

A DIFFUSION SOURCE MECHANISM FOR THE ATMOSPHERES OF MERCURY AND THE MOON; A.L. Sprague (Tyler); LPL U of AZ.

This paper presents a source model for the atmospheres of the Moon and Mercury which relies on the diffusion of a loosely bound component of Na and K residing in microcrystals and grainboundaries through the regolith and fractured crust of these bodies. Abundances of neutral sodium (Na) and potassium (K) in the lunar atmosphere can be compared with those at Mercury. Surface atmospheric abundances are about 500 times higher for both Na and K at Mercury than at the Moon (1,2,3). The low abundance of neutral atmospheric Na and K at the Moon could be attributed to photoionization and interactions of ions with the magnetic field of the solar wind leading to loss. Or, the difference could lie in the source of Na and K. A meteoritic source like that described by Morgan *et al.*, (4) cannot explain the observed ~ 500 factor enhancement of Na at Mercury over that at the Moon. Furthermore Apollo observations did not reveal the presence of oxygen present in the lunar atmosphere that would be expected from volatilization of chondritic material. My calculations show mercurian and lunar crusts depleted in volatiles can provide the observed global budget of atmospheric atoms over the lifetime of the solar system. The spatial and time dependent diffusion equation is solved applying the initial conditions that composition be homogeneous from the bottom of the megaregolith up to the bottom of the depleted layer. An exact solution is found. For Mercury and the Moon rapid diffusion of Na and K through the regolith occurs after Na and K have reached fissures and cracks. The flux is controlled by *grain boundary diffusion* and *solid state diffusion of loosely bound Na and K component at grain surfaces*. The diffusion problems for Mercury and the Moon are similar, varying only in physical parameters of temperatures, temperature sensitive parameters such as activation energies, surface residence times and fractional content of Na and K. An infinite sink is present at the atmosphere/surface interface, realistically mimicing the vacuum of space and the photoionization environment at Mercury and the Moon. Table 1 lists observed Na and K abundances, scale heights, and globally averaged loss fluxes for both the Moon and Mercury. The problem has been solved without the recycling of ionized constituents back to the surface by means of electric fields. If a recycling term were added, there would be no substantive change in the conclusion that grain boundary diffusion can be the source of the Na and K in the mercurian and lunar atmospheres. Likewise, the temporary sink of adsorbed neutrals onto cool nighttime surfaces is ignored. Once the surface is heated by the morning sun and the constituents are liberated from the surface, their ballistic trajectories quickly distribute them in a Maxwellian distribution to be lost within hours to photoionization (see Table 1). The short timescales of these processes make their effects minimal, important only as refinements to the overall picture, not as additional sink processes. The higher temperature at Mercury than that at the Moon results in a higher source flux to the atmosphere.

The surface regolith (<1 meter) on the moon is composed of a mixture of brecciated rocks of centimeter to meter size and finely comminuted dust and glasses from working by meteoroid impact over geologic time. Mercury's surface is assumed to be similar. Solid state diffusion in this region of alkali metals through amorphous glasses or lattices in crystalline grains was considered and found to be insignificant. Although diffusion coefficients are low for feldspar phases ($\sim 10^{-16}$ cm²/s) and slightly higher for glasses ($\sim 10^{-13}$ cm²/s) for glasses, it would be expected that at the high daytime temperatures on Mercury (725 K) and the Moon (450 K) and after times on the order of the age of the solar system ($\sim 10^{17}$ seconds) these small size particles would be entirely depleted of Na and K. This does not occur because charge neutrality must be preserved within the micro structure and diffusion slows as unfilled vacancies increase in number if other elements such as Ca, Al, Rb, and B are not available to increase coordination number and accommodate the anions in nearby locations. At some point the Na and K remain tightly bound despite high daytime temperatures and long time scales. Returned surface lunar fines contain Na and K in abundances, on average, an order of magnitude lower than those common in highland anorthosites. This reflects the tightly bound component. Regolith diffusion is also important in this surface region. Regolith diffusion occurs when neutral Na or K resides on the grain or glassy surface for some time due to a combination of Van der Waals forces and low temperatures (adsorption). The probability of evaporation from the surface into the vacuum of space or along walls of nooks and crannies in the surface materials is large and upward diffusion will occur by hopping in a random walk under the influence of the negative density gradient to the surface. Grain surface residence times in this paper have been calculated using the theory of Shemansky and presented in Appendix A of Hunten *et al.* (5). Path lengths will depend upon the energy

of the departure from the grain, which is directly related to the temperature and the size of open spaces in nooks and crannies. A hop length of 1.0×10^{-4} cm was used. My calculations show that once a Na or K atom reaches this zone it will rapidly enter the vacuum above the surface becoming part of the *source flux* for the observed atmosphere. Because the top tens of centimeters of surface powders and rocks are almost certainly no longer providing local (they provide reworked meteoritic material; Killen (6)) Na and K to the atmosphere the calculations did not have to consider the steep thermal gradients present in the top few centimeters of airless bodies in direct radiative equilibrium to the vacuum of space. Furthermore, because maximum depths are shallow (<50 km on the Moon and <80 km on Mercury), only slightly beyond where temperatures rise above the black body equilibrium temperature, the diffusion calculation is remarkably simple. Blackbody temperatures of a slowly rotating bodies in thermal equilibrium with insolation from the sun are used and listed in Table 1. To estimate the thermal gradient at depth, a model of Mercury by Zharkov *et al.*, (5) was used. A simple surface area to volume relationship was used to scale the temperature gradient of the Moon.

Diffusion of Na and K through the megaregolith (2 - 50 km) proceeds by three mechanisms, only grain boundary controls the flux to the atmosphere. Lunar seismic experiments indicate the fractured crust extends to depths of ~ 50 km on the Moon. In this region grain boundary and solid state diffusion control the flux of Na and K to fractures in the crustal material where rapid regolith diffusion can occur. In this paper these fractures are considered to be well distributed throughout the crust. Regolith diffusion similar to that at the surface occurs at the equilibrium temperature of the megaregolith (see Table 1) for each body. Grain boundary diffusion at the blackbody temperature is found to control the source flux to the atmosphere. Here empirically derived diffusion coefficients are $\sim 10^4$ higher than those within the silicate lattices themselves. An initial abundance of loosely bound Na and K consistent with those derived following the return of lunar samples to Earth were used (Na ~ 0.004 , K ~ 0.002 Mercury; Na ~ 0.002 , K ~ 0.002 Moon) During basaltic igneous processes, K acts as an incompatible element and is stored between crystals in the grain boundaries and microcrystal matrix. There are conditions in which Na could be expected to behave similarly. Because so little is known of the rock types and elemental distributions in them on Mercury and the Moon, the diffusion mechanism deserves consideration as a source which can explain the greater observed abundances at Mercury relative to those at the Moon.

Table 1.	Parameter	Mercury	Moon
* Values from Sprague Kozlowski, Hunten	* Na #/cm ³	$\sim 5.0 \times 10^5$	~ 75
† Value from Potter and Morgan	† K #/cm ³	$\sim 1.0 \times 10^4$	$\sim \dagger 15$
	Scale height _{Na} km	51	79
	Scale height _K km	30	47
	$\tau_{ion Na}$ sec	$\sim 8.3 \times 10^3$	$\sim 5.2 \times 10^4$
	$\tau_{ion K}$ sec	$\sim 5.7 \times 10^3$	$\sim 3.5 \times 10^4$
	Na loss flux #/cm ² sec	$\lesssim 1.8 \times 10^7$	$\lesssim 1.5 \times 10^4$
	K loss flux #/cm ² sec	$\lesssim 4.4 \times 10^5$	$\lesssim 3.4 \times 10^2$
	Equilibrium Temp. K	530	325

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REFERENCES: (1) Potter and Morgan, *Science*, (1988); (2) Tyler, A.L., Kozlowski, W.H. and Hunten, D.M., *GRL*, (1988); (3) Sprague (unpublished); (4) Morgan, T.H., Zook, H.A. and Potter, A.E., *Icarus*, (1988); (5) Hunten, D.M., Morgan, T.M., and Shemansky, D.E., *Mercury*, (1988); (6) Killen, R.M., *GRL*, (1989), (7) Zarkov, N.V. and Trubitsyn, V.P., *Physics of Planetary Interiors*, (1978).