Mars: A Primer on Modern Research and the Martian Past

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Introduction

There is a particular draw in all humans to the night sky and what lies beyond our planet in outer space. For thousands of years, humans have been studying the stars, the moon, and the planets for religious reasons, scientific research, and just out of pure curiosity. Particularly, the planet Mars has been under intense study as far back as the 1400s BCE. As discovered by maps decorating the tomb of Senenmut and the Ramesseum, the ancient Egyptians nicknamed Mars 'Horus-the-Red' and were aware of its retrograde motion in the sky, a phenomenon where Mars appears to change directions in the sky every couple of years (Novakovic, 2008; Parker, 1974). As early as 368 CE, the Chinese were also aware of this strange motion of Mars and were recording occultations, or planetary eclipses (Pannekoek, 1989). Famous astronomers like Ptolemy, along with less famous ancient sources like the Indian text *Surya Siddhanta,* estimated the size of Mars and studied its elliptical orbit as early as the second century (Thompson, 1997). These calculations were renewed during the renaissance with the work of Copernicus, Brahe, and Kepler (Sheehan, 1996).

Considering the fact that all of these astronomers were studying Mars through naked eye observations and with their contemporary planetary knowledge, it is remarkable that they were able to discover anything about the planet at all. However, our knowledge of Mars began to truly develop in 1610 with the invention of the telescope by Galileo. Between 1610 and 1877, the scientists Galileo (1610), Cassini (1666), Herschel (1783), and Dawes (1864) learned an immense amount about the Red Planet through use of stronger and stronger telescopes. They were able to discover the Martian phases, the length of a day on Mars, the Martian polar ice caps and their movement, and the two moons of Mars (Campbell, 1896).

Throughout the 20^{th} century and especially since the end of World War II, our knowledge of and interest in Mars has again exploded. We now have high power telescopes that take crystal clear photos of Mars. We have orbiters encircling Mars taking constant satellite imagery, high-tech rovers wandering the surface of the planet, and remote sensing instruments on Earth taking precise measurements of the Red Planet. With these tools, we have been able to discern the Martian surface minerology, atmospheric composition, and surface features with incredible detail. For the remainder of this paper, I will paint a clear picture of what we know about Mars today by giving a chronology of the technology and discoveries we have made through the 20^{th} and early 21^{st} centuries. Then, I will briefly summarize how our knowledge of Mars feeds the current leading theories about the planet's past.

Pre-Space Exploration Research

The biggest question about Mars, and any other planet, through history has been whether or not life exists or ever did exist on the planet. We humans are naturally curious if we are alone on Earth as the only forms of life in the universe. Because of this, research on Mars has been directed at investigating the many different conditions that are conducive to life, especially in early studies. Interestingly, at the start of the 19^{th} century, it was commonly believed that life existed on Mars. Scientists like P. Lowell, who published a study of the history of life on their planets in 1908, believed that Mars offered us a glimpse of the Earth's future. Being smaller than Earth, he believed Mars cooled faster than Earth did at the birth of the solar system and began its history of life sooner as well. In his mind, Mars slowly lost its atmosphere and the intelligent life that had apparently created the “canals” on the surface were unable to continue living (Lowell 1908).

Picture Taken by NASA’s Hubble Telescope July 5th, 2001, showing the polar caps, red areas, and dark areas.

With early improvements in telescope and photography technology, we already had a good idea of the appearance of the Martian surface by the beginning of the 1900s. It was clear that there were dramatic albedo and color contrasts around the planet. The poles were of course white from the ice caps, and all of the space in between (the area of which changes as the ice caps wax and wane) was either a bright red or a darker hue – potentially gray or green (Slipher 1962).

One of the first important studies of the 1900s came from Edison Pettit and Seth Nicholson, who made the first temperature estimates of the Red Planet in 1924. They attached a vacuum thermocouple to a high-power telescope and observed Mars for eleven days. A thermocouple takes advantage of the Seebeck effect, which states that two different metals in the same circuit will heat to different temperatures, creating a voltage in the circuit. The thermocouple can then interpret this voltage and give a temperature reading (e.g., Atkins, 2013). In the case of Mars, Pettit and Nicholson measured radiation differences between Mars and stars close to Mars in the night sky (the radiation of these stars had been determined by other studies). Over eleven days, they found that the temperature on Mars reaches 280 K, or about 7 °C, at the equator and 205 K, or -68 °C at the pole (Pettit and Nicholson, 1924).

That same year, scientist Donald Menzel detected a temperature phenomenon on Mars that is one of the planet's defining features today. He, along with William Coblentz and Carl Lampland, measured a temperature of -100 °C at the Southern pole in August followed by a temperature of -15 °C in the same spot in October. As their measurements progressed from August to October, they realized that each day, they were observing the same spot on Mars at a later time in the morning when the sun was higher in the Martian sky. From this, they deduced that Mars must experience extreme diurnal temperature fluctuations between daytime and nighttime, or "enormous diurnal fluctuation," as they put it. (Menzel, Coblentz, Campland, 1924)

Discovering this temperature range was a great step for research on Mars. Not only did it give a general framework for further research, but it also answered some questions about the possibility of life on Mars. Research from the British Antarctic Survey shows that microbial cells cannot survive in temperatures colder than about -20 °C, and that even the best temperature-regulators on Earth, the Emperor Penguins, can only survive at about -40 °C (Clarke et al., 2013). Though scientists may have not known these exact temperatures at the time, they were well aware of the limits cold temperatures propose to life (Novakovsky, 1924).

In 1947, a breakthrough in research came at the McDonald Observatory in Texas when carbon dioxide was detected in the Martian atmosphere through infrared spectroscopy. Previously, researchers were aware of a Martian atmosphere due to the observation of clouds by scientists such as E.C. Slipher (1927), but there was no definitive identification of any gases present. Attempts at detecting specific gases in the atmosphere using infrared spectroscopy date back to 1924 when scientists at Mount Wilson Observatory claimed to have measured Martian water vapor at about 3 percent that of Earth and oxygen at about 16 percent of that on Earth (Adams and St. John, 1926). These claims were immediately controversial and later proved to be dramatically too high (Anders and Owen, 1977).

However, the spectroscopic work in 1947 by Gerard Kuiper was accurate and marked the beginning of infrared spectroscopy's massive impact on planetary research. Infrared spectroscopy is a method used in many different fields to properly identify different elements, whether they be solids, liquids, or gases. It works by shining a beam of infrared light at a sample and measuring the reflected spectral signature. Put simply, each element reflects light in its own unique way, and by comparing measurements from Mars to known measurements on

Earth, we can identify the composition in the atmosphere and on the surface (Bell, 2012; Rennie, 2016).

The first legitimate measurement of water vapor in the Martian atmosphere came a couple of decades later in 1963 (Dollfus, 1963; Owen, 1992). This was another big moment in the history of human observation of Mars. Every discovery on Mars that verified a similarity to Earth gave hope that there might be or had been life on Mars. With the knowledge that there was H_2O ice at the poles and water vapor in the air, many would assume that there is also liquid water on the planet as well, a commonly believed ingredient for life as we know it. However, as we will see, the presence of liquid water on Mars today is hotly debated and is likely not present at all.

Observing Mars from Earth poses several difficult challenges. When using infrared spectroscopy, an instrument on Earth will receive data from many different sources, or absorption bands. For example, the infrared light from the spectrometer will be absorbed and reflected by Earth's atmosphere, the Martian atmosphere, and the surface of Mars. This means that if you want to observe the Martian surface, you have to be knowledgeable about what information you will receive due to the Earth and Martian atmosphere so that you can remove its effects and focus only on the Marian surface. You have to take into account that your spectrometer will detect the water vapor, oxygen, ozone, carbon dioxide, and many other gases on Earth, along with the gases in the Martian atmosphere.

It is for these reasons that the first successful infrared spectroscopy of the Martian surface was not until 1964 when Vassili Moroz detected H_2O in common areas away from the poles (Soderblom, 1992). Moroz could not specify the form of the H_2O, but subsequent studies by other researchers were able to shed light on that uncertainty. In 1973, Houck et al. utilized spectrometers on board aircraft high in Earth's atmosphere. From their positions, those spectrometers were able to avoid much of the water vapor and carbon dioxide in earth's atmosphere and therefore get clearer readings from Mars. Houck et al. (1973) found that the soils on Mars were around 1 percent H_2O by mass, though still could not pinpoint the exact form.

In addition to all of the challenges related to interference from Earth, performing infrared spectrometry on the Martian poles has the extra difficulty of the poles' constant change. The polar caps recede and grow on short timescales due to the massive temperature swings on the planet, and the actual composition of the Northern ice caps fluctuates as well between carbon dioxide ice and water ice. The first observations of the Northern cap through infrared spectrometry done on Earth came in 1952. At first, the Northern cap appeared to be an even mix of carbon dioxide and H_2O ice; however, it was soon discovered that H_2O made up the majority of the ice thanks to the recognition of an absorption pattern where 1.5 um light was prominently absorbed, a feature unique to H_2O ice (Kuiper 1952). The Southern polar cap was first observed 20 years after the Northern in 1972 and was quickly deemed purely carbon dioxide ice (Larson and Fink, 1972) – a claim that holds until today.

These studies were done at a time of year when the ice at the caps was receding. It should be noted that the amount of carbon dioxide ice at the caps varies with the season. As temperatures rise, the ice carbon dioxide ice sublimates directly into carbon dioxide gas, skipping over the liquid phase, because of the low surface pressure on Mars. Because carbon dioxide has a lower freezing point that H_2O, it was found that there is H_2O ice year-round at the Northern pole, but only carbon dioxide ice in the North when temperatures are low enough (Clark and McCord, 1982).

Studying Mars from Earth has some obvious challenges and limitations. With the invention and application of infrared spectroscopy and various other remote sensing techniques, we were able to discover a remarkable amount about the Red Planet. However, breaking through the clouded and controversial information we had to arrive at a clear, more concise version of Mars was only possible with the use of spacecraft. Using the instruments that worked well from Earth, and putting them very near or even on the surface of Mars was the step we needed to get to the next level.

Summary of Missions to Mars

A great transition in our research and knowledge of Mars took place with the first successful missions to Mars. Up until the 1960s, the vast majority of work relating to Mars involved guesswork with interpreting absorption lines or horribly blurry photos. We thought we knew a lot about the Red Planet, but we soon found out otherwise. Estimates of the surface minerology, atmospheric composition, surface pressure, topography, and conditions were all both inaccurately described and insufficiently described. With the first missions, however, we began to literally get a clearer picture of Mars. Throughout this section, I will highlight the early successes in space exploration that allowed us to know Mars as we do today.

During the Cold War, the United States and the Soviet Union competed militarily and technologically for decades. Luckily, this competition extended to space exploration and included research on Mars. Throughout the 1950s and 1960s, many missions from both sides failed miserably. Some missions did not even attempt to leave Earth due to complications before launch. Others did not successfully exit Earth's orbit on their way to Mars. Still some managed to start their journey but not reach Mars, and closest of all, some missions made it to Mars but lost communication in the process.

The first big time success was the United States' Mariner 4 which reached Mars in 1965 after an eight-month flight through space. Mariner 4 flew by Mars, taking certain measurements and performing experiments, and then continued on to orbit around the sun for a couple of years before we finally lost contact with it (Leighton et al., 1965). Mariner 4 was able to provide new, exciting information about the surface and atmosphere of Mars that will be discussed later in this paper. The next big success came in 1971 with the United States' Mariner 9, which was able to orbit Mars for about a year. Whereas Mariner 4 provided some novel information and changed the way we thought about Mars, Mariner 9 seemed to bombard us with information critical to the understanding of the planet. Armed with both ultraviolet and infrared spectrometers and high-power cameras, Mariner 9 gave us precise details about the surface through over 7000 photographs and transmissions of large hordes of information (McKay, 1984).

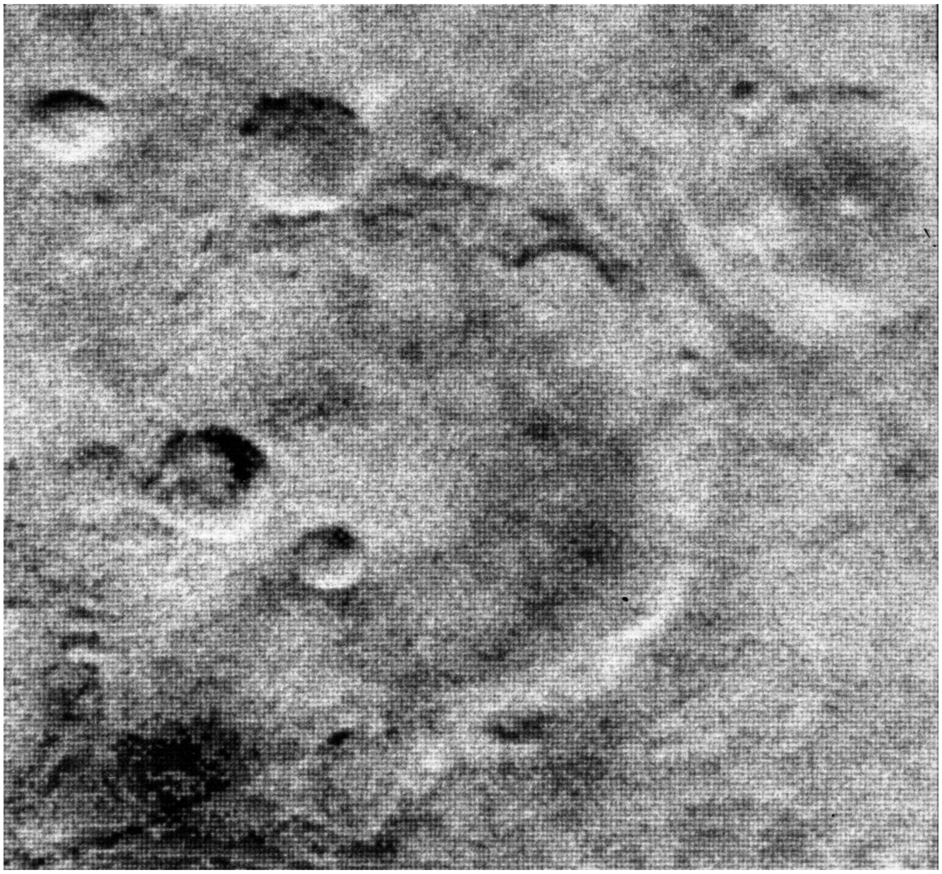
Post Mariner, the United States' Viking missions gave us our next update on the Red Planet. Not only did Vikings 1 and 2, which arrived at Mars in 1976, each enter orbit, but they also each successfully landed spacecraft onto the surface. (This was not the first time a lander made it to the Martian surface. The USSR had landers on Mars in 1971 and 1973, but in one instance their communications failed and in another they were only able to provide a small amount of data.) Though Vikings did not dramatically change the way that we viewed Mars, which had happened with Mariner 9, they did give us massive improvements in our data. In every category, Vikings greatly improved upon what we had learned from Mariner 9. We had better pictures, more surface area covered, and better details of the atmosphere and surface (Snyder and Moroz, 1992).

Since the 1970s, there have been more than 20 space exploration attempts to study Mars, many of which have been successful. Each mission and each country that sends a mission has had a different goal, but in general, the focus is on gaining a deeper understanding of the planet's geologic history, current atmospheric and mineralogical conditions, and potential habitability. In 1996, the United States successfully landed the first mobile lander, or "surface rover," called Sojourner. Since 2012, the United States' rover called Curiosity has been travelling the surface of the Red Planet in search of microbes or evidence of their past existence. Numerous orbiters are still circling Mars taking high resolution photos and precise measurements (see "A Chronology of Mars Exploration").

Research from Space Exploration

In 1965, data from the Mariner 4 flyby caused a large shift in the way people thought about Mars. It was clearly known before the flyby that there was carbon dioxide in the Martian atmosphere, but most believed carbon dioxide to be only a small component of the overall atmosphere – clearly an assumption born from the fact that the carbon dioxide is only a very small part of Earth's atmosphere. The Mariner 4 flyby, however, measured the total surface pressure on Mars to be only about 5 mbar, drastically less that the 80 to 100 mbar estimate beforehand (Kliore et al. 1965). With this knowledge, scientists began analyzing Mars with a newfound perspective, and it was quickly found that almost all of the air in the Martian atmosphere was carbon dioxide (Young, 1971).

Besides revealing the low atmospheric density on Mars, Mariner 4 made one other important discovery. Flying between 17000 km and 12000 km from the Martian surface, Mariner 4 was able to take 22 photos of Mars that covered about one percent of the planet's surface. In these photographs were about 70 craters, some over 100 km in diameter and some only a few kilometers in diameter (Leighton et al., 1965). This was significant for a number of reasons. First of all, almost nobody thought that Mars would be cratered, so it was a shock (Snyder and Moroz, 1992). A highly-cratered surface indicates a number of assumptions about the past, but we will get to those later. In addition, whereas the telescopic observation of Mars from Earth allowed scientists to describe the surface of Mars as "dark" or "light" (Slipher, 1962), Mariner 4 provided the first knowledge of some actual topography to discuss.



A Picture from the Mariner 4 mission showing the cratered surface

Details of the topography were increased many fold with NASA's next successful mission, Mariner 9. In fact, Mariner 9 made such progress with our knowledge of the Mars that some deemed the planet "The New Mars" (Hartmann and Raper, 1974). With over 7000 photos, around 80 percent of the surface was photographed and at a much better resolution than Mariner 4. The clarity of the new maps made from Mariner 9 was such that the 22 photos and 70 craters from Mariner 4 were made inconsequential.

Much better resolution for pictures from Mariner 9

With the new imagery in 1971, we essentially knew exactly what the surface of Mars looked like. Mariner 9 discovered that Mars had mountains and volcanoes, the tallest being Olympus Mons – which is the biggest volcano in our solar system (Snyder and Moroz, 1992). It discovered the great system of canyons covering around 25 percent of the planet called the Valles Marineris. It found that there are two different types of surface: a younger, smoother surface of volcanoes and large plains and a very old, cratered surface. The Mariner 9 mission also discovered the valleys, channels, and riverbeds on the surface that appear to indicate flowing water in the history of Mars. Furthermore, Mariner 9 was able to observe weather and climate phenomena such as ice clouds, small dust storms, and morning fog. All of this was done through photography alone (McCauley et al., 1972).

The other instruments on board Mariner 9 were able to make even more discoveries. The infrared spectrometers took measurements of the surface pressure at numerous locations on the planet and found readings anywhere from about 2.5 mbar to 8mbar. Infrared spectroscopy also show that the dust floating around the atmosphere was around 60 percent silica. The ultraviolet spectrometer also worked to find the atmospheric pressure over many parts of the planet, and from this information, scientists were able to estimate the altitude of certain features like Olympus Mons, which was 25 km higher than the lowlands around it (Hord et al., 1972).

Several years later in 1974, the United States Vikings 1 and 2 continued to build on the details from Mariner 9 and successfully updated much of the numbers we had. Vikings were able to give the specific composition of the Martian atmosphere at 95.3% carbon dioxide, 2.7% nitrogen, and 1.6% argon (Shimizu, 1979). Additionally, the landers detected a number of trace gases in the atmosphere that had not previously been discovered. These gases included nitrogen, nitrogen oxide, argon, xenon, and krypton.

The Viking landers also told us important information about the surface composition of Mars. Instruments on board the landers first discovered that the dirt and dust around the planet is about 20 percent iron oxide or FeO by weight (Toulmin et al., 1977). This confirmed many previous ideas that the reason Mars is red is essentially from oxidized minerals, or rust. This discovery also led insight into the past of Mars. If about one fifth of the weight of the soil and dust cover on the planet includes an oxygen atom, it is logical to believe that the atmosphere of Mars used to contain higher amounts of oxygen in the past.

Shortly after the iron content estimation, both of the Viking landers were able to take direct and precise measurements of the Martian soil. These measurements provided a deep insight into the homogeneity of the surface. One of their samples was dug up from beneath the red dust coating into the rocks below. Despite the two landers being very far away from each other in different regions on the planet, the rock was incredibly similar at both sites. For example, for deep samples dug up with the “sampling arm,” one lander found SiO_2 at 44%, Al_2O_3 at 7.3%, Fe_2O_3 at 17.5%, MgO at 6%, CaO at 5.7%, and SO_3 at 6.7%. Comparatively, the other lander found 43% SiO_2, 7% Al_2O_3, 17.3% Fe_2O_3, 6% MgO, 5.7% CaO, and 7.9% SO_3 (Clark et al., 1982). The numbers are practically identical.

Since Mariner 9, space missions and research performed from Earth have made great advancements in the precision of the details we know about Mars, but there have not been many new and exciting ‘breakthroughs’. Between 1996 and 2006, for example, NASA’s Mars Global Surveyor orbiter created outstanding maps of the Martian surface including high resolution details of such features as wind-eroded rocks, valleys and channels seemingly carved by water, and volcanic landscapes (Bell, 2008) – nothing that was not already known, but still very valuable data for researchers to investigate. Additionally, NASA’s Sojourner, Opportunity, and Curiosity rovers are or were (Sojourner was only active 1996 and 1997) armed with spectrometers that have thoroughly examined the chemistry and geology of the Martian surface (Bell, 2008).

A photo of NASA's Curiosity rover on the surface of Mars

Today, the Curiosity rover, which landed on Mars in 2012, travels up to about 90 meters in a day in search of evidence for habitability on Mars (Curiosity Mission Updates). Scientists continue to search for evidence of water and life on Mars, whether it be sporadically flowing on the surface or in underwater reservoirs (NASA, 2015a), but nothing has been found for certain. Future missions, such as NASA's InSight mission set to launch in 2018 (NASA, 2015c), aim to probe the Martian interior through seismology, giving us the first completely novel information since the last Mariner mission in the 1970s. Most exciting to the general public, however, are claims of putting a human on Mars. Barack Obama was keen to remind the United States in October of 2016 of plans to have human(s) on Mars by the 2030s (https://www.theguardian.com/science/2016/oct/11/obama-mars-mission-nasa-habitats-space-travel-2030). Of course, he will have nothing to do with these plans after early 2017 when his term ends, and a lot has to go right for this to actually happen, but the claim is nevertheless thrilling.

Deconstructing Martian History

With the help of all of the research done to observe the current state of Mars, scientists are able to piece together information about the Martian past. Clues from the current mineralogy, surface features, and atmospheric conditions combined with inference from knowledge of processes here on Earth all lend help in explaining the creation of the planet and its history.

There are three distinct geologic time periods used for Mars: the Noachian, the Hesperian, and the Amazonian (e.g., Elhmann, 2014). The Noachian starts with the creation of the planet around 4.6 billion years ago (Gyr) and lasts until about 3.7 Gyr. The Hesperian takes up the longest amount of time, lasting from 3.7 Gyr to 1 Gyr, and the Amazonian period is the name for the last one billion years (Ehlmann and Edwards, 2014). Each of these periods is distinct from the other by some major, defining characteristics that we will continue to explore.

Mars is believed to have formed much the same way that Earth and other terrestrial planets in our solar system did. Before any of the planets existed, there was instead a solar nebula, or a massive cloud of dust and gas. At some point this nebula collapsed under its own weight and took on a flattened shape, which would end up becoming our solar system. While much of the mass of the nebula gravitated to the center to form the sun, other parts of the dust and gases began to attract each other and create smaller masses. As more and more of these particles collided, more energy was added to the system and the high kinetic energy from constant impacts lead to molten surfaces. The larger these masses became, the more gravity they exerted on other nearby masses, and eventually massive clumps of matter were coming together to form the planets that we are familiar with today (Sharp, 2016).

From photographic observation of Mars, we know that the planet exhibits two distinct types of surfaces: a highly-cratered, higher altitude surface in the Southern hemisphere and a smoother lowland in the Northern hemisphere characterized by plains, volcanoes, and much fewer craters. It is widely accepted that the region in the South is a very ancient surface of the Noachian time period due to the high density of craters, whereas the Northern areas are surfaces from the Hesperian and Amazonian epochs (Baker, 2001).

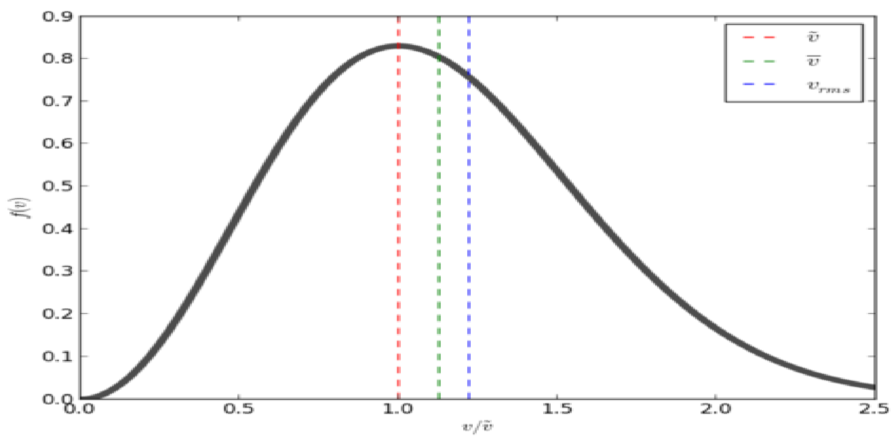
By analyzing the minerology of these different areas where the crust is exposed to the surface, we are able to deduce knowledge about the past. For example, where Noachian crust is exposed on Mars, we see the highest percentage of clay minerals. This includes both the Southern highlands and the impact basins where the Northern Amazonian and Hesperian crust is cut straight through, leaving the Noachian exposed. In these areas, we see minerals such as nontronite ($Na_{0.3}Fe_2((Si,Al)_4O_{10})(OH)_2 \cdot nH_2O$), saponite ($Ca_{0.25}(Mg,Fe)_3((Si,Al)_4O_{10})(OH)_2 \cdot nH_2O$), and chlorite ($(Mg, Fe^{2+})_5Al(Si_3Al)O_{10}(OH)_8$). All of these hydrated minerals have either water molecules or hydroxide (OH) built straight into their formulas (Ehlmann and Edwards, 2014). Additionally, only the Noachian surface displays the dendritic networks of valleys. Wherever you find areas with high densities of impact craters, you almost always find valleys carved into the surface that resemble river systems on Earth (Carr and Clow, 1981).

Hesperian and Amazonian crusts do not exhibit these same clay minerals or valleys. Instead, these areas show smoother surfaces and exhibit the normal olivine-rich basaltic rock that does not have any irregularities such as clay minerals (Ehlmann and Edwards, 2014). From this information, scientists hypothesized in the 80s and 90s that the early period of Martian history was characterized by warmer temperatures that accommodated flowing liquid water (Ehlmann et al., 2011). It is not known for sure of course that water created the valleys and channels, but it is very improbable that wind, ice, or lava created them, so water seems a likely culprit (Fanale et al. 1992). Additionally, the mechanism by which water carved the valleys came into question following the initial claim of higher temperatures and is still hotly debated. If precipitation supplied (and resupplied over many years) the water that created the valleys, then temperatures must have indeed been higher (Ehlmann et al., 2011). On the other hand, it is possible that the water was supplied through the sapping of groundwater, a process by which water exits the ground from a singular area (Fanale et al., 1992). However it happened, it is only with prolonged contact with water that these clay minerals and dendritic valley networks could have developed (Ehlmann et al., 2011).

Whether you favor a warmer or colder Martian past when explaining the presence of water, a higher surface pressure is still required to enable the liquid phase of H_2O to even exist (Lammer et al., 2013). Many scientists have proposed models of an ancient Martian atmosphere with a much more powerful greenhouse effect, including Cess, Ramanathan, and Owen (1980) and Pollack et al. (1987). They commonly cite carbon dioxide and water vapor as the two gases deemed primarily responsible for this greater greenhouse effect. There are a number of processes that could have resulted in a denser early atmosphere on Mars. At the birth of the planet, this includes the gravitational attraction of gases from the solar nebula that formed the solar system, the release of gases from the cooling of the early molten surface, and the large amounts of volatiles brought to Mars by meteors (Rafikov 2006; Lammer et al., 2013). Later on when the planet was more mature, the potential for volcanic processes to have released large amounts of gas could have continued to maintain a thicker atmosphere (Lammer et al., 2013). Using the carbon dioxide and water content of Earth magmas as a model, researchers were able to predict a Martian atmosphere that could have temporarily reached as high as 200 mbar (Craddock and Greeley, 2009).

A common question then would be how the Martian atmosphere changed so dramatically from the past to the current cold, low-pressure conditions. The answer lies with a number of atmospheric escape and sink processes. Solar wind, a process whereby charged particles discharged by the sun interact with and excite gas molecules in the upper Martian atmosphere, ejects over 8000 kg of atmospheric gas per day according to measurements by NASA's MAVEN orbiter (NASA, 2015b). Each planet exerts a gravitational force on its own atmosphere, but if a particle or molecule in that atmosphere has a high enough velocity, it can overcome this gravitational force a fly straight into space. Solar wind is one process that can give particles enough energy to reach this speed, which is called the escape velocity (Halekas et al., 2015).

Other processes capable of accelerating atmospheric gas to the escape velocity include dissociative recombination, Jeans escape, and impact escape. Dissociative recombination is a process by which ultra violet radiation from the sun splits up a molecule, leaving each with higher velocities than before. On Mars, it is believed that large quantities of water molecules were split this way and discharged into space (Terada et al., 2009). In addition, Jeans escape involves the fact that in a large population of like atoms or molecules, the velocities of the particles can be described by a Maxwell distribution (see below) (Volkov et al., 2011).



At the far right of the spectrum, some of the particles will have velocities much higher than the average, and in some cases this velocity can exceed the escape velocity of a planet. Lastly, impact escape is a process by which the additional kinetic energy added to a planet from the impact of a meteor is enough to shoot some fraction of the atmospheric gas into space (Barabash et al., 2007). On Mars, the escape velocity is 5 km/s (Walterscheid, Hickey, and Schubert, 2013), a speed that can be reached through all of these mechanisms.

Besides these escape processes, it is widely believed that a significant portion of the older, denser atmosphere has been siphoned into the surface. Evidence from Martian meteorites on Earth (Lammer, 2013) and in situ measurement by surface rovers (Elhmann, 2014) indicates a presence of carbonates on Mars. Carbonates, or rocks containing carbonate, are almost always formed through interaction of carbon dioxide (or carbonic acid) (Elhmann, 2014). Over time, more and more exposure between the surface rock and carbon dioxide in the atmosphere has led to more sequestration of the gas into the rock.

All of these factors are believed to explain our observations and measurements of Mars during the last 100 years; however, the majority of the Martian past is guesswork. New theories come out all the time questioning the status quo on the past of Mars (e.g., Lanza, 2016), but we cannot say anything for certain with our current evidence. On Earth, we can find concrete evidence for the planet’s history through dating techniques such as mass spectrometry (e.g., Elmore, 1987). On Mars, we have no such luxury. Only through inference and deduction can we tie our observations to the Martian past. However, as the allure of space exploration continues to thrive in modern society, I think we will see sustained efforts at research and knowledge of the Red Planet.

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