

Solar Luminosity Variations and the Climate of Mars

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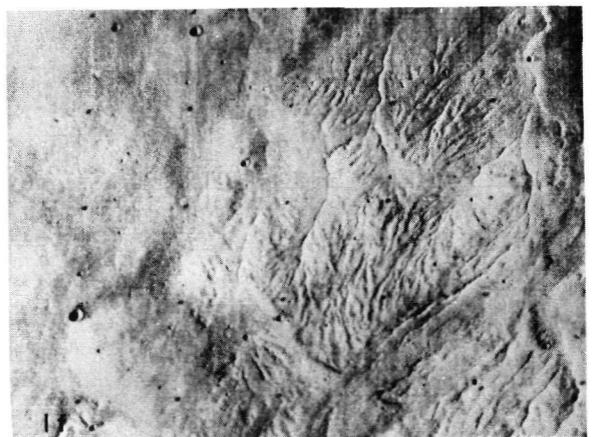
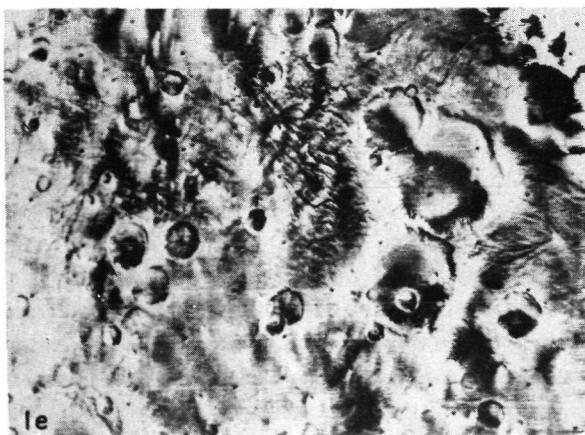
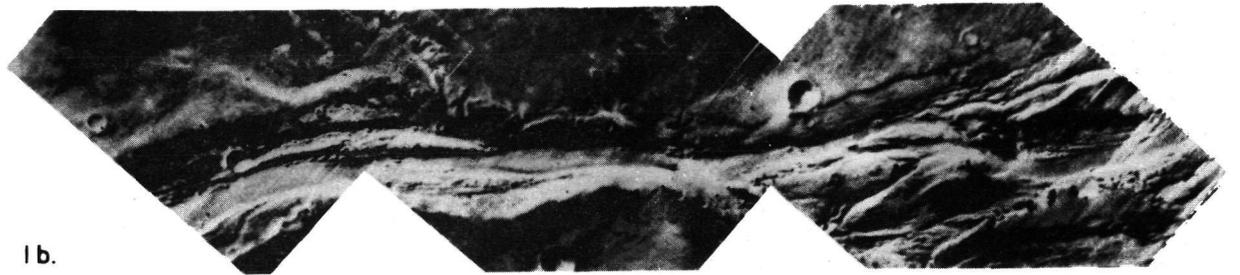
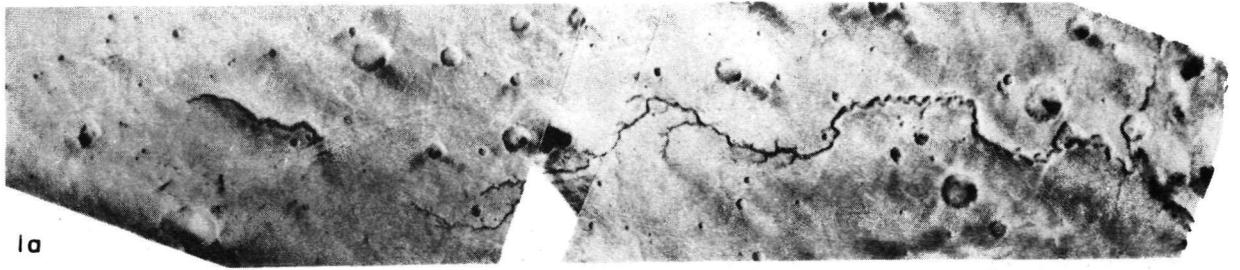
Attempts to resolve the solar neutrino flux problem have led to suggestions of large-scale oscillations in the solar luminosity on a geological time scale. A simple climatological model of Mars indicates that its climate may be much more sensitive to luminosity changes than Earth's because of strong positive feedback mechanisms at work on Mars. Mariner 9 photographs of Mars show an abundance of large sinuous channels that point to an epoch of higher atmospheric pressures and abundant liquid water. Such an epoch could have been the result of large-scale solar luminosity variations. However, our climatological model suggests that other less controversial mechanisms, such as obliquity or polar albedo changes, also could have led to such an epoch. As more becomes known about Mars, it may prove possible to formulate a history of Martian climate. By discovering effects that cannot be due to other mechanisms, one may be able to form a chronology of solar luminosity variations to compare with data from Earth.

Attempts to explain the current low solar neutrino flux have led to suggestions of oscillations of solar luminosity on a geological time scale. Luminosities during the bulk of Cambrian time may have been 7 to 35 percent greater than at present (Ezer and Cameron, 1972). Great ice ages, such as the one during the last few million years, would correspond to relatively short epochs of reduced luminosity. Evidence that luminosity fluctuations of this magnitude might actually occur comes from studies of the color-magnitude diagram of the galactic star cluster Praesepe (Sagan and Young, 1973).

Luminosity variations would have affected Mars as well as Earth. Figure 1 illustrates a variety of large-scale Martian surface features that have been interpreted as dried out river valleys. Other evidence including cratering statistics and widespread hydration of surface materials also suggests a wetter epoch in the Martian past. (See Sagan et al., 1973.) An important point is that the current Martian atmosphere pressure is below the triple point of water. This makes it impossible to have permanent bodies of liquid water on

presentday Mars and suggests a higher atmospheric pressure in past epochs.

The basic question that needs to be answered, then, is what can lead to higher atmospheric pressures on Mars? An important feature of Martian climatology is that the atmospheric pressure seems to be just the vapor pressure of CO₂ at Martian polar temperatures. Thus the atmospheric pressure is a sensitive function of polar temperature. A recent study (Gierasch and Toon, 1973; Sagan et al., 1973) shows that an instability is possible. A small increase in polar temperature due, for example, to orbital perturbations, polar albedo variations, or solar luminosity changes leads to an increase in atmospheric pressure. However, atmospheric heat transport to the polar ground increases with atmospheric mass so there is a strong positive feedback leading to further increases in polar temperature. Because of the strong positive feedback, Martian climate is probably much more sensitive to long-term solar luminosity variations than Earth's. Figure 2 shows the results of solving a simple heat balance equation that contains these ideas



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FIGURE 1.—Mariner 9 photographs indicative of running water on Mars. The details of flow—for example, whether produced by rainfall or underground rivers—differ from case to case. (a) Mosaic of sinuous dendritic channel system in Mare Erythraeum 29° S, 40° W, ~ 1000 km long. Note the evidence of tributaries buried under sand and the possible covered segment of the main channel at left (Image Processing Laboratory product, pictures 122/6354843, 131/6283032, 211/9160800). (b) Mosaic of about one-third (~ 120 km) of the Amazonis-Memnonia Channel. This segment, exhibiting banks, bars, and braids, is centered at 7° S, 151° W (Mission Test Video System (MTVS) product, revolution 458, pictures 12499650, 12499720, 12499790). (c) Narrow-angle (B-frame) closeup of braided portion of Amazonis-Memnonia channel at 6° S, 150° W. The feature, about 40 km across, is reminiscent of the results of episodic flooding in terrestrial river systems (MTVS product, picture 224/9628649). (d) Tear-drop-shaped islands ~ 5 km long in a channel between Aetheria and Elysium (31° N, 229° W) (IOP product, picture 204/8910729). Similar streamlined islands in the Lunae Palus channel darkened during the Mariner 9 mission, probably because of deflation of bright overlying dust by winds coursing down the channel. (e) Network of gullies in Sabaeus Sinus (10° S, 330° W) on old cratered terrain, suggestive of cutting by rainfall. The field of view is ~ 600 km across (MTVS product, picture 423/116205331). (f) Possible mountain drainage system in Alba (45° N, 116° W). This is not a perfect replica of terrestrial mountain drainage systems because some of the flow appears to be uphill, which poses interpretation problems with all hypothesized liquids. The field of view is ~ 70 km across (MTVS product, picture 152/7039903). (This figure is adopted from Sagan et al., 1973).

(Gierasch and Toon, 1973). One discovers that the annual average solar heating at the poles

$$S = \frac{S_0(1-A)\sin\sigma}{\pi a^2(1-e^2)^{1/2}}$$

is critical. The semimajor axis of Mars a and the eccentricity of the orbit e do not change enough to affect S . However, obliquity σ and albedo A changes are large enough to lead to very large changes in atmospheric pressure as are the changes in the solar constant S_0 predicted by solar neutrino flux theories.

The obvious features that indicate climatic change on Mars, such as the channels shown in figure 1, could have easily been caused by changes in albedo or obliquity rather than by

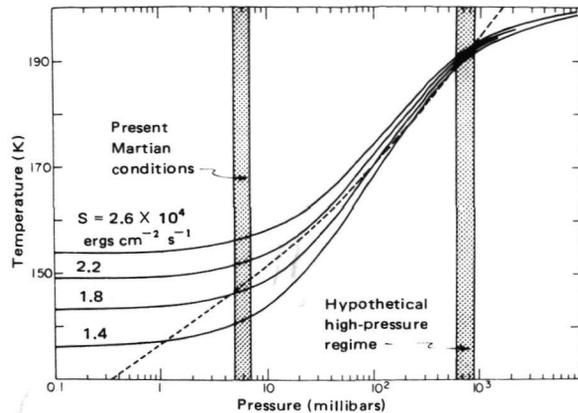


FIGURE 2.—A solution of a simple climatological model of Mars. The dashed line is the vapor pressure curve of CO_2 . The solid line is a solution of a simple energy balance model that includes parameterizations of heat transport from atmosphere to polar ground by conduction and radiation, and heat transport from equator to pole by baroclinic waves. The axes are atmospheric pressure and polar ground temperature. An equilibrium climate requires that dashed and solid curves intersect. Current conditions on Mars require that $S \cong 1.8$; this is a reasonable value for S to take. If S increases to 2.2, there is no equilibrium climate until pressures near 1 bar are reached. To increase S this much, σ must increase by about 6°, A must decrease by about 0.05, or S_0 must increase by about 15 percent. The model is discussed more fully in Gierasch and Toon (1973).

more speculative changes in S_0 . Definitive evidence for solar luminosity variations may still exist, however, in more subtle features. Some of these may hopefully be understood without extensive future observations.

The polar albedo may be changed during epochs characterized by global duststorms. Duststorms in turn may be favored by times when perihelion isolation is high so that the polar albedo may vary with a few-million-year period (Murray et al., 1973). Likewise, the obliquity of Mars undergoes very large oscillations ($\pm 10^\circ$) with a period on the order of a few million years (Ward, 1973). The period of solar luminosity variations, which would be the time between great ice ages on Earth, is a hundred times greater than the period of albedo or obliquity oscillations. There may be features on Mars that reflect very-long-term oscillations in contrast with the shorter ones. Figure 3 shows a small part of an interest-



FIGURE 3.—A view of the polar laminas. These features are found in both polar regions. The finest dark bands are thought to be about 30 m thick. The distance across the layered region is about 5 km at the widest part. The laminas are thought to contain both dust and a volatile, probably H₂O. Their regular structure and the fact that they occur in both polar regions indicate that their formation may be controlled by climatic changes. (MTVS product picture 4213-21, DAS 08080243.)

ing set of features, known as the polar laminas, that are found in both north and south polar regions. Unfortunately, how these features were formed, what they are made of, and how old they may be is unknown at present. It is likely that their formation is influenced by climatic changes, and they do show evidence of doubly periodic formation with tens of laminas adding to form distinct plates. It is the edge of one plate which is shown in figure 3. Figure 4 shows the North Pole of Mars and the dark bands seen in

the ice illustrate the edges of several plates that are arranged one on top of the other. Future studies of the laminas and plates may provide us with a climatic history of Mars.

As we pointed out, the river valleys seen by Mariner 9 seem to require a much higher atmospheric pressure for their formation. They do not require higher planetary temperatures, however (Sagan et al., 1973). There is some indirect evidence for rainfall on Mars (Sagan et al., 1973). The conditions required for rainfall are



FIGURE 4.—A view of the North Pole of Mars. The circular, concentric dark bands are the edges of plates. Each plate is composed of many tens of laminas as seen in the previous figure. The plates lie one on top of the other and extend far out from the poles in both hemispheres (MTVS product, picture 529/13028127).

not yet well understood. However, from terrestrial experience, it seems likely that higher Martian equatorial temperatures will be required. It is possible that a CO_2 , H_2O greenhouse effect may be enough to provide this (Gierasch and Toon, 1973). If this is not the case, then solar luminosity variations will become attractive because they both raise the planetary mean temperature and lead to increased pressures through the instability we have described.

Mars is climatologically simpler than Earth in many ways. There are no oceans and at present there is no rainfall. Moreover, strong positive feedbacks accentuate climatic changes on Mars. These factors partly compensate for the remoteness of the planet from Earth. We have now entered an era when studies of the planet may be of real use in understanding Earth. There is some hope that an understanding of the more subtle features we have observed on Mars may

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provide information about possible solar luminosity variations, and that such an understanding can be achieved in the relatively near future.

The climate of Earth has undergone changes on many time scales other than the one we have concentrated on in this paper. If any of these climatic changes has been caused by extraterrestrial mechanisms, there may be evidence of similar climatic changes on Mars. Exciting discoveries undoubtedly await us in our future explorations of the planets.

ACKNOWLEDGMENT

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REFERENCES

Ezer, D., and A. G. W. Cameron, 1972, "Effects of Sudden Mixing in the Solar Core on Solar Neutrinos

- and Ice Ages," *Nature (London) Phys. Sci.*, **240**, p. 180.
 Gierasch, P. J., and O. B. Toon, 1973, "Atmospheric Pressure Variation and the Climate of Mars," *J. Atmos. Sci.*, **30**, pp. 1502-1508.
 Murray, B. C., W. R. Ward, and S. C. Young, 1973, "Periodic Insolation Variations on Mars," *Science*, **180**, p. 638.
 Sagan, C., and A. T. Young, 1973, "Solar Neutrinos, Martian Rivers and Praesepe," *Nature*, **243**, p. 459.
 Sagan, C., O. B. Toon, and P. J. Gierasch, 1973, "Climatic Change on Mars," *Science*, **181**, p. 1045.
 Ward, W. R., 1973, "Large-Scale Variations in the Obliquity of Mars," *Science*, **181**, p. 260.

DISCUSSION

QUESTION: Can the finer divisions be annual variations?

TOON: I think it is very unlikely that there are annual variations. The thickness of the finer layers is about 30 m. It is pretty hard to think of anything annual that would make a 30-m thick layer of dust. The layers are very uniform in thickness, remarkably uniform one layer compared to the next.