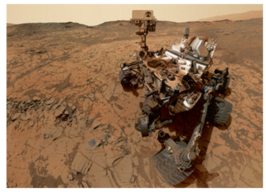
Feature



Planetary geology: an historical and philosophical overview

The use of geological interpretations to better understand features that are observed outside the Earth defines what is known as planetary geology. It is a highly multi-disciplinary field, using concepts from many areas of human knowledge to better understand the many objects of the Universe. Interpretations tend to be based on analogue models, created from observations made on the Earth and extrapolated to the many geological contexts of other celestial bodies. It is assumed that these models can always be used, as long as corrections considering differences in properties such as temperature, mass, atmospheric, crustal and mantel composition, amongst others, are made. In most cases, such correlations are possible, requiring minor to no significant modifications. However, a reasonable number of extra-terrestrial features cannot be explained using the Earth as the unique comparison ground, requiring the use of other analogues as a basis, or even the creation of models and theories from scratch. Here, we present an overview of planetary geology: what it is, the limits of its application, the current state of the art and the meaning of this line of research in the era in which we live, where the exploration of other objects of the Solar System is a reality.

Hely Cristian Branco[1] & Fernando Mancini[2]

[1]Geology Department, Earth Sciences Sector, Federal University of Paraná (UFPR), Curitiba, Brazil
[2]Curitiba, Brazil
helycbranco@gmail.com

Generally speaking, the geological study of planetary bodies is based on analogies with Earth processes. These studies are often based in morphological similarities and physical/computational models, with known peculiarities of the studied feature often being used as boundaries. When such studies are focused on a body's geology, such as surface characteristics and internal structure, they are said to be part of planetary geology. This is a highly interdisciplinary field that integrates concepts from sciences such as geology, astronomy, chemistry, biology and others into a single approach.

To some extent, instrumental innovations are fundamental for the development of this field of science, given that new technologies usually provide more precise and vast sets of data to be analysed. To some degree, technological progress is a limiting factor in the quality of the results obtained in planetary geology. This becomes evident, for example, in the study of Mars, where the level of detail is a direct consequence of the quality of the data available. Until the mid-twentieth century, only observational data obtained from the surface of the Earth provided relevant information about the 'red planet', with resolutions of 0.2 arcseconds at best (~60 km on the surface of Mars during its higher approximation period), allowing researchers to divide the surface into three units based on colour: continents (brighter portions), maria (darker portions) and polar caps. At present, data collected by modern tools allow a more accurate classification of observed features, culminating in achievements such as geological maps or outcrop-scale evolutionary models. Similar results now exist for many planetary bodies outside the Earth (e.g. Mercury, Venus, Pluto, etc.), with many more under development (e.g. Ultima Thule, Eris, Haumea, etc.), allowing an enhanced comprehension of the variety of objects scattered throughout the Universe.

In recent years, the prospect of studying planetary bodies other than the Earth became a more tangible and accessible reality. This fact is at least partially demonstrated by the number of publications in the fields of planetology that incorporate planetary geology, especially the ones related to findings of space probes (e.g. Curiosity and New Horizon). For the first time, scientists are able to access detailed geological information (e.g. outcrop scale images) of many of the Solar System's objects, achieving high-level geological interpretations about their past and current conditions, and forever changing our understanding about geology.

Despite its exponential growth, planetary geology is still only rarely discussed in geology courses in most institutions, at least in Brazil, where this study was developed. This work aims to fill this gap at least partially, providing an accessible introduction to the topic. It is the first in a series of papers on planetary geology, presenting some of the main aspects related to the history and philosophical basis of this field of science.

The history of planetary geology is directly linked to the history of astronomy. Only after centuries of observations, and after the advent of instruments that aided these observations, mankind was able to differentiate the many types of celestial bodies and start to speculate about their characteristics and evolution. Following are some important remarks about this history.

Origins of astronomy: from the Sumerians to Copernicus

Accordingly to F.R.R. Évora, writing in 1993, astronomy may have originated in Babylon, strongly related to mythology and mysticism. The first records consist of stellar catalogues of around 1200 BC attributed to the Sumerians due to names written in the cuneiform language developed by them. The origin of their knowledge is uncertain, especially due to the rarity of preserved records from the great majority of civilizations that lived in the region. There are common characteristics between the astronomy developed by these people, such as the strong bond with mythology, associating stars with divinities, and the lack of concern in explaining the functioning of the Cosmos. Nevertheless, the Babylonians deserve special attention, having incorporated science from other Mesopotamian civilizations into their own, and created a new observationally and empirically based astronomy, as well as a philosophical interpretation of the universe. These ideas were subsequently incorporated by the Greeks, who continued to develop Astronomy and Cosmology as sciences, now unlinked from mythology and based on astronomical observations.

The first astronomical system created by the Greeks was possibly the one developed by the Pythagorean school of thought, around the fifth century BC. According to this model, all celestial bodies were perfect spheres orbiting Zeus's Altar, the main divinity of Greek mythology. Although strongly based on an aesthetic conception in which spheres are considered the most perfect of shapes, this system established many key-concepts used in subsequent models (e.g. the concept of orbits) and the philosophical fundaments that would later culminate in the heliocentric model. The Pythagorean model was succeeded by the one envisioned by Plato in the fourth century BC, a model that for the first time tried to explain the planets' movements: according to it, the planets were positioned in their own celestial spheres, circling around the Earth. Aristotle used these ideas to develop his own model, also centred on Earth, in which all celestial bodies (with the exception of Earth), were composed of 'aether' and were disposed in two main celestial spheres; the first composed of many interconnected mobile planetary spheres, occupied by the planets (Sun, Moon, Mercury, Venus, Mars, Jupiter and Saturn), and the second containing all the fixed stars, unmovable in relation to one another.

The Aristotelean model was, in turn, used by Ptolemy to build the Epicycle and Deferent System; accordingly to it, the orbits of all celestial bodies could be explained by epicycles (circular orbits containing circular orbits) centred on Earth, whose movement resulted in the patterns observed in the sky (Fig. 1). The Epicycle and Deferent System persisted with minor modifications and improvements until the seventeenth century, around the time Copernicus proposed his heliocentric model of the Solar System (Fig. 2). In

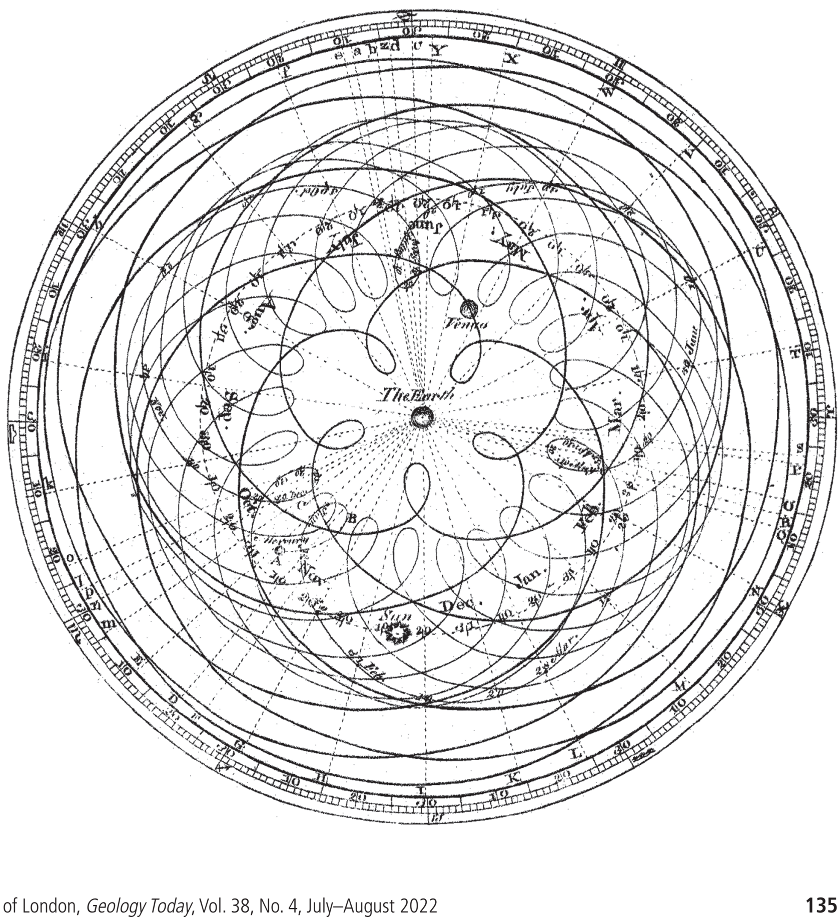


Fig. 1. Graphical representation of Ptolemy's Epicycle and Deferent System. (Modified from Ferguson, 1971.)

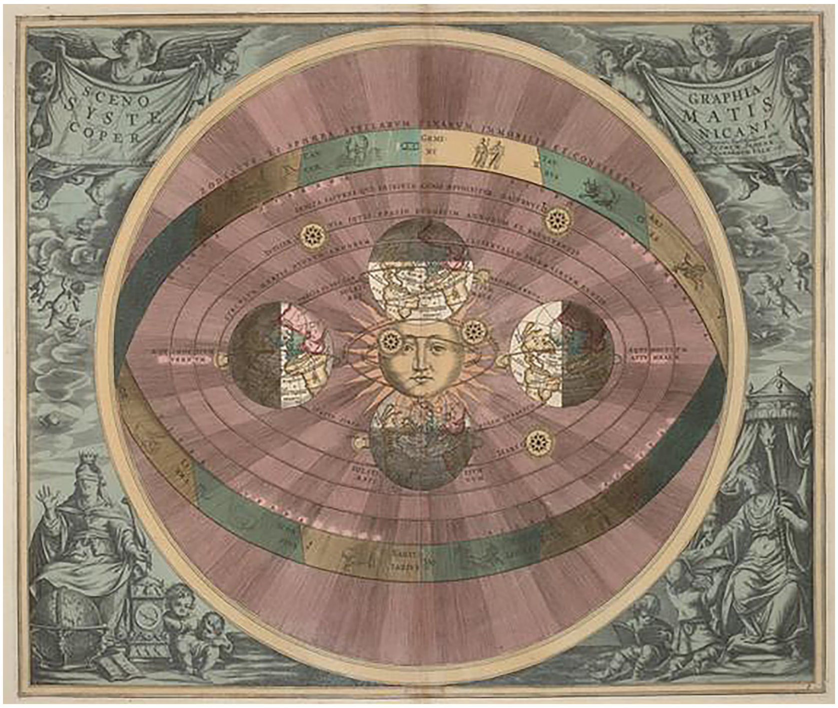


Fig. 2. Illustration of Copernicus's Heliocentric model, made by Andreas Cellarius in the book Harmonia Macrocosmica. (From Cellarius, 1708.)

part motivated by neoplatonic ideas of beauty, priming mathematical simplicity and harmony in the scientific explanations, Copernicus proposed the Sun as the centre of the Solar System. The celestial spheres occupied by the planets were ordered by proximity to the Sun in the now familiar sequence of Mercury, Venus, Earth, Mars, Jupiter and Saturn, ending with the fixed stars sphere. Copernicus also attributed three types of movement to the Earth: rotation around a central axis, translation around the Sun and variation in the inclination of the rotation axis. This model not only disrupted the geocentric paradigms that had dominated for more than 1000 years, but was the first to completely abandon the distinction between celestial and terrestrial mechanics that was introduced by Aristotle. This represented a somewhat limited reformulation of the planetary theory, in agreement with the general structural lines of the accepted Aristotelian science, initiating a scientific revolution that would only be concluded by the next generation of astronomers.

Astronomy as a science: Galileo and the telescope

Copernicus's heliocentrism was strongly criticized by contemporary thinkers until the end of the sixteenth century, amongst who Tycho Brahe deserves special attention. Brahe opposed the Universe's gigantic size in relation to the Earth implied by Copernicus's model; he considered inadmissible the vast difference of scale and its principal consequence: that all the stars that appeared to be even slightly bright should be bigger than Earth's orbit around the Sun. Concomitantly, other thinkers, including Galileo, continued to use Ptolemaic ideas in their works, keeping Earth as the centre of the Universe and ignoring the new possibilities allowed by the heliocentric model.

It was only at the start of the seventeenth century—after the telescope was accepted as a scientific instrument—that significant changes happened to this scenario. The precise date of the creation of this instrument is uncertain. According to J.R.R. Évora, the first proper telescope was created by Galileo, based on a more rudimentary optical instrument that had been created in the Netherlands in 1608. Galileo, by trial and error, improved the optical principles used in the Dutch instrument, creating a series of prototypes that culminated in the 'final version' that he presented to the Italian intellectuals in 1610.

The first Moon observations were made by the Italian scientists in 1609, using an instrument with approximately 20-times magnification. They were recorded as a series of sketches of the many phases of the satellite (Fig. 3), revealing for the first time the mountainous aspect of its surface. In 1610, he made his first observations of a planet, Jupiter; also recorded as a series of sketches, these observations allowed him to conclude the existence of moons, or 'planets orbiting planets'.

The new discoveries made by Galileo lead him to abandon the Ptolemaic model and defend Copernicus's Heliocentric model, as his findings countered some of the strongest critiques made against it. Still, his conclusions were strongly challenged, especially the ones related to the nature of the phenomena observed with the telescope, often contrary to common sense. The apparently antagonistic behaviour of planets and stars when observed through a telescope is a good example, as the first seemed to enlarge whilst the second seemed to shrink, or in other words, '[...] the first were brought closer, while the last were seen distant' (quoted by Feyrabend, and discussed by Évora in 1994). As response, Galileo refined his observations in the following years and developed a new physical theory. Although at times based purely on logic, therefore closer to philosophical instead of physical reasoning, it established many fundaments of scientific thinking later used by Kepler and Newton, such as the use of math to quantify movement, the principle of inertia, and the first theory of relativity.

Planetary sciences: a part of modern science

The history briefly summarized above enlightens the connection between advancements in planetary sciences and the quality of instruments available. Galileo's discoveries, for example, were only possible due to the creation of the telescope, allowing observations that resulted in profound changes in the

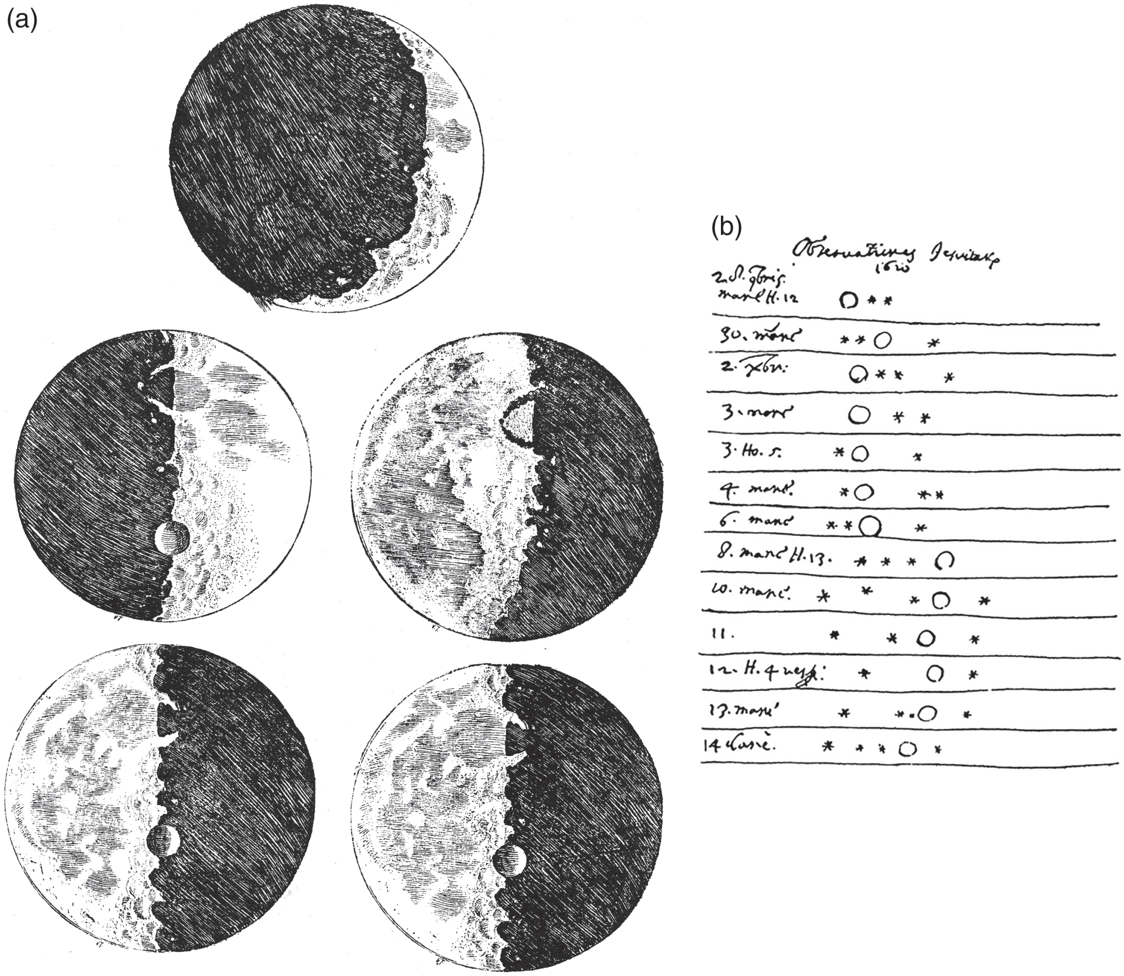


Fig. 3. Moon sketches made by Galileo (**a**), from the book *Siderus Nuncius*, and records of the relative positions of Jupiter and its moons as observed by Galileo (**b**). (From Galileo, 1610a, 1610b.)

understanding of the bodies of the Solar System, with the same logic valid to this day.

In the centuries following Galileo's discoveries, many improvements in the telescope were made, leading to the creation of instruments with progressively bigger magnifications and higher precisions. However, until the mid-twentieth century, detailed observations of bodies more distant than Mars were not possible, due to instrumental (e.g. telescope capacities) and methodological (e.g. related to atmosphere distortions) limitations (mode details in subsequent sections). Images of the surface of Mars, for instance, were limited to resolutions of 0.2 s of a degree (~60 km) and strongly dependent on the proximity to the Earth. This was such a strong limitation that some of the Solar System's planets, such as Uranus and Neptune, were nothing but dim light dots even when observed by the best telescopes, whilst many other types of celestial bodies, such as asteroids and moons, were not observable or even known.

From a planetary geology standpoint, changes in this scenario commenced in 1957, with the launching of the first space probes and the start of space exploration. The first probes (e.g. Sputnik 1 and 2) did little with regard to data collection, aiming at establishing the required routines for the successful launching and operation of vehicles in orbit. It was in 1959 that the mission Luna 3 launched from the Soviet Union sent the first photos of the dark side of the Moon, the first dataset collected by a space probe outside Earth. Many missions followed, an endeavour that persists to this day. The resulting continuous improvement in the quality, quantity and variety of the data collected expanded the frontiers of planetary sciences in an unprecedented way, transforming the technical barriers. Currently, we experience a phase of constant discovery with no prospects of ending, demonstrated, for example, by the increasing number of publications linked to planetology and planetary geology worldwide, and the great number of active and planned missions to other objects in the Solar System.

Planetary geology: a building block of planetary sciences

The creation of planetary geology, or astrogeology, as an independent branch of astronomy/Earth sciences can be attributed to the American geologist Eugene

Merle Shoemaker, who, for the first time, brought geological principles to the study and mapping of planetary bodies in the early 1960s. Whilst studying uranium deposits in the states of Colorado and Utah in 1948, Shoemaker came into contact with the volcanic edifices and impact craters of the Colorado Plateau. This led him to his first studies on impacts, a work he continued for the rest of his life. Amongst his achievements, Shoemaker created the Astrogeology Research Program in the United States Geological Survey and made significant contributions to the study of impact craters, Moon mapping (e.g., see Shoemaker and others, 1970, *Science*, v.167, pp.452–455) and comet and asteroid studies.

From its origin, planetary geology was integrated into the research framework of many institutions, such as the University of Arizona, the University of Colorado, the Massachusetts Institute of Technology, Cambridge University, Oxford University, amongst others. It evolved as a highly interdisciplinary field, according to Bell and others writing in 1999 (p.999): 'In order to successfully interpret the various types of remote sensing and other data that are available, the planetary geologist must have a good background not only in geology, but also, depending on the specific application, in such diverse subjects as astronomy, mineralogy, geochemistry, geophysics, chemistry or even biology. [...] [The field] includes a substantial element of exploration and discovery. Many times, students and researchers in the field will be exposed to completely new terrains or processes that have no clear terrestrial analogs. [...] In these situations the multidisciplinary nature of the field provides its greatest advantage, because the skilled planetary geologist must be able to apply universal sets of physical laws effectively to new or unusual situations.'

This vision was shared by Faure & Mensing in 2007, (p.xvii), who affirmed that:

> […] planetary science tends to unify subjects in the Earth Sciences that are customarily taught separately: geophysics, volcanology, igneous petrology, mineralogy, geomorphology, geochemistry, hydrogeology, glaciology, tectonics, economic geology, historical geology, as well as meteoritics, microbiology, physics, astronomy, atmospheric science, and even geopolitics and international relations. […] The exploration of space is by necessity a cooperative enterprise in which national borders, cultural differences, and even language barriers fade.

In this context, the presence of Earth scientists is essential, due to the fact that these scientists are 'accustomed to constructing realistic hypotheses from large sets of numerical data and visual information'. Under this approach, Greeley & Bender writing in 1998 attribute the advent of a unified vision of the processes responsible for the origin and evolution of planets to space exploration. According to the authors, other planets can preserve on their surface, evidence of evolutionary phases long ago erased on Earth, what allows, through interpretative correlation, the creation of a general evolution panorama of this type of celestial body based in their respective geological evolutions. They still vouch that other planets, in certain circumstances, can be considered as giant scientific experiments conducted under different conditions than the Earth, and that could never be carried by scientists in our planet.

The term 'planet' and other relevant definitions

According to the Online Etymology Dictionary, the term 'planet' was originated from the greek *planetai*, which means 'wandering star'. It was originally used to refer to the five celestial bodies that appeared to move in the night sky (Mercury, Venus, Mars, Jupiter and Saturn), in some cases including the Sun and the Moon. After the creation of the telescope, the term was extended to include illuminated bodies (i.e. that do not emit light) that orbit the Sun. In 2006, the term gained a formal scientific definition. According to it, for a body to be considered a planet, it needs to meet three fundamental criteria: (1) orbit the Sun; (2) be massive enough for its gravity to reduce it to a hydrostatic equilibrium shape (nearly spherical) and (3) have cleared its orbit and its surroundings from other objects. The same resolution also defines a dwarf planet as: (1) a celestial body that orbits the Sun; (2) has sufficient mass for its gravity to reduce it to a hydrostatic equilibrium shape (nearly spherical); (3) has not cleared the neighbourhood around its orbit; and (4) is not a satellite (i.e. orbits another object that is not the Sun). With the exception of satellites, all other objects are collectively designed as 'small Solar System bodies' and are often divided into asteroids (orbits within the Inner Solar System), centaurs (orbits between Jupiter's and Neptune's) and transneptunian objects (orbits beyond that of Neptune's), although not formally. Planetary bodies, i.e., objects similar to planets and often composed of rocky materials and volatiles (e.g. ices) include all the above categories and are the main study objects of planetology and planetary geology.

Probes and other sources of data

Data used in planetary sciences comes from three main sources: probes, telescopes and models, both computational and analogue. According to Burns, writing in 2010, until the mid-1960s astronomical studies

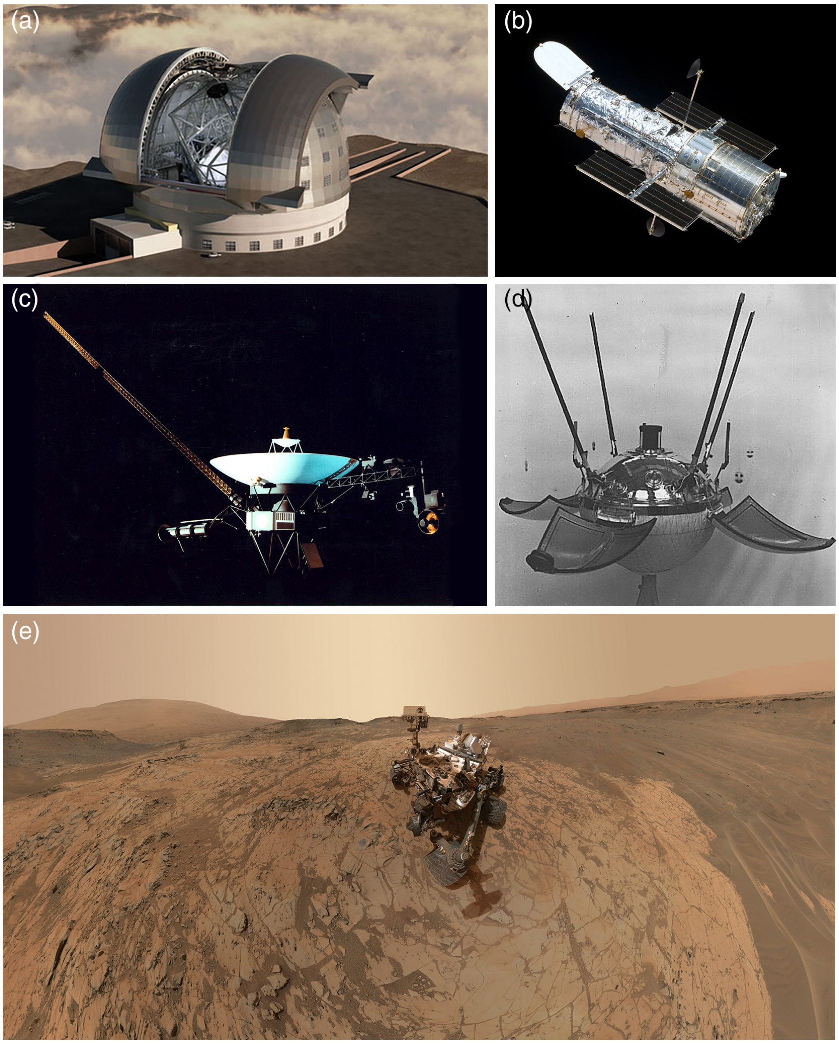


Fig. 4. Examples of instruments for data collection. **a.** the European Extremely Large Telescope (E-ELT), an example of a large ground telescope. (Source: ESO, 2009.) **b.** Hubble Space Telescope, the most famous telescope ever built. (Source: NASA, 2009b.) **c.** The interplanetary space probe Voyager 1. (Source: Williams, 2018.) **d.** The Luna 9 lander. (Source: Williams, 2021d.) **e.** a 'selfie' of the Curiosity rover. (Source: NASA, 2017a.)

mostly used data from ground telescopes (Fig. 4a). These instruments remained as the main source of information for more than two decades, with an even higher relevancy in current comet and asteroid studies.

Due to some atmospheric properties, that is, absorption of many bands of radiation and turbulence effects, the resolution of data collected from the Earth's surface is limited. A way to avoid the problem is to transfer the telescopes to space, where there is no atmospheric disturbance (Fig. 4b). This was made possible due to advances of the aerospace industry due to the Cold War, allowing not only the placement of telescopes in orbit, but also the launching of space probes.

Space probes are non-piloted devices sent to explore space and collect scientific data. They can be classified in three categories accordingly to their functionality: interplanetary probes (that fly between different celestial bodies, Fig. 4c), orbital probes or orbiters (that orbit specific celestial bodies, e.g. Rosetta) and surface probes or landers (they land of the surface of the targeted celestial body, Fig. 4d). Landers can be subdivided into two types accordingly to their mobility: stationary probes, or just landers, and mobile probes, called rovers (Fig. 4e).

Also according to Burns, the advent of new technologies led to drastic quality improvements of the collected data. For common orbiters in Mars and Saturn, there has been an increase in resolution of around 105 and 106 times respectively in relation to images collected by telescopes on Earth, which is equivalent to approximately 1010 and 1012 times the number of pixels per image. In addition to that, the presence of instruments orbiting and in the surface of other objects allows gathering of other types of information, such as outcrop-scale images, physical and chemical measurements, and, most importantly, detection of unexpected features. Data gathered by Curiosity, for example, lead to drastic alterations in our understanding of Mars, revealing new outcrop scale structures previously though as exclusive to Earth. Until now, probes have been sent to the eight planets, to a significant numbers of smaller bodies, and in missions to reach the edges of the Solar System.

Models also have central importance in the study of planetary bodies. Broadly speaking, they can be computational or analogue. Computational models consist of computer simulations using known laws of nature and based in data collected by probes or telescopes. Analogue models consist of the study of analogues on the Earth to better comprehend observed features, made through direct comparison and involving natural environmental observations and/or controlled laboratory experiments. The last is of particular importance in planetary geology, not only representing a new way of making field geology, but also a new paradigm for geology, in which integration of human and robotic work is of uttermost importance.

Other sources of data include the study of meteorites and the information gathered by manned missions to other celestial bodies. The study of meteorites is not considered here, as it is a complex and vast field of the Earth sciences; however, it is of fundamental importance, having provided essential clues regarding the formation and evolution of rocky bodies of the Solar System. Manned missions may be the richer sources of data available and will surely result in unprecedented discoveries in the future. Six NASA Apollo missions landed on the Moon, bringing a total of 12 astronauts to its surface, including one geologist (Fig. 5). Amongst them, Apollo 11 deserves special attention, as the first manned sample recovery mission to a planetary body and, therefore, a mark in the history of science.

Recent discoveries in planetary geology

Recent advances in planetary geology can be divided into two main groups. The first consists of discoveries made by the use of telescopes; the second, by advances related to data collection by space probes. Discoveries related to direct sampling (e.g. the Apollo missions), although important, are too rare to be considered a trend.

Telescope observations lead to the discovery of a great number of bodies not directly observable due to the huge distances separating them from the Earth (e.g. exoplanets) or to their extremely small size (e.g. small bodies of the Solar System), being more directly related to astronomy. An example is the discovery of Proxima Centauri B, an exoplanet with a mass similar to that of the Earth, situated in its system's habitable zone. This find not only changed our understanding of the Proxima Centauri system, thought to be devoid of planets, but also brought new perspectives for direct exploration of exoplanets; Proxima Centauri is one of the closest stars in our galactic neighbourhood, ~4.2 light-years away from the Sun, being feasible to send a space probe and receive information within a human lifespan.

Data collected by space probes lead to more profound changes in our comprehension of some celestial bodies, including the Moon, Mars, Jupiter, Saturn, Pluto and some small bodies. The most recently launched probes, especially the ones that started their missions after the year 2000, gathered primary data from the referred bodies, such as magnetic and electric field measurements, spectroscopic analysis results and high-resolution satellite images. Some examples are the first high resolution images from Pluto and Charon (whose surface features were observed for the first time in 2015), the many images of the Martian landscape sent by the Curiosity rover and the first *in-situ* measurements of a comet's core made by Rosetta lander, amongst many others. The resulting findings include the discovery of liquid water on Mars, both confirming hypotheses regarding the planet's evolution and renewing theories about the origin of life, and of Martian outcrops with sedimentary structures, confirming hypotheses regarding its geological evolution.

A significant portion of the mentioned missions are still active, generating large volumes of data and allowing the creation of progressively more refined and detailed models. Besides that, new missions are being planned for the next few years that will surely provide more information and allow even more discoveries.

Planetary geology under a philosophical perspective

The increasing number of studies related to or including planetary geology illustrates the fundamental importance of analogue models in planetary sciences. Most of the affirmations, hypotheses and theories regarding the origin, characteristics and evolution of planetary bodies from inside or outside the Solar System, are based, to a greater or lesser degree, on the Earth analogue models. The reason for this is simple: Earth is the only planetary system that we can directly access. We can walk freely on its surface and study its geological record in detail, understanding the processes that took place in the 4.6 Ga of its existence.

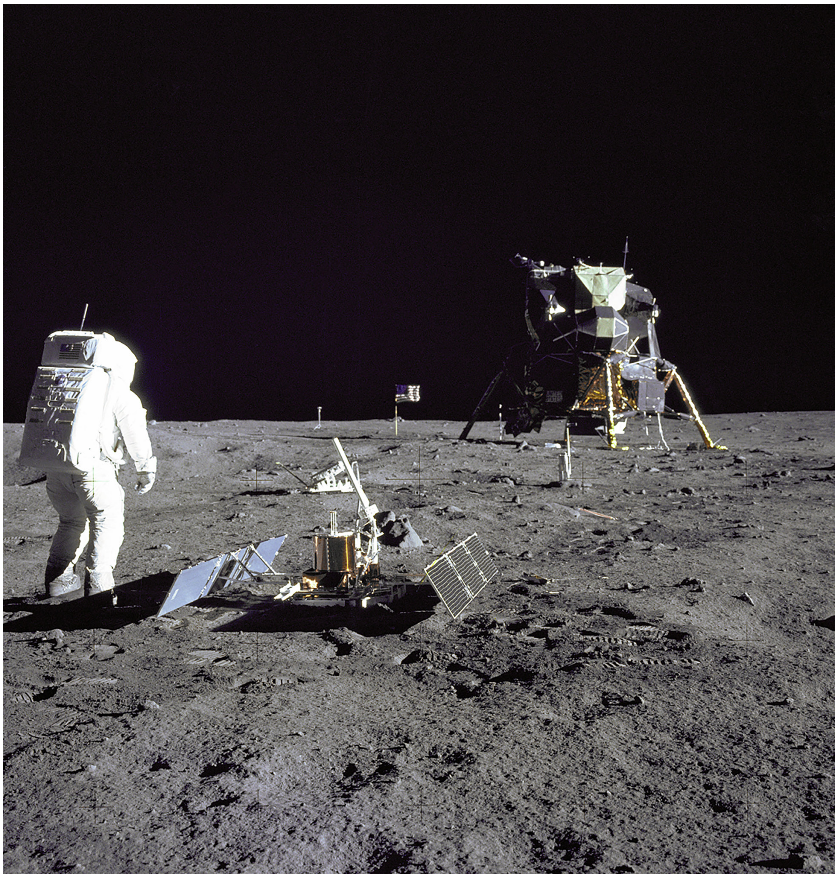


Fig. 5. Astronaut and lunar module pilot Buzz Aldrin during his extra-vehicular activities in Apollo 11 mission on the Moon, including some of the equipment used. (Source: NASA, 2017b.)

Through correlation between products—in this case the geological record expressed as rocks and geological features—and processes, many studies using modern analogues and also those sometimes based on physical models, it is possible to slowly trace our planet's evolution through the Eons. The process as a whole can be seen as a succession of brief scientific revolutions followed by longer phases of small increments and corrections, or normal science, in the long run contributing to the creation of a cumulative body of knowledge as proposed by Karl Popper in 1968 for sciences in general. Even abandoned ideas, such as the geosynclinal theory, have their importance in the elaboration of new hypotheses, whether by providing concepts reusable on the light of new perspectives, or by defying new models with more precise predictions for specific conditions, therefore functioning as falsifiers of the new paradigm.

From the process described above, it becomes clear that the Earth has a central role, being the basis for the development of our understanding of other planetary bodies. When confronted by new situations, such as the study of ice dynamics in Pluto or the dune fields on

Mars, it is natural to use well-stablished models from the Earth as a first approach instead of elaborating explanations from scratch. These models are adapted and used as necessity demands; in other words, our planet can be used as described by Garry and Bleacher in 2016 (p.xi) as a 'rosetta stone or analogue for the comprehension of the Geology of the Solar System', providing general lines for the study of other planetary bodies.

Established models, however, are far from perfect. As stated by Massé and others in 2016 (p.428), there are fundamental differences between the Earth and other planetary bodies, as the difference of fluids behaviour on the surface of Earth and Mars '[...] demonstrates that interpretation of any current activity suspected to be water-driven on Mars cannot be based solely on terrestrial flow morphologies'. Pluto also is an excellent example of the limits of the use of the Earth analogue models. Recent data collected by New Horizons revealed a body far more complex than expected, whose evolution appears to be controlled by processes that are almost insignificant on the Earth's. Consequentially, the use of Earth analogue models faces serious limitations, providing appropriate conclusions only if properly adapted. Considering how singular the celestial bodies of the Solar System are, the conclusion stated above can be extrapolated to virtually all processes taking place on other planets: interpretations regarding geological processes on other objects cannot be based solely on the Earth, even if based on Earth analogues; corrections are often necessary, with models being developed and refined through use.

Due to the current embryonic development stage of planetary geology, the modus operandi and fundamental concepts and theories are still being defined, with no clear path to follow. Hypotheses and theories can be derived, but affirmatives cannot be made until practical verifications are feasible. Therefore, conclusions have to take into account high levels of uncertainty, and be very clear about their limitations. As is the case with many frontier fields of knowledge, it is necessary to emphasize the inherently speculative nature of some of the results obtained. The methods used have to be carefully selected and analysed prior to their application, and verified thoroughly before the elaboration of conclusions. Maybe more importantly, it is necessary to emphasize the necessity of further studies. Each new set of analysed data brings new questions; it is clear that each new answer obtained reveals how much we still do not know and how much we still have to learn.

Acknowledgements

We would like to thank the Federal University of Paraná (UFPR) for allowing this research to be made. In particular, the first author would like to thank his undergrad thesis supervisor and co-author for the time and patience, the fellow students and professors of the Geology Department, and all friends and family members for all the conversations, discussions and incentive throughout the elaboration of the report that originated this paper; it made the research all the more enjoyable and fun.

Suggestions for further reading

Bell, J.F., III, Campbell, B.A. & Robinson, M.S. 1999. Planetary geology. In: Rencz, A.N. (ed). *Remote sensing for the Earth Sciences: Manual of Remote Sensing*, 3rd edn. John Wiley & Sons, pp.509–564.

Braga, B., Pope, B. & Druyan, A. 2014. Cosmos: a Spacetime Odyssey. 2014. Cosmos Studios, Fuzzy Door Productions.

Bryner, J. 2008. The storied history of the word 'planet'. goo.gl/hMPNX2 [accessed August 2021].

Burns, J.A. 2010. The four hundred years of planetary science since Galileo and Kepler. *Nature*, v.466, p.575. https://doi.org/10.1038/nature09215.

Cellarius, A. 1708. Valk, G. & Schenk, P. (eds). *Harmonia Macrocosmica*. https://stanford.io/3z0DxIv [accessed August 2021].

Chao, E.C.T., Shoemaker, E.M. & Madsen, B.M. 1960. First natural occurrence of coesite. *Science*, v.132, pp.220–222.

Chapman, M. 2007. Preface: the rationale for planetary analog studies. In: Chapman, M. (ed). *The Geology of Mars: Evidence from Earth-based Analogs*. Cambridge University Press, Cambridge.

Dreyer, J.L.E. 1953. *A History of Astronomy from Thales to Kepler*. Dover Publications.

Dyches, P. 2016. Mars rover views spectacular layered rock formations. goo.gl/9wq9jr [accessed August 2016].

European Southern Observatory [ESO]. 2009. *Rendering of the ELT*. https://bit.ly/3z1cpct. [accessed August 2021].

European Space Agency [ESA]. 2014. History of cometary missions. goo.gl/xcPdDk [accessed May 2021].

Évora, F.R.R. 1993. *A revolução copernicano-galileana vol. 1 – Astronomia e cosmologia pré-galileana*, 2nd edn. Center of Logic, Epistemology and History of Science, Campinas. UNICAMP.

Évora, F.R.R. 1994. *A revolução copernicano-galileana vol. 2 – A revolução galileana*, 2nd edn. UNICAMP, Center of Logic, Epistemology and History of Science, Campinas.

Faure, G. & Mensing, T.M. 2007. *Introduction to Planetary Science–The Geological Perspective*. Springer, Dordrecht.

Ferguson, J. 1771. *Encyclopaedia Britannica (facsimile reprint 1971)*, 1st edn. https://bit.ly/3y0WBF2 [accessed August 2021].

Galileo, G. 1610a. Sketches of the Moon. In: Galileo, G. (ed). *Siderus Nuncius*. https://bit.ly/3AWHkXI [accessed August 2021].

Galileo, G. 1610b. Moons of Jupiter. In: Galileo, G. (ed). *Siderus Nuncius*. https://bit.ly/2UxmVJt [accessed August 2021].

Garry, W.B. & Bleacher, J.E. (eds). 2016. *Analogs for Planetary Exploration: Geological Society of America Special Paper*. doi: https://doi.org/10.1130/2011.2483(02).

Greeley, R. & Bender, K. 1998. *Planetary geology: A teacher's guide with activities in Physical and Earth Sciences*, 2nd edn. NASA, Solar System Exploration Division, Planetary Geology Office.

Hodges, K.V. & Schmitt, H.H. 2011. A new paradigm for advanced field geology developed through analog experiments on Earth. In: Garry, W.B. & Bleacher, J.E. (eds). *Analogs for planetary exploration: Geologic Society of America special paper*, pp.17–31. https://doi.org/10.1130/2011.2483(02.2016

Howell, E. 2014. What is a planet? goo.gl/cpy9EQ.

2006. *Resolution B5 - Definition of a planet in the Solar System*. International Astronomical Union [IAU]. goo.gl/5JvZL2.

Kaula, W.M. 1968. *An Introduction to Planetary Physics – The Terrestrial Planets*. John Wiley & Sons.

Kuhn, T.S. 1970. *The Structure of Scientific Revolutions*. University of Chicago Press, Chicago.

Loff, S. 2015. Apollo 11 Mission Overview. goo.gl/i2YBAP.

Massé, M., Conway, S.J., Gargani, J., Patel, M.R., Pasquon, K., McEwen, A., Carpy, S., Chevrier, V., Balme, M.R., Ojha, L., Vincendon, M., Poulet, F., Costard, F. & Jouannic, G. 2016. Transport processes induced by metastable boiling water under Martian surface conditions. *Nature Geoscience*, v.9, pp.425–428.

National Aeronautics and Space Administration [NASA]. 2009a. *What is a planet?* goo.gl/FIMiZM [accessed October 2016].

National Aeronautics and Space Administration [NASA]. 2009b. *The Hubble Space Telescope as seen during its final servicing mission, in 2009*. https://go.nasa.gov/380cD7L [accessed August 2021].

National Aeronautics and Space Administration [NASA]. 2017a. *Curiosity Self-Portrait at 'Mojave' Site on Mount Sharp*. https://go.nasa.gov/3gbIpTN [accessed August 2021].

National Aeronautics and Space Administration [NASA]. 2017b. *Aldrin Gazes at Tranquility Base*. https://go.nasa.gov/3iYnSUj [accessed August 2021].

National Aeronautics and Space Administration [NASA]. n.d. Missions. https://www.jpl.nasa.gov/missions [accessed March 2021].

Noffke, N. 2015. Ancient sedimentary structures in the <3.7 Ga Gillespie Lake Member, Mars, that resemble macroscopic morphology, spatial associations, and temporal succession in terrestrial microbialites. *Astrobiology*, v.15, pp.169–192.

Popper, K.R. 1968. *The Logic of Scientific Discovery*. Hutchinson, London.

Ruggles, C.L.N. 2005. *Ancient Astronomy: An Encyclopedia of Cosmologies and Myth*. ABC-Clio, Santa Barbara.

Shoemaker, E.M., Hait, M.H., Swann, G.A., Schleicher, D.L., Dahlem, D.H., Schaber, G.G. & Sutton, R.L. 1970. Lunar regolith at Tranquility Base. *Science*, v.167, pp.452–455.

Simmons, C. (ed.) 2011. *Space probes*. National Geographic Society. Production: Wasser, J. goo.gl/cF8qhG [accessed July 2021].

Szabó, T., Domokos, G., Grotzinger, J.P. & Jerolmack, D.J. 2015. Reconstructing the transport history of pebbles on Mars. *Nature Communications*, v.6, p.8366.

United States Geological Survey [USGS]. n.d. *Gene Shoemaker – founder of astrogeology*. goo.gl/pbdsFt [accessed May 2016].

Wenz, J. 2016. *The exoplanet next door*. goo.gl/EpSN0K [accessed July 2021].

Williams, D.R. 2018. *Voyager Project Information*. https://go.nasa.gov/3ATnug7 [accessed August 2021].

Williams, D.R. 2021a. *Chronology of lunar and planetary exploration*. goo.gl/abgxoc [accessed August 2021].

Williams, D.R. 2021b. *Chronology of lunar and planetary exploration – mission timeline*. goo.gl/W7NHOs [accessed August 2021].

Williams, D.R. 2021c. *Luna 3*. https://go.nasa.gov/3sy1SCR [accessed August 2021].

Williams, D.R. 2021d. *Luna 9*. https://go.nasa.gov/3D0xnu9 [accessed August 2021].

