September, 1978

(NASA-CR-157987) INTERDISCIPLINARY INVESTIGATIONS OF COMPARATIVE PLANETOLOGY Annual Status Report, 1 Oct. 1977 - 30 Sep. 1978 (Cornell Univ., Ithaca, N. Y.) 18 p HC A02/MF A01 CSCL 03B G3/91
N79-13973
Unclas
40356

CORNELL UNIVERSITY

Center for Radiophysics and Space Research

ITHACA, N. Y.

ANNUAL STATUS REPORT

to the

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

under

NASA Grant NGR 33-010-220

INTERDISCIPLINARY INVESTIGATIONS OF COMPARATIVE PLANETOLOGY

October 1, 1977 - September 30, 1978

Principal Investigator: Professor Carl Sagan

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Laboratory for Planetary Studies

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Carl Sagan
Principal Investigator

APPENDIX I

The following are summaries of papers published within the tenure of the last grant year (or in press) on scientific results supported wholly or in part by the Planetology Programs Office, NASA Headquarters, and written by personnel of the Laboratory for Planetary Studies.

(1) "Evaporation of Ice in Planetary Atmospheres: Ice-Covered Rivers on Mars," D. Wallace and C. Sagan, submitted to Icarus; abstract in "Reports of Planetary Geology Program, 1976-1977," NASA TM X-3511, and in Bull. Amer. Astron. Soc., 9, 539, 1977.

The evaporation rate of water and ice under present martian conditions involves an equilibrium between solar heating and radiative and evaporative cooling of the ice layer. The thickness of the ice is governed principally by the solar flux which penetrates the ice layer and then is conducted back to the surface. These calculations differ from those of Lingenfelter et al., (1968) for putative lunar channels in including the effect of the atmosphere. Evaporation from the surface is governed by two physical phenomena: wind and free convection. In the former case, water vapor diffuses from the surface of the ice through a laminar boundary layer and then is carried away by eddy diffusion above caused by the wind. The latter case, in the absence of wind, is similar, except that the eddy diffusion is caused by the lower density of water vapor than martian atmosphere. For mean martian insolations the evaporation rate above ice is of the order of 10^{-8} gm $cm^{-2}s^{-1}$. Thus, even under present martian conditions a flowing channel of liquid water will be covered with ice which evaporates sufficiently slowly that the water below can flow for hundreds of kilometers even with quite modest discharges. Evaporation rates are calculated for a wide range of wind velocities, atmospheric pressures, and insolations and it seems clear that at least some subset of observed martian channels may have formed as ice-covered rivers. Typical equilibrium thicknesses of such ice covers are about one meter. Ice-covered channels or lakes on Mars today may be of substantial biological interest. Ice is a sufficiently poor conductor of heat that sunlight which penetrates it can cause melting to a depth of several meters or more. Because the obliquity of Mars can vary up to some 35°, the increased polar heating at such times may cause subsurface melting of the ice caps to such a depth which corresponds to the observed lamina thickness and may be responsible for the morphology of these polar features.

(2) "Reducing Greenhouses and the Temperature History of Earth and Mars," C. Sagan (1977), Nature, 269, 224-226.

Earlier calculations of the climatic effect of an early terrestrial greenhouse in a barely reducing atomsphere (Sagan and Mullen, Science, 177, 52, 1972) are supported by recent measures of archaeotemperatures back to the Precambrian (Knauth and Epstein, Geoch. Cosmoch. Acta., 40, 1095, 1976). Comparable time dependent calculations for Mars suggest that a mild reducing atmosphere early in martian history could produce an adequate greenhouse effect to raise the planetary temperatures on the average above the freezing point of sea water and contribute to channel formation in the early history of Mars.

(3) "Particle Motion on Mars Inferred from the Viking Lander Cameras," Carl Sagan, David Pieri, Paul Fox, R.E. Arvidson, and E.A. Guinness, J. Geophys. Res., 82, 4430-4438 (1977). Abstract in Bull. Amer. Astron. Soc. 9, 535. Reprinted in "Scientific Results of the Viking Project," (Washington: American Geophysical Union).

The cameras of the Viking landers have uncovered several lines of evidence for fine particle mobility on the Martian surface, including particulate drifts, rock-associated raised streaks, and probable ventifacts. Inferred peak wind directions in both Chryse and Utopia are roughly the same and are consistent with peak winds inferred by orbiter photography. A 24° systematic offset between the direction of rock-associated streaks in the Viking 1 landing site and Mariner 9 and Viking observations of crater-associated streaks is consistent in both sign and magnitude with a Coriolis acceleration of particles entrained by high-velocity winds in the course of the production of crater-associated streaks. If a significant fraction of the impact energy upon collision goes into deformation, strain, and rupture, there should be a preferential destruction of the most easily saltated grains, which are here called kamikaze particles, and a depletion of 150-μm-diameter grains. Observations of fine particulates dumped on the VL-1 grid indicate that major saltation events occurred between sols 96 and 207 and were caused by winds of >50 m s^{-1}, normalized to the top of the velocity boundary layer. This is the first observation of saltation on another planet and a rough confirmation of the usual Bagnold saltation theory applied to another planet.

(4) "On the Nature and Visibility of Crater-Associated Streaks on Mars," J. Veverka, P. Thomas and C. Sagan, *Icarus*, in press.

R.O. Kuzmin has proposed that all crater-associated wind streaks on Mars are depositional and consist of unresolved barchan-like dunes. He claims that any streak can appear either bright or dark relative to its surroundings depending on the azimuth of the Sun relative to the streak axis and on the elevation of the Sun above the horizon. Our study of the entire Mariner 9 picture collection as well as of available Viking data lends no support to these ideas. We find that the conditions for visibility of bright and dark streaks are identical. In Mariner 9 images both types of streaks are visible for viewing angles $\varepsilon \leq 60^{\circ}$, illumination angles of $15^{\circ} \lesssim i \lesssim 75^{\circ}$, and over the whole range of phase angles covered (about 15° to 85°). There are numerous examples of dark <u>and</u> light streaks visible at the same azimuth angle of the Sun, contrary to Kuzmin's claim. There is much evidence to indicate that bright and dark streaks differ both in morphology and in character. The common ragged dark streaks are probably erosion scars, while most bright streaks probably represent accumulations of bright dust-storm fallout. There is no evidence at present that these accumulations have a barchan-like texture.

(5) "The Equilibrium Figure of Phobos and Other Small Bodies," S. Soter and A. Harris, Icarus, 30, 192-199 (1977).

The shape of a close planetary satellite is distorted from a self-gravitating sphere into a triaxial ellipsoid maintained by tidal and centrifugal forces. Using the family of Roche ellipsoids calculated by Chandrasekhar, it should be possible in some cases to determine the density of an inner satellite by an accurate measurement of its shape alone. The equilibrium figure of Phobos is expected to be the most extreme of any satellite. The shape of Phobos as observed by Mariner 9 approaches but appears not to be a Roche ellipsoid, although the uncertainties of measurement remain too large to exclude the possibility. In any case, Phobos is so small that even the low mechanical strength of an impact-compressed regolith is sufficient to maintain substantial departures from the equipotential figure. If larger close satellites, particularly Amalthea, are found to be Roche ellipsoids, their densities can be estimated immediately from the data presented.

Asteroids of size comparable to Phobos and Deimos appear to have more irregular shapes than the Martian satellites. This may reflect the absence of a deep regolith on those asteroids due to the low effective escape velocity for impact ejecta. For Phobos and Deimos, on the other hand, ejecta will tend to remain in orbit about Mars until swept up again by the satellite, contributing to a deeper equilibrium layer of debris.

(6) "Are Striations on Phobos Evidence for Tidal Stress?," S. Soter and A. Harris, Nature, 268, 421-422 (1977).

The pattern of parallel grooves on Phobos may be due to the readjustment of the satellite's figure with increasing tidal stress as the orbit evolves inward under the action of tidal friction. Subsurface permafrost would facilitate this process.

(7) "Radiation Pressure and Poynting-Robertson Drag for Small Spherical Particles," S. Soter, J.A. Burns and P.L. Lamy, in Comets, Asteroids, Meteorites: Interrelations, Evolution and Origins, A.H. Delsemme, ed., p. 121-125 (1977).

A new heuristic derivation of the radiation pressure and Poynting-Robertson drag forces is presented for particles with general optical properties; previous derivations considered only perfectly absorbing materials. The equation of motion for a particle of mass m and geometrical cross-section A, moving with velocity v through a radiation field of energy flux F, is (to terms of order v/c)

$$m\dot{v} = (FA/c)Q_{pr}\ [(1 - \dot{r}/c)\ \hat{r} - v/c]\ ,$$

where $\hat{r}$ is the radial unit vector, $\dot{r}$ is the radial velocity, and c is the speed of light. The radiation pressure efficiency factor Q_{pr} includes both scattering and absorption; it is evaluated using Mie theory for small spherical particles with measured optical properties that are irradiated by the actual solar spectrum. Very small particles (<0.01 μm) are not substantially affected by radiation forces.

(8) "Direct Imaging of Extra-Solar Planets With Stationary Occultations Viewed by a Space Telescope," J. Elliot, Icarus, in press.

The feasibility of detecting planets outside the solar system through imaging at optical wavelengths by a telescope in space is considered. The "black" limb of the moon can be used as an occulting edge to greatly reduce the background light from the planet's star. With this technique and if certain other technical requirements can be realized, a hypothetical Jupiter-sun system could be detected at a distance of 10 pc. For this system, a signal-to-noise ratio of 9 could be achieved in less than 20 minutes with a 2.4 m telescope in space. For diffraction limited optics, the required integration time is inversely proportional to the 5th power of the telescope aperture. An orbit for the telescope is described that could achieve a stationary lunar occultation of any star that would last nearly two hours, providing 6 times more integration time than required by the hypothetical Jupiter-sun example.

(9) "Exploration of the Planets: An Invited Discourse Presented Before the 16th General Assembly of the International Astronomical Union," in "Highlights of Astronomy," (Reidel, Dordecht: Holland), 4 (Part I), pp. 37-67 (1977). C. Sagan.

A discussion of comparative planetology with an emphasis on the Mars and Viking missions; and a discussion of the relation between planetology and conventional astrophysics.

(10) "Martian Surface Composition; Comparison of Remote Spectral Studies and In Situ X-Ray Fluorescence Analysis," O.B. Toon, B.N. Khare, J.B. Pollack and Carl Sagan, abstract in Reports of the Planetary Geology Program, 1977-1978, NASA TM-79729, Strom and Boyce, eds., p. 115.

X-ray fluorescence spectromotry (XRFS) by Viking has determined many of the major elements composing the surface materials on Mars, but it does not directly specify the mineralogy of the Martian surface, although it may allow mineralogy to be inferred. Many minerals have characteristic spectral features in the ir (0.7 to 50 μm). Analyses of Mariner 9 ir transmission spectra of dust in the great 1971 Martian dust storm, and analysis of Viking near-ir broadband spectrophotometry of atmospheric dust are informative about mineralogy. Here we compare mineralogy inferred from the Viking XRFS with mineralogy indicated by spectral data. The comparison is done both by taking laboratory spectra of Viking analog minerals and by calculating spectra of Viking analog mineral mixtures. We find XRFS and ir data are consistent with clays as the dominant SiO_2-containing minerals on Mars. The X-ray fluorescence data might also be consistent with the dominance of certain mafic SiO_2 igneous minerals, but the spectral data are probably inconsistent with such materials. Sulfates, inferred by XRFS, are consistent with the spectral data: indeed inferences following Mariner 9 that high-SiO_2 minerals were important on Mars may have been biased by the presence of sulfates. Calcium carbonate, in the quantities indirectly suggested by XRFS (≈ 7%), are inconsistent with the spectral data, but smaller quantities of $CaCO_3$ are consistent, as are large quantities of other carbonates. Spectral data do not exclude maghemite, but they do require opaque minerals with a near ir band structure closely resembling that of magnetite. The quantities of magnetite thus required equal those observed as soil components by the Viking magnetic experiments. Hence the spectral and magnetic data suggest magnetite as the dominant magnetic iron compound, rather than maghemite as inferred by X-ray fluorescence studies.

(11) "Small Channels on Mars from Viking Orbiter," D. Pieri, abstract in Reports of the Planetary Geology Program, 1977-1978, NASA TM-79729, Strom and Boyce, eds., p. 267.

Viking data show a rich heterogeneity of small channel morphology which may imply both a diversity of material response to the process which creates small channels and a diversity in the genetic processes themselves. Good quality imaging of channel systems in the Margaritifer Sinus region shows four distinct small channel morphology classes in that area (smooth and crenelated walled channels with V or U shaped cross sections), most likely related to differential erosion in varying lithology. Structural control varies systematically from strong (highly rectilinear graben controlled) to weak (dendritic in intercrater plains) and is likely evidence of heterogeneity of genetic processes. Interior talweg-like channel reaches have been discerned along with possible terracing. Ubiquitous flood lavas have buried the original terrain, although the higher, heavily cratered sub-regions have tended to preserve pre-existing networks. Small channel networks are observed to occur in several planimetric geometries; (a) radially inward to shallow old basins, (b) radially inward and outward on the rims of some older basins, (c) dendritic-like in inter-cratered plains and (d) occasionally allo-genous showing few or no tributaries away from "source" areas. Deposits concentric to the rim of Schiaparelli Basin correlate with the penetration of the rim by small channels and may be deltaic. Small channel networks occuring in northern high albedo terrains imaged by Viking show muting due to overlying debris blankets. Viking Orbiter images of Nirgal Vallis demonstrate that (1) slope processes are active on valley walls, including landsliding, (2) wall scalloping due to slope failure can produce alcoves which may mimic meandering, (3) debris accumulations on the valley floor indicate that any channel interior crater size-frequency distributions represent only a minimum bound and (4) headward branching valleys in the Nirgal system widen distally. Nirgal and the few other Nirgal-type channels (e.g., Neredi Vallis) may represent a unique combination of lithology and process which may not be entirely relevant to small channel formative processes generally. Although the small channels are probably the result of a spatially and temporally diverse (though ancient) erosion process in cratered terrain, they exhibit systematic branching networks extremely suggestive of either downhill overland flow of water or, perhaps more likely, subsurface erosion by wet or dry sapping.

(12) "Junction Angles of Martian Channels," David Pieri and Carl Sagan, abstract in Reports of the Planetary Geology Program, 1977-1978, NASA TM-79729, Strom and Boyce, eds. p. 268.

Small channels on Mars exhibit stream branching ratios high by terrestrial standards (5-8) implying relative immaturity of system development. However, since Shreve (1966) predicts a branching ratio of 4 for any dendritic, non-reentrant network, little more can be accomplished in this manner with regard to genetic process. A general model for tributary junction angle as a function of Shreve link-magnitude has been developed for terrestrial river and arroyo systems and has been tested for a wide range of terrains and climatic regimes. At least 1500 junction angles have been measured in about 10 major terrestrial systems at scales varying from the small Perth Amboy badlands to Landsat images of the Rocky Mountains. The fit to predicted curves is quite good at all scales, although the scatter varies. Several martian systems have been analyzed so far, including Nirgal, 3 systems in Margaritifer Sinus, and the dendritic channel system in Thaumasia. Martian networks depart in two important ways from terrestrial systems analyzed in this fashion: (1) martian systems never exhibit, for a given tributary link magnitude, mean junction angles >40° and (2) the standard deviation of martian tributary junction angles is about three times that of terrestrial networks. These data coupled with the remarkable incision of the martian either artesian or purely gravity-induced, or even dry sapping by sublimation, with little or no surface watershed development. The argument of generally shallow junction angles and inter-channel septum retention being the result of general overland flow on a very shallow surface is weakened by the lack of low magnitude tributary deflection into major trunk valleys, as is seen in terrestrial networks, even in the highly incised streams of the Colorado Plateau.

Simple scaling of the laws of flow for rivers on the Earth imply for Mars (1) that for turbulent flow the reduction in threshold velocity matches the reduction in available flow velocity due to gravity, (2) assuming that the variability of stream junction angles scales inversely as the ratio of inertial to tractive forces, that the variability of junctions angles for a given trunk-tributary magnitude ratio is gravity-independent and is both density and, indirectly, viscosity-dependent (this should apply universally for tractive erosion by fluid flow), and (3) that cavitation should be a major force in hypothetical breakout flooding based on a simple consideration of Bernoulii's Law.

(13) "Constraints on Aeolian Phenomena on Mars from Analysis of Viking Lander Camera Data," R. Arvidson, E. Guinness, C.E. Carlston, D. Pidek, K. Jones, C. Sagan and S. Wall, abstract in EOS, Volume 59, p. 313 (1978).

The Viking Landers touched-down in the northern hemisphere during the onset of northern summer. The lander cameras have been monitoring the sky and surface on a regular basis since then, providing information on the nature and rate of aeolian processes that extends over nearly a full martian year. Results that impact our understanding of aeolian dynamics on Mars are: (1) Wind-blown drifts of soil at both landing sites extend from rocks and point in a southerly direction. The southerly direction for the drifts is consistent with the direction of bright streaks seen from orbit at these latitudes and with the wind direction inferred from the Mariner 9 IR measurements near the end of the 1971 dust storm. However, Viking lander meteorology results suggest a much more complex distribution of winds. Two large "perihelion" dust storms occurred during Viking. Winds did not blow consistently from north to south at either site, during either storm. (2) Viking Lander X-ray fluorescence results and Lander camera multispectral data (0.4 - 1.1 μm) are consistent with the soils being composed of a mixture of weathering products derived from iron-rich igneous rocks. Similarities of composition and spectra at both landing sites imply that the soil has been homogenized by winds on a global scale. (3) No obvious topographic changes have been found in comparing pictures of drifts and other undisturbed areas taken on various days with the lander cameras. Soil material within one of the footpads on VL1 has been significantly scoured by winds. The material in the footpad is loose, and in addition the footpad surface slopes some 30°. Thus the shear stress needed to entrain material will be lower than that needed to erode material on a flat surface. Soil material dumped onto the lander deck has been considerably shaped by wind and by the action of subsequent dumps of soil, where the soil material impacted onto older deposits and reshaped them. Unfortunately, soil deliveries and dumps have continued throughout the mission, making it very difficult to tell if wind alone has done any of the reshaping. (4) Reference gray patch charts mounted on the lander, used for calibration of multispectral imagery, have obtained a coating of red dust. Some of the dust was blown off the charts at the onset of high winds associated with the two perihelion dust storms. That is not too surprising since the chart surfaces slope at 79° to the horizontal, and the grains must have been held largely by adhesive forces. (5) In sum, the past year on Mars has been a relatively quite one in terms of aeolian activity at the landing sites. With the exception of some wind induced redistribution of disturbed material, no obvious changes have been detected. Yet, the soil at the landing site has, in the past, been shaped in a significant way when local climatic conditions were different. One possibility is that aeolian erosion is strongly controlled by the location of the subsolar latitude at perihelion. At present that latitude is below the equator, while both landers are in the northern hemisphere.

(14) The Geology of Mars (book review), C. Sagan, Icarus, 31, 292 (1977).

The following paper was also published during the last year by Steven Squyres, then an undergraduate at Cornell; his work is now supported by this grant:

(15) 'Martian Fretted Terrain: Flow of Erosional Debris," S. Squyres, Icarus, 34, 600-613 (1978).

Viking orbital photographs of two regimes of martian fretted terrain have revealed a number of landforms which appear to possess distinct flow lineations. These range from valley floors with lineations which parallel the valley walls to debris aprons with distinctly lobate profiles and lineations which radiate outward from the source area. These features are attributed to the deformation and flow of a mass consisting of erosional particles and ice incorporated from the atmosphere. Such a flow should behave much like a terrestrial rock glacier. A plastic deformation model is presented which is consistent with the known mechanical properties of rock glaciers and with the observed features of the landforms. The valley floor lineations are interpreted as being due to compressional forces resulting from debris flowing inward from the valley walls. Climatic implications of the features are discussed.

During the past year the principal investigator was the recipient of the Pulitzer Prize for non-fiction; the NASA Medal for Distinguished Public Service; and, with many co-workers, the Newcomb Cleveland Prize of the American Association for the Advancement of Science. He received honorary doctoral degrees from the University of Wyoming, Clark University, and Whittier College; was elected President-elect of the Planetology Section of the American Geophysical Union; and continued as Chairman of the Study Group on Machine Intelligence and Robotics at NASA Headquarters, as a National Director of the American Astronautical Society, as a member of the Council of the Federation of American Scientists, and as a member of the Fellowship Panel of the John S. Guggenheim Memorial Foundation. He was also elected an honorary member of Phi Beta Kappa and a Fellow of the American Academy of Arts and Sciences. He served as Stahl Lecturer at Bowdoin College, Johnson Lecturer at Penn State, Christmas Lecturer at the Royal Institution in London, Menninger Lecturer for the American Psychiatric Association and Damon Lecturer for the National Science Teachers Association.