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Simultaneous estimation of the masses of Mars, Phobos, and Deimos using spacecraft distant encounters

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Abstract. The masses of Mars and its satellites, Phobos and Deimos, have been estimated from the Mariner 9 and Viking 1 and 2 Orbiter tracking data. These spacecraft were sensitive to the gravitational force of Mars as well as to its satellites. Although the satellite masses are eight orders of magnitude smaller than Mars, their regular effect on the orbits of the spacecraft is evident in the tracking data and has enabled us to derive their masses simultaneously with that of Mars. Our method for estimating the satellite masses uses the many "distant encounters" of the spacecraft with these small bodies rather than the few "close encounters" used in previous studies. The mass estimate for Phobos leads to a mean density of 1530±100 kg m^{-3} based on a volume of 5748±190 km^3 (Thomas, 1993), while the mass estimate of Deimos leads to a poorly constrained mean density of 1340±828 kg m^{-3} based on a volume of 1017±130 km^3 (Thomas, 1993). Our analysis confirms, within the bounds of error, the anomalously low density of Phobos using an independent method and data set. If the result is valid within several times the estimated error (1σ), then factors other than composition, *i.e.*, porosity, a thick regolith and/or a significant interior ice content, are required to explain the observed mass of this body.

Introduction

The origin and composition of Mars' natural satellites, Phobos and Deimos, has been a subject of considerable interest since it was first realized that Phobos appeared to have an average density much lower than that of intact silicate rocks [Avanesov et al., 1989; Duxbury and Callahan, 1989a Thomas, 1993; Avanesov et al., 1991]. This information, in combination with spectral evidence [Britt and Pieters, 1988; Bibring et al., 1989; Bell et al., 1993], implied that Phobos' present physical structure is probably an assemblage of non-uniform material held together by a combination of gravity and material forces, and may indicate a possible origin as an asteroid captured by the planet during its distant past [Burns, 1992; Thomas et al., 1992]. Both objects are approximately triaxial in shape with dimensions of approximately ~13x11x9 km^3 for Phobos and ~8x6x5 km^3 for Deimos [Batson et al., 1992]. The derived densities are based largely on mass estimates obtained from orbital perturbations [Christensen et al., 1977; Tolson et al., 1977; Hildebrand et al., 1979; Williams et al., 1981; Williams et al., 1988; Kolyuka et al., 1991] and from volume estimates based on images obtained from remote spacecraft [Duxbury and Callahan, 1988; Duxbury and Callahan, 1989b Duxbury, 1991, model; Batson et al., 1992 Martian; Thomas, 1993].

Mass estimates of these small planetary bodies have generally been obtained from "flybys" of the objects by a spacecraft. They rely on being able to correctly position both the spacecraft and the natural satellite so that their relative positions are well known and the gravitational force between the objects can be computed accurately. Such opportunities for a spacecraft to pass close to another body are usually engineered and are therefore relatively infrequent. A sequence of orbital maneuvers allowed the Viking 1 Orbiter to make 17 flybys of Phobos within 350 km in February 1977. Similarly, the Viking 2 Orbiter was targeted to make a single close flyby of Deimos at a distance of 30 km on October 15, 1977 [Snyder, 1979]. The Soviet Phobos 2 spacecraft rendezvoused with Phobos, flying within 500 km for one week or 22 orbits [Kolyuka et al., 1991]. The various analyses of flyby data have provided a range of published masses (and therefore densities) of Phobos and Deimos (*cf.* Table 5), and this has motivated us to investigate the utility of an independent technique in the estimation of these masses.

We have thus determined the masses of Mars' natural satellites, Phobos and Deimos using an alternative approach -- from the many small perturbations of the orbits of the Mariner 9 and Viking 1 & 2 Orbiter spacecraft during the regular and the extended missions. In our method, the spacecraft "senses" the moons of Mars on every revolution, usually at large distances, in a regular periodic fashion over a period of a year or more from which the mass of the disturbing body can be extracted. Although based on weaker gravity forces due to the greater distance between the spacecraft and body, this approach is more tolerant of errors in the positions of the bodies involved and also benefits from the regularity of the perturbations. Further, it utilizes a completely independent data set from which to estimate the mass. Given the differences between our

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Table 1. Orbits of Phobos, Deimos, Mariner 9, Viking 1 & 2 Orbiters

Satellite	Inclination (degs)	Periapse Altitude (km)	Period (hrs)	Eccentricity	No. of Orbital Arcs
Natural Satellites					
Phobos	1.03	5846	7.65	0.0152	-
Deimos	1.83	20064	30.3	0.0002	-
Artificial Satellites					
Mariner 9	64	1600	12	0.62	32
Viking 1	38	1500	22 to 24	0.75	30
Viking 1	38	300	22 to 24	0.81	81
Viking 2	55 & 75	1500	24 to 27	0.76	18
Viking 2	80	800	23 to 27	0.80	51

method and the flyby method, it is difficult to formally determine which approach yields an inherently more accurate mass estimation. It is clear, however, that the agreement of our result for Phobos with those of previous flyby analyses gives greater confidence to these earlier estimates.

Mars' mass provides the central attracting force for both the spacecraft and the natural satellites. Phobos and Deimos, however, attract the spacecraft away from Mars and therefore affect the estimation of the mass of Mars if they are neglected in the analysis. Similarly, any error in the assumed mass of Mars might affect the results for Phobos and Deimos since the error in the mass of Mars is nearly two orders of magnitude greater than the mass of Phobos and nearly three orders of magnitude greater than the mass of Deimos. Consequently we chose to estimate the mass of Mars simultaneously with those of Phobos and Deimos. Our analysis has improved the estimates of the masses of Mars and Phobos from the Viking and Mariner 9 data, and has confirmed the very low mass of Deimos [Hildebrand et al., 1979; Williams et al., 1988].

Data Analysis

The tracking data for Mariner 9 (1971), and the Viking 1 & 2 Orbiters (1976-78) by NASA's Deep Space Network (DSN) formed the basis of our analysis. These same data were used to derive the GMM-1 gravity model for Mars [Smith et al., 1993]. We inspected the data and removed those few orbital arcs in which the spacecraft came within 350 km of either Phobos or Deimos because of their sensitivity to relative position errors. As discussed in *Smith et al.* [1993], we processed the Doppler data in arcs of four to seven days in length. We estimated the GM, or universal constant of gravitation multiplied by the mass of the body for Mars, Phobos, and Deimos. Table 1 summarizes the orbits of Phobos, Deimos, Mariner 9 and the Viking 1 & 2 Orbiters.

It is useful to characterize the distribution of "distant" encounters for each of the sets of data used in our analysis. This information is presented in Table 2. For Mariner 9, 75% of the arcs had encounters at distances of 3900 to 4800 km. The regularity of these encounters is in part due to the near 3 to 2 resonance of the Phobos and Mariner 9 orbital periods. As we will show, the regularity of this gravity signal strengthens the sensitivity of the Mariner 9 data to the Phobos GM. During the 1500 km periapse phases of the Viking Orbiter 1 & 2 missions, encounters with Phobos occurred routinely at 2000 to 3000 km, and occasionally at closer distances. After the periapse of the Viking 1 Orbiter was lowered to 300 km in March 1977, the spacecraft and Phobos orbital periods were in a shallow 14 to 43 resonance. After the change in orbital period to nearly 23.98 hours on July 1, 1977, encounter distances usually ranged from 4000 to 6000 km until the orbit geometry became more favorable in July and August 1978. In the case of the Viking 2 Orbiter, after the change in inclination to 80° in December 1976, and the concomitant lowering of periapse altitude to 800 km, encounters with Phobos most frequently ranged from 4000 to 6000 km. We emphasize that although the gravity signals at these larger distances are extremely small, they are regular, with known periods and phases, and this makes the signal detectable and recoverable.

The largest sources of error are those associated with the gravity field of Mars and with the effect of air drag on the Viking Orbiters. The *a priori* gravity model used was GMM -1 [Smith et al., 1993], a 50 x 50 spherical harmonic coefficient set. The air drag during the low altitude phases (periapse height of 300 km) of the spacecraft missions was estimated from the data but was poorly determined due to the nature of the highly eccentric orbits and their approximately 1-day periods. The difficulty of separating the atmospheric drag from the gravity signal of Mars, both of which are greatest in the periapse region of the orbit, has been discussed by *Smith et al.* [1993]. We used the Phobos and Deimos ephemerides as computed by *Jacobson et al.* [1989].

Table 2. Distribution of Phobos and Deimos Encounters for Mariner 9 and Viking Orbiter Arcs

Spacecraft Data Set	Phobos Encounter Distance (km) Minimum / Mean / Maximum	Deimos Encounter Distance (km) Minimum / Mean / Maximum
Mariner 9	3970 / 4640 / 13100	5175 / 8590 / 18210
Viking-1 1500 km	1050 / 3200 / 6950	2820 / 8790 / 16500
Viking-1 300 km	940 / 4310 / 10690	1250 / 10120 / 22975
Viking-2 1500 km	820 / 3250 / 5400	7900 / 11320 / 17160
Viking-2 800 km	2450 / 4950 / 10350	850 / 7755 / 21050

Table 3. Estimated Masses of Mars, Phobos, and Deimos

Satellite	Periapse Altitude (km)	GM, Mars (km^3s^{-2})	GM, Phobos ($10^{-3}km^3s^{-2}$)	GM, Deimos ($10^{-3}km^3s^{-2}$)
Mariner 9	1600	42829.345 ± 0.568	0.562 ± 0.065	0.157 ± 0.101
Viking 1	1500	42828.402 ± 0.052	0.539 ± 0.046	0.061 ± 0.072
Viking 1	300	42828.232 ± 0.071	1.172 ± 0.871	1.053 ± 0.849
Viking 2	1500	42794.088 ± 17.42	0.728 ± 0.088	0.267 ± 0.253
Viking 2	800	42832.054 ± 4.85	0.770 ± 0.580	0.103 ± 0.291
Combined Solution	-	42828.350 ± 0.042	0.587 ± 0.033	0.091 ± 0.055

Results

Table 3 shows the results obtained for Mars and its natural satellites. Mariner 9, Viking 1 at 1500 km, and Viking 2 at 1500 km, all provide strong input into the Phobos mass; and Mariner 9 and Viking 1 (at 1500 km) provide the main strength of the estimate for the Deimos mass, which is a rather weak determination. That the Deimos GM estimates are less robust than for Phobos reflects the smaller signal of its perturbation in the tracking data. In addition, because of the Deimos orbital period of 30.3 hours (compared to approximately 24 hours for the Viking Orbiters), in a given data arc the Deimos perturbation is not only smaller, but is sampled less frequently. For the 300 km Viking 1 orbits, the effects of air drag and the need to estimate a drag coefficient for each orbital arc, reduce the sensitivity of the data to the Phobos GM.

Table 4 shows the results obtained by us and other investigators for the masses of these bodies. Generally, there is little disagreement about the GM of Mars. All five estimates for the GM of Phobos are within 25%, with the lowest value being obtained in this analysis. Interestingly, one of the largest values [Kolyuka et al., 1991], which was obtained from the Phobos 2 spacecraft approach to Phobos during 7 days in March of 1989, also has the smallest standard deviation. Our result is lower than the *Kolyuka et al.* value by approximately 4σ. Unfortunately, it is difficult for us to rigorously evaluate their result due to limited details in their paper concerning the description of the data or the processing. It is also worth noting that all other solutions in Table 4 for Phobos are based on the same Viking 1 flyby data while our solution is based on a combined solution of independent data from Mariner 9, Viking 1 and also Viking 2.

There is really only one other estimate (in addition to ours) for the mass of Deimos [Williams et al., 1988], which is an improvement over an earlier solution by the same authors [Hildebrand et al., 1979] based on the same data. Their result is obtained from a single Viking 2 flyby of Deimos on October 15, 1977 at a distance of about 30 km. The result appears to be of high quality but is only available in an abstract and therefore difficult to evaluate. Our result, although weak, is derived principally from Viking 1 and Mariner 9 data and agrees with the value obtained by *Williams et al.* [1988], largely because of the uncertainty of our result. We feel these two results tend to at least confirm the low mass of Deimos.

Table 5 shows the current estimates for the volumes of Phobos and Deimos derived from numerous images of these bodies obtained by visiting spacecraft. There seems to be general agreement within a few percent for the volumes of both objects.

Evaluation

The results presented in this study confirm previous estimates [Christensen et al., 1977; Williams et al., 1988; Avanesov et al., 1991; Duxbury, 1991] that the masses of the two natural satellites of Mars are much lower than that of intact silicate rock (ρ~3000 kg m^{-3}). The approach that we have taken is subject to different sources of error and uses different data than previous studies; indeed we deliberately excluded flyby data from this analysis. The density we determine for Phobos of 1530±100 kg m^{-3} and for Deimos of 1340±828 kg m^{-3} based on our combined solution for the GM's (Table 3) and the volume estimates of *Thomas* [1993] (Table 5), are less than that for even the least dense meteorites, the CI and CM chondrites [Wasson, 1974], which are not, in any case, the best spectroscopic match for the Martian moons [Britt and Pieters, 1988; Bibring et al., 1989]. A purely compositional explanation would be inconsistent with a density as low as the one we have calculated. Alternative possibilities, such as unconsolidated, ice-rich or porous interiors [Dobrovolskis, 1982; Fanale and Salvail, 1989; Fanale and Salvail, 1990;

Table 4. Comparison with Other Results

Reference	GM, Mars (km^3s^{-2})	GM, Phobos ($10^{-3}km^3s^{-2}$)	GM, Deimos ($10^{-3}km^3s^{-2}$)	Comments
Null, 1969	42828.32 ± 0.13	-	-	Mariner 4 flyby
Andersen, 1970	42828.22 ± 1.83	-	-	Mariner 6 flyby
Christensen, 1977	-	0.66 ± 0.08	-	14 Viking 1 flybys
Tolson, 1977	-	0.73 ± 0.07	-	11 Viking 1 flybys
Kolyuka, 1991	-	0.722 ± 0.005	-	5 day rendezvous
Hildebrand, 1979	-	-	0.12	1 Viking 2 flyby
Williams, 1988	-	0.85 ± 0.07	-	8 Viking 1 flybys
Williams, 1988	-	-	0.12 ± 0.01	1 Viking 2 flyby
This paper	42828.350 ± 0.042	0.587 ± 0.033	0.091 ± 0.055	"distant encounters"

Table 5. Volume Estimates of Phobos and Deimos

Reference	Phobos Volume (km^3)	Deimos Volume (km^3)	Comments
Duxbury , 1989b	-	1052 ± 250	
Duxbury, 1991	5680 ± 250	-	
Thomas, 1993	5748 ± 190	1017 ± 130	
Williams, 1988	5751	1052	Nominal values

Hartmann, 1990; Burns, 1992; Bell et al., 1993] have also been proposed. Unfortunately, our results do not resolve contrary dynamical and physical property information as to whether Phobos and Deimos formed in martian orbit or are captured asteroids.

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