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INTERDISCIPLINARY INVESTIGATIONS OF COMPARATIVE PLANETOLOGY

July 1, 1975 through June 30, 1976

Principal Investigator: Prof. Carl Sagan

TABLE OF CONTENTS

The following are abstracts of papers published within
the last 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:

A. MARTIAN CHANNELS

(1) Distribution of Small Channels on the Martian Surface.
Icarus 27, 25-50 (1976).

The distribution of small channels on Mars has been
mapped from Mariner 9 images, at the 1:5 000 000 scale,
by the author. The small channels referred to here are
small valleys ranging in width from the resolution limit
of the Mariner 9 wide-angle images ($\sim$ 1 km) to about 10
km. The greatest density of small channels occurs in
dark cratered terrain. This dark zone forms a broad sub-
equatorial band around the planet. The observed distribu-
tion may be the result of decreased small-channel visibility
in bright areas due to obscuration by a high-albedo dust
or sediment mantle. Crater densities within two small-
channel segments show crater size-frequency distributions
consistent with those of the oldest of the heavily cratered
plains units. Such crater densities coupled with the
almost exclusive occurrence of small channels in old
cratered terrain and the generally degraded appearance
of small channels in the high-resolution images ($\sim$ 100 m)
imply a major episode of small-channel formation early
in Martian geologic history.

1

(2) A Comment on the Paper by Florenski et al., _Icarus_
_26_, 230 (1975).

The nature of Nirgal Vallis may compromise the findings
of Florenski et al.; comprehensive image references would
enhance the analysis.

B. VARIABLE FEATURES ON MARS

(3) A Numerical Circulation Model with Topography for
the Martian Southern Hemisphere. _Journal of the Atmospheric
Sciences_, in press.

A quasi-geostrophic numerical model, including friction,
radiation, and the observed planetary topography, is applied
to the general circulation of the Martian atmosphere in the
southern hemisphere at latitudes south of about 35°. Near
equilibrium weather systems developed after about 5 model
days. To avoid violating the quasi-geostrophic approximation,
only 0.8 of the already smoothed relief was employed.
Weather systems and velocity fields are strikingly tied to
topography. A 2mb middle latitude jet stream is found of
remarkably terrestrial aspect. Highest surface velocities,
both horizontal and vertical, are predicted in western Hellas
Planitia and eastern Argyre Planitia, which are common sites
of origin of major Martian dust storms. Mean horizontal
velocities > 30 m/s and mean vertical velocities < 0.2 m/s
are found just above the surface velocity boundary layer,
apart from eddy velocity contributions. When consideration

is taken of scaling to full topography and the probable
gustiness of Martian winds, it seems very likely that the
general circulation is adequate, at certain times and
places, to transport dust from the surface of Mars, as
observed. Certain sources and sinks of vertical dust
streaming are suggested; the entire south circumpolar
zone appears to be a dust sink in winter.

(4) Fluid Transport on Earth and Aeolian Transport
on Mars. Icarus 26, 209-218 (1975).

Experimental data on cohesion-free particle transport
in fluid beds are applied, via a universal scaling relation,
to atmospheric transport of fine grains on Mars. It may
be that cohesion due to impact vitrification, vacuum sinter-
ing, and adsorbed thin films of water are absent on Mars--
in which case the curve of threshold velocity versus grain
size may show no turnup to small particle size, and one
micron diameter grains may be injected directly by saltation
into the Martian atmosphere more readily than 100 micron
diameter grains. Curves for threshold and terminal velocities
are presented for the full range of Martian pressures and
temperatures. Suspension of fine grains is significantly
easier at low temperatures and high pressures; late after-
noon brightenings of many areas of Mars, and the generation
of dust storms in such deep basins as Hellas, may be due
to this effect.

(5) Physical Properties of Suspended Aerosols from their Infrared Spectra: Application to the Martian Dust Storm of 1971. Icarus, submitted for publication.

Infrared spectra of Mars obtained from the Mariner 9 spacecraft during the Martian dust storm of 1971 were analyzed to determine the chemical composition and size distribution of the suspended dust grains. The infrared optical constants of granite and montmorillonite were measured for the analysis which employs a new, approximate, technique for calculating the emergent intensity from a scattering, emitting dust cloud. The results show that the dust was composed of an intermediate or acidic igneous rock or a weathering product such as a clay. The clay mineral montmorillonite was not the only component of the dust, but the results do not exclude (or require) mont- morillonite as a component of a possible mixture. The dust could not have been composed of a basic igneous rock like basalt, nor could basalt have played a dominant role as a component of a mixture. The mean dust particle radius was a few microns, the dust size distribution closely resembled terrestrial dust size distributions in regions remote from a dust source, and the Martian dust size dis- tribution did not change significantly during the dust storm dissipation. The composition and size distribution of Martian dust have a number of geological and meteorological implications for Mars. We have also studied the way optical

properties of dust interact to create infrared spectra.
The transmission spectrum maximum (Christiansen frequency)
is not compositionally significant for dust particles
in the size distributions we studied. Many optical properties
interact to create transmission spectra of dust powders
and we show that powder transmission spectra cannot be
used to obtain infrared optical constants.

(6) Variable Features on Mars. V: Evidence for Crater
Streaks Produced by Wind Erosion.   Icarus 25, 595-601 (1975).

   Evidence is presented to show that the ragged dark
streaks which appeared behind many Martian craters severa.
months after the end of the 1971 global duststorm were
produced by wind erosion of a thin surface veneer of dust-
storm fallout.

(7) Variable Features on Mars. VI. An Unusual Crater
Streak in Mesogaea. Icarus 27, 241-253 (1976).

   An unusual, prominent dark streak located in Mesogaea
(near 8°N, 191°W) is described. Its appearance is unlike
that of most dark streaks on Mars, many of which have ragged
outlines, are variable on short time-scales, and are pre-
sumed to be erosional. The Mesogaea streak has a tapered,
smooth outline, and no changes within it were observed. We
suggest that this streak is depositional and that the
low-albedo material originated within the associated crater
itself. The source area is identified with a compact,

low-albedo region on the crater floor. Two possible
origins for the dark material are suggested: (1) deflation
from a recently exposed, relatively unconsolidated sub-
surface deposit, and (2) production of ash by a volcanic
vent.

(8) Variable Features on Mars. VII. Dark Filamentary
Mar ngs on Mars. Icarus, in press.

Some Mariner 9 B-frames show networks of criss-crossing
rectilinear albedo markings typically 10 km long by 100
meters wide. This paper discusses the location, variability
and possible nature of these dark filamentary markings.
Although not common on Mars, the markings are concentrated
in at least two areas: Depressio Hellespontica and Cerberus/
Trivium Charontis. For Depressio Hellespontica their
emergence coincided with a general darkening of the region
which occurred 3 months after the end of the 1971 global
duststorm. The very definite criss-cross pattern of many
of these markings suggests that they may be controlled by
joints. It is unlikely that the markings are linear dunes.

(9) Variable Features on Mars. VIII. Pandorae Fretum.
Icarus, to be submitted.

During the Mariner 9 mission a region near (343°W,
24°S) was monitored for changes over a period of 5 months
(25 Jan to 30 June, 1972). This region lies within the
boundaries of the classical albedo feature Pandorae Fretum
whose changes are well-documented at low resolution by

Earth-based photography. The Mariner 9 picture provides
a record of the changes at sufficiently high resolution
that the likely mechanism, aeolian redistribution of
surface materials, can be inferred.

C. THE SURFACES AND ORIGINS OF THE MARTIAN SATELLITES

(10) Photometric Functions of Phobos and Deimos. I. Disc-
Integrated Photometry. Icarus, in press.

We have used the integrated brightnesses from Mariner
9 high-resolution photographs to determine the large phase
angle (20° to 80°) phase curves of Phobos and Deimos. The
derived phase coefficients are β = 0.032 $\pm$ 0.001 mag/deg
for Phobos and β = 0.030 $\pm$ 0.001 mag/deg for Deimos, while
the corresponding phase integrals are q_{Phobos} = 0.52 $\pm$ 0.03
and q_{Deimos} = 0.57 $\pm$ 0.03. The predicted intrinsic phase
coefficients of the surface material are β_i = 0.019 mag/deg
and β_i = 0.017 mag/deg for Phobos and Deimos, respectively.
The phase curves, phase coefficients and phase integrals
are typical of objects whose surface layers are dark and
intricate in texture, and are consistent with the presence
of a regolith on both satellites. The relative reflectance
of Deimos to Phobos is 1.15 $\pm$ 0.10. The presence of
several bright patches on Deimos could account for this
slight difference in average reflectance.

(11) Photometric Functions of Phobos and Deimos. II.
Surface Photometry of Deimos. Icarus, in press.

To a good approximation the face of Deimos observed

by Mariner 9 is covered uniformly by a dark, texturally
complex material obeying a Hapke-Irvine scattering law.
The intrinsic 20° to 80° phase coefficient of this material
is $\beta_1 = 0.017 \pm 0.001$ mag/deg, corresponding to a disc-
integrated value of $\beta = 0.030$ mag/deg. There is also
evidence of a slightly brighter (by ∿ 30%) unit near some
craters, which may have been produced by the cratering
events. Its texture appears to be identical to that of
the average material. No evidence of quasi-specular
reflection has been found, suggesting that large-scale
exposures of unpulverized rock are absent.

(12) Photometric Functions of Phobos and Deimos. III.
Surface Photometry of Phobos. _Icarus_, in press.

At least three large areas on the surface of Phobos
are covered by a dark material of complex texture which
scatters light according to the Hapke-Irvine Law. The
average intrinsic and disc-integrated phase coefficients
of this surface material are $\beta_1 = 0.020 \pm 0.001$ mag/deg
and $\beta = 0.033$ mag/deg, respectively. These values are
slightly greater than the values found for Deimos in
Paper II. On the largest scale the surface of Phobos is
rougher than the surface of Deimos, perhaps accounting
for the slightly greater phase coefficients. Contrary
to the situation on Deimos, no definite regions of intrin-
sically brighter material are apparent on Phobos. This
difference could account for the slightly lower average

reflectance of Phobos relative to Deimos. No evidence
for large exposures of solid rock has been found in the
three areas studied.

(13) Predicted Lightcurves of Phobos and Deimos. _Icarus_,
in press.

Using Mariner 9 results on the shapes, rotation periods
and photometric functions of Phobos and Deimos we calculate
approximate orbital lightcurves for the two Martian satel-
lites. The prediction is that both Phobos and Deimos
should show orbital brightness fluctuations detectable
from Earth. For Phobos the detectable amplitude is pre-
dicted to be about 0.1 mag; for Deimos, 0.2 mag.

(14) Mars: Satellite Origin and Angular Momentum.
Icarus 25, 588-594 (1975).

The origin of Phobos and Deimos is considered with a
view to accounting for the existence of very small satel-
lites with circular orbits in the Martian equatorial plane,
and simultaneously for the suspected angular momentum
deficiency of the Mars system. All models considered
failed to satisfy at least one requirement, and the problem
is considered more puzzling than is at first apparent.
The Martian angular momentum deficiency, if physically
significant, may be unrelated to the present satellites'
origin, but might relate to a large ancient satellite,
long ago destroyed. Accretion onto Mars of large amounts
of asteroidal dust brought in by Poynting-Robertson drag

may have some bearing on the angular momentum
problem.

(15) The Equilibrium Figures of Phobos and Other Small
Bodies. _Icarus_, in press.

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 satel-
lites. This may reflect the absence of a deep regolith
on those asteroids due to the low effective 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.

D. THE SURFACE OF VENUS

(16) Erosion and the Rocks of Venus. Nature, in press.

The remarkable photographs of the surface of Venus
returned by the Venera 9 and 10 spacecraft have revealed
the presence, in two different sites, of a variety of
rocklike forms, some angular and some smooth. Press re-
ports express surprise at the absence of very efficient
erosional mechanisms. It may be useful to point out that,
instead, it is the presence, not the absence, of erosional
mechanisms on Venus which is surprising. The degree of
erosion of surface rocks on Venus will, of course, be
determined by an equilibrium between the rate of production
and the rate of destruction of surface rocks. The prin-
cipal causes of erosion of terrestrial rocks -- running
water; diurnal and seasonal temperature changes, particularly
in deserts; and aeolian abrasion -- are all absent on Venus:
The surface temperature of 750 K is above the critical
point temperature of water. Ground-based radioastronomical
measurements; a comparison of the temperatures measured by
Venera spacecraft at a variety of solar zenith angles;
and the high heat capacity of the massive Venus atmosphere
together clearly demonstrate that the diurnal temperature
differences are a few degrees K at most. The obliquity

of the rotation axis of Venus is so small that there are effectively no seasons on the planet. The efficiency of aeolian abrasion depends on the velocity to a power $\geq$ 3; since both theory and observation show the velocities in the lower atmosphere of Venus to be about an order of magnitude less than at comparable regions in the Earth's atmosphere, it follows that sandblasting on Venus is at most 10^{-3} as efficient as on Earth.

The problem is to find a suitable source of erosion of surface rocks -- a problem somewhat similar to that caused by the radar discovery of large, presumably impact, basins which, in comparison to their lunar, martian and mercurian equivalents, are remarkably shallow. Two mechanisms for the erosion of crater ramparts on the surface of Venus can be suggested; I propose that they also may be important for erosion of the rocks photographed by Venera 9 and 10. The atmosphere of Venus contains hydrochloric acid at mixing ratio of about 10^{-6}; hydrofluoric acid at mixing ratio of about 10^{-8}; and sulfuric acid at larger mixing ratios which, however, are as yet undetermined for the lower atmosphere of the planet. Chemical weathering by such a mixture of strong acids, even in very dilute concentrations, may, over sizeable periods of time, be quire adequate to erode angular projections of siliceous rocks.

A second possibility arises from the high surface temperature of Venus. While these temperatures are not

so high as to melt silicates, they are high enough to
bring many materials of not exceptional geochemical rarity
near or to their melting points -- NaOH, KOH, HgS and KNO_2
to mention a few. If the rocks of Venus are comprised of
such materials even in abundances of a few tenths of a
percent, the rheological properties of their low melting
point components may, over long periods of time, be
adequate to soften the contours of surface rocks. Deforma-
tion of the walls of large basins will occur over long
periods even if the lowest melting point of abundant con-
stituents is considerably above 750 K.

With typical terrestrial values of the subsurface
temperature gradient, the high surface temperature of Venus
implies that the melting points of silicates should be
reached a few tens of km subsurface. The "granitic" values
of the uranium/potassium/thorium radioisotope ratios, as
determined by Venera 8, suggests that a terrestrial value
to the subsurface temperature gradient may be a good first
approximation. In this case, access of magmatic material
from the interior of Venus to its surface should be con-
siderably easier than on Earth and significant fractions
of the surface may be frozen lava fields having reached
thermal equilibrium at the low temperature of 750 K. This
may provide both a source of rocks too young to have yet
been eroded and a means of filling large craters and impact
basins.

Venera 9 and 10 are the first spacecraft to obtain _in situ_ photographs of the surface of another planet. The remarkable photographs which they have obtained open a new field of small scale planetary geology.

E.   MISCELLANEOUS

(17) The Canals of Mars: An Assessment after Mariner 9. _Icarus_ 25, 602-612 (1975).

The Lowellian canal network has been compared with the results of Mariner 9 photography of Mars. A small number of canals may correspond to rift valleys, ridge systems, crater chains, and linear surface albedo markings. But the vast bulk of classical canals correspond neither to topographic nor to albedo features, and appear to have no relation to the real Martian surface.

(18) Kepler and Mariner 9. _Vistas in Astronomy_, Vol. 18, pp. 905-908, Oxford: Pergamon Press (1975).

The historical connection of the speculations of Johannes Kepler about martian moons with the exploration of these moons by Mariner 9 is outlined.

(19) On Solar System Nomenclature. _Icarus_, in press.

Arguments are presented for naming topographic features on other solar system objects after human beings other than astronomers; and to institute a more consistent scheme for Jovian satellite nomenclature.

During the course of the grant year a wide range of
other work has been accomplished which is not yet in press,
and which is more fully described in the body of the renewal
proposal.   Included are some important advances in the
general theory of fluvial channels on Earth and Mars; the
physics of ice-choked rivers on Mars; substantial progress in
the development of a computer accessed catalog of martian
channel and micro-channel characteristics important for any
comprehensive understanding of channel physics and climatic
change on Mars; martian climatic models; an analysis of the
diversity of planetary systems which can be generated by
computer simulations of gravitational accretion under a variety of
initial conditions; near completion of the reduction of the Arecibo
1973 delay doppler radar mapping of Mars and its cross correlation with
Mariner 9 photography; significant progress in the development
of simple deductive theories of sand ripples on Earth and Mars;
discussion of the origin of sand and dust storms on Mars with
particular attention to the Hellespontica/Hellas site; and an
overall pre-Viking review of windblown dust on Mars.

Within the past year the principal investigator served
as Chairman of the Division for Planetary Sciences of the
American Astronomical Society; as Chairman of the Astronomy
Section of the American Association for the Advancement of
Science; and has recently been appointed a member of the
Physical Sciences Committee, SPAC, NASA Headquarters. He
served as Jacob Bronowski Lecturer at the University of

Toronto, as Royal Institution Lecturer at the Royal Institution
in London and as Danz Lecturer at the University of Washington.
He also received three honorary Doctor of Science degrees,
from Rensselaer Polytechnic Institute, Denison University,
and Skidmore College. Among his popular works published which
relate to the subject matter of this grant were British,
German, French, Spanish, Dutch and Italian editions of The
Cosmic Connection: An Extraterrestrial Perspective, and a
British edition of Other Worlds; as well as "The Solar System"
(Scientific American, Vol. 233, pp. 22-31) and "The Planets"
in Man and Cosmos: The Guggenheim Lectures (New York, W. W.
Norton), pp. 68-100.