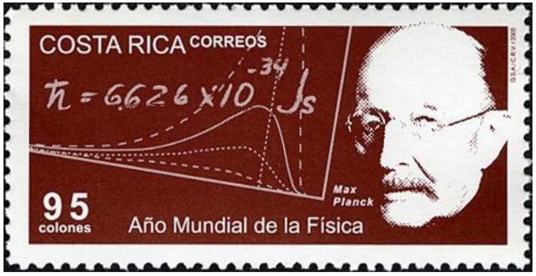


Figure 9. Costa Rica, Sc585b, 2005

The heat transfers in a dense atmosphere act to "smooth out" the possible range of temperatures. In space the range is much greater. For example, the infrared instruments of the *JWST* (James Webb Space Telescope) are designed to operate at very cold temperatures and so must be shielded from solar radiation. The shield's hot side is near 85 °C, while its shaded side is at around -233 °C.

Scientific knowledge about the Moon accumulated rapidly in the Space Age. Wikipedia provides a list of lunar spacecraft missions. There were many early failures. The Soviet *Luna-2* was the first to reach the lunar surface (a crash) on 14 September 1959. *Luna-9* was the first to soft land on the Moon, on 3 February 1966. The American space program surged after Kennedy placed the nation on the road to manned lunar missions. Many American spacecraft of the 1960s were partially or completely in support of the forthcoming Apollo missions. In particular, the Ranger, Surveyor and Lunar Orbiter programs gathered scientific information and demonstrated the feasibility of lunar landings. *Surveyor-1* (Fig 10) was the first American spacecraft to make a soft lunar landing, on 2 June 1966.

Figure 10. Paraguay, Sc980, 1966

The Apollo missions provided much more detailed information about the lunar environment than the robotic landers. During *Apollo-11's* brief sojourn on the Moon, Edwin Aldrin deployed the EASEP (Early Apollo Lunar Surface Experiments Package), a forerunner of the ALSEP (Apollo Lunar Surface Experiments Package) that was part of subsequent Apollo missions (Fig 11). In Fig 12, Aldrin and the EASEP are depicted. It included the *Apollo-11* DTREM (Dust, Thermal and Radiation Engineering Measurement) package.

Figure 11. Apollo 12 Kim Cachet Covers, ALSEP Deployed on Moon, 1969. Apollo-12 ALSEP as deployed on the Moon depicted in the starred rectangle.

Figure 12. Sierra Leone, Sc1070d, 1989. Aldrin and the *Apollo-11* EASEP on the Moon.

The DTREM used a radiometer to measure the surface temperature and provided values (https://archive.org/details/lunarsurfacetemperaturesfromapollo11data) from -23 °C to +7 °C while *Apollo-11* was on the surface, and from -53 °C to +67 °C during a full cycle of lunar day and night.

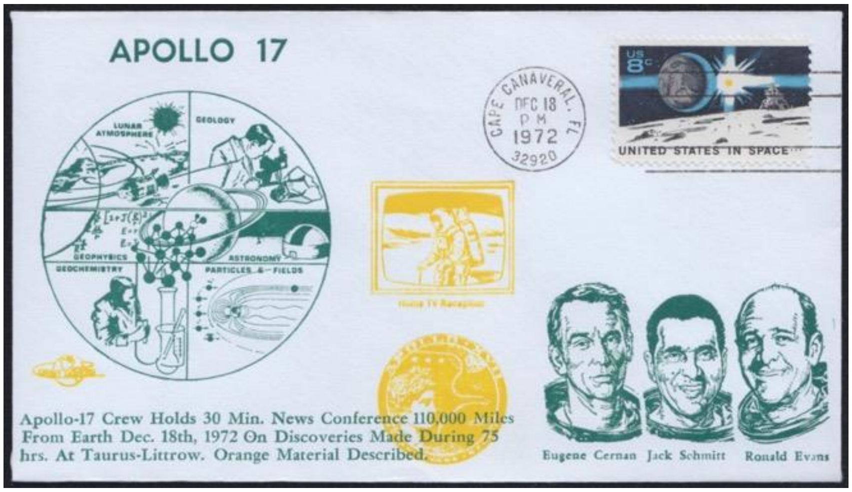
Aldrin also deployed the SWCE (Solar Wind Composition Experiment), whose goal was to sample the solar wind at a location outside Earth's magnetosphere (a protective magnetic "sheath" around Earth). It was also part of the *Apollo-12, 14, 15* and *16* science packages. It was a simple sheet of metal foil exposed to the solar wind for the duration of the landings and then returned to Earth for analysis. Fig 13 features Aldrin and the SWCE. The SWS (Solar Wind Spectrometer), deployed by *Apollo-12* and *15*, also made solar wind measurements. The SWS is in the foreground in Fig 14 (David Scott, in the center of the stamp, is setting up other elements of the *Apollo-15* ALSEP). The SWCE and the SWS are space weather instruments but are relevant to studies of the lunar atmosphere because it is affected by the solar wind.

Figure 13. Mauritania, Mi782, 1983.
Aldrin and the Apollo-11 SWCE

Figure 14. Ajman State, Mi1268a, 1971.
Apollo-15 SWS (in foreground);
astronaut David Scott (in stamp center)

Apollo-15, 16 and *17* carried a package called the SIM (Scientific Instruments Module). It included a mass spectrometer designed to study the lunar atmosphere from the orbiting Service Module. The *Apollo-17* SIM also included an ISR (IR Scanning Radiometer) to measure lunar nighttime temperatures and cooling rates, and a Far-UV Spectrometer to study the lunar atmosphere through its UV emissions.

The *Apollo-17* ALSEP included one major new instrument: a mass spectrometer known as the LACE (Lunar Atmospheric Composition Experiment). LACE updated the CCG (Cold Cathode Gauge) experiments of the *Apollo-14* and *15* ALSEPs. They had proven the existence of a tenuous lunar atmosphere and provided an upper bound for its density but could not measure its composition. All this scientific activity culminated in the last Apollo lunar mission and is summarized in the green circular part of the cachet of an *Apollo-17* event cover (Fig 15). Studies of the "lunar atmosphere" are symbolized in the upper-left portion of that circle.



Apollo-17 Crew Holds 30 Min. News Conference 110,000 Miles From Earth Dec. 18th, 1972 On Discoveries Made During 75 hrs. At Taurus-Littrow. Orange Material Described.

Figure 15. Apollo 17 Cover. Orbit Cache, News Conference, 18 December, 1972

Researchers examined the Apollo data and published their results in the 1970s. Chapter 17 of the 1973 Apollo-17 Preliminary Science Report discussed the results of the LACE. Other related papers are devoted entirely to the lunar atmosphere. Its total mass is miniscule - around 25,000 kg. Its primary components are argon, helium, and neon, while trace amounts of many others, including sodium, potassium, hydrogen, ammonia, methane, and carbon dioxide, have also been detected. Some of them come from "sputtering" (a sort of space weathering in which microscopic particles from the lunar surface are ejected when it is bombarded by the energy of sunlight, the solar wind, and micrometeorites).

Another source is the outgassing of some elements from the lunar interior. The main sink is the loss of gases to space, facilitated by the low lunar gravity, the lack of a lunar magnetosphere, and the way that atoms and molecules move without collisions. Light elements such as hydrogen and helium can gain enough thermal energy from sunlight to escape directly and quickly. Heavier elements need more energy to feed their motion. That energy can come from solar photoionization, which kicks them into a sort of random walk of ballistic trajectories in which they bounce repeatedly off the surface. About half of those ions are eventually captured by the electric field of the solar wind and escape to space. There are also surface effects to consider. Adsorption (deposition) of gases onto the frigid surface in the lunar night thins out the atmosphere, which "falls to the ground" (https://www.space.com/18067-moon-atmosphere.html). Their subsequent boiling off with the return of the Sun increases the atmospheric density at the sunrise terminator, but later during the lunar day the energy and escape effects outlined above reduce it again. Certain density variations can be related to lunar latitude, and possibly to some other surface chemical effects. Assuming that the lunar atmosphere is stable overall, there must be a balance among the various sources and the sinks.

The *Apollo-14* ALSEP included the SIDE (Suprathermal Ion Detector Experiment). It was left on the Moon and on 7 March 1971 it observed ions consistent with water vapor. Analysis of the data concluded that the signal was probably leftover mission-related water vapor. Nevertheless, the search for lunar water/ice continued. *Apollo-17* included a package called the SEP (Surface Electrical Properties) Experiment (Chapter 15 of the Apollo-17 Preliminary Science Report). It was designed with several goals in mind, including the detection of subsurface ice. None was found.

Figure 16. Grenada, Sc2956, 2000. Clementine spacecraft (incorrectly spelled “Clemintine”)

Figure 17. Bhutan, Sc1290d, Lunar Prospector

After the Apollo program ended, there was a long hiatus in lunar exploration, which resumed only with the spacecraft *Clementine* (1994 launch, Fig 16) and *Lunar Prospector* (7 January 1998 launch, Fig 17). They found some tantalizing hints that water ice might exist at the lunar poles through their observations of hydrogen (one component of water). In 2008, a reanalysis of some Apollo moon rocks found hydrogen inside tiny beads of volcanic glass. This was a clue that water might have emerged from erupting volcanoes in the dim lunar past. Could some of it still be around?

Chandrayaan-1 (2007 launch, Fig 18), using NASA’s M3 (Moon Mineralogy Mapper) instrument, is credited with the discovery of ice in the Shackleton crater at the lunar South Pole on 14 November 2008 (and somewhat later at locations near the North Pole, before the spacecraft failed in August 2009). This was the first solid observational confirmation of Watson’s 1961 theory that craters near the poles act as cold traps that can sustain ice.

Figure 18. St. Thomas, Sc1963c, 2009

Figure 19. St. Thomas, Sc2155, 2009

LRO (Lunar Reconnaissance Orbiter) and *LCROSS* (Lunar Crater Observation and Sensing Satellite) (Fig 19) were launched together in June 2008 and marked NASA’s return to active lunar research. *LCROSS* sent an empty rocket as an impactor into the permanently shadowed region of Cabeus crater near the South Pole and then flew into the plume, making measurements for four minutes before hitting the surface itself. Along with other materials, it found ice crystals – a major result that confirmed the presence of ice on the Moon! Meanwhile *LRO*, in orbit, mapped the distribution of hydrogen. The data led to the conclusion that lunar ice is found not only in the shadowed cold traps, but also in pockets that lie outside the shadowed polar regions. “The proportion of volatiles to water in the lunar soil indicates that a process called ‘cold grain chemistry’ is taking place. Scientists theorize that this process could take as long as hundreds of thousands of years and may occur on other frigid, airless bodies, such as asteroids; the moons of Jupiter and Saturn, including Europa and Enceladus; Mars' moons; interstellar dust grains floating around other stars; and the polar regions of Mercury.” [22 October 2010, Science; https://newatlas.com/much-more-than-water-found-on-the-moon/16713/].

Could future lunar explorers harvest water, air and fuel from ice and other compounds found there? NASA’s *VIPER* (Volatiles Investigating Polar Exploration Rover) has been designed to provide at least part of the answer. Beginning in late 2024, its mission will be to map the distribution and concentration of ice at the lunar South Pole.

LRO also observed temperatures from orbit and found that the thermal environment of the lunar surface is “one of the most extreme of any planetary body in the solar system” (https://www.sciencedirect.com/science/article/pii/S0019103516304869#bib0058). At the equator, the average maximum surface temperature is around +120 °C, while the average minimum, just before sunrise, is -178 °C – a range of nearly 300 degrees! Near the poles, the average high is -71 °C and the average low is -223 °C – a range of just over 150 degrees. Permanent shadows in craters near the poles hide some of the coldest spots in the solar system – as cold as -250 °C. That frigid darkness acts as a trap for ice, which would vaporize if sunshine ever struck it. With those measurements, we now know that the temperature ranges provided by *Apollo-11’s* DTREM radiometer were not at all representative of the full lunar environment.

NASA’s *SOFIA* (Stratospheric Observatory for Infrared Astronomy) was a 2.7 m IR telescope aboard a Boeing 747. Its last flight took place on 29 September 2022. It operated around 12 km for a view to space that avoided almost all of Earth’s atmospheric water vapor, which can block some ground-based observations. In 2020, *SOFIA* detected, for the first time ever, water molecules on the sunlit surface of the Moon. That is not to say that the Moon is a humid place. The data indicate that such molecules are embedded within grains of lunar dust, or perhaps are stuck to them, but that those areas are still 100 times drier than the Sahara desert! Nevertheless, this result shows that ice is not confined to the cold dark polar areas. Are there pathways of water through the lunar atmosphere? Could it be more dynamic than anyone realized? Those are questions for future research.

The Apollo astronauts had some problems with lunar dust, mostly kicked up from the surface. Is some dust also suspended in the atmosphere? “There is some evidence that the Moon has a tenuous layer of moving dust particles constantly leaping up from and falling back to the Moon's surface [through electrostatic levitation], giving rise to a ‘dust atmosphere’ that looks static but is composed of dust particles in constant motion” (https://en.wikipedia.org/wiki/Lunar_soil#Moon_dust_fountains_and_electrostatic_levitation). This may be the cause of the lunar horizon glow, or LHG (https://www.space.com/8715-mysterious-moon-light-glowing-dust-fountains.html) that was observed at sunrise and sunset by some Surveyor landers and various Apollo astronauts. The physical process is poorly understood. It may be strongest at the terminator. The *LADEE* (Lunar Atmosphere and Dust Environment Explorer) spacecraft (Fig 20) was launched into a low lunar orbit in 2013 with instruments to measure the composition of the atmosphere and to collect its dust. The data showed that argon, helium, and neon are the principal constituents of the lunar atmosphere, and that the solar wind is the ultimate source of the latter two. *LADEE* also recorded at least 11,000 impacts from dust particles. However, they correlated with Geminid meteoroid lunar impacts and no evidence for electrostatically lofted dust was found. The mystery remains unsolved.

Figure 20. Benin, illegal, 2014

Recent lunar spacecraft such as *LADEE* are also important for a more general reason: the increasing numbers of lunar missions in the coming decades, and particularly those carrying humans. The Moon's atmosphere is so tenuous that it could be significantly modified by those missions. We need to nail down the scientific details as best we can before it's too late.

Part III in this series will consider Mercury. Stamps for all the spacecraft mentioned above, and many more, are found in the authors' website for un-manned satellites. Our Planetary Environments page incorporates all known relevant stamps and philatelic items.

About the Authors

Garry Toth, M.Sc., now retired, worked many years with the Meteorological Service of Canada. Correspondence to gmt.varia@gmail.com is welcome.
Don Hillger, Ph.D., now retired, was a research meteorologist with the National Oceanic and Atmospheric Administration (NOAA) and held a cooperative position at Colorado State University. Correspondence to don.hillger@colostate.edu is welcome.

We have researched and written extensively about weather, climate, and unmanned spacecraft on stamps and covers, as well as some other topics. See our complete list of our publications, with electronic reproductions.