(NASA-CR-155004) SOLAR WIND SPUTTERING OF THE MARTIAN ATMOSPHERE (Yale Univ., New Haven, Conn.) 4 p HC A02/MF A01 CSCL 03B
N77-33020
Unclas
G3/92 47442

SOLAR WIND SPUTTERING OF THE MARTIAN ATMOSPHERE[*]

P. K. HAFF

A. W. Wright Nuclear Structure Laboratory
Yale University, New Haven, Connecticut 06520[†]

and

W. K. Kellogg Radiation Laboratory 106-38
California Institute of Technology, Pasadena, California 91125

Z. E. SWITKOWSKI[‡]

School of Physics
University of Melbourne, Parkville 3052, AUSTRALIA[†]

and

W. K. Kellogg Radiation Laboratory 106-38
California Institute of Technology, Pasadena, California 91125

T. A. TOMBRELLO

W. K. Kellogg Radiation Laboratory 106-38
California Institute of Technology, Pasadena, California 91125

ABSTRACT

The interaction between the solar wind and a planetary atmosphere is evaluated as a cause of atmospheric mass loss. For the case of Mars, calculations suggest that an amount of material has been sputtered which is of the same order as the mass of the present atmosphere.

---

[*] Supported in part by the National Science Foundation [Grant number PHY76-83685], the National Aeronautics and Space Administration [Grant number NGR 05-002-333] and the Energy Research and Development Administration [Contract number EY-76-C-02-3074].

[†] Permanent address.

[‡] Queen Elizabeth II Fellow.

ONE OF THE LIME AID PREPRINT SERIES
IN NUCLEAR GEOPHYSICS AND COSMOCHEMISTRY

August 1977

SOLAR WIND SPUTTERING OF THE MARTIAN ATMOSPHERE*

P. K. HAFF
A. W. Wright Nuclear Structure Laboratory
Yale University, New Haven, Connecticut 06520†
and
W. K. Kellogg Radiation Laboratory 106-38
California Institute of Technology, Pasadena, California 91125

Z. E. SWITKOWSKI‡
School of Physics
University of Melbourne, Parkville 3052, AUSTRALIA†
and
W. K. Kellogg Radiation Laboratory 106-38
California Institute of Technology, Pasadena, California 91125

T. A. TOMBRELLO
W. K. Kellogg Radiation Laboratory 106-38
California Institute of Technology, Pasadena, California 91125

ABSTRACT

The interaction between the solar wind and a planetary atmosphere is evaluated as a cause of atmospheric mass loss. For the case of Mars, calculations suggest that an amount of material has been sputtered which is of the same order as the mass of the present atmosphere.

ONE OF THE LIME AID PREPRINT SERIES
IN NUCLEAR GEOPHYSICS AND COSMOCHEMISTRY
August 1977

In the sputtering process an incident particle beam loses a portion of its energy to recoil motion of target atoms, some of which may escape through a nearby surface. The sputtering yield, S, is defined as the number of atoms ejected per incident particle. In the solar system, sputtering will occur whenever the solar wind, consisting mainly of 1 keV/amu hydrogen and helium ions, strikes a material body. Many years ago Wehner et al.[1] suggested that solar-wind-induced sputtering of the lunar surface should be an important cause of erosion; recently, analyses[2] of returned lunar material have been interpreted quantitatively[3] in terms of such solar wind sputtering.

Mars provides another example of the interaction of the solar wind with a planetary body. However, in contrast to the lunar surface, the Martian surface is largely protected from direct solar wind bombardment by its atmosphere. The primarily CO_2 atmosphere is thin by terrestrial standards but still opaque to the solar wind. It seems pertinent to ask whether solar wind sputtering of the Martian atmosphere is a mechanism leading to significant mass loss. As solar wind particles slow down in the outer atmosphere, they will cause sputtering of atmospheric atoms and molecules in a manner very similar to the case of a solid target. The magnitude of the effect depends upon the extent to which the solar wind actually impacts the neutral atmosphere. Although Mars lacks a significant magnetic field, the Martian ionosphere may partially deflect the solar wind[4]. However, for sputtering to occur the solar wind need only reach the uppermost layers of the neutral atmosphere (say, on altitude ≈ 200 km); thus we have assumed for these calculations that all the impinging solar wind is effective in sputtering. The mechanism by which gaseous targets may be sputtered has not been previously addressed explicitly. We propose to evaluate Martian atmospheric mass loss

---

*Supported in part by the National Science Foundation [Grant number PHY76-83685], the National Aeronautics and Space Administration [Grant number NGR 05-002-333] and the Energy Research and Development Administration [Contract number EY-76-C-02-3074].

†Permanent address.

‡Queen Elizabeth II Fellow.

by solar wind sputtering by analogy with models of sputtering of solid surfaces and by using empirical data for the lunar surface.

The Martian atmospheric density at an altitude of 200 km differs by a factor of about 10^{12} from that of common solids. However, the sputtering yield is not expected to be a function of target density. At lower densities the beam particle will, on the average, penetrate a surface more deeply before generating a primary recoil. On the other hand, longer mean free paths (mfp) allow secondary and tertiary recoils to escape more easily. In the upper atmosphere, the critical level, h_c, where the mfp in the horizontal direction just equals the scale height, distinguishes approximately between a lower region of diffusive motion and an upper region of ballistic motion. If the solar wind ion interacts with an atmospheric molecule too far below h_c, the lower energy recoil cannot easily escape. Too far above h_c, the probability for generating a recoil is vanishingly small. This is analogous to the case of a solid where sputtered atoms originate from within the top few monolayers[5]. Of course, sputtering results from a complex network of sub-surface collisions[5] and this must also be true in the atmospheric example. To illustrate the scales involved for the example of Mars, if we assume a 200 °K isothermal atmosphere, then we obtain the scale height $H \approx 10$ km and the critical level $h_c \approx 200$ km above the surface. The horizontal mfp for a low energy recoil atom here is ~ 10 km which may be compared with the corresponding interatomic spacing within a typical solid of ~ 2 Å.

A further possible difference between the sputtering of a solid and an atmosphere lies in the nature of the target binding forces. To escape from a solid target, a recoil atom must have sufficient energy to overcome chemical bonds. The appropriate surface binding energy is usually taken to be the sublimation energy whose value is a few eV. In an atmosphere, the binding is provided by the gravitational field. Thus, on Mars an energy of ~ 5.3 eV is required for a CO_2 molecule to escape from an altitude of 200 km. Therefore, these chemical and gravitational energies are seen to be comparable.

We conclude from these comparisons that sputtering should proceed in much the same way in the Martian atmosphere as on the lunar surface. The sputtering-induced mass loss from the moon has been estimated to lie in the range 1 to 13×10^6 atoms/cm^2-sec which corresponds to the erosion of a surface layer of thickness 0.05 to 0.5 Å/yr (ref. [6]). For purposes of discussion, we adopt a yield of 7×10^6 atoms/cm^2-sec. This implies a sputtering yield of 3×10^{-2} atoms per solar wind ion.
These yields are consistent with measured values for solids involving keV projectiles and targets of similar mass to the constituents of the lunar surface[7]. Furthermore, those yields are consistent with the predictions of standard theoretical models[5,8]. [It is interesting to note that in these theoretical models of sputtering the binding of atoms in the bulk of the solid to their lattice sites is neglected. In this respect such theories are especially applicable to the treatment of gas targets.] Taking into account the fact that the solar wind flux is decreased by a factor of $(1.5)^2$ at the orbit of Mars, we estimate the mass loss from the planetary atmosphere to be 2.45×10^{24} CO_2 molecules/sec. Integrated over the course of 4×10^9 years, the total mass loss becomes 3.1×10^{41} CO_2 molecules, a number independent of variations in the density of the atmosphere during its evolutionary history. This result may be compared with the present mass of the Martian atmosphere of 4×10^{41} molecules (calculated on the basis of a ground level pressure of 7.5 millibars[9]).

Given the necessarily approximate nature of the present calculations, the interpretation of these results is that solar wind sputtering must be considered as a potentially important mechanism for atmospheric mass loss from Mars. More detailed calculations now seem advisable.

In addition to mass loss, sputtering may also lead to preferential loss of light elements and isotopes. This phenomenon is known to occur during ion bombardment of many alloys and compounds[10,11] and has been proposed[3] as the source of the isotopic fractionation observed on the surface of fine lunar dust grains subjected to solar wind bombardment. It may also occur in the Martian atmosphere where certain isotopic anomalies have been reported[12]. Within a collision cascade[5], lighter isotopes recoil on the average with higher velocities[11] so that they will be preferentially lost from the top of the atmosphere. The efficiency of this process for the lightest atmospheric constituents will be enhanced by the fact that their distribution extends to higher altitudes, so that more particles are exposed to the solar wind.

In summary, by extrapolation from the characteristics of the sputtering of solids, it seems likely that solar wind sputtering of the Martian atmosphere has led to appreciable mass loss and perhaps contributed to isotope fractionation.

We gratefully acknowledge helpful discussions with Professors C. A. Barnes, D. S. Burnett, and Yuk Ling Yung.

References

[1] Wehner, G. K., KenKnight, C. E. & Rosenberg, D. L., Planet. Space Sci., 11, 1257-1261 (1963).

[2] Epstein, S. & Taylor, H. P., Proc. Sixth Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl. 6, Vol. 2, 1771-1778 (1975) and references contained therein.

[3] Switkowski, Z. E., Haff, P. K., Tombrello, T. A. & Burnett, D. S., J. Geophys. Res. (1977) in press; Haff, P. K., Switkowski, Z. E., Tombrello, T. A. & Burnett, D. S., Proc. Eighth Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl. 8, (1977) in press.

[4] Michel, F. C., Rev. Geophys. Space Sci., 9, 427-435 (1971).

[5] Sigmund, P., Phys. Rev., 184, 383-416 (1969).

[6] Zinner, E., Walker, R. M., Chaumont, J. & Dran, J. C., Proc. Seventh Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl. 7, Vol. 2, 953-984 and references contained therein.

[7] Roth, J., Bohdansky, J., Poschenrieder, W. & Sinha, M. K., J. Nucl. Mat., 63, 222-229 (1976).

[8] Weissmann, R. & Sigmund, P., Radiation Eff., 19, 7-14 (1973).

[9] Nier, A. O., Hanson, W. B., Seiff, A., McElroy, N. W., Spencer, N. W., Duckett, R. J., Knight, T. C. D. & Cook, W. S., Science, 193, 786-788 (1976).

[10] Liau, Z. L., Brown, W. L., Homer, R. & Poate, J. M., Appl. Phys. Lett., 30, 626-628 (1977).

[11] Haff, P. K., Appl. Phys. Lett., 31, 259-260 (1977).

[12] Nier, A. O., McElroy, M. B. & Yuk Ling Yung, Science, 194, 68-70 (1976).