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Introduction to Mars

1.1 Historical observations

1.1.1 Pre-telescopic observations

Mars has been the focus of intense scientific interest and study throughout recorded history. Even before the advent of the telescope in 1609, astronomers carefully charted the motion of Mars across the sky. The planet's obviously reddish-orange color led many ancient civilizations to name the planet after war or warrior gods. Our current use of the name Mars comes from the Roman God of War. Large martian sinuous valleys (*vallis*) are named after the term for Mars in different languages: hence Ares Vallis (Greek name for Mars), Augakuh Vallis (Incan), and Nirgal Vallis (Babylonian).

Careful observations of Mars' motion across the celestial sphere led early astronomers to deduce two things about the planet. First they determined that Mars' sidereal period (time to return to same position relative to the stars) is about 687 Earth days (1.88 Earth years). The Polish astronomer Nicolaus Copernicus found that the sidereal period (P) of a planet located beyond the Earth's orbit is related to its synodic period (S; time for planet to return to same Earth–Sun–planet configuration) by

$$\frac{1}{P} = 1 - \frac{1}{S}. \qquad (1.1)$$

Using this relationship, we can determine that the synodic period of Mars is 2.14 Earth years.

The second thing that pre-telescopic observers noticed about Mars was its strange looping path across the sky. While planets tend to slowly travel from west to east across the background of stars over the period of several nights, occasionally they reverse course and travel east to west for a period of time before resuming their normal west-to-east motion. This retrograde (east-to-west) motion is most noticeable for planets closest to the Earth, and thus Mars' retrograde motion is apparent even to naked-eye observers. The geocentric model of the universe had extreme difficulty explaining retrograde motion, requiring the use of hundreds of small circles upon orbital circles (epicycles and deferents). However, retrograde motion was easily explained when Copernicus rearranged the view of the Solar System in 1543 by placing the Sun at the center and having Earth orbit the Sun along with the other planets. In the heliocentric model, retrograde motion results when one planet catches up to and overtakes another during their orbital motions.

Mars also played a major role in determining the shapes of planetary orbits. It was Tycho Brahe's very accurate and voluminous observations of Mars' celestial positions that led Johannes Kepler in 1609 to deduce that planetary orbits were elliptical with the Sun at one focus of the orbit. Mars has the second most elliptical orbit of the eight major planets in the Solar System – Mercury's orbital eccentricity is higher but the planet is difficult to observe due to its proximity to the Sun.

1.1.2 Telescopic observations from Earth and space

Although Galileo's small telescope was unable to reveal anything other than the reddish-orange disk of the planet in 1609, larger telescopes slowly coaxed more information from the planet. By 1610, Galileo reported that Mars can show a gibbous phase, which subsequent observers verified. The first report of albedo markings on the surface was published in 1659 by Christiaan Huygens, whose map showed a dark spot which was likely Syrtis Major. The identification of surface albedo markings allowed astronomers to determine that the rotation period of Mars was approximately 24 hours. The bright polar caps apparently were not noticed until Giovanni Cassini reported them in 1666. Cassini's nephew, Giacomo Maraldi, made detailed observations of the polar caps during several oppositions, including the favorable opposition of 1719. Among his discoveries were that the south polar cap was not centered on the rotation pole, that the polar caps and equatorial dark areas displayed temporal variations, and that a dark band occurs around the edge of the receding polar cap (which he interpreted as meltwater).

Sir William Herschel observed Mars from 1777 to 1783 and was the first to determine that Mars' rotation axis was tipped approximately 30° from the perpendicular to its orbit. This result showed that Mars experiences four seasons, similar to the Earth. Herschel also determined the planet's rotation period to be 24 hours 39 minutes 21.67 seconds. Herschel deduced the presence of a thin atmosphere around Mars based on the changes he saw in the appearance of the planet, which he attributed to clouds. These were primarily the white clouds which are now known to be composed of ice particles. The yellow dust clouds were first reported by Honoré Flaugergues in 1809.

Major advances in our understanding of Mars began in 1830 during a close approach between Mars and Earth. The first complete map of Mars was derived from observations during this time and published in 1840 by Johan von Mädler and Wilhelm Beer – this was the first map to establish a latitude–longitude system for the planet, with the zero longitude line defined through a small, very dark spot. They also refined the rotation period of Mars to 24 hours 37 minutes 22.6 seconds (within 0.1 second of the currently accepted value). Numerous drawings of Mars were made between 1830 and the early twentieth century and these drawings were gradually incorporated into maps by William Dawes in 1864, Richard Proctor in 1867, Nicolas Flammarion (1876), and E.M. Antoniadi (between 1901 and 1930). Although Proctor and Flammarion both named features on their maps, the nomenclature system currently used for martian features is based on one proposed by Giovanni Schiaparelli on his 1877 map.

Mars and Earth were very close in 1877, resulting in a surge of new discoveries. Principal among these was the discovery of Mars' two small moons, Phobos and Deimos, by Asaph Hall. High-altitude clouds were detected as white spots along the morning and evening limbs of the planet by Nathaniel Green and the first attempts to photograph the planet were also made this year by M. Gould. But it was another observation made in 1877 that would focus considerable attention on Mars for many years to come: Schiaparelli's observations of thin dark lines crossing the martian surface, which he called *canali*.

Schiaparelli reported thin dark lines crossing the martian surface, but he was unsure of their origin. As a result, he used the generic term "channel" to describe these features. A channel is a natural feature which can be formed by flowing liquid/ice, tectonics, or wind. The Italian word for channel is "canali," which unfortunately was mistranslated into English as "canal," a word that implies a waterway constructed by intelligent beings.

The discovery of these "canals" simply augmented several other observations which people felt supported the idea of life on Mars. Mars displays a number of Earth-like characteristics which were already known in the nineteenth century. Mars' rotation period is about 37 minutes longer than an Earth day, and, due to the tilt of its rotation axis, it undergoes four seasons just like the Earth. Telescopic observations had revealed the presence of polar caps and an atmosphere, although their compositions were unknown. But one of the most intriguing observations for possible life on Mars was the "wave of darkening." Telescopic observations revealed that as one hemisphere's polar cap began to recede in the spring, the region immediately surrounding the polar cap became noticeably darker. As the polar cap continued to recede into summer, the area of darkening extended towards the equator. As fall arrived and the polar cap began to increase in size, the "wave of darkening" reversed itself and the hemisphere

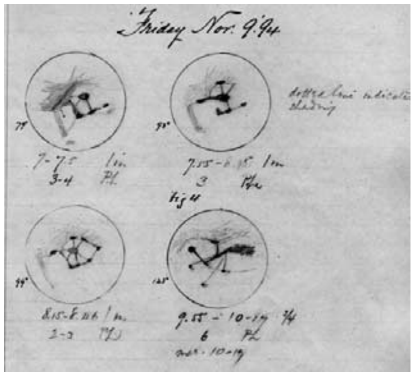

Figure 1.1 Image of the martian canals (dark lines) and putative lakes (round dots), drawn by Percival Lowell on the night of 9 November 1894. (Image courtesy of Lowell Observatory Archives.)

underwent a “wave of brightening” from the equator toward the poles. Most people attributed the wave of darkening to the melting of water ice at the polar caps in the spring and summer and the greening of surface vegetation as it absorbed this water.

Schiaparelli’s *canali* were quickly accepted as evidence that not only vegetation but also intelligent life existed on Mars. This idea was promulgated by Percival Lowell, a wealthy Bostonian who founded the Lowell Observatory in Flagstaff, AZ, in 1894 specifically to study the martian canals. Lowell observed hundreds of single and double canals using the 0.6-m Clark refracting telescope at the Observatory (Figure 1.1) and wrote several books describing his thoughts on the origin of these canals. According to Lowell, ancient Mars retained a thicker atmosphere, which led to temperate conditions on the surface, including abundant liquid water. A race of Martians arose under these conditions and settled the entire planet. But since Mars is only 52% the size of the Earth, the atmosphere gradually began to escape to space, cooling the surface and making liquid water less abundant. The Martians moved to the warm equatorial region of the planet and constructed the elaborate network of canals to bring water from the polar regions to the thirsty masses at the equator. Lowell realized that the canals themselves would likely be too small to be resolved with any Earth-based telescope, so he argued that the dark lines he observed were regions of vegetation bordering the canals. Lowell’s books and public lectures always drew large, enthusiastic crowds and many science fiction books about Martians resulted from this discussion (e.g., *The Martian Chronicles* and *The War of the Worlds*).

Most astronomers, however, were not convinced that martian canals existed. More powerful telescopes did not show dark lines but dark blotches across the surface. Scientists argued that the linear canals were optical illusions caused by the human mind "connecting the dots" when observing at the limits of a telescope's ability. Such conditions are exacerbated by the turbulent atmospheres of both the Earth and Mars. Testing of human subjects confirmed these arguments. Lowell countered that the excellent seeing at his Flagstaff site allowed him to observe features that other telescopes did not reveal. The controversy continued after Lowell's death in 1916 and the development of large telescopes such as the 5-m telescope at Palomar Observatory in California in 1948. It was only after the advent of spacecraft exploration that astronomers were able to say definitively that canals do not exist on Mars and that the "wave of darkening" simply results from the movement of dust and sand across the planet by seasonal winds.

Advances in telescope size and technology have greatly affected the quality and type of astronomical observations in recent years, and Mars studies have been one of the areas to reap these benefits. Infrared observations of Mars from Earth-based telescopes and the Hubble Space Telescope provided evidence of mineralogical variations across the surface, including the presence of hydrated minerals. The advent of adaptive optics, together with observations from the Hubble Space Telescope, have provided dramatic improvements in resolution and allow study of martian features which previously were only seen by orbiting spacecraft at Mars. Radar observations from ground-based radio telescopes have provided important constraints on surface roughness which have been important in the selection of landing sites for landers and rovers. These ground-based roughness measurements have only recently been surpassed by the acquisition of Mars Orbiter Laser Altimeter (MOLA) data from Mars orbit.

Some people argue that ground-based observations of Mars are no longer needed because of the large number of orbiters and landers currently invading the planet (Section 1.2). Nothing could be further from the truth. Ground-based observations can provide the continuous or near-continuous monitoring of rapidly changing events, such as atmospheric phenomena (including dust storm formation and propagation) and polar cap changes. Due to orbital constraints, orbiting spacecraft cannot continuously monitor one location or event each day and landers/rovers are even more restricted in their observations. The wavelengths of observation also are restricted on spacecraft instrumentation. Hubble Space Telescope observations of Mars are few due to the demand for observing time. Thus, ground-based observations still fill an important niche in our ongoing observations of Mars.

1.2 Spacecraft missions

Mars has been a major spacecraft destination ever since the early days of space exploration. This was partly driven by its proximity to Earth, but primarily this

Table 1.1 *Missions to Mars*

Mission	Country	Launch date	Type of mission	Results
[Unnamed]	USSR	10 Oct 1960	Flyby	Did not reach Earth orbit
[Unnamed]	USSR	14 Oct 1960	Flyby	Did not reach Earth orbit
[Unnamed]	USSR	24 Oct 1962	Flyby	Achieved Earth orbit only
Mars 1	USSR	1 Nov 1962	Flyby	Radio failed at 106×10^6 km
[Unnamed]	USSR	4 Nov 1962	Flyby	Achieved Earth orbit only
Zond 2	USSR	30 Oct 1964	Flyby	Passed Mars but radio failed
Mariner 3	US	5 Nov 1964	Flyby	Shroud failed to jettison
Mariner 4	US	28 Nov 1964	Flyby	Successfully flew by 14 July 1965
Mariner 6	US	24 Feb 1969	Flyby	Successfully flew by 31 July 1969
Mariner 7	US	27 Mar 1969	Flyby	Successfully flew by 5 Aug 1969
Mariner 8	US	8 May 1971	Orbiter	Failed during launch
Kosmos 419	USSR	10 May 1971	Lander	Achieved Earth orbit only
Mars 2	USSR	10 May 1971	Orbiter/lander	No useful data; lander failed
Mars 3	USSR	28 May 1971	Orbiter/lander	Arrived 3 Dec 1971; some data
Mariner 9	US	30 May 1971	Orbiter	In orbit 13 Nov 1971 to 27 Oct 1972
Mars 4	USSR	21 July 1973	Orbiter	Failed; flew past Mars 10 Feb 1974
Mars 5	USSR	25 July 1973	Orbiter	Arrived 12 Feb 1974; lasted a few days
Mars 6	USSR	5 Aug 1973	Orbiter/lander	Arrived 12 Mar 1974; little data return
Mars 7	USSR	9 Aug 1973	Orbiter/lander	Arrived 9 Mar 1974; little data return
Viking 1	US	20 Aug 1975	Orbiter/lander	Orbiter lasted 19 June 1976–7 Aug 1980; lander operated 20 July 1976–13 Nov 1982
Viking 2	US	9 Sept 1975	Orbiter/lander	Orbiter lasted 7 Aug 1976–25 July 1978; lander operated 3 Sept 1976–7 Aug 1980

Phobos 1	USSR	7 July 1988	Orbiter/lander	Lost en route to Mars
Phobos 2	USSR	12 July 1988	Orbiter/lander	Lost March 1989 near Phobos
Mars Observer	US	25 Sept 1992	Orbiter	Lost just before Mars arrival
Mars Global Surveyor	US	7 Nov 1996	Orbiter	Operated 12 Sept 1997–2 Nov 2006
Mars 96	Russia	16 Nov 1996	Orbiter/lander	Launch vehicle failed
Mars Pathfinder	US	4 Dec 1996	Lander/rover	Operated 4 July 1997–27 Sept 1997
Nozomi	Japan	4 July 1998	Orbiter	In heliocentric orbit
Mars Climate Orbiter	US	11 Dec 1998	Orbiter	Lost on arrival 23 Sept 1999
Mars Polar Lander/Deep Space 2	US	3 Jan 1999	Lander/penetrators	Lost on arrival 3 Dec 1999
Mars Odyssey	US	7 Apr 2001	Orbiter	Arrived 24 Oct 2004; still operating
Mars Express	ESA	2 June 2003	Orbiter/lander	Arrived 25 Dec 2003; orbiter operating, lander lost upon landing
Mars Exploration Rovers:				
Spirit	US	10 June 2003	Rover	Arrived 3 Jan 2004; still operating
Opportunity	US	7 July 2003	Rover	Arrived 25 Jan 2004; still operating
Mars Reconnaissance Orbiter	US	12 Aug 2005	Orbiter	Arrived 10 Mar 2006; still operating

interest resulted from the question of whether life could ever have existed on our neighbor. Even today much of the incentive for Mars exploration is driven by questions related to whether the planet could have supported life in the past or even today. NASA's mantra of "Follow the water" focuses on how water has affected the geologic and climatic evolution of the planet and its implications for biologic activity. Although there is considerable interest in exploring Mars, it has not been the easiest place to explore. Approximately two-thirds of all spacecraft missions to date have been partial or complete failures. A list of the missions which have been launched through 2006 is given in Table 1.1. These missions are described in more detail in the following sections.

1.2.1 US missions to Mars

The United States began its spacecraft exploration of Mars in 1964 when it launched the Mariner 3 and 4 spacecraft. Although both missions launched successfully, the solar panels powering Mariner 3 did not deploy and that mission ended up in solar orbit. Mariner 4 became the first successful flyby mission of Mars when it passed within 9920 km of the planet's surface on 14 July 1965. It returned 22 close-up photos, revealing a heavily cratered surface (Figure 1.2). Spacecraft instruments confirmed that Mars is surrounded by an atmosphere primarily composed of carbon dioxide (CO_2) and that this atmosphere exerted a surface pressure in the range of 500 to 1000 Pascal (Pa). Mariner 4 also reported the existence of a small intrinsic magnetic field. After its successful flyby of Mars, Mariner 4 went into solar orbit where it remains to this day.

Mariners 6 and 7 expanded upon the discoveries made by Mariner 4. Mariner 6 passed within 3437 km of the planet's equatorial region on 3 July 1969 and Mariner 7 followed on 5 August 1969, passing 3551 km over the south polar region. Mariners 6 and 7 returned over 200 pictures of the martian surface and provided measurements of the surface and atmospheric temperatures, surface molecular composition, and atmospheric pressure.

These three flyby missions returned important new information about Mars, but the amount of surface area covered by their cameras was very small and suggested that Mars was a heavily cratered, geologically dead world. That view changed dramatically when Mariner 9 entered orbit on 24 November 1971. Mariner 9 was one of two orbiters launched in May 1971, but its companion, Mariner 8, failed to reach Earth orbit. Mariner 9, along with its Soviet counterparts Mars 2 and 3 (Section 1.2.2) arrived when Mars was shrouded in a global-wide dust storm. Most of the scientific experiments were delayed because of the dust storm and the spacecraft was reprogrammed to image the two martian moons, Phobos and Deimos. By January 1972, the dust storm began to subside and Mariner 9 resumed

Figure 1.2 View of the martian surface taken by the Mariner 4 spacecraft. Craters can be seen, but little else is discernible in this image. (Image PIA02979, NASA/JPL.)

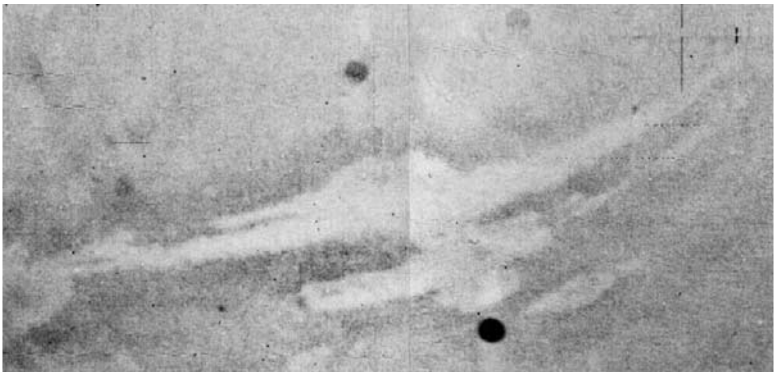

Figure 1.3 One of the first views of the Valles Marineris canyon system, taken by the Mariner 9 spacecraft as the global dust storm was subsiding. (Image PIA02998, NASA/JPL.)

its planned activities. The mission was an outstanding success and operated until 27 October 1972. Among the discoveries made by Mariner 9 were the existence of young volcanoes, canyons (Figure 1.3), and channels in addition to the heavily cratered ancient terrain; meteorological phenomena such as local dust storms, weather fronts, ice clouds, and morning fog; detailed information about the size and shape of Mars, Phobos, and Deimos; temperature gradients within the atmosphere; thermal properties of the surface and atmosphere; and better constraints on the atmospheric composition and pressure.

The discovery of channels formed by a flowing liquid, most likely water, was one of the most exciting results from the Mariner 9 mission. Although Mariners 4, 6, and 7 had unequivocally shown that liquid water cannot exist under the low pressures and temperatures present at the surface today, the channels showed that conditions

Figure 1.4 Viking 1 lander view of the surface of Mars. Viking 1 lander landed in the Chryse Planitia region within material deposited by flooding through the outflow channels. Large rock on the left ("Big Joe") is ~2 m high. Rocks and dunes/drifts are visible in this image. (Image PIA00393, NASA/JPL.)

had likely changed through martian history. With the possibility that liquid water had existed on the planet's surface, the question of life on Mars again arose. In response to this resurgence of interest in biology, NASA's next two missions, Vikings 1 and 2 (Soffen, 1977; Kieffer *et al.*, 1992), included landers which tested the soil for evidence of microorganisms. In addition to the landers, each spacecraft also consisted of an orbiter to provide detailed views of the entire planet.

The Viking 1 orbiter/lander spacecraft was launched 20 August 1975 and arrived at Mars on 19 June 1976. The spacecraft spent approximately one month imaging the martian surface to find a safe site for the lander. On 20 July 1976 (the seventh anniversary of Apollo 11 landing on the Moon), the Viking 1 lander set down at 22.48°N 312.03°E in Chryse Planitia within the outwash deposits of several large channels. The lander operated until 13 November 1982, taking pictures of its surroundings (Figure 1.4) and testing the soil for evidence of microorganisms. The orbiter was deactivated on 7 August 1980 when it ran out of attitude-control propellant.

Viking 2 was launched 9 September 1975 and went into Mars orbit on 7 August 1976. The lander set down on 3 September 1976 in the Utopia Planitia region of Mars at 47.97°N 134.26°E. The orbiter ran out of attitude-control gas and was deactivated on 25 July 1978. The lander then used the Viking 1 orbiter as a communication relay and had to be shut down when that orbiter was deactivated on 7 August 1980.

The Viking orbiters mapped the entire surface of Mars and acquired over 52000 images. They provided detailed views of the surface geology and atmospheric phenomena for about two Mars years, including the first close-up long-term view of seasonal variations. The Mars Atmospheric Water Detector (MAWD) provided