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History of telescopic observations of the Martian satellites ☆

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ABSTRACT

This article intends to review the different studies of the Mars satellites Phobos and Deimos realized by means of ground-based telescopic observations as well in the astrometry and dynamics domain as in the physical one. This study spans the first period of investigations of the Martian satellites since their discovery in 1877 through the astrometry and the spectrometry methods, mainly before the modern period of the space era. It includes also some other observations performed thanks to the Hubble Space Telescope. The different techniques used and the main results obtained for the positionning, the size estimate, the albedo and surface composition are described.

1. Discovery

Gingerich (1970, 1978) informed us that in the 18th century the belief that Mars had two moons was pervasive, and justified on the basis of analogy, or by some form of harmonic progression. The argument went like this: If Mercury and Venus have no moons, Earth has one, Jupiter has four and Saturn has five, then Mars must have two moons. Such unscientific reasoning, and the failure of astronomers to find those satellites, caused satirists, such as Voltaire and Jonathan Swift, to ridicule the scientists of the day (Gingerich, 1970, 1978; Dick, 1988).

Asaph Hall, Sr., a highly experienced and motivated satellite observer, was in charge of the Alvan Clark 26-inch "Great Refractor" (Hall, 1878) of the United States Naval Observatory (USNO), the largest refractor in the world and effectively larger (more powerful) than the Grubb or Parsons speculum reflectors. In August, 1877, at the very favorable opposition of Mars, Hall turned the giant refractor to Mars with the express goal of finding a moon or two. His unique search technique was to place Mars on the rotation axis of his micrometer, move the eyepiece along its slide so that Mars was just out of the field of view, and then rotating the micrometer head. This scheme produced a search area in the shape of an annulus a few arcmin wide around Mars but absent the "dazzling" light of the planet (Hall, 1878).

With this technique the moons were discovered quickly – when they first became visible (from behind/in front of Mars). Once the light from the planet was blocked, it was not difficult to detect them by eye. In fact they have been seen and photographed with this telescope at every opposition from the favorable opposition of 1971 through the favorable opposition of 1988 and beyond, including all "unfavorable" oppositions.

The immediate significance of the discovery: (1) An accurate mass for Mars was determined, considerably improving Newcomb′s planetary theories, (2) the smallest moons yet, suggested the presence of small (faint) moons around the other planets and motivated observers to search for them, (3) Phobos, arguably the most peculiar and interesting satellite – it orbits Mars faster than Mars rotates, rising in the West (or setting in the East) three times in a Martian day – a first in the Solar System! Another first, Phobos orbited inside the stationary orbit, motivating theoreticians to look for a secular acceleration in the longitude of the moon (see discussion on the secular acceleration below) (Fig. 1).

2. Astrometric observations

From the time of their discovery, ground-based observations (measurements) of the Martian satellites have been almost exclusively astrometric (positional) except for a handful of photometric studies.

☆This article intends to review the different studies of the Mars satellites Phobos and Deimos realized by means of ground-based telescopic observations as well in the astrometry and dynamics domain as in the physical one. It includes also some others peformed thanks to the Hubble Space Telescope.

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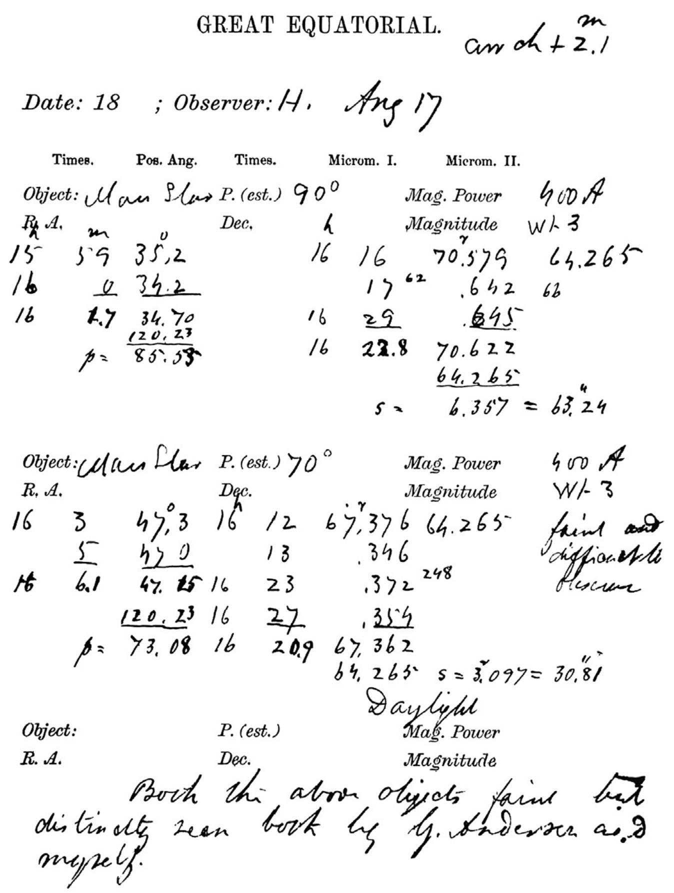

Fig. 1. Copy of the observer's logbook for the 26-inch on the night of 17/18 August 1877. Asaph Hall's comment at the bottom reads: "Both the above objects faint but distinctly seen both by G. Anderson and myself". While Deimos had been seen on the 11th, it was on the 17th that Phobos was discovered and it became clear that there were two satellites. George Anderson was the 26-inch night assistant (Courtesy USNO Library).

Observations of the satellites were carried out around the times of Martian opposition which occur on average every 26 months. Because Mars′ orbit has a significant eccentricity, Mars distance from Earth is about half the distance at a "favorable" opposition than at an "unfavorable" one. Favorable oppositions occur every 15 or 17 years.

Three distinct periods are identified based on the motivations giving rise to them and the observational techniques used.

2.1. First generation: visual observations

During the classical period, 1877–1941, visual astrometric observations were carried out, principally with the long-focus great equatorial refractors, constructed by the American optician, Alvan Clark. This included not only the USNO 26-inch, but also the Lick 36-inch, and the Pulkovo 30-inch. And it employed many of the eminent observers of the day, including Asaph Hall Sr., W. W. Campbell, and Hermann Struve. The filar micrometer was used to obtain separation and position angle measurements of each satellite relative to Mars, bisecting Mars for position angle, while making limb measurements for separation. Some observers, such as Asaph Hall, bisected Mars for both. Struve, however, advocated the use of rectangular coordinates (x,y) and tangential settings of the measuring crosshairs on the four planetary limbs as well – demonstrating their superior accuracy (Pascu, 1977, 1978).

Hermann Struve also introduced, into general practice, the measurement of intersatellite positions – the measurement of (Δx, Δy) or (ΔPA, ΔSep) of one satellite relative to another. While the advantage of such observations was obvious – the large measuring errors on the disk of the planet were eliminated – the drawbacks were more subtle. In this scheme, the conditional equations included the orbital corrections for both satellites, which increased the correlations between the parameters, especially the eccentricities of the two satellites. This affected the accuracy of the semi-major axis and, thus, the resulting mass of Mars. Struve was aware of this problem and made observations of the satellites relative to Mars (Struve, 1888, 1898).

For the Martian moons, the classical period lasted until the favorable oppositions of 1939/1941. The last micrometer observations made with the USNO 26-inch were in 1941 (there is indication that the Soviet observers made micrometric observations as late as 1970). This 70-year period produced some 3000 "quality" observations of the satellites, with an external precision of about 0.5 arcsec, and resulted in a mass for Mars accurate to 0.1%, (compared to 0.0003% from Mariners 6 &7 (Anderson et al., 1970)), accurate orbital elements for Phobos and Deimos, a value for the dynamical oblateness of Mars, a value for $J2$, and the orientation of Mars′ pole of rotation. But most interestingly, it culminated in the report of a secular acceleration in the longitude of Phobos by Sharpless (1945).

Although the secular acceleration of Phobos was a first in the solar system, it was not a surprise. Struve understood the dynamics of a satellite orbiting inside the stationary orbit of Mars. Following the favorable opposition of 1909, Struve (1911) analyzed the residuals in longitude for Phobos, looking for an acceleration. While his results were not definitive, they were suggestive. Following the favorable opposition of 1926, Harold Burton (1929) of the USNO, repeated Struve′s analysis, using the observations made with Alvan Clark′s Great Refractors. He found evidence for the secular acceleration but, apparently, was not confident enough in his results to claim it. Plans were made for observations at the favorable opposition of 1939. Photographic observations were made by Bevan Sharpless with the USNO 40-inch Ritchy-Chretien while Burton made visual micrometer observations with the 26-inch. The observations were continued at the oppositions of 1941 and 1943. The photographic effort apparently was not very successful as there is no record of the observations, neither published nor in manuscript form. Part of the reason must have been the weather in 1939 since only one visual observation was recorded. Since Sharpless used Washington observations from both 1939 and 1941 in his new analysis, some of the 1939 photographic observations must have been used. In his 1945 paper, he reported an acceleration in the longitude of Phobos as +0.001882 deg/yr^2. Burton, in a memorandum to the Superintendent of the USNO (dated 9 August 1944) claimed that the reported acceleration was a confirmation of his own 1929 results. The irony is that Sharpless apparently did not believe that his (Sharpless) results indicated a true acceleration, but rather, part of a long period term in the longitude of Phobos (Reuning, 1981).

In the ensuing years, theoretical studies failed to find a plausible explanation for the acceleration, such as atmospheric drag or tidal effects (Burns, 1972), thus, the analysis and observations which led to those results became suspect. In the mid 1960 s, G. Wilkins, director of HMNAO (Her Majesty′s Nautical Almanac Office), reanalyzed all the observations, including the few Mt. Wilson 60-inch photographic observations made in 1956. He included an acceleration term in the solution for each satellite. Although Wilkins (1967, 1970) found a significant secular acceleration for Phobos, he also found a number of irregularities in the solutions. In particular, he found that an orbital fit to observations over a single opposition gave an rms residual of $\pm$ 0.3 arcsec, but when fit to the complete set of observations, the rms increased to $\pm$ 0.5 arcsec. Wilkins interpreted this to indicate that the Struve orbital theory was inadequate. His successor, Sinclair (1972), improved the theory, but it had little effect on the residuals, indicating systematic errors in the observations. Sinclair also found a well determined solution for the secular acceleration in Phobos′ longitude, but discovered that various subsets of the observations gave

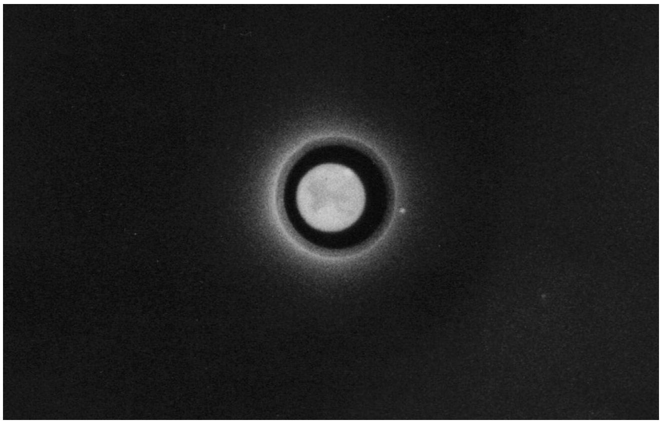

Fig. 2. Photographic plate of the Martian moons taken with the USNO 26-inch in 1988. In this image, (N down, E right) the moons are NE of Mars. The image of Mars, behind the metallic Nichrome filter, shows features such as the south polar cap and the Syrtis Major region. (Courtesy D. Pascu, USNO).

incompatible values for the acceleration. Wilkins and Sinclair concluded that the observations were not accurate enough for reliable solutions for the orbits and the accelerations of the satellites and made a request for new observations.

2.2. Second generation: photographic observations

While photographic observations of the Martian satellites were first made at the end of the 19th century, photographic methods never replaced or superceded the visual technique until the opposition of 1956, when it was replaced by default, not by the precision of those photographic observations. There simply was no longer any interest in pursuing visual observations. The photographic observations had already been shown to be superior in other satellite systems, but the Martian satellites had more serious problems detrimental to good astrometry than, say, the Galilean or Saturn satellite systems (Pascu, 1978). Mars was brighter relative to its satellites than Jupiter was to the Galileans or Saturn was to its satellites, and Phobos and Deimos were closer to Mars than most other satellites were to their primary. Consequently, Phobos was always buried in the halo surrounding Mars. In a shorter exposure, Phobos would be well exposed on a light halo, but Deimos would be barely visible. On a longer exposure, Deimos would be well exposed, but Phobos would be lost in the halo. In the visual technique, the eye could accommodate this large dynamic range, although not without consequences. In addition, both satellites could be observed for only about half the time, so intersatellite observations would be limited (Fig. 2).

The solution was to reduce the brightness of the planet to that of the satellites by applying exposure interruption techniques or filter techniques – both used in photographic parallax studies. The interruption technique used by Kanaev (1970) with the Pulkova 26-inch refractor was a vibrating slit. The residuals for these observations were quite good (0.3 arcsec) but they do not appear to have been continued. Russian astronomers experimented with other techniques aimed at measuring the position of the image of Mars to obtain planet satellite coordinates. Their most successful photographic observations were made in 1988, at Maidanak, in Uzbekistan, in support of the Russian PHOBOS project. About 1000 exposures of the Martian system were taken with a 1 m Ritchey-Chretien telescope (Bugayenko et al., 1990). A new reduction of these plates was made using secondary reference stars (Evstigneeva et al., 1992). Right ascension and declination coordinates in the FK5/J2000.0 system were reported for 660 positions for Phobos and 639 positions for Deimos (Kudryavtsev et al., 1992). In the orbital adjustment of Lainey et al. (2007), the satellites′ coordinates were combined with the Martian ephemeris to obtain coordinates relative to the planet. The resulting rms residual $\pm$0.19 arcsec was good, but had systematic displacements in both RA and Dec, similar in values for both satellites. Jacobson (2010), however, used 1198 intersatellite positions in his orbital adjustment, with a post-fit rms of $\pm$0.12 arcsec, apparently avoiding the systematic displacements. Filter techniques were used at USNO by Pascu (1975, 1977, 1978) with the 61-inch in Flagstaff, Arizona, and with the 26-inch refractor in Washington. A very small, partially transparent thin metallic film of NiChrome was deposited in the center of a yellow (Schott GG14) filter, placed 1 mm in front of the photographic plate in the plateholder (camera). The image of Mars was measureable, making it possible to obtain astrometric positions for the satellites even when only one satellite was visible. When both satellites were visible, planet-satellite as well as intersatellite positions could be obtained. These observations were continued at every opposition from 1967 to 1997, with the exception of 1993 (poor weather). Most of these photographic plates have been measured, reduced and used in all spacecraft reconnaissance of the Martian system. The external precision (rms residual from definitive orbit) of these observations was about 0.15 arcsec. Efforts are underway to digitize and remeasure these plates by the Institut de Mécanique Céleste et de Calcul des Ephémérides (IMCCE) and the Royal Observatory of Belgium (ROB).

Photographic observation of the Martian satellites increased at the favorable opposition of 1988 in support of the Russian PHOBOS mission and then effectively ended, due not only to the termination of production of photographic plates by Kodak, but also by the introduction of CCDs which were ideal for the observation of faint satellites close to their primaries. In fact CCD observations were already reported for the opposition of 1988.

This short-lived second generation lasted only a little more than 20 years but it produced about 3000 observations for each satellite. The external precision of these data vary widely, but for the long-focus instruments, it was between 0.1 and 0.2 arcsec, which was a considerable improvement over the visual technique. In addition to supporting the US and Soviet space reconnaissance of the red planet for those years, the secular acceleration in the longitude of Phobos was well established as +0.001270 deg/yr^2, including volumes of improved photographic, CCD, and spacecraft data. But, Morley (1989) finds a value of +0.001398 deg/yr^2 for ground-based observations only, and +0.000132 deg/yr^2 from the Mariner and Viking data only. Combined, Morley finds +0.001271 deg/yr^2, in agreement with the current value (Lainey et al., 2007; Jacobson, 2010) and about 33% smaller than that reported by Sharpless.

2.3. Third generation: CCD observations

The CCD detector is well suited to making observations of faint satellites near their primary, especially satellites embedded in the halo of the planet. The scattered light in the halo can be reduced with a Lyot type coronagraph. Furthermore, since the CCD frame is digital, the halo light can be modeled and removed when centroiding the satellite image. And since the CCD response is linear, the systematic positional error caused by the halo gradient is removed. The major drawback to the CCD for this work is its diminutive size which makes it difficult to calibrate for scale and orientation. This problem has been addressed with the introduction of larger CCD chips (10 cm) and the densification of high accuracy star catalogs (Zacharias, 2004; Zacharias and Gaume, 2010).

For the Martian satellites, the first reported CCD observations were made at the opposition of 1988 by Jones et al. (1989) with the Kapteyn 1 m reflector on La Palma and by Colas and Arlot (1991) and Colas (1992) with the 1 m on Pic-du-Midi. Jones et al. (1989) calibrated their CCD using the wide double 61 Cygni and measured the position of Mars when possible. They reported both planet-satellite positions as well as intersatellite positions. Jacobson (2010) gives their rms residual as about 0.15 arcsec, which is better than expected for their 0.5 s integration times. Colas and Arlot calibrated their CCD with M15 for scale and orientation, and measured only intersatellite positions. Their rms residual, based on the Chapront–Touzé (1990) orbits was 0.15–0.20 arcsec, but on the Jacobson (2010) orbits, their rms residual was 0.24 arcsec. The small difference is due, most likely, to the larger and more current data set.

At the next favorable opposition in 2003, the USNO 1.55 m astrometric reflector with a Lyot-type coronagraph and 800×800 Texas Instruments CCD were used to obtain over 400 intersatellite observations. A portion of the Pleiades cluster was used to determine the scale of the CCD images and star trails were used for orientation. The rms residual relative to both Jacobson′s orbits, as well as Morley′s was 0.06 arcsec (Rohde et al., 2004).

It is not possible to identify specific quantities or contributions of the CCD observations alone to the knowledge of the parameters of Mars or its moons because all observations – visual, photographic, CCD and spacecraft observations are now used in global solutions. However, it is clear that, despite the short exposures, the CCD observations have been a major step forward in precision for the Martian satellites. Part of this was due to the more southern latitude of the telescopes used and to their greater altitude compared to those of the photographic or visual observations; the deleterious effects of the atmosphere were reduced. Part was also due to the greater signal-to-noise ratio, and finally to the ability to remove the effects of the planetary halo – instrumentally as well as computationally. The problem of CCD size has been addressed, but the problem of short exposures will be more problematic. Since the satellites/planet move fairly rapidly, exposures longer than 5 sec are counterproductive. However, combining astrometric residuals (O-C)′s over short intervals may prove useful. CCDs will be the method of choice for ground-based astrometric observations for the Martian moons for years to come.

3. Physical characterization

3.1. Size determination

An exhaustive effort was made by Pickering (1879a, 1879b) in 1877 and 1879 to determine the sizes of the satellites with the Harvard 15-inch refractor. Several types of photometers were used since the problems posed were unique and difficult. And since the eye was the detector in those photometers, several experienced observers, including Pickering, participated in the observations in order to reduce personal errors. Pickering′s technique was to compare the brightness of the satellites directly to the light from Mars coming through a pinhole in a piece of foil placed over the planet′s focal image. From the measured diameter of the pinhole and the photometer reading, the difference in magnitude between the satellite and Mars was derived. From this magnitude difference and the absolute magnitude of Mars, the absolute magnitude of the satellite was obtained. Pickering combined this magnitude with the geometric albedo of Mars, resulting in diameters of 12 and 10 km for Phobos and Deimos respectively. The value for Deimos, 10 km, was not far from the modern equivalent elongation (*x*-section in orbit plane) diameter of 12.5 km, and the correct geometric albedo would have brought it even closer. However the value for Phobos was far from the equivalent elongation diameter, 22.2 km, and the correct albedo would not have made much difference. The problem was with the photometry of Phobos. The actual difference in V magnitude between Phobos and Deimos is in the range 1.0–1.2 mag. Pickering′s photometry found only 0.3 mag! Pickering understood that the halo surrounding Phobos due to the red light of Mars and the out-of-focus blue light of the refractor could make the image of the Phobos appear fainter due to contrast with the background. He also considered what effect the color difference of the artificial Mars star and Phobos would be. A Purkinje-like effect might make Phobos appear brighter. To examine the effect of the background, Pickering flooded the field around the artificial star with light of different colors and intensities. He concluded that illuminating the field around the artificial star was more important for Phobos than for Deimos, and pointed out the observer′s (Pickering) notes on one set of “discordant” measurements: “illuminated field brighter and browner than before”. He could not account for the large deviation and unfortunately dismissed the measurements. Ironically, that set would have given him the correct result.

The first photoelectric photometry of the satellites was performed by Kuiper at the favorable opposition of 1956 (Harris, 1961). His results are listed in the table below. Combining the $V(1,0)$ for Phobos and Deimos with the geometric albedo of Deimos determined by Zellner (1972) from polarization measurements, yields equivalent elongation diameters of 19.2 km for Phobos and 11.0 km for Deimos. With the Zellner and Capen (1974) revised magnitudes, the equivalent elongation diameters are 21.0 km for Phobos and 13.0 km for Deimos. This is much closer to the actual values of 22.2 km and 12.5 km for Phobos and Deimos respectively, and as well as can be determined solely from ground-based observations.

Before accurate diameters were derived from Mariner 9 images of the satellites, Smith (1970) found an image of Phobos transiting Mars in one Mariner 7 frame. His measurements yielded an $18\ \text{km} \times 22\ \text{km}$ cross-section perpendicular to the long axis of the synchronously rotating satellite, and an improved albedo of 0.065. With these new data, the longest axis could be computed. Using the ground-based $V(1,0) = 11.9$ for Phobos results in a long axis of 26.6 km, compared to 26.8 km measured on Mariner 9 images.

3.2. Physical properties

Telescopic observations of physical properties of the Martian satellites started with photometric measurements in the visible (UBV filters). Later, they focused on spectroscopy, mostly in the visible/near-IR range, but also with some thermal IR data. A few polarization measurements and radar observations were also performed in various periods. Being an easier target from the ground, Deimos has been observed more often than Phobos.

Telescopic observations of the Martian satellites are actually so difficult that the first reference spectra were acquired from orbit by the early Mars missions: Mariner 9 and Viking orbiters (Pang et al., 1978, 1980) and Viking landers (Pollack et al., 1978). The composite spectra of Phobos and Deimos by Pang et al. (1978, 1980) in particular were interpreted as similar to powdered carbonaceous chondrites (flat in the visible range, with marked drop-off below 0.4 μm). The strong UV drop-off in the 0.2–0.3 μm range, although not observed in meteorites spectra, is observed on samples irradiated with protons to simulate solar wind effects (e.g. Shkuratov et al., 1986). Together with the low density of Phobos and Deimos, this led to the “carbonaceous chondrite asteroid paradigm” for the Martian satellites, which still largely dominates today, although successive Martian missions (as well as most telescopic observations) provided data which are largely inconsistent with it: Phobos 2 (Murchie and Erard, 1996), Mars Pathfinder (Murchie et al., 1999), MRO (Fraeman et al., 2012).

Carbonaceous chondrites are not thought to condense in the primitive nebula so close to the Sun, therefore such a composition implies an origin as a captured body. Alternatively, Britt and

Pieters (1988) pointed out that the spectra may be equally consistent with black chondrites (i.e. ordinary chondrites darkened by optical mechanisms affecting the regolith), which might be consistent with a formation of the two bodies at the distance of Mars.

Analysis of the Phobos-2 data showed that Phobos is not spectrally uniform. This fact has important consequences regarding ground-based observations, which are never spatially resolved and may mix units with different spectra and albedos. It seems that the early composite spectrum of Pang et al., 1978 actually mixed measurements from different areas, and did not represent the spectrum of any particular area of Phobos.

The first photoelectric measurements of the Martian satellites were performed by G. Kuiper in 1956 (reported by Harris, 1961) This led to a first estimate of the reduced visible magnitudes $V(1,0)=12.1$ for Phobos, 13.3 for Deimos, yielding a geometric albedo of 0.046 in both cases (as derived by Pascu, 1973, using preliminary dimensions). The measured color index is $B-V=0.6$ for both, corresponding to a flat reflectance spectrum in the visible range.

The polarization of Deimos was measured in B filter by Zellner (1972) at Lowell Observatory. The deep negative branch and the steep positive branch of the polarization curve were found to be similar to Ceres', but different from the Moon's. This was interpreted as resulting from a significant surface coverage by dark dust or powder.

Pascu (1973) analyzed photographic plates of Phobos acquired in 1967 at Flagstaff. The geometric albedo was estimated in V band through careful reduction processing, under several assumptions. The simplest one yields a value of 0.061 for Phobos and 0.070 for Deimos.

Refined UBV photometry of both satellites was performed by Zellner and Capen (1974). This provided geometric albedos in V band of $p=0.065$ for both satellites, which were later recomputed using refined dimension estimates to be $p=0.05\pm0.01$ (Phobos) and 0.06 ± 0.01 (Deimos) (Veverka and Burns, 1980). These values were considered to be the most reliable ones in the successive years, mostly due to the large uncertainties affecting the absolute calibration of space-borne instruments. The retrieved albedos are very low, and identify Phobos and Deimos as some of the darkest objects in the solar System. However, they were considered consistent with either basaltic or carbonaceous chondrite materials, not discriminating between them. There are few observations of Phobos in this data set but the Deimos data provides clear evidence of phase effects, including large phase reddening and a significant opposition effect. The spectra of Deimos appeared to be unusually flat in the visible range, reinforcing the carbonaceous chondrite/C-type asteroid similarity.

In the Viking era, telescopic observations were very scarce and studies focused on morphologic analysis from resolved images. By the end of 80's though, visible and infrared spectroscopy became reliable for these objects, thanks to recent CCD-based instruments, in particular at NASA InfraRed Telescope Facility in Hawaii (IRTF) and later on HST.

UV–visible–NIR spectroscopy was first performed from Mauna Kea and reported by Lucey et al. (1989) and Bell et al. (1989). This data set encompasses the 0.3–1.1 μm range for both satellites, and the 1.2–3.2 μm range for Deimos only. The spectra were rather noisy ($S/N<45$ to 90) and affected by strong radiometric artifact (~10%). In these conditions, no absorption bands were detected, consistently with resolved observations which took place six months later from the Phobos-2 spacecraft. The observations confirmed the flat visible spectrum and indicated different UV drop-offs on the two satellites. The 3 μm hydrated minerals band was not detected at the 5–10% level on Deimos, in agreement with the first results from ISM/Phobos-2 on Phobos, indicating very small water content, if any.

Deimos spectrum, in particular its marked red slope in the 1.2–2.2 μm range, was found consistent with D-type asteroids, while the closest match to Phobos was provided by P-type 65 Cybele. Accordingly, the authors conclude to an origin as captured asteroids from the outer belt. Limited spectral variations were identified, suggesting that Deimos and Phobos could be fragments of a single body with different metamorphic zones, perhaps belonging to the Themis parent-body family which spans the range of spectral variations observed. This conclusion is to be weighted by the poor congruence of the Mauna Kea Deimos spectrum not only with the Mariner 9 UV data (Pang et al. 78), but also with following NIR spectra. The later point may indicate that data calibration was not accurate enough to address this level of detail.

The next observations were reported by Grundy and Fink (1991) in the 0.5–1.0 μm range, and cover the leading and trailing sides of Deimos. The spectra appear featureless except for a possible subdued absorption at 0.55 μm. A markedly red slope was observed, which is much steeper than any carbonaceous chondrite, C-type or P-type asteroid. No similarity was found with black chondrites either, those being usually less red with residual Fe^{2+} absorption at 0.9 μm. The only matches reported in terms of spectral slope were outer belt D-type asteroids, although Deimos appeared still redder than any known D-type object. A tentative composition dominated by dark organics and hydrated clays was proposed, albeit inconsistent with previous measurements in the 3 μm range. This assumption however is in line with later observations in the mid-IR range from the MGS and Mars-Express spacecraft (Roush and Hogan, 2001; Giuranna et al., 2011).

A first set of HST observations was acquired with the Faint Object Camera from 0.21 to 0.80 μm (Zellner and Wells, 1994). These data cover the leading side of Phobos and both sides of Deimos, plus several D and C type asteroids. Again a very red spectral slope was observed, similar to D-type asteroid 1144 Oda longward of 0.45 μm. The spectrum of Phobos was compared to existing space borne spectra, and was found to cover only the "bluer unit" identified in the Phobos-2 data (Murchie and Zellner, 1994). Comparisons ruled out CI/CM carbonaceous chondrites, and did not match dark ordinary chondrites or high-grade carbonaceous chondrites either. The data are not strongly discriminating however, because the 1 μm Fe^{2+} band was not covered.

A much larger set of HST observations dedicated to Phobos was later acquired by Cantor et al. (1999) using the Wide Field Planetary Camera 2. These data encompass the 0.25–1.04 μm range in 8 filters. The phase angle varies from 10.6° to 40.5°, allowing to study a large fraction of the phase function, but not the opposition effect or the normal albedo. However, the phase function is consistent with Hapke modeling of the Viking observations (Simonelli et al., 1998), which uses a normal albedo of 0.069.

The average spectrum is similar to space borne measurements of the bluer unit on Phobos. A marginal 1 μm feature was reported, suggesting possible pyroxene absorption, but no meteorite analog was identified. Although Marsshine was suspected to affect the data longward of 0.502 μm in the sub-Mars regions, spatial variations are observed which correlate with Phobos-2 observations.

Another program was later performed at IRTF using a Circular Variable Filter and a cold coronograph, encompassing the 1.65–3.5 μm range in 11 filters (Rivkin et al., 2002). This covers Deimos and the trailing/leading hemispheres of Phobos. Correction from surface thermal emission was constrained using a previous observation of Deimos by Veeder et al. (1987) at three wavelengths (4.8, 10, and 20 μm).

These observations confirm the contrasts on Phobos: significant difference of albedo is observed between the 2 hemispheres, although their average spectra are similar. Deimos appears spectrally similar to the leading hemisphere of Phobos, with a much lower albedo. The spectra are very red in the NIR range. No 2 μm

Table 1
Various historical physical characterization of Phobos and Deimos by photometry, spectroscopy and radar. $p(V)$=geometric albedo in V computed using the 26.8 km × 18.4 km X-section for Phobos and the 15.0 km × 10.4 km X-section for Deimos. V(sun)= −26.75. If the photometry was not measured in the plane of the orbits, the albedos are upper bounds.

Photometry

Source	V(1,0)	B–V	U–B	p(V)
Kuiper (Harris, 1961)	12.1 ± 0.1	0.6		0.052
Kuiper (Harris, 1961) Deimos	13.3 ± 0.1	0.6		0.055
Pascu (1973)	11.8 ± 0.1			0.069
Pascu (1973) Deimos	12.84 ± 0.05			0.084
Zellner and Capen (1974)	11.9 ± 0.2			0.063
Zellner and Capen (1974) Deimos	12.95 ± 0.05	0.65 ± 0.03	0.18 ± 0.03	0.076
Zellner (1972)				
Zellner (1972) Deimos				0.07
Veverka and Burns (1980)				0.05 ± 0.01
Veverka and Burns (1980) Deimos				0.06 ± 0.01

Spectroscopy

Source	Range	Absorptions reported	Spectral slope	Best asteroid match
Lucey et al. (1989) and Bell et al. (1989)	0.3–1.1 μm	No band (< 10%) UV drop-off		65 Cybele (P-type)
Lucey et al. (1989) and Bell et al. (1989) Deimos	1.2–3.2 μm	No band (< 10%) Hydrated minerals < 10% UV drop-off	Markedly red in the NIR	D-type
Grundy and Fink (1991), Deimos	0.5–1.0 μm	Subdued at 0.55 μm?	Markedly red in vis	D-type, but redder
Zellner and Wells (1994)	0.21–0.80 μm		Markedly red	1144 Oda (D-type)
(same as above) Deimos			Markedly red	
Cantor et al. (1999)	0.25–1.04 μm	Marginal at 1 μm	Markedly red	
Rivkin et al. (2002)	1.65–3.5 μm	No 2 μm band (< 4%) No hydrated minerals (< 5–8%)	Markedly red	Marginally D and T-type Mature lunar terrains
Lynch et al. (2007), Deimos	1–2.5 μm	none	Extremely red	

Radar

Source	Radar albedo	Retrieved regolith density	Best asteroid match
Ostro et al. (1989)	0.049 ± 0.012 (revised by Busch et al., 2007)	1.5 g/cm^3	Large C-type in Main Belt (not NEOs)
Busch et al. (2007)	0.056	1.6 ± 0.3 g/cm^3	
Busch et al. (2007) Deimos	0.021	1.1 ± 0.3 g/cm^3	

pyroxene feature was detected on Deimos or on either side of Phobos (< 4%, less than ordinary chondrites). No hydrated minerals absorption was detected at 3 μm, with an upper limit of 5–8%.

The best spectral match is provided by mature lunar terrains and heated, dehydrated carbonaceous chondrites. No Main Belt asteroid analogs were found, but some consistency with T and especially D-type asteroids was underlined. D-type asteroids lie beyond the Main Belt and are expected to possess an ice core, which would have melted at the distance of Mars and would have produced hydrated products. The very low upper limit for hydrated minerals conversely suggests that no ice core was ever present on Phobos.

Finally, Lynch et al. (2007) analyzed near- and thermal-IR spectra acquired from IRTF and Lick Observatory during the close 2003 opposition. The spectrum of Deimos in the 1–2.5 μm range appears still redder than the average ISM/Phobos-2 spectrum of the red unit from Murchie and Erard (1996), and contains no hints of a 1 μm band or any other absorption. The 3–13 μm range however could not be interpreted in terms of standard thermal model of asteroids, and provides surface temperatures much higher than physical modeling in all cases. No spectral feature were identified in this range either, whereas the thermal spectrometers on board MGS and Mars-Express clearly measured fundamental vibrational transitions, Christiansen peaks and transparency features – although their interpretation is ambiguous.

The Martian satellites were observed with radar in two occasions. The first observation by Ostro et al. (1989) was performed at Goldstone and provided a very low radar albedo (~0.049 ± 0.012, value revised afterwards by Busch et al. (2007) using a 3D shape model and a new antenna calibration), indicating a low density regolith (~1.5 g/cm^3, revised value). The radar echo more closely resembles large C-type Main Belt asteroids than NEOs. Busch et al. (2007) performed new observations of both satellites from Arecibo. Measured radar albedo was 0.056 for Phobos and 0.021 for Deimos. Near-surface regolith density was derived to be 1.6 ± 0.3 g/cm^3 (Phobos) and 1.1 ± 0.3 g/cm^3 (Deimos). Although small, these values are consistent with current mean density estimates (1.876 and 1.471 g/cm^3 respectively).

Last, it is interesting to note that Adaptive Optics observations of the Martian satellites seem not to be feasible with the current technics. A tentative AO observation of Mars was performed as a technical program in 2003 by Douté et al. (private communication) with the NACO instrument at the VLT. Phobos was to be used as a target for the wave front sensor. The program was unsuccessful because Phobos was too faint a target against the intense Mars scattered light (making it impossible to close the loop on Phobos) and because Phobos angular distance from Mars varies very quickly.

Table 1 lists values for the most important quantities resulting from the ground-based observations.

In conclusion, as we can see, Phobos and Deimos have inspired many ground-based telescopic observations and attempts of measurements since their discovery. In spite of the faint magnitude and closeness to their bright planet, ground-based astronomers were able to get estimates of the physical properties, in particular the size, albedo, and spectrum of the satellites. Compositional interpretation of spectral data were limited by more general effects resulting in very subdued spectral contrast. Such effects, perhaps related to the physical state of the surface (grain size, space weathering…), are not specific to the Martian satellites but also affect the observations of less-challenging targets such as bright asteroids.

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