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Secular Changes and Dark-Area Regeneration on Mars

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Martian secular changes, and the "regeneration" of dark areas after being covered with dust from the bright areas, have in the past been attributed to biological activity. There are no fundamental objections to this view, but it does imply a biology on Mars more prominent and extensive than that on Earth. From radar Doppler spectroscopy and other observations we find that the dark areas have systematically higher elevations than the bright areas on Mars, but that the slopes and elevations of areas that characteristically undergo secular changes are smaller than the slopes and elevations of major dark areas. Furthermore, the dark areas exhibiting secular changes are completely or almost completely surrounded by bright areas. We are therefore led to hypothesize that the secular changes are due to the movement of sand and dust from the bright areas onto and off from adjacent dark areas of shallow slopes which share most of their borders with bright areas, and that "regenerative" properties of the dark areas are due to winds scouring small deposited particles off the sloping highlands.

By the end of the nineteenth century it was clear that not all topographical features on the Martian surface retained their shapes over a period of decades (Antoniadi, 1930). For example, in Fig. 1 we see four views of the same region of Mars—the area around Solis Lacus—drawn in 1877, 1911, 1924, and 1926, the last three drawings having been made by the same observer, E.-M. Antoniadi. It is clear that major changes in surface features of the order of 1000 km in extent have occurred in the space of a few years. (These secular changes should be distinguished from such seasonal changes as the Martian wave of darkening.) While some regions of Mars such as Solis Lacus are characteristically subject to secular changes, others—particularly the darkest dark areas such as Syrtis Major—have remained apparently unchanged for more than a century. To what can this selective variability be attributed?

The most popular explanation of *seasonal* changes of the Martian dark areas has been the annual response of vegetation inhabiting the Martian dark areas to the increased warmth and humidity of the Martian spring (For a recent discussion see Sagan, 1966.) In this view a natural explanation of the secular changes would be a major ecological succession on Mars. The incursion of dark areas into bright areas is interpreted as the proliferation of organisms in previously uninhabited territory, perhaps due to local geothermal activity and outgassing (see Lederberg and Sagan, 1962); the disappearance of a dark area is attributed to the extinction of a local population of dark

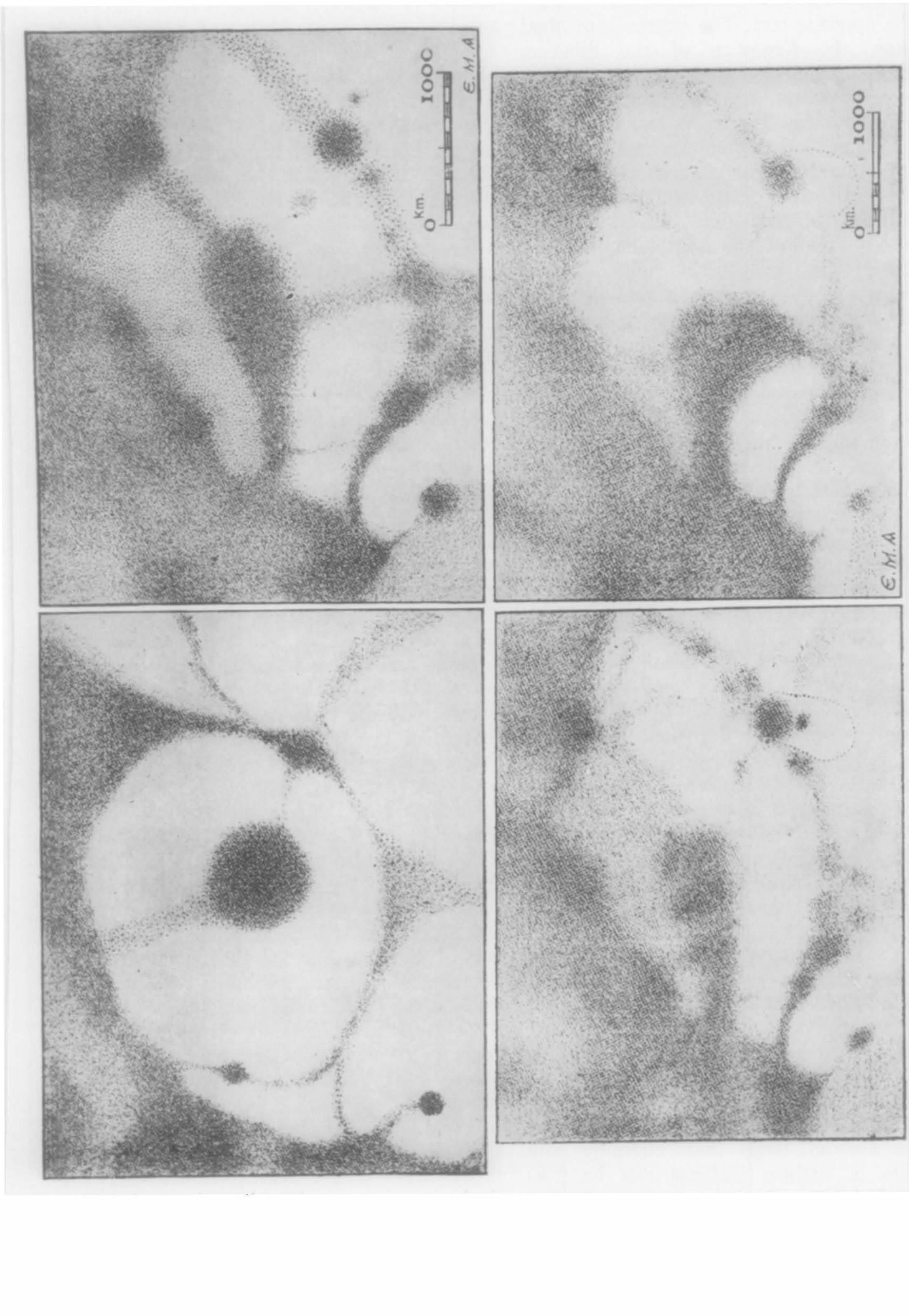

FIG. 1. Drawings of the Solis Lacus region. Upper left, 1877 (drawn by G. Schiaparelli); upper right, 1911; lower left, 1924; lower right, 1926 (all by E.-M. Antoniadi). The scale is in kilometers. The dotted regions at bottom were obscured by clouds. After Antoniadi (1930).

organisms due to environmental changes of the opposite sort. The existence of algal blooms, the flowering of the Siberian steppes, or the lush and verdant appearance of terrestrial semideserts after annual rains (Cloudsley-Thompson and Chadwick, 1964) suggests that biological activity over regions hundreds or thousands of kilometers in extent can produce a major alteration in the gross appearance of extended areas of the Earth. On internal grounds the hypothesis that secular changes are due to growth and degeneration in biologically marginal areas of Mars appears self-consistent; but it implies a very widespread and densely populating form of life flourishing in the Martian dark areas. Observations of the Earth by meteorological satellites with one to two orders of magnitude superior resolution than the best telescopic views we have of Mars show it to be very difficult to detect vegetated regions on Earth (Kilston, Drummond, and Sagan, 1966).

Related to Martian secular changes is the so-called regeneration of Martian dark areas after being covered with dust from the bright areas. Material from the Martian bright areas is observed transported to and across the borders of the dark areas where it is deposited. But within several days after the subsidence of this dust storm the dark areas reappear (see, e.g., Slipher, 1962). Öpik (1950) suggested that the repeated deposition of bright area material into dark areas over the history of Mars should completely obscure the dark areas unless some regeneration process existed. He concluded that the organisms hypothesized for the dark areas grow through the overlying cover of dust. Hutchinson (1954) came to a similar conclusion.

Both phenomena illustrate one difficulty in dealing with the question of life on Mars. The varieties of life on Earth and of possible organisms that we can imagine on Mars are so large that virtually any change in surface features can be "explained" by a necessarily vague attribution to biological processes. The true explanation may in fact be biological, but there is no way—short of landing a space vehicle on the surface of Mars—of testing the hypothesis. Inorganic models of secular changes and the reappearance of dark areas after dust storms may at least have the virtue that they can be tested from the Earth. For example, Kuiper (1957) hypothesized that the Martian dark areas are vitreous lava fields. He pointed out that such fields in the American Southwest, although adjacent to deserts, are not covered by dust; because they are smooth, local winds scour them clean. However, infrared radiometric measurements of the thermal inertia of the Martian dark areas (Sinton and Strong, 1960; Leovy, 1966) clearly show that the dark areas must be composed of a fine powder, as do the prominent negative branches in the polarimetric observations of Dollfus (1957). The observations seem to exclude smooth lava fields as the dark areas. In the course of our studies of elevation differences on Mars we have been led to an alternative inorganic model of both secular changes and dark area regeneration, which we now present.

In an analysis of radar Doppler spectroscopy of Mars performed at 12.5-cm wavelength with the Goldstone tracking station of the Jet Propulsion Laboratory, we have found a variety of evidence that the dark areas of Mars have systematically higher elevations than the bright areas (Sagan, Pollack, and Goldstein, 1967). The evidence comes from the contours and displacements of the quasispecular component of the radar return, from frequency-shifted satellite reflectivities, and from a comparison of the positions of the quasispecular component with the positions of Martian dark areas. Additional evidence that the dark areas are highlands comes from the regression contours of the polar caps and other frost phenomena, and from the motions of clouds; it is consistent with infrared and other observations (Sagan and Pollack, 1966b; Wells, 1965). The resulting mean slopes $\bar{\alpha}$ and peak altitudes h_{max} of dark areas compared to the adjacent bright areas are given in Table 1, for dark areas observed by radar during the 1963 and

1965 oppositions. The values of both $\bar{\alpha}$ and h_{max} are uncertain to at least 50%. Despite the uncertainties in these numerical results, due to the generally low signal-to-noise ratio of the radar spectra, a striking correlation emerges. Major dark areas with more or less permanent contours have mean slopes of several degrees and peak elevations in excess of 10 km. The areas Nodus Laocoöntis, Trivium Charontis, and Nepenthes have slopes of 1° or 2° and maximum altitudes of several km. These three areas are just the three areas encountered in the 1965 radar swath that characteristically undergo secular changes.

TABLE I
MEAN SLOPES AND PEAK ELEVATIONS OF SELECTED MARTIAN DARK AREAS[a]

Region	$\bar{\alpha}$	h_{max} (km)
Moeris Lacus	3°	≤16.5
Niliacus Lacus	3°	15
Syrtis Major	4°	12
Nodus Laocoöntis	2°	7
Trivium Charontis	2°	5
Nepenthes	1°	4

[a] After Sagan, Pollack, and Goldstein (1967).

Trivium Charontis was known to undergo secular variations as early as the 1830's, and is one of the principal secularly variable regions of Mars (Antoniadi, 1930). The area of Nepenthes-Thoth has exhibited some of the most striking secular variations in the history of astronomical observation of Mars. Figure 2 shows the variations observed between 1909 and 1911. Similarly extensive changes in this region occurred between 1952 and 1954. Nodus Laocoöntis, a feature not prominent in early maps, has developed during the last few years into a major dark area and is prominent on maps of Mars prepared during the 1965 opposition and kindly supplied to us by Dr. J. H. Focas.

These differences in elevation and slope lead naturally to a possible explanation of the fact that some regions characteristically undergo major secular changes while others seem immune to this phenomenon. From both photometric and polarimetric observations it follows that there are generally smaller particles in the Martian bright areas than in the dark areas. This is in accord with our expectation that small particles will be carried preferentially by winds from highlands to lowlands, and can be used to explain quantitatively a wide variety of Martian surface phenomena (Sagan and Pollack, 1966a, and to be published; Sharanov, 1958; Rea, 1964). The small particles in the bright areas are observed to be mobile and transported by the winds, as we see in major dust storms; and, on a less spectacular scale, we expect slowly drifting sand and dust to be pervasive on Mars. The boundaries between bright and dark areas should be time-variable due to such mobile and drifting particulate matter; but those dark areas which have gentle slopes and are completely surrounded by bright areas should be much more liable to alternative obscuration and uncovering by sand and dust than are regions which have steeper slopes and are only partially exposed to bright regions. The variations should correspond to nonseasonal changes in the prevailing wind patterns. The larger particles that cover the dark highlands would be much less readily moved by winds that cause movements of smaller particles (see, e.g., Bagnold, 1964). This hypothesis does not depend on the precise nature of the dark areas—only on their mean slopes and nearness to bright areas.

The observations to date are consistent with the above model. Not only do Nodus Laocoöntis, Trivium Charontis, and Nepenthes have very shallow slopes, but they are also either completely or almost completely surrounded by bright regions. As pointed out, these regions have exhibited marked secular changes. On the other hand, Moeris Lacus, Niliacus Lacus, and Syrtis Major have exhibited topographical stability, again in accord with prediction. Other regions which show secular variations, such as Solis Lacus, border on almost all sides with desert regions and are expected to have gentle slopes. Future radar observations should be able to test this prediction.

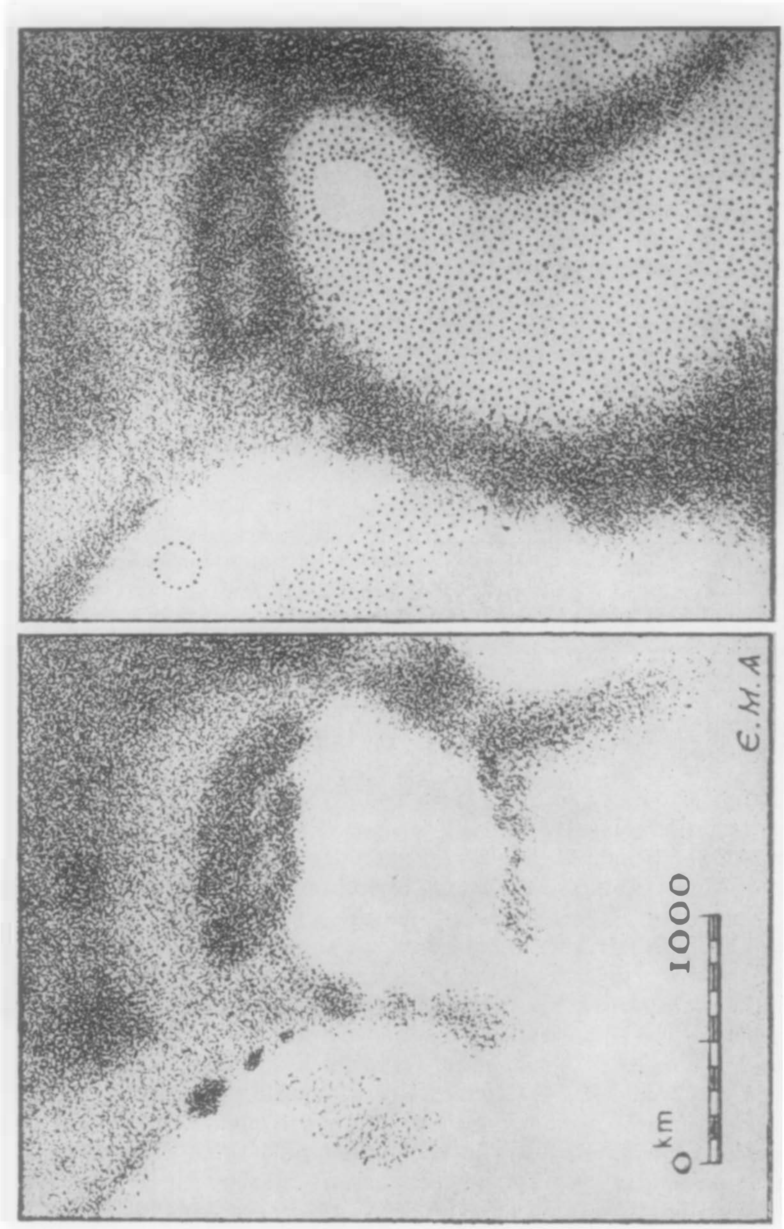

FIG. 2. Secular changes in Nepenthes-Thoth between 1909 (left) and 1911 (right). The dotted regions at right were obscured by clouds. After Antoniadi (1930).

Note that if the hypothesis presented here is valid, secular changes should exhibit certain topological regularities. Highlands should tend to remain dark and lower regions, connecting them with other highlands, should show greater variability. Secular changes should tend topologically to be homomorphic deformations with few cuts and insertions of new features. The changes observed in fact show such regularities (cf. Fig. 1).

If the dark areas are generally highlands, then a straight-forward explanation of the regenerative property of the dark areas immediately arises. Major Martian weather systems may deposit bright area material on the dark areas. But this almost never occurs in the centers of major dark areas; almost always on their peripheries (Sagan and Pollack, 1966b). Thus the small particles are deposited on the slopes of the highlands. We note that the prevailing wind velocities over the highlands should, from the equation of mass continuity and because of diminished friction with the ground, be greater than prevailing winds in the lowlands (Sagan and Pollack, 1966b). This tends to preferentially deposit small particles on lowlands. It is easy to calculate that winds should be able in a few days to scour the small deposited particles off the sloping highlands, thus giving the dark areas the appearance of regeneration.

Acknowledgments

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