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DYNAMICS AND A VOLATILE LOSS MECHANISM
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PHOBOS AND DEIMOS:
ANALYSIS OF SURFACE FEATURES, EJECTA DYNAMICS AND A VOLATILE LOSS MECHANISM

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FINAL REPORT

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TABLE OF CONTENTS

TASK I. INTERPRETATION AND ANALYSIS OF SATELLITE CRATER POPULATIONS

A. INTERPRETATION OF CRATER POPULATIONS ON PHOBOS

A significant question about the crater population on Phobos is whether it represents a production population or an equilibrium population. If it were an equilibrium population, a plausible process of crater degradation and destruction would be the effects of what I call "saturation equilibrium." This concept need not imply a geometric saturation of craters because the crater ejecta and other features of the cratering process serve to degrade and obliterate pre-existing craters before geometric saturation could be achieved. It is presently a matter of controversy about what fraction of geometric saturation is appropriate for saturation equilibrium. A variety of studies by Marcus, Schultz *et al.*, and others have demonstrated that this fraction varies from planet to planet (indeed from unit to unit) depending on the various physical parameters defining the cratering process (e.g., material properties, size of largest crater of the planet, population index of projectiles, etc.).

Several useful comparisons of the Phobos cratering data (as shown by Thomas *et al.*, 1979) with other crater density results can be made. (1) Crater densities on Phobos tend toward the -2 slope (actually closer to -1.8) on standard cumulative frequency plots, consistent with simple saturation equilibrium conditions. (2) The densities of craters on Phobos lie far below geometric saturation; moreover, they lie near but consistently below an extrapolation to small diameters of Hartmann's (1973) curve for large lunar uplands craters. This curve has been widely referred to as a reference line against which to measure crater densities, although it is generally understood that the processes governing saturation equilibrium densities of large lunar craters are different from those governing populations of different-sized craters on different bodies. (3) Although quantitative measurements have not been reported yet, it appears that all degradation states of craters are represented on Phobos - a requirement of equilibrium conditions. (4) There appear to be statistically significant differences in crater densities on different parts of Phobos (although all are with a factor of 2 of the average density) yet all have distribution slopes close to the -1.8 characteristic of the composite average for all of Phobos. (5) The steep slope predicted by Neukum and Wise (1976) for primaries at small crater diameters is not recorded on Phobos. If the observed craters represent a production rather than equilibrium population, then the Neukum and Wise "standard curve" is not applicable to Phobos; otherwise, the population is in equilibrium.

These observations are all consistent with, though not necessarily diagnostic of, saturation equilibrium. As described by Chapman and Jones (1977), the equilibrium density at a given diameter is the ratio of the cratering rate to obliteration rate times the process-dependent "amount" of obliteration necessary to remove a crater. Although the crater density on Phobos is variable and rather low compared to the Hartmann reference line, the densities are similar to, or even greater than, some small-crater populations on the lunar surface. Relative to the large-crater processes responsible for Hartmann's saturation reference line, the low densities of small craters on the moon and on Phobos could be ascribed plausibly to the greater scaled distances of ejecta redistribution for smaller craters combined with a possibly steeper slope for the production population at small sizes.

More diagnostic of equilibrium is a diameter-independent mix of crater degradation states, especially the case of a preponderance of degraded craters. This study has not quantified crater morphologies yet. But the qualitative appearance of high-resolution images of Phobos show an abundance of fresh craters in the sub-200m diameter range that appears inconsistent with some other examples of saturation equilibrium populations. (The apparent morphologies are so striking as not to be due to artifacts of image processing. But consideration of processing artifacts must be included in future quantitative studies of crater morphologies.) Larger craters do exhibit a more representative range of morphologies. Possibly episodic blanketing due to formation of the larger craters yields oscillation about a quasi-equilibrium state in the degradation states of smaller craters; the relatively fresh population might mainly reflect recratering since the last major blanketing episode. In this manner, the craters on Phobos can be deemed to be in quasi-equilibrium with the inherently episodic process of crater saturation.

Thus observations (1) through (5) can be reconciled with a kind of saturation equilibrium population, produced by a production population with a somewhat steeper slope than observed. On the other hand, one cannot rule out the possibility that the craters on Phobos represent a production function of relatively modest slope. There is no empirical knowledge about the size distributions of projectiles near Mars capable of cratering Phobos, so there is no constraint on the slope of the production function other than some rather uncertain theoretical expectations of steeper slopes. The relatively large fraction of reasonably fresh craters on Phobos combined with the relatively low density both are consistent with a distribution not substantially modified from production.

If the production population slope is near -2, then the observed density of craters approaches the maximum density possible before the probability becomes high that Phobos would be catastrophically disrupted by a large impact. The details of the relevant calculations, based on the model of Housen _et al_. (1979), are given by Thomas _et al_. (1979). Therefore a consistent interpretation for the craters on Phobos could be: (a) a production population of slope ∿ -2; and (b) the surface of Phobos was renewed by a catastrophic collision subsequent to the early heavy bombardment.

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B. PHOBOS: ABSOLUTE AGES OF CRATERED SURFACES

Let us consider the question of the age of units on Phobos by comparison with adopted cratering ages for Mars. Hartmann *et al*. (1979) adopted crater production rates on Mars of 1 to 4 times those on the moon for the last 3.4 b.y. Impact velocities on Phobos are comparable to those on Mars since the change in potential from Phobos's orbit to Mars adds little to the impacting object's velocity. The population and flux of impacting bodies has been the same as that for Mars so long as Phobos has been in orbit about Mars.

A major difficulty is scaling crater sizes between Phobos and Mars. The diameter of craters on two bodies scales as the ratio of surface gravities to the $-k$ power. Published values of k range from 0.12 to 0.25. Gault and Wedekind (1977) reported experimental values of about 0.16. If the number of impacting bodies varies roughly as D^{-2}, the cratering rate correction, Z, is given by the ratio of surface gravities to the $-2k$ power. How does one extrapolate k to very low values of g? Reference to Housen *et al*. (1979) shows that craters counted in this paper are dominated by gravity scaling if the surface layers of Phobos are very weak, but by energy scaling if Phobos is strong. Lunar and Martian craters are all predominantly in the gravity-scaling regime.

Particularly uncertain are the relative crater sizes due to different strengths of target surfaces on Phobos compared with the moon and Mars. Using the Housen *et al*. parameters for "strong" and "weak", and applying the appropriate scaling laws, we find that a given projectile forms a crater 4.9 times as large on a weak Phobos compared with a strong Mars (using k = 0.16) and 2.1 times as large on a strong Phobos. Since the correction factor Z goes as D^2, the target strength uncertainty alone introduces more than a factor of 5 uncertainty in age for the surface of Phobos.

If the crater production rate on Mars is twice the lunar cratering rate (factor of 2 uncertainty each way) then the best age for the composite surface of Phobos is about 3×10^9 years. In one extreme case (weak Phobos, k = 0.25, Martian cratering rate 4 times lunar) the observed crater densities may indicate exposure to cratering for only 1/10th the nominal duration, implying an age of 3×10^8 years. The opposite extreme (strong Phobos, k = 0.12, Martian and Lunar cratering rates equal) yields 10 times the nominal exposure, implying that the surface of Phobos dates well back into the presumed epoch of early intense bombardment.

In these comparisons, we have assumed that the lunar cratering production function is given by a power-law with slope -2 rather than by a curve having the shape observed on the lunar maria in these size ranges, which approaches a slope of -3.5 at some diameters. Lunar cratering specialists dispute whether the steep portion represents primary cratering or secondary cratering. If it is primary cratering, as argued by Neukum, then the age comparisons are confused. If the impacting populations on the different bodies have different size distributions, then the calculation is rendered meaningless. Alternatively, as discussed above, the Phobos/Deimos data represent equilibrium populations, in which case the deduced ages are lower limits.

In summary, the surface of Phobos (and also of Deimos) is quite old, perhaps 3 b.y. Ages younger than 1 b.y. as well as older ages approaching the age of the solar system are also quite possible.

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TASK II. DYNAMICAL STUDIES OF EJECTA DISTRIBUTION AND SATELLITE SURFACES

A. TRAJECTORY DYNAMICS AND EJECTA DISTRIBUTION

The surfaces of Phobos and Deimos are both heavily cratered, but differ significantly in other ways. Deimos apparently has been blanketed with material which has partially covered many small or medium-sized craters and given the surface a rather smooth appearance. The surface of Phobos exhibits little evidence of blanketing and has a more battered appearance. If the blanketing material on Deimos is crating ejecta, it is surprising that the smaller satellite has been more effective at retaining regolith. However, the Martian satellites are small bodies located deep within a gravity well. As such, they provide an unusual dynamical environment for the ballistic transport of ejecta.

To investigate dynamical effects on ejecta transport and retention, we have developed a computer program to study the dynamics of material ejected from the Martian satellites. Each satellite is modeled as a rotating, homogeneous, triaxial ellipsoid. The gravity field of Mars is included in the calculation. Trajectories of particles ejected from a given point on the surface are determined by numerically integrating the equations of motion.

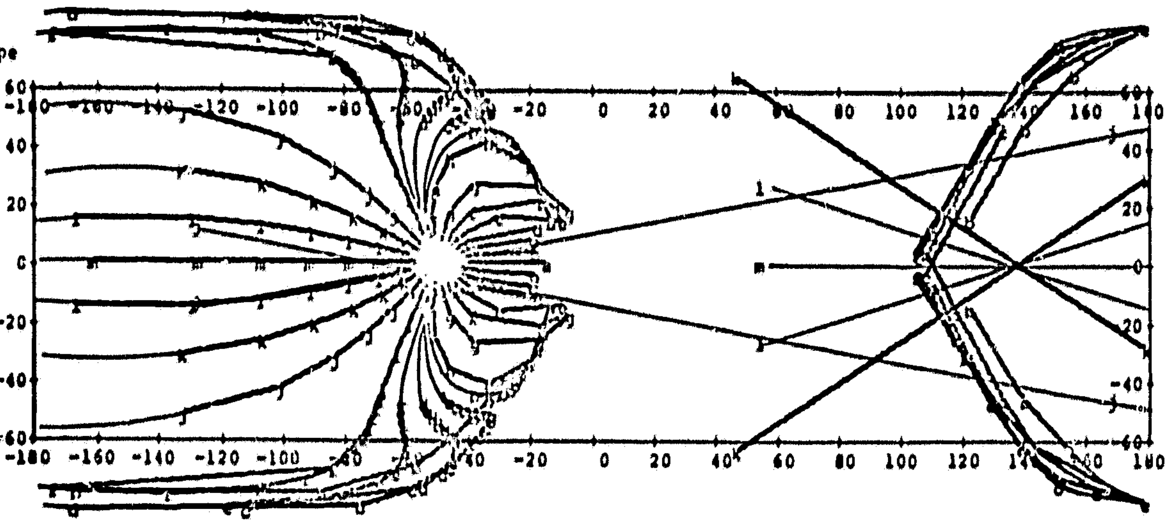
Prior to the current funding period, preliminary calculations were made to determine escape velocities for the satellites and to study the distribution of deposits produced by non-escaping ejecta (Housen et al., 1979, Appendix B.2; Housen and Davis, 1978, Appendix B.3). Escape velocities were found to depend on location on the satellite surface and on launch direction. Also, escape velocities are much more variable over the surface of Phobos than on Deimos. The modeled ejecta azimuthal distributions on Phobos are much more distorted than those on Deimos due to the proximity of Phobos to Mars. On both satellites, material is everywhere gravitationally bound to the surface.

Since the start of the present funding period, we have used our numerical program to investigate the hypothesis that at least some of the extensive sets of linear features discovered on the surface of Phobos could be the result of secondary cratering from the Stickney impact as suggested by Head and Cintala (1979). The appearance of the features ranges from nearly continuous "grooves" to strings of discrete circular pits. Studies of the surface morphology of Phobos (Thomas, 1978) demonstrated a relationship between the large crater, Stickney, and the grooves. Thomas suggests that the grooves are most likely manifestations of internal fracturing of Phobos due to the formation of Stickney. While the fracture theory for the origin of the grooves seems plausible, we should not rule out other possible modes of formation until detailed analysis can be made.

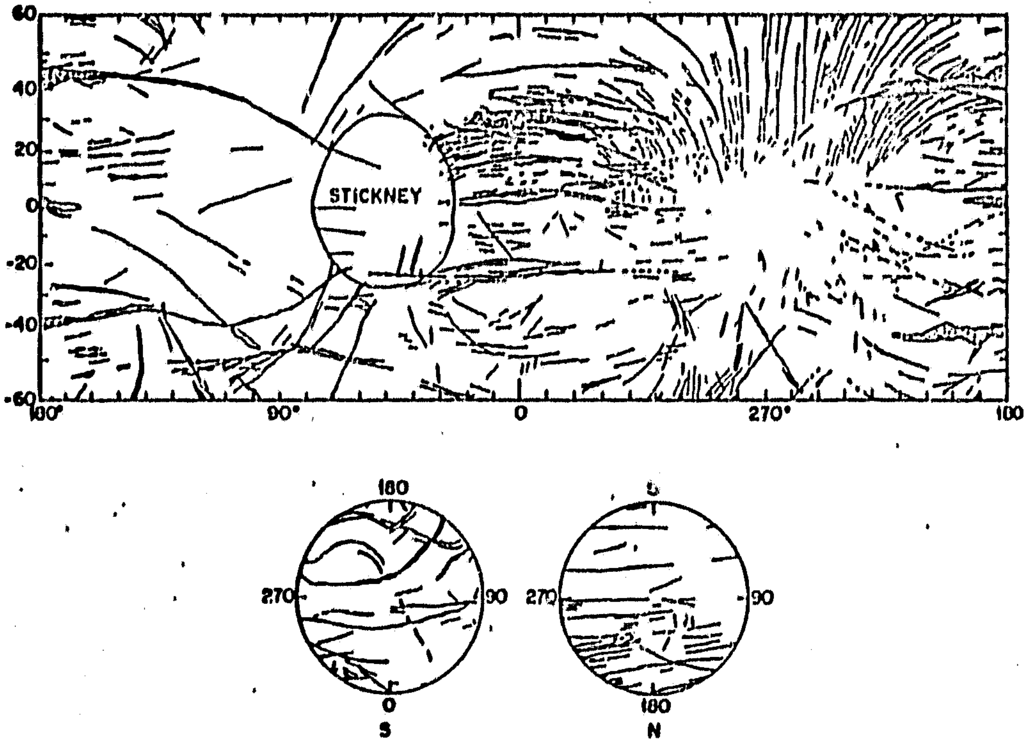
In order to simulate the formation of crater chains, we determine the impact sites of particles ejected from Stickney with different velocities. Hypervelocity impact studies by Gault show that during a cratering event the ejection velocity of particles varies while the launch elevation angle remains nearly constant. Therefore, in the program, we eject particles at a given azimuth and elevation angle with a range of velocities. Each trajectory is integrated until it impacts the surface or escapes from the satellite. The program iterates the launch velocity until the escape speed is determined to within a few percent and plots the locus of impact points for each launch azimuth. Different launch angles are used to map the total impact distribution.

Some results are shown in Figure 1a for Phobos at its present distance and spin period. The escape speeds for each azimuth angle are also shown. For comparison, a map of the observed linear features, constructed by Thomas, (1978), is shown in Figure 1b. For the most part, the program produces crater chains whose impact loci only partially resemble those observed. One striking difference between

Azimuth	vel of escape
0.0	362.50
15.0	362.50
30.0	375.00
45.0	400.00
60.0	450.00
75.0	512.50
90.0	625.00
105.0	875.00
120.0	1100.00
135.0	1100.00
150.0	1100.00
165.0	1100.00
180.0	1100.00



a) Calculated secondary impact pattern on present day Phobos



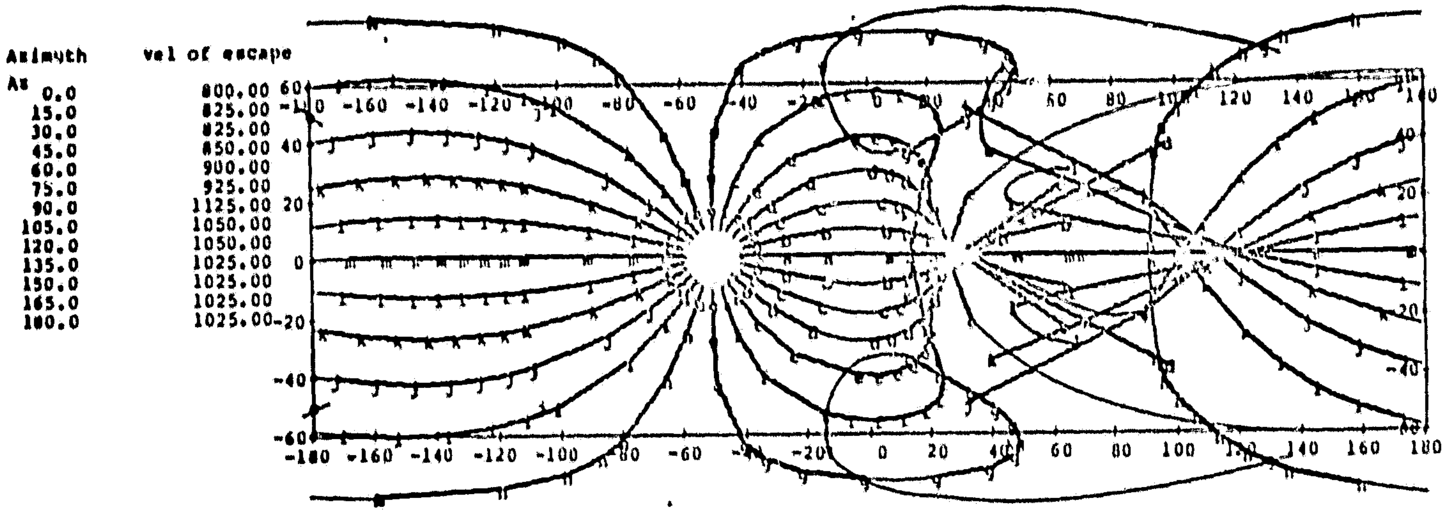
b) Observed groove distribution pattern from Thomas (1978)

FIGURE 1

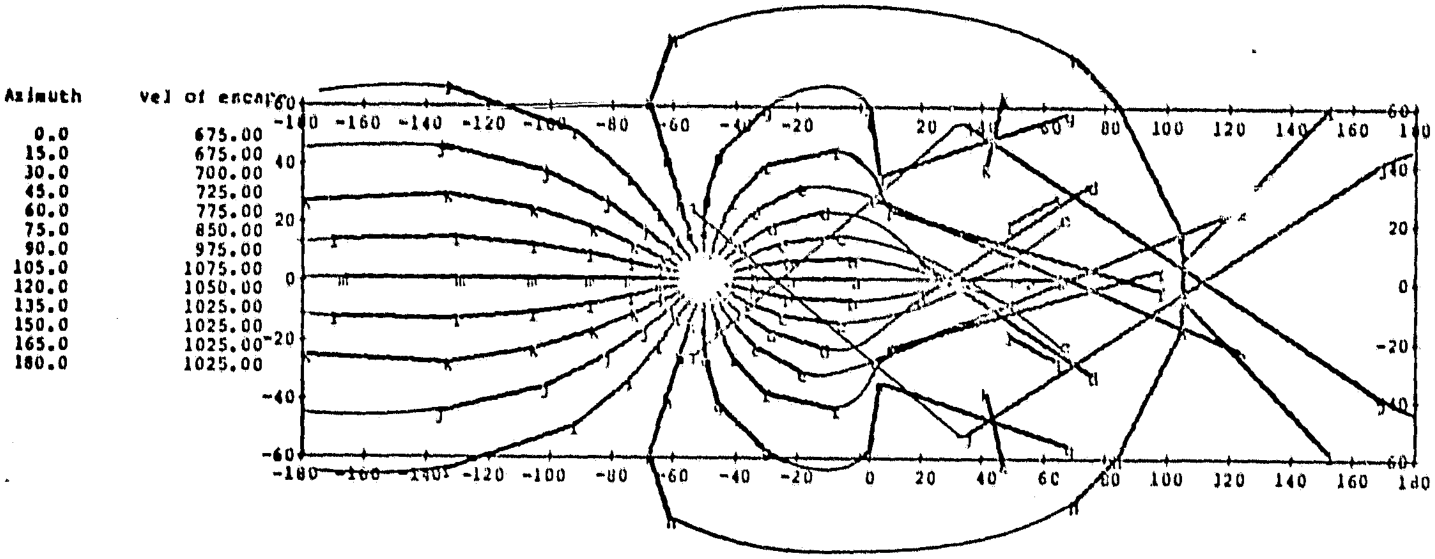
Figures 1a and 1b is the paucity of features produced by the program in the region of 270°-0° longitude.

However, formation of Stickney probably did not occur in recent times. In fact, age dating studies via crater counting by Thomas (1978), indicate that Stickney was likely formed ∿3.0 Gy ago, however, there is considerably uncertainty in this estimate (see Appendix A.4) This, coupled with the fact that Phobos is tidally evolving inward towards Mars, means that the grooves were formed when Phobos had a larger orbital semi-major axis than the current value. The range of observed secular accelerations coupled with the range of ages for Stickney means that, Phobos was likely located between the synchronous orbit distance and halfway between the present distance and the synchronous orbit distance. Calculations for these two limiting cases are shown in Figure 2. Once again, the modeled pattern of crater chains differs from the observed pattern. For example, even though features are now produced in the 0°-270° longitude region, these chains cross one another in a manner not characteristic of the features on Phobos.

Another important point to consider is the rotation rate of Phobos. Estimates of the energy involved in the formation of Stickney suggest that Phobos was probably knocked out of synchronous rotation (see Appendix A.3). We illustrate the effect of changing the rotation rate by a factor of 2



a) Phobos at synchronous orbit altitude



b) Phobos midway between current position and synchronous orbit distance

FIGURE 2

(both spinning up and slowing down Phobos) (Figure 3). The model crater chains still differ in important ways from the observed features.

In short, it would appear difficult to produce by secondary cratering, the observed pattern of grooves on Phobos when the satellite is located inside the current orbit of Deimos. However, if we consider Phobos either as a distant satellite of Mars, or a slowly rotating asteroid, a better match to the observed groove pattern is obtained (Figure 4). The near-equatorial region near longitudes 90°-100° is depleted in chains because most material escapes Phobos and only a small fraction impacts in this region. There are two subtle differences between Figure 4 and Figure 1b. (1) the void region in Figure 1b is centered on (270°-0°), while the analogous region in Figure 4 is shifted eastward roughly 10°-20°. (2) Chains on Phobos are seen to cross one another in the vicinity of 320° longitude. This overlap is not seen in Figure 3. These differences may be reconciled by spinning up Phobos somewhat.

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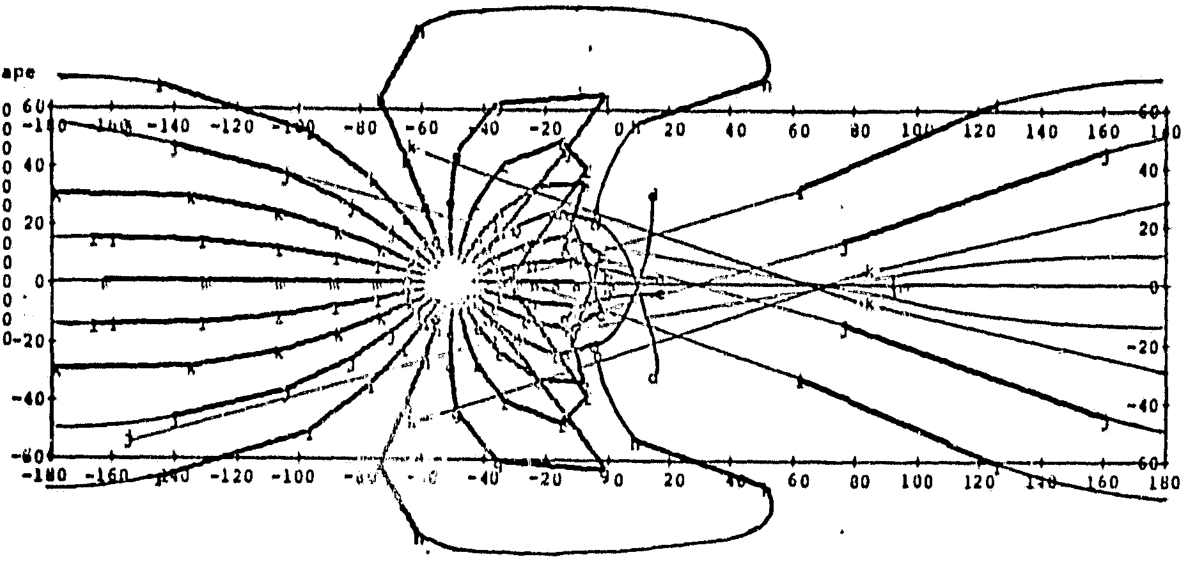
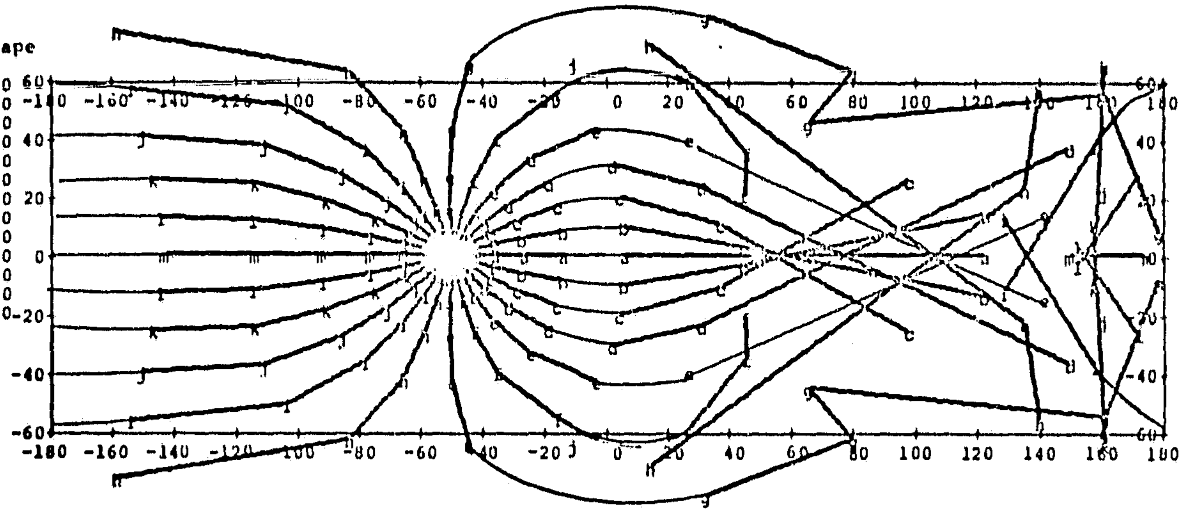
Azimuth	vel of escape
0.0	750.00
15.0	750.00
30.0	775.00
45.0	800.00
60.0	850.00
75.0	875.00
90.0	975.00
105.0	1100.00
120.0	1075.00
135.0	1075.00
150.0	1075.00
165.0	1075.00
180.0	1075.00



a) Phobos at synchronous distance with $\omega = 2\omega_{syn}$

Azimuth	vel of escape
0.0	850.00
15.0	850.00
30.0	850.00
45.0	875.00
60.0	925.00
75.0	925.00
90.0	1125.00
105.0	1050.00
120.0	975.00
135.0	1000.00
150.0	1000.00
165.0	1000.00
180.0	1000.00



b) Phobos at synchronous distance with $\omega = 1/2\omega_{syn}$

FIGURE 3

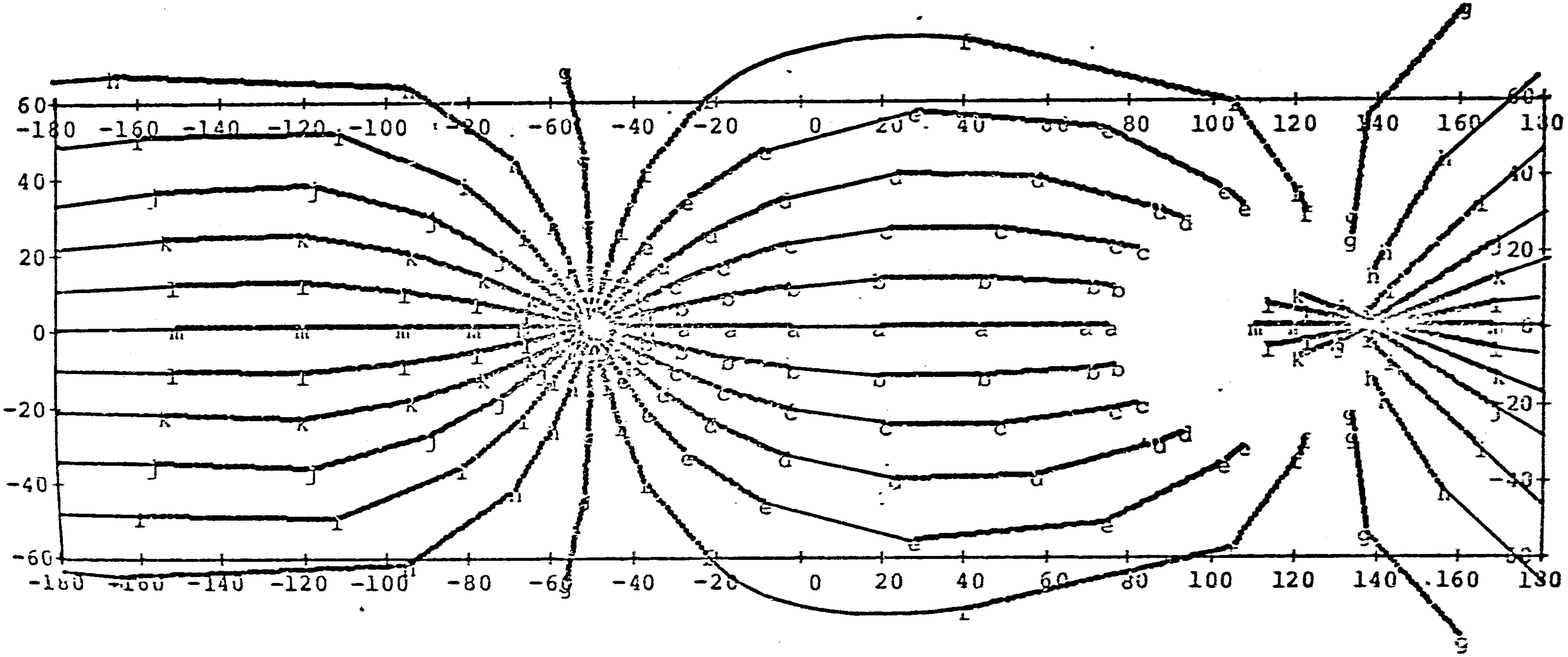


FIGURE 4. Ejecta impact loci on a slowly rotating Phobos on an independent solar orbit.

B. SATELLITE LIFETIMES

An extreme hypothesis to explain the differences in the satellite surfaces might be that Deimos was catastrophically disrupted by a large impact but subsequently reaccreted since most of its mass must have remained in orbit about Mars. Sweepup of a significant fraction of Deimos mass at low relative velocities could explain much of the blanketing of Deimos surface. This suggestion raises the question of whether it is probable that the projectile flux in the vicinity of Mars would have catastrophically disrupted either satellite since Mars formed. This calculation cannot be made with any certainty for we don't know whether Phobos and Deimos are made of strong, consolidated material or if they are materially weak and held together mainly by gravity. However, an upper bound can be set on the probability of catastrophic disruption by assuming the satellites are gravitationally bound.

The gravitational binding energy per unit mass on Phobos is 4.7×10^5 erg/gm which corresponds to an effective impact strength (the kinetic energy per unit volume necessary to disrupt a body) of 1.0×10^6 erg/cm^3, which is about a factor of 30 less than solid rock but ∿100 times that for loosely bonded regolith. In other words, Phobos would have to be made of rather strong, mostly consolidated material in order for its material strength to dominate its gravitational binding.

The equivalent impact strength for a gravitationally bound Deimos is $\sim 3 \times 10^5$ erg/cm^3, about a factor of three less than for Phobos.

The ease with which the satellites are disrupted strongly depends on the fraction of the collisional energy that is converted into the kinetic energy of fragments and ejecta. We will consider two extreme cases, one assuming all the input energy is converted, while the other assumes that only 10% goes into ejecta energy.

The impacting flux on the satellites is essentially the same as that on Mars. We estimate the probability of a catastrophic impact on the satellites in two steps. We calculate the crater size on Mars produced by a body carrying just enough energy to disrupt a satellite. Then from the density of craters equal to or exceeding the threshold size, we calculate the probability of a body hitting targets with the cross-section of the satellites. Table 1 summarizes the steps in this calculation for two limiting cases on both Phobos and Deimos. The collisional kinetic energy required to disrupt the satellites is given in Column 2, while Column 3 lists the crater diameter that this impact energy would produce on Mars. The crater scaling algorithm of Housen *et al.* (1979) is used with gravity scaling numerical coefficients, which is appropriate since $S/\rho g D << 1$ assuming reasonable geologic materials. Both strong ($S \sim 3 \times 10^7$ erg/cm^3) and weak ($S < 1 \times 10^5$ erg/cm^3)

TABLE I

	FRACTION OF INPUT KE CONVERTED TO EJECTA KE	COLLISIONAL KE FOR DISRUPTION	CRATER DIAMETER PRODUCED ON MARS C_t (km)		CUMULATIVE DENSITY OF CRATERS > C_t (km^{-2})		EXPECTED NUMBER NUMBER OF IMPACTS	
			Strong	Weak	Strong	Weak	Strong	Weak
PHOBOS	100%	3×10^{24}	6	10	$1.2\text{x}10^{-3}$- $5\text{x}10^{-4}$	$5\text{x}10^{-4}$	1.9-0.8	0.8
	10%	3×10^{25}	12	19	$3\text{x}10^{-4}$	$1.1\text{x}10^{-4}$	0.5	0.2
DEIMOS	100%	3×10^{23}	3	5	$6\text{x}10^{-3}$	$2\text{x}10^{-3}$- $6\text{x}10^{-4}$	3.0	1.0-0.3
	10%	3×10^{24}	6	10	$1.2\text{x}10^{-3}$- $5\text{x}10^{-4}$	$5\text{x}10^{-4}$	0.6-0.2	0.2

materials are considered for Mars. The fourth column gives the cumulative number of craters having diameters equal to or exceeding the corresponding threshold crater sizes from Column 3. These data were taken from counts of Neukum and Wise on the intensely cratered uplands of Mars, which are thought to be the oldest existing geologic units on Mars. The crater retention age of these areas is estimated to be 3.5-4.0 Gy, and could be as young as 1.8 Gy at the small crater diameter. If the crater populations are in equilibrium rather than production, then our calculation will yield upper bounds on the ages of the satellites.

The expected number of collisions capable of disrupting gravitationally bound satellites is of order 1 or greater if all the collisional energy is partitioned into ejecta energy and about a factor of 2 less if only 10% goes into ejecta motion. Hence, gravitational binding alone is sufficient to account for the survival of the satellites against the Mars impacting flux over the last 4 Gy. That one satellite (Phobos) probably had an impact nearly large enough to disrupt it appears consistent with the above estimates of collision frequencies. Note that the lifetime of Deimos is not appreciably less than that of Phobos even though an order of magnitude less energy is required to disrupt it; the impacting population and smaller cross-section of Deimos compensate for the lower required energy.

REFERENCE: Housen, K.R., L. Wilkening, C.R. Chapman, and R. Greenberg (1979). Icarus, in press.

C. GROOVE FORMATION ON PHOBOS

The following paper by Stuart J. Weidenschilling, published in NATURE, describes one phase of research carried out under Task II.

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[illegible]

A possible origin for the grooves of Phobos

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The surface of Phobos, the inner satellite of Mars, is marked by a series of linear depressions or grooves. These have been interpreted as surface manifestations of internal fractures[1,2]. The origin of these fractures has been ascribed to tidal stresses induced by the decay of Phobos' orbit[3], or to a nearly catastrophic cratering event[2]. I suggest here that the age and distribution of the grooves may be explained by a hybrid origin due to varying tidal stresses induced after a large impact altered the satellite's rotation rate.

The orbital decay hypothesis was suggested by Soter and Harris[3], who noted that Phobos is subjected to increasing tidal stresses as it approaches Mars. As the rate of orbital decay increases with time, this mechanism would require the grooves to be extremely young features. Later imaging at higher resolution revealed an appreciable number of impact craters superimposed on the grooves. Their implied age is $>10^9$ yr (ref. 2), effectively ruling out this explanation.

Thomas *et al.*[2] noted that the grooves are most prominent near the largest crater, Stickney, and concluded that the fractures were produced by that impact. However, the relationship of the grooves with respect to the crater is not simple. They are neither concentric nor radial to the crater; rather, they seem to define three sets of planes: one parallel to the equatorial plane, another perpendicular to the longest axis of the satellite, and a third intermediate between those two[1,2]. While crater counts show that all of the grooves have roughly the same absolute age, some of them show cross-cuttting which implies that they did not form simultaneously[1]. If the material excavated from Stickney went into orbit about Mars, it should have been re-accreted by Phobos[4]; if uniformly distributed, it would blanket the surface to a depth of about 20 m. Many of the grooves exhibit relief of <10 m without apparent mantling by debris[1], suggesting that they were formed or renewed after the bulk of Stickney ejecta had settled.

Apparently then the existence and location of the grooves are related to the Stickney impact, but they formed shortly after that event, with orientations determined by the shape of Phobos. That shape is far from spherical, resembling a triaxial ellipsoid. The present rotation period of Phobos is equal to its orbital period. The longest axis of the satellite points towards Mars; this orientation minimises the internal stresses due to the combination of topography and tidal forces. These conditions almost certainly prevailed before the formation of Stickney, as the time scale for tidal despinning is $<10^6$ yr (ref. 5). If the impact destroyed the condition of synchronous rotation, or simply induced a large libration amplitude, the changing orientation of Phobos in the gravitational field of Mars would subject its interior to periodically varying stresses. These could cause faulting along planes of maximum shear stress, producing the systems of grooves.

A quantitative estimate shows that this mechanism is plausible. In the stable synchronous state, the rotational energy is $Cn^2/2$, where C is the maximum moment of inertia and n is the mean motion. The criterion for destroying synchroneity, producing circulation rather than libration, is a change in rotational energy of magnitude $3(B-A)n^2/2$, where A and B are the moments of inertia about the other principal axes[6]. Modelling Phobos as an ellipsoid of mass 10^{19} g and semi-major axes of 13.5, 10.8, and 9.4 km, $C \simeq 6\times10^{30}$ g cm^2, and $(B-A)/C \simeq 0.25$. The change in rotational energy required to break synchroneity is, coincidentally, of the same order as the total rotational energy in the synchronous state. At present, these quantities are of the order 10^{23} erg. They vary as r^{-3}, where r is the orbital radius; as the orbit of Phobos is decaying, they may have been smaller in the past by one order of magnitude.

Thomas estimates the energy of the Stickney event at about 10^{26} erg. This figure should be regarded as having an uncertainty of at least an order of magnitude. In any case, only a small fraction of the impact energy would need to be partitioned into rotational energy of Phobos to remove it from synchroneity. For an impact energy of 10^{26} erg, at a velocity of 10 km s^{-1} and an impact parameter of 10 km, the angular momentum imparted is $\sim10^{26}$ g cm^2 s^{-1}. The present rotational angular momentum of Phobos is $\sim10^{27}$ g cm^2 s^{-1}, but varied in the past as $r^{-1/2}$. Within the uncertainties of the estimate, the change in rotational angular momentum could have been comparable to total pre-impact value. In that case, the spin axis could have been appreciably displaced from the axis of maximum moment of inertia. The resulting nutation might account for those grooves which are not aligned with the principal axes. It is unlikely that the lesser impacts which Phobos experienced could have removed it from synchronous rotation; in this sense, the Stickney event was unique.

The excess rotational energy dissipated within Phobos during despinning after the impact was much less than the impact heating, and would have been negligible if uniformly distributed. However, it was presumably released along planes of faulting, and might have aided the escape of volatiles from the grooves[1]. The time scale for despinning is $\sim10^4$–10^6 yr (ref. 5), while re-accretion of ejecta orbiting Mars would take $\sim10^2$ yr (ref. 4). Hence, it is reasonable that the grooves show no signs of burial by ejecta from Stickney.

Since Phobos shows no recent cracking in its synchronous state, the present stresses must be less than those produced during non-synchronous rotation. For a tidally stressed elastic sphere[7], the maximum tensile and shear stresses would be a few times 10^4 dyn cm^{-2} near the surface, with the centre in compression at $\sim10^6$ dyn cm^{-2}. These values are probably overestimates, as when the long axis is towards Mars, Phobos is nearer to hydrostatic equilibrium than a spherical body would be (its present shape would be almost exactly in equilibrium at 1.25 times its present distance from Mars[8]). Even though Phobos is within the classical Roche limit for a liquid satellite (as its density is less than that of Mars), the stresses within it are quite small. However, in non-synchronous rotation, the topographic relief of $\simeq 3$ km would produce shear stresses of the order of a few times 10^5 dyn cm^{-2} (ref. 9). The tidal stresses would be added to this topographic stress when the long axis of the satellite was pointed away from Mars.

The region opposite Stickney shows few grooves; therefore a shear strength $>10^5$ dyn cm^{-2} is implied for the undisturbed material. This value is consistent with a carbonaceous chondrite composition, but a stronger material cannot be ruled out. The region near the crater is presumably weaker due to fracturing by the impact, and may not constrain the properties of the pristine material. The low strength implied is for repeated loading; the yield strength under unidirectional stress may be greater. More realistic calculations of the stress field in a tidally distorted, ellipsoidal elastic body are needed to refine these strength estimates, and to determine whether the groove orientations are indeed consistent with this origin.

If the grooves are simply due to impact fractures, then such features might be common on asteroids, as predicted by Thomas *et al.*[2] If a strong tidal gravity field is also necessary, as suggested here, then only close satellites could possess regular systems of grooves. The absence of grooves on Deimos could then be due to its greater distance from Mars and smaller size, which resulted in lower stresses, or lack of an impact large enough to remove it from synchronous rotation. The best additional candidates for grooves would be Amalthea, the inner satellites of Saturn, and possibly the larger particles in planetary rings.

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TASK III. STUDIES OF VOLATILE RELEASE FROM LOW-VELOCITY IMPACTS

Work was initiated in reviewing data films obtained at Ames Research Center on impact experiments into regolith containing trapped gases. Analysis is in progress on the ability of sub-surface volatiles to displace and transport regolith, the morphology of the resulting surface features and the subsequent evolution of the displaced material. Applications of these results to the Martian Satellites and possibly to comets will be carried out in the next portion of this program.