Is Phobos Artificial? This suggestion by Shklovsky, based on the observed secular acceleration of the first Martian satellite, has been generally received sceptically (*cf. I.A.J.*, 6, p. 40, 1963). Recently, however, arguments were put forward by him (I. S. Shklovsky, "The Universe, Life, and Mind", 239 pp. in Russian, *Acad. of Sc. USSR,* Moscow, 1962; cf. pp. 156/165) which give more weight to the hypothesis without, of course, proving it (nobody can prove it at this stage). Leaving aside tidal action (which still is a possible explanation, Ö.), if it is an effect of atmospheric resistance, there is an upper limit to the possible atmospheric density set by *escape* of the molecules to space; and this limiting density is so small that it can produce an observable effect only when Phobos is a thin hollow structure. Shklovsky applies the argument to nitrogen, but it can be shown that it is generally valid.

From the theory of escape (evaporation to space) (E. J. Öpik, "Selective Escape of Gases", *Geoph. J. R.A.S.*, 7, pp. 490-509, 1963; *Armagh Obs. Contrib.* No. 39), the fractional loss of mass, in units of the planet's mass, equals

$$\Delta M = 2.18 \times 10^{-16} \mu s^{-1} B^{\frac{1}{2}} (1 + B) \exp(-B)$$

per second, where

$$B = 8.023 \times 10^{-16} M \mu / aT$$

is the ratio of gravitational to thermal energy per molecule. Here M = total mass of the planet, μ = molecular weight of the gas, s = velocity of escape from the level whose radius is a and temperature T, all in C.G.S. units.

At present there is very little material in the Martian atmosphere which can be lost, and an upper limit to the present rate of loss is such that not more than 1000 gr could be lost per cm² of the Martian surface in 4.5 billion years. This sets

$$\Delta M < 2 \times 10^{-23}$$

and, with $\mu > 8$ (ionized oxygen),

$$B > 10$$

for the level of Phobos ($a = 9.35 \times 10^8$ cm, $s = 3 \times 10^5$ cm/sec). The density of the Martian atmosphere at 500 km above the surface is closely of the order of $\rho_1 = 1.1 \times 10^{-13}$ gr cm^{-3}; an upper limit of the density ρ at Phobos level we then obtain from ρ_1 by assuming a constant temperature for the atmosphere, so that $B_a \sim a^{-1}$ and $B_1 = 2.41\ B$ for the level of 500 km. Hence, from the hydrostatic (Boltzmann) equation,

$$\rho < \rho_1/\exp(1.41\ B) = \rho_1/\exp(14),$$

and

$$\rho < 10^{-19} \text{ gr/cm}^3.$$

From equation (2) on p. 227, *I.A.J.* Vol. 4 (1957, "Artificial Satellites") the average density of a satellite subject to orbital change from atmospheric drag can be set equal to

$$\delta = 3 \pi \rho a R^{-1} (\Delta a/a)^{-1},$$

where R is the radius of the satellite, and $\Delta a/a$ is the relative shrinkage of its orbital radius per revolution. With $\Delta a/a = 5 \times 10^{-12}$ according to the data of Sharpless as discussed by Kerr and Whipple (*Astron. J.*, 59, p. 124, 1954), we obtain

$$\delta < 0.0002 \text{ gr/cm}^3,$$

corresponding to an iron hollow sphere of $R = 8$ km and a thickness of less than 6 cm.

In a paper that clearly and cautiously reviews the observational and theoretical aspects of the problem, G. F. Schilling ("On Exospheric Drag as the Cause of the Supposed Secular Acceleration of Phobos", *Journ. of Geoph. Res.*, 69, p. 1825, 1964) states that certain Martian atmospheric models lead to atmospheric densities which could account for the acceleration of Phobos by atmospheric drag even when this satellite is a dense and tight chunk of rock. This is quite correct. However, an atmosphere that serves such a purpose will necessarily evaporate into space at a rate 10,000 times higher than Mars could afford now, or in the past. Only a thin atmosphere can be visualized at the level of the orbit of Phobos; this thin atmosphere is capable of producing the observed effect only when the satellite is hollow inside, thus artificial !

Schilling (*loc. cit.*) also points out the similarity between the general trend of the curve of sunspot numbers (if averaged over the 11-year cycles) and the residuals of the orbital longitude of Phobos over the period of observation 1877-1941. Both can be represented by ordinary second-order parabolas, the Martian observations almost precisely (B. P. Sharpless, *Astron. J.*, 51, p. 185, 1945), the sunspot numbers approximately (they are higher at the beginning and end of the period and have a broad minimum in the middle). It is known that the terrestrial upper atmosphere rises or contracts in response to the heating by solar short-wave and corpuscular radiations; small variations in the temperature may cause large variations in atmospheric density (first suggested by Öpik, *Armagh Obs. Leaflet* No. 47 and *I.A.J.*, 4, p. 253, 1957). The heating follows the cycle of solar activity, and when there are more sunspots, the exosphere rises and is denser at higher levels, the drag on the satellite increases and it spirals faster inwards while *accelerating*.

However, the parallel trend of the two parabolae, superficially to be taken as a possible correlation proving the atmospheric character of Phobos' acceleration, may prove rather the opposite. The parabolic run of the longitude residuals (Sharpless), of constant curvature (second-order term coefficient) indicates a closely *constant* acceleration over the entire period, thus *not* influenced by the variable sunspot numbers. And, if the acceleration were proportional to sunspot number, the *second derivative* (curvature) of the longitude would be a parabola of second order, the longitude residuals themselves—a parabola of the fourth order, of variable curvature and with characteristic "angularity" which the observations do not show. Of course, the observations were made only around the "grand" oppositions of Mars when the planet was nearest to earth and yielded only five normal points spaced 15 years apart; there is some freedom in adjusting curves to it. In any case, this material rather disproves than proves the correlation of the acceleration of Phobos with the sunspot numbers.

We are left thus with the following choice :

(1) Systematic errors in the reduction of the longitude of Phobos. The direct

motion of its apsides (periastron), opposite and equal to that of the nodes, is 159°.4 ± 0°.5 annually, or a period of 2.262 ± 0.007 years (E. W. Woolard, *Astron. J.*, 51, p. 33, 1944). This is rather close to the synodic period of Mars, 2.135 years, the difference being 0.127 ± 0.007 years. As a result, in consecutive oppositions the line of apsides maintains a similar orientation; the error in its assumed motion then reflects in the calculated longitudes but gradually, which under circumstances may produce an apparent acceleration of motion. Over the entire interval 1877-1941, of 30 synodic revolutions, the error in the longitude of the apsides has accrued to ± 0°.5 × 64 = ± 32° and possibly more. With the given eccentricity of its orbit (0.019), an uncertainty in the longitude of the apsides of ± 32° could mean a corresponding systematic error in the calculated longitude of Phobos of about ± 1°.5 which is of the order of the observed residuals in longitude. The internal consistency of the data makes this explanation somewhat improbable, but not impossible.

(2) Atmospheric drag, and then necessarily a hollow, artificial structure of the satellite.

(3) Tidal interaction (H. Jeffreys, "The Earth", 3d Ed., Cambridge Univ. Press, 1952, p. 240; Kerr & Whipple, 1954, *loc. cit.*; Öpik, *Progress in the Astronaut, Sc.*, Vol. 1, p. 296, North Holland Publ., 1962), as depending on the inelastic response of the solid mantle of Mars to the gravitational pull of Phobos. If the acceleration is real, this is the most probable cause of it. In this case, however, as well as in the case of atmospheric drag, the remaining lifetime of Phobos is of the order of 10-30 million years only. If the observed acceleration is real, whatever its cause, we are witnessing the very last stage of the satellite's existence which will end by it ultimately coming down on the mother planet, in the same manner as are ultimately descending the artificial satellites of the earth.

E. Öpik