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Interaction of the Surfaces of the Moon and Mercury With Their Exospheric Atmospheres

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The atmospheres of the moon and Mercury are controlled entirely by gas atom–surface interaction. Model calculations describing the steady state atmospheres have all been based on the assumption that the atmospheric particle source is a 'saturated' adsorbed surface layer of gas. We suggest that this is in disagreement with what is known of the physics of gas-surface interaction. On the assumption that interaction is with solid atoms bound in a lattice structure, most collisions with the light atmospheric particles are free-free, not free-bound. The observational and theoretical evidence indicates that energy accommodation per collision for He and H on the moon and Mercury is dominated by first-order interaction terms and is generally less than 0.1 per collision. As a result, estimated thermal escape is drastically reduced for the light atoms on both bodies. We consequently require much reduced solar wind collection efficiencies for protons and α particles. It is suggested that some peculiarities observed in the Mercury He and H atmospheres could be explained by the nature of the gas-surface coupling. The formation of H_2 may not be efficient as a surface or subsurface phenomenon, and the H/H_2 atmospheric ratio may be large.

INTRODUCTION

Measurable atmospheres on the moon and Mercury have prompted interest, since they may provide clues to the evolutionary processes of these bodies. Helium and atomic hydrogen have been measured on Mercury [*Broadfoot et al.*, 1976], and helium, neon, and argon have been measured at the lunar surface [*Hoffman et al.*, 1973].

The atmospheres are very tenuous and, in fact, are exospheric down to the surface. The neutral atmospheric particles are thus possibly kinetically controlled by photodissociation and subsequent energy exchange with the surface in the case of hydrogen or by energy exchange with the surface alone in the case of atomic hydrogen and the noble gases. The kinetic energy distribution of the atomic species, whatever the source of the particles may be, is thus modified for practical purposes only by the interaction with the solid interface. Therefore the nature of the interaction of the atmospheric particles with the surface is of critical importance to the determination of the dominant loss mechanisms, the global distribution of the gas, and the influence of the source geometric and energy distributions on the atmospheric characteristics.

Given the condition described above it is clear that the most critical aspect of calculating atmospheric models is the determination of a reasonable interaction regime at the surface. All of the atmospheric models developed to this point are based on the simplest interaction regime one can devise. That is a complete thermal accommodation to the surface on impact. A particle ejected from the surface has no memory of preimpact energy and, indeed, may not be the same particle. The accretion of solar wind particles by the moon has been discussed on this basis [*Gold*, 1959; *Hinton and Taeusch*, 1964], and the assumption has carried over into the calculation of atmospheric interaction with the surfaces of both the moon and Mercury [*Johnson*, 1971; *Hodges et al.*, 1973; *Hodges*, 1973; *Hodges et al.*, 1974; *Hodges and Johnson*, 1968; *Hartle and Thomas*, 1974; *Hodges*, 1974; *Hodges and Hoffman*, 1974; *Hartle et al.*, 1975]. However, the penetration of surfaces by keV particles differs from the processes involving low-energy neutrals. The energy accommodation of low-energy particles on a surface is strictly a surface phenomenon, and the interaction is very short lived even when adsorption (free-bound as opposed to free-free) events occur for those cases in which heats of adsorption are of the order of the surface temperature or lower. The model atmospheres have been generated on the basis of an infinite lifetime on the surface. This concept and the concept of surface saturation are very difficult to reconcile with present knowledge of surface physics, even in the case of an assumed chemical bond with the surface. We suggest that for the lighter atoms, model atmospheres must be calculated by taking a more detailed account of the surface interaction in order to produce realistic estimates of atmospheric distributions and thermal loss rates. The interaction of a light particle such as helium with a surface for most collisions does not involve adsorption, and when adsorption does occur, the interaction time with the surface is of the order of 10^{-13} s. Most of the collisions are thus described qualitatively in terms of De Broglie wave reflection and diffraction.

The De Broglie wave nature of the surface interaction has been well established [see *Massey and Burhop*, 1952] experimentally, and the theory has undergone subsequent development to a fair degree [*Logan*, 1973; *Goodman*, 1971; *Trilling*, 1967]. Helium in particular has a notoriously low accommodation coefficient on a wide variety of surfaces [*Trilling*, 1967; *Thomas*, 1967]. There is a dearth of measurements with atomic hydrogen, but the behavior of H_2 is generally consistent with He on those surfaces where chemical bonding does not occur. The major reason for a lack of accommodation with these two species in particular is the low mass ratio with the surface atoms. In general, entrapment on the surface occurs with a low probability. The heat of adsorption of He, for example, is less than 70°/molecule on most surfaces [cf. *Trill-*

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ing, 1967]. Theoretical descriptions of the gas-surface interaction are for the most part in qualitative and, for the lighter gases, in quantitative agreement with well-defined experimental work.

This general description of the gas-surface interaction is clearly at variance with the assumptions controlling the present theoretical global exospheric distributions. The thermally accommodated saturated models have in fact been tested by the observations of the helium and hydrogen atmospheres of Mercury [*Broadfoot et al.*, 1976]. The observations do not correspond well with the models, and it has been suggested that the difficulty lies with the assumption of complete thermal accommodation. The lunar observations have been restricted to ground level density measurements in the antisolar region and do not provide a good test of the models, but albedo measurements suggest that the surfaces of Mercury and the moon are very similar in composition.

The introduction of a low thermal accommodation coefficient introduces varying degrees of complexity in the modeling process depending on the magnitude of the coefficient. The ramifications of a lack of thermal accommodation could be rather widespread. The surface temperature tends to lose control of the local atmospheric energy distribution. The atmosphere is not in detailed energy balance, since the surface is an infinite source and sink. Hence in the relaxation limit the energy distribution of the gas particles depends on the nature of the surface interaction, and this does not necessarily provide Maxwell-Boltzmann statistics. The atmospheric loss mechanism depends on the accommodation rate and on gas-surface coupling. The nature of the source takes on more importance as a function of decreasing accommodation. In the following text we discuss these considerations in more detail in the light of present knowledge of the lunar and Mercury atmospheres.

ENERGY ACCOMMODATION

Before going on to discuss the lunar and Mercury atmospheres we provide here a brief discussion of the status of experimental and theoretical work on gas-surface accommodation. Good reviews of the subject have been given by *Massey and Burhop* [1952], *Trilling* [1967], *Thomas* [1967], and *Logan* [1973].

The thermal accommodation coefficient was defined by Knudsen in 1911 [cf. *Knudsen*, 1950] as a result of experimental observations indicating inefficient surface-gas heat transfer. The energy accommodation coefficient α is defined as

$$\alpha = (E_2 - E_0)/(E_1 - E_0) \tag{1}$$

where E_0 is the mean energy per atom of the impacting particle, E_2 is the mean energy per atom leaving the surface, and E_1 is the mean energy per atom in the limiting case of thermal equilibrium with the surface.

Values of $\alpha < 1$ did not attract much theoretical interest until measurements of surface scattering [*Frisch and Stern*, 1933; *Estermann and Stern*, 1930] indicated that the problem should be treated from the point of view of wave mechanics. Further interest was stimulated by *Roberts'* [1930, 1932] careful measurements of He on tungsten indicating very small values of α (≤ 0.02). His work pointed out how extremely difficult it is to obtain sufficiently clean smooth surfaces for valid measurements. Experimental work in this field on various surfaces before and since that time has been plagued with this problem. We raise the question of surface decomposition here from the point of view of attempts to observe surface reactions of lunar samples in the laboratory. *Bowden* [1967], for example, points out the near impossibility of producing suitable glass and quartz surfaces for measurement purposes, owing to development of microcracks on exposure to the atmosphere.

Quantum mechanical theories based on Van der Waals type interaction potentials at the surface were developed by *Jackson and Mott* [1932] for a purely repulsive case and by *Devonshire* [1937] [cf. *Lennard-Jones and Strachan*, 1935] for a Morse interaction potential. Although these formulations were defective in a number of respects, they did provide reasonable comparisons with the light atom experiments for reasonable values of equilibrium internuclear distance and values of dissociation energy comparable to observed heats of adsorption. The exact formulation is too complex to be described in this general discussion. However, an approximation to the equations, which reduces to the classical formula of London [cf. *Devonshire*, 1937], provides a measure of the dependence on physical quantities:

$$\alpha = \left(\frac{3}{8}\right)\left(\frac{1}{m^{1/2}M}\right)\left(\frac{8\pi\hbar^2\kappa^2 T}{k\theta^2}\right)^{3/2} \tag{2}$$

where m, M are the masses of the gas atom and the surface atom, $1/\kappa$ is the equilibrium internuclear distance, T is the gas temperature, and θ is the Debye characteristic temperature of the crystal. This reduction of the Devonshire formulation is obtained by assuming that there are no bound states with the surface and that $(\pi/kh)(2mE)^{1/2} \gg 1$, where E is gas atom energy, $E \gg h\nu$, where $h\nu$ is energy loss of the impacting atom, and $kT \gg h\nu$. Thus we have a dependence of α on mass, equilibrium internuclear distance, crystal lattice constant, and temperature. There is also a dependence on dissociation energy D which does not appear in (2), since it is reduced to zero in this limiting case.

Other formulae have been developed for noncrystalline solids with essentially similar results [*Karamcheti and Scott*, 1968; *Trilling*, 1970]. Virtually all theoretical work on the subject has been classical in nature since the time of the Lennard-Jones–Strachan–Devonshire development [cf. *Goodman*, 1971].

Table 1 shows a list of measured accommodation coefficients for He, Ne, and Ar on various metal surfaces, taken from a compilation by *Trilling* [1967]. The values of α are uniformly low over the wide range of solid mass represented in the table because a low mass is generally counterbalanced by a large Debye characteristic temperature. Values of α for helium on alkaline metals are in the range $\alpha = 0.02 \rightarrow 0.1$ [cf. *Trilling*, 1970]. Measurements on materials more appropriate to lunar and Mercury surface composition, such as glass, are scarce at least partly because of difficulty in obtaining clean surfaces. The only measurements on glass that we are aware of are those of *Keesom and Schmidt* [1936*a*, *b*]. The value obtained was α = 0.3, but the authors suggested that the results were probably representative of the accommodation of at least one layer of H_2O dipoles on glass, owing to their inability to obtain a clean surface. We have applied the *Trilling* [1970] formula to obtain a more realistic value of α for the He/SiO_2 system. The value α = 0.08 is obtained from Trilling's equation 4.10 for T = 300°K, θ = 470°K, and a potential well depth equivalent to 50°K. A high temperature limit to α can be obtained from the *Karamcheti and Scott* [1968] formulation. The value α_{lim} = 0.12 is obtained by using an elastic modulus (7.3×10^{11} dyn/cm^2) suitable for fused silica or pyrex. This value is obtained after normalizing the range parameter to the well-defined experimental value α_{lim} = 0.02 for the He/W system.

TABLE 1. Accommodation α of Inert Gases on Clean Nonalkali Metal Surfaces*

	θ, °K	D/k, °K	m	M	$1/\kappa$	T_{gas}, °K	T_{min}, °K	α_{comp}	α_{meas}
He-W	330	50	4	184	1.00	65	65	0.0116	0.009
						300		0.0168	0.0167
						500		0.0207	0.021
Ne-W	330	200	20	184	1.15	200	268	0.0455	
Ar-W	330	950	40	184	1.25	200	1400	0.219	0.29†
Kr-W	330	2250	84	184	1.35	300	3950	0.459	
He-Mo	380	50	4	96	1.00	300	65	0.027	0.026
Ne-Mo	380	200	20	96	1.15	300	268	0.060	0.055
He-Ni	320	50	4	59	1.00	90	65	0.0453	0.048‡
						195		0.0549	0.060
He-Pt	230	50	4	195	1.00	300	65	0.0229	0.038
He-Al	400	50	4	27	1.00	300	65	0.075	0.073
He-Be	1000	50	4	9	1.00	300	65	0.067	0.145
Ne-Fe	470	200	20	57	1.15	300	268	0.064	0.055
Ne-Al	400	200	20	27	1.15	300	268	0.100	0.159
Ne-Be	1000	200	20	9	1.15	300	268	0.346	0.315
He-Cs	40	50	4	133	1.00	240	65	0.0388	0.0379
Ne-Cs	40	200	20	133	1.15	240	268	0.125	0.1399
He-K	110	50	4	39	1.00	273	65	0.049	0.0449
Ar-Cs	40	950	40	133	1.25	240	1400	0.604	0.668

*From *Trilling* [1967].
†Uncorrected for end effects.
‡Cleanliness of surface?

We also estimate $\alpha = 0.04$ for the He/CaO system at $T = 300$°K in a similar manner. Thus the estimated He accommodation coefficients on the dominant materials of the lunar surface are below $\alpha = 0.1$. Atomic hydrogen would have values of α at least a factor of 2 below those for He. There are uncertainties in these estimates due to some unmeasured fundamental physical quantities required for the estimation of α. We do not have an exact measure of the dissociation energy D (i.e., heat of adsorption). However, we do know that the value is low and in the region of 50°K/molecule for most materials; the heat of adsorption of a gas atom on its own solid is relatable to the same physical quantity on other solids [cf. *Lander*, 1967]. Moreover, when D is this low, it does not have a great deal of influence on energy exchange at the temperatures that we are concerned with here. Under these conditions, most of the energy exchange on an atom-surface encounter takes place on the repulsive part of the interaction potential curve [cf. *McCarroll and Ehrlick*, 1963]. There is some uncertainty in the value of the range parameter or equilibrium internuclear distance which has a substantial effect on the value of α. But this quantity is primarily dependent on the effective atomic radii and is not expected to vary greatly from material to material for a given gas. It thus seems reasonable to expect the estimated values of α to be in error by no more than a factor of 2 for the dominant lunar compounds. We feel that there is more uncertainty in the effective accommodation coefficient α_n as a result of surface roughness, as will be discussed below.

Unfortunately, the theory has not been developed to the point where it can provide the detail required for atmospheric modeling. We illustrate the difficulty here without going into detail. Figure 1 shows a plot of the accommodation coefficient on smooth SiO_2 as a function of temperature for helium and atomic hydrogen, calculated by using the appropriate [*Trilling*, 1970] formulation. The coefficient is calculated by assuming a cold surface and an impacting gas in a Maxwell-Boltzmann distribution. The temperature in Figure 1 thus refers to the gas temperature. As such, the plotted curve provides a measure of the dependence of energy accommodation on the energy of the impacting gas but does not provide a measure of the detailed energy exchange probability required for atmospheric modeling. All of the theories developed to this point contain this defect, including the early quantum mechanical formulations. The minimum in the accommodation curve depends on the magnitude of the heat of adsorption. The increasing energy accommodation at low energies is due to increasing numbers of adsorption collisions; accommodation would otherwise decrease monotonically to zero at $T = 0$°K, according to theory.

Magnitude of energy exchange per collision with the surface. We wish to emphasize some aspects of energy exchange at a solid surface because of their importance in determining atmospheric characteristics.

According to theory, in qualitative agreement with experiment the energy exchange probability declines with decreasing gas atom energy to the point where adsorption collisions occur at a significant rate (see Figure 1, He data in Table 1, and the above text). In a gas-surface system in statistical equilibrium with no homogeneous collisions it is therefore possible, given a reasonably low heat of adsorption, that a high population of low-energy particles relative to a Maxwell-Boltzmann distribution would be maintained.

Collisions with the surface which involve adsorption and subsequent desorption of the gas atom, according to first-order theory, result in an atom with translational energy normal to the surface limited to a maximum determined by the Debye characteristic temperature of the solid [*Devonshire*, 1937; cf. *McCarroll and Ehrlick*, 1963]. Accommodating collisions which do not involve adsorption are also limited by the Debye characteristic temperature in the amount of energy per collision that may be gained by the gas atom. First-order theory is valid for weak interaction involving light gas atoms to the extent that most surface collisions in which energy exchange occurs are single-phonon events. Heavy gas atom collisions have a relatively higher probability of multiple-phonon transitions [*McCarroll and Ehrlick*, 1963]. A light gas in statistical equilibrium with a surface would then have a depressed high-energy tail with respect to a Maxwell-Boltzmann distribution, to a greater or lesser extent depending on the magnitude of the

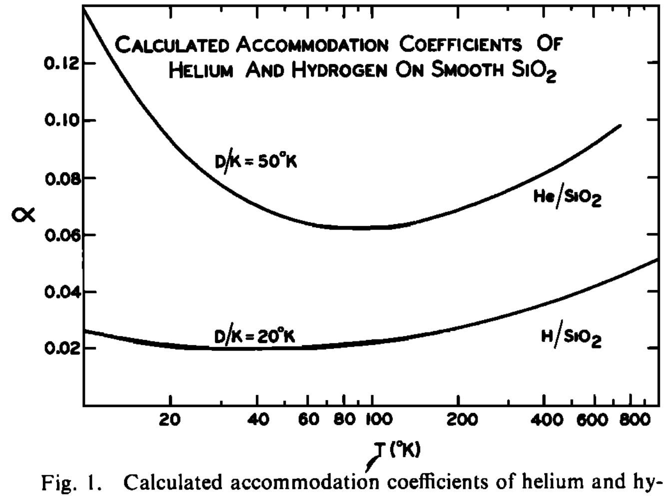

Fig. 1. Calculated accommodation coefficients of helium and hydrogen on smooth SiO_2 [after *Trilling*, 1970]. The surface is assumed to be cold. The temperature scale relates to gas temperature.

Debye characteristic temperature. The Debye characteristic temperature for most solids is less than 1000°K. Table 2 lists values of θ for the dominant lunar solids.

Surface roughness. The roughness of a surface affects the thermal accommodation rate of a gas. A simple random surface results in an average of two collisions per encounter. For small values of α this results in a twofold increase ($\alpha_n = 2\alpha$, $n = 2$) in accommodation as compared with a smooth surface of the same material. This is clearly the largest uncertainty in making an independent estimate of accommodation on the lunar or Mercury surfaces.

Little experimental work has been done in the area of surface roughness; most work has been concerned with producing smooth uncontaminated surfaces for accommodation measurements. Prolonged heating of tungsten at high temperatures produces microscopic irregularities resulting in increased values of α_n [*Roberts*, 1930]. However, one cannot determine how many collisions are associated with the lowest measured values, and the experimental data thus generally provide only a measure of the upper limits of accommodation. Roberts' lowest values compared with the more recent measurements suggest that there were about three collisions per encounter in his experiment, on the assumption that the recent data represent α_1.

The degree of roughness presented by the lunar and Mercury surfaces is uncertain, since it depends on a largely unknown history of formation. The direct observational evidence [*Cadenhead et al.*, 1972] suggests that the lunar surface probably cannot be treated as a simple rough surface, since some degree of porosity does exist in fines and breccias. However, the crystalline rock fragments, including external exposed surfaces, had low surface areas. Micrometeorite impact appears as shallow glassy pits, which tend to decrease the surface area [*Cadenhead et al.*, 1972]. The relative quantities of these two material types are uncertain.

Lattice defects. Lattice defects can affect the efficiency of energy transfer, and ledges, kinks, and atomic wells resulting from formation processes and solar extreme UV radiation can provide localities with higher trapping ability. However, the density of defects must be rather high in order to affect energy transfer. Trapping on the surface is not significantly affected unless the defect concentration is greater than about 1 in 10^3 lattice locations [*McCarroll and Ehrlick*, 1963]. The experimental work of *Cadenhead et al.* [1972] on lunar breccias and fines determined no measurable semichemical bonding of H_2 or H_2O and no indication of penetration. Measurable adsorption of H_2 was obtained only at 77°K. The heat of adsorption for H_2 is thus below 77°K for the samples examined by Cadenhead et al. Exposure of fine fines to atomic hydrogen indicated a surface reduction [*Cadenhead and Jones*, 1973] and suggested a range of chemisorbed bond strengths. However, there is uncertainty concerning exactly what the atomic hydrogen is reacting with, since the sample was exposed to atmospheric pressure. As we have noted above, obtaining a clean surface under these conditions is almost impossible, and as *Cadenhead et al.* [1972] point out, there are no uncontaminated lunar samples.

We suggest that surface particle size is not critical to the magnitude of the atom-surface interaction. That is, the calculated accommodation coefficient on a 10-μ particle would be no different from the value on larger particles. As will be pointed out below, the number of lattice defects must be fewer than 1 in 10^3 before energy accommodation is measurably increased.

Population of adsorbed surface gas. The steady state coverage of the surface by adsorbed gases is negligible from the point of view of the effect that they would have on thermal accommodation, as will now be shown. A pressure of 10^{-10} torr of helium at 200°K produces a surface collision rate of $n \approx 2 \times 10^{11}$ cm^{-2} s^{-1}. The mean residence time of an adsorbed gas can be obtained from the first-order adsorption equation when the coverage is low [*Lander*, 1967; cf. *Lennard-Jones and Strachan*, 1935].

$$\tau = \tau_0 \exp (Q/RT) \qquad (3)$$

where τ_0 is a statistical vibration factor and Q is the heat of adsorption. At 200°K the residence time of helium is $\tau \simeq \tau_0 \simeq 10^{-13}$ s. The steady state number of adsorbed atoms is then of the order of $\eta\tau = 2 \times 10^{-2}$ cm $^{-2}$. The value of $\eta\tau$ for 10^{-10} torr of neon is about the same and a factor of about 30 larger for argon.

DIRECT OBSERVATIONAL EVIDENCE

The measurements of the lunar atmosphere were made on the surface with mass spectrometers [*Hoffman et al.*, 1973]. The measurable data were confined to the lunar darkside. Measurements on the subsolar side were severely contaminated by instrumental outgasing, and direct measures of global surface distributions are not available. It therefore appears that there is not enough observational evidence to make inferences concerning the efficiency of thermal accommodation of the atmospheric gases.

Observations of the Mercury atmosphere by the Mariner 10

TABLE 2. Debye Characteristic Temperatures of Dominant Lunar Surface Solids

Substance	θ, °K*
Al	428
Ca	230
CaO	~400†
Si	640
SiO_2	470
Ti	420
TiO_2	760

*From *Gray* [1972].
†Rough estimate.

UV spectrometers do provide a measure of the global distribution of atomic hydrogen and helium and are amenable to analysis. Comparison of the helium data with model calculations by assuming $\alpha = 1$ does not fit the data satisfactorily [*Broadfoot et al.*, 1976]. Differences with the observed distribution arise in a number of observational details.

1. The model predicts an antisolar/subsolar number density ratio, $N_a/N_o = 200$, at the surface (however, see *Smith et al.* [1977]). The abundance measurements across the planet suggest a much smaller value.
2. Altitude distributions observed across the terminator appear not to agree with the model [*Broadfoot et al.*, 1976]. This becomes more evident as one examines data as a function of decreasing range to the planet.
3. There appears to be a real phase effect in the relative locations of peak abundance between model and data in the evening terminator region. The locations of peak abundance projected onto the planet differ by as much as 600 km in the particular case in which the modeled surface temperature distribution was derived from *Chase et al.* [1976] [*Smith et al.*, 1977].

Observations of the atomic hydrogen Mercury atmosphere in scattered 1216-Å radiation are shown in Figure 2. We have included model calculations of atomic hydrogen in a Maxwell-Boltzmann equilibrium distribution with the surface. About 20% of the atoms leaving the surface escape thermally according to this model. The atmosphere above the subsolar point, as shown in the figure, has a large apparent population of cold atoms with an estimated surface number density an order of magnitude larger than the component thermally related to the surface temperature [*Broadfoot et al.*, 1976]. The scale height of the cold component is approximately what one would expect on the darkside of the planet (110°K). The reactivity of atomic hydrogen presents a special problem and will be discussed in some detail in the following section.

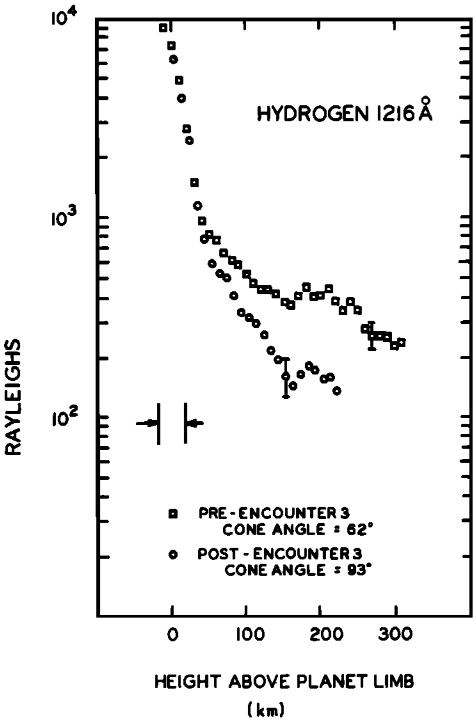

Fig. 2*a*. Mariner 10 UV system observations of Mercury subsolar 1216-Å radiation at Mercury 3 encounter. Instrumental spatial resolution is shown. Altitude zero corresponds to the planet subsolar limb. The increase in brightness at the limb is due to surface albedo. The interplanetary background has been subtracted. These observations show only the cold component, representing temperatures of ~100°–150°K. Squares represent preencounter, cone angle 62°; circles, postencounter, cone angle 93°. Error bars indicate statistical accuracy.

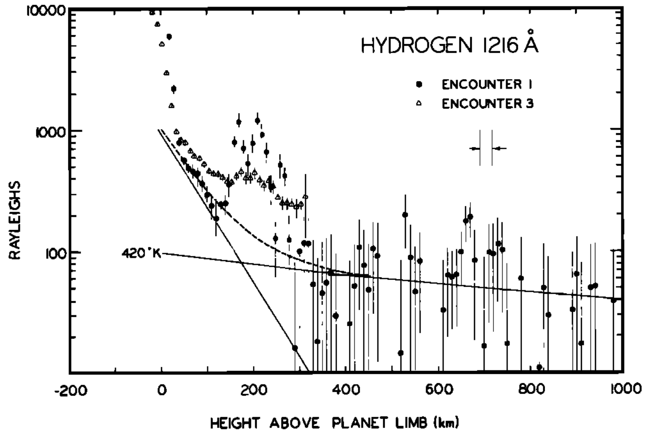

Fig. 2*b*. Mariner 10 UV system observations of Mercury subsolar 1216-Å radiation at Mercury 1 and 3 encounters. The more extensive Mercury 1 data demonstrate the transition to a large-scale height approximately related to the surface temperature of a barometric atmosphere. The cold component may be due to physical atom-surface coupling, as discussed in the text. The smooth curves represent a best fit double-scale height atmosphere for the Mercury data. Triangles represent Mercury 3, preencounter, cone angle 62°; solid circles, Mercury 1, postencounter, cone angle 95°. The sharp feature centered at 200 km occurs with different magnitude on both encounters but appears not to be due to 1216-Å radiation (see text).

The observations on both encounters with Mercury show a sharp feature in 1216-Å radiation in the region of 200 km above the subsolar limb (Figure 2). The origin of this feature is not easily explained. The observational geometry in the two encounters tends to rule out direct association with the passage of the MVM/UVS instrument through the bow shock region. The phenomenon appears to be associated with the planet limb. The instrumental response is not typical of electron noise, and short wavelength radiation $\lambda < 400$ Å appears to be a possible explanation. The feature will be discussed in more detail in a forthcoming final Mariner 10 Mercury data paper. The following discussion is based on the assumption that the 200-km altitude feature is not due to atomic hydrogen scattering.

SOURCE DISTRIBUTIONS APPLIED TO MODEL CALCULATIONS: PHYSICAL JUSTIFICATION

All of the model calculations of the lunar and Mercury exospheres to date are calculated on the basis of the same assumptions concerning the surface interaction. The physical argument for making the assumptions has never been stated, as far as we are aware, with enough clarity to present a basis for discussion. However, we wish to bring forth in this review the difficulty one encounters in attempting to justify the assumptions on which the mechanics of the models are based.

For modeling purposes the nature of the gas-surface interaction has been described in the following way.

1. The surface is assumed to be saturated. This is defined by a process in which an impacting atom must be accompanied by the release of another atom at the impact site.
2. The subsequent ejection of a new source particle is

chosen from a source based on a Maxwell-Boltzmann distribution. Thus in this regime, each impact with the surface must be accompanied by a new source particle. Before going on to discuss physical detail we first point out the important implications of this system and some peculiarities in source distributions that have been applied in the model calculations. First, the mechanism of control of energy distribution of the exospheric gas in these calculations places the source energy distribution in the position of sole determinant. The chosen source energy distribution therefore places any discussion of evolutionary development of the exosphere in direct dependence on the argument for the choice. Second, those model calculations that have utilized the Monte Carlo method [*Hodges*, 1973; *Hodges*, 1974; *Hartle et al.*, 1975] have applied two different source energy distributions. This fact was pointed out only recently by *Smith et al.* [1977] and appears never to have been mentioned in earlier literature. The details of the nature of the two sources are not discussed here [see *Smith et al.*, 1977], but we note that the sources have widely differing implications for atmospheric evolution. One of the sources produces a barometric atmosphere under ideal conditions and appears to have been borrowed from exospheric models based on an atmospheric, rather than a solid surface, interface. A comparison of the physics of scattering and energy transformation characteristics of the two interfaces has never been made to our knowledge. The other source produces a nonbarometric atmosphere, with a much reduced thermal escape rate. A physical argument for the use of either source has not been given and is not forthcoming here, since we are unable to establish a physical basis for discussion. Some of the model calculations cited used a mixture of the two sources; thus a mistake in the application of the Monte Carlo method [*Smith et al.*, 1977] is suggested.

The physical implication of the model assumptions described above is that the impacting particle must reside for some indefinite unspecified long period of time on the surface. This is where the basis for the models in this discussion encounters serious difficulty, for in order to define the nature of the atmospheric source function in terms of physics at the surface, one must specify an average residence time. As we implied earlier in this article, this fundamental quantity must be determined before a discussion of the nature of the surface interaction can begin.

As was discussed above, most collisions with the surface are free-free, not free-bound as the model calculations assume; most encounters do not result in a surface source of accommodated particles. If, for example, all collisions with the surface were free-free and the interaction provided a Maxwell-Boltzmann distribution to the gas, then the atmosphere would be barometric, as is the case with the application of one of the sources in the earlier models. However, not all collisions are free-free, and the interaction does not provide a Maxwell-Boltzmann distribution to the gas. A weak interaction can deliver a maximum energy increment of, say, 500°K per molecule per collision, limited by θ. An examination of the Devonshire quantum theory with the appropriate physical parameters indicates that the probable energy gain per impact will be of the order of $\frac{1}{10}$ or less of this quantity, and a hot atom has a higher probability of losing more energy (D. E. Shemansky, unpublished manuscript, 1977). The temperature equivalent of the energy of escape on Mercury is 1100°K for atomic hydrogen and 4400°K for helium. The corresponding values for the moon are 340°K and 1360°K. We do not presently have an accurate computed measure of the energy distribution in a gas in statistical balance with a surface, owing to defects in the quantum theory. However, it is clear that since the Debye characteristic temperature is low in relation to the escape temperature, especially for Mercury, thermal escape loss could be lower by an order of magnitude in relation to the estimates based on a barometric atmosphere. Figure 3 shows a plot of the computed energy distribution using the quantum theory, modified to take into account surface temperature for the He/SiO$_2$ system (D. E. Shemansky, unpublished manuscript, 1977). The quantum theory is essentially that of *Devonshire* [1937] with some modifications and corrections. The distribution is not correct in the low-energy region, since adsorption collisions were not built into the calculation, but it does present a valid illustration of the depression of the high-energy tail. The details of the calculation are not given in this article, since our intent is to present only the semiquantitative results. Basically, the argument is that first-order quantum theory places an upper limit on the amount of energy per collision that can be delivered to an impacting gas atom, whereas the energy loss by a gas atom is not strictly limited to the quantum limit determined by the Debye characteristic temperature. Apparently, this first-order theory holds for the lighter gases. Thus if we have a light gas at low pressure in statistical equilibrium with a surface, the high-energy region of the distribution is expected to be depressed in relation to a Maxwellian gas. This statement does not depend on a particular source distribution or any particular value of the accommodation coefficient. There is an indirect relationship between the steady state energy distribution of the gas and α, since both depend on the magnitude of θ, but however long it takes to achieve statistical equilibrium, the energy distribution will not neces-

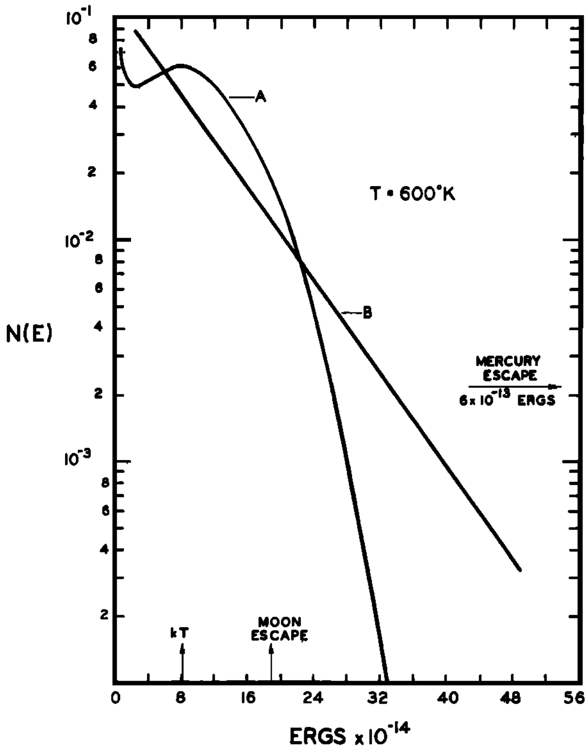

Fig. 3. One-dimensional energy distribution of accommodated helium atoms on an SiO$_2$ surface (calculated according to first-order quantum theory (D. E. Shemansky, unpublished manuscript, 1977)). The calculation does not include adsorption and desorption interaction and consequently does not provide the correct low-energy distribution. Curve A: Calculated energy distribution; curve B: Boltzmann distribution.

sarily relax to a Maxwell-Boltzmann distribution. Very large values of the Debye characteristic temperature will tend to provide a greater share of energy to the higher-energy particles and thus tend to approach a Maxwellian gas. However, the vast majority of materials have values of θ less than 700°K, and variations in the surface materials of the moon and Mercury are not likely to alter our conclusions.

ENERGY ACCOMMODATION ON PLANET SURFACES

An estimate of helium energy accommodation on the planet surface is difficult to make without direct comparison with a model atmosphere containing the details of the surface interaction. This in turn depends on the completeness of the theory. Qualitative agreement with experimental laboratory observations has been obtained, but there remain uncertainties owing to the extreme difficulty encountered in making valid measurements. The calculated coefficients for the He/SiO$_2$ system shown in Figure 1 as we have noted above are judged to be fairly accurate. But this classical calculation of α cannot provide the detail necessary to model planetary atmospheres. The quantum theory does inherently contain the necessary detail for modeling but requires correction and modification to include exchange with a surface at a finite temperature and adsorption collisions (D. E. Shemansky, unpublished manuscript, 1977). The distribution in Figure 3 is obtained with the Devonshire theory modified to include the delivery of energy from solid lattice vibration, but adsorption collisions have not yet been included, and detailed comparison has not been made with atomic beam experiments. The accommodation rate depends directly on surface roughness, as discussed above, and we have not established the quality of agreement with atomic beam experiments. However, we can make a reasonable estimate of the range of magnitude of helium energy accommodation on the moon and Mercury based on the experimental data at hand. We have assumed throughout that the surface interaction involves molecules bound in a lattice structure with chemical bond strengths and that the number of loosely bound atoms on the surface is negligible. We have no reason to believe anything to the contrary. However, comparison with a surface of this kind tends to set an upper limit to α. The energy accommodation of helium on an irregular surface composed of lampblack deposited on a copper plate is only 0.5 [*Devienne*, 1965]. If we assume a minimum of two collisions per encounter, this makes $\alpha_1 \leq 0.3$. It therefore appears that we cannot expect helium to accommodate to any surface with a high degree of efficiency. If we assume that SiO$_2$ dominates the determination of α, the value for single collisions is $\alpha_1 = 0.09$ at the subsolar point of Mercury and the moon. Three collisions per encounter would produce a value $\alpha_3 = 0.25$ at the subsolar point and $\alpha_3 = 0.17$ on the darkside. We expect the surface compositions of the moon and Mercury to be similar. The albedos of the two bodies are unique in the solar system and very similar to one another over the wavelength range 0.33–1.06 μm [*Vilas and McCord*, 1976]. The Mercury/moon EUV relative albedo is below 1.0 and decreases from 0.8 to 0.6 in the 1600- to 600-Å region [*Broadfoot and Wu*, 1977], but this does not necessarily imply serious compositional differences. Thus if the surfaces of Mercury and the moon do not contain serious complications in physical surface structure, we would reasonably expect helium energy accommodation coefficients of 0.25 or lower. A crude model calculation using the method described by *Smith et al.* [1977] indicates that a value of α of this order reduces the ratio N_a/N_0 by a factor of about 5 relative to the results for $\alpha = 1$. However, the calculation does not include any details of the surface interaction, and as one may expect, comparison with the observational data does not indicate substantially improved agreement. The energy distribution of the gas in statistical equilibrium with the surface is also an important factor determining the global variation of surface number density. The fact that the high-energy tail is depressed in comparison to a Maxwellian gas suggests a lower mobility and a consequently higher N_a/N_0 ratio. An example of this is given by *Smith et al.* [1977] in a comparison of the two sources used in the earlier model calculations. The two parameters, θ and its somewhat dependent quantity α, thus tend to have opposing effects in the determination of surface number density distribution in that a decreased value of θ tends to reduce global mobility of the gas, whereas a decreased value of α tends to increase mobility.

ATOMIC HYDROGEN SURFACE AND SUBSURFACE RECOMBINATION

The atomic hydrogen atmosphere presents a special problem in that possible chemical activity must be taken into account. The lack of measurable atomic hydrogen on the moon has been attributed to the formation of H$_2$ [see *Hodges*, 1975]. The exact mechanism by which H$_2$ can be formed as a consequence of proton collection from the solar wind has not been discussed in detail. This problem is too complex to be adequately examined in this general article. However, it should be pointed out that there are difficulties in producing a plausible mechanism for hydrogen recombination. Subsurface combination requires some fairly stringent conditions. Hydrogen atoms bound in the lunar subsurface lattice structure as a result of penetration by solar wind protons must have a certain amount of mobility for H$_2$ formation. However, subsurface binding energy cannot be too low, since the resulting low number densities of atoms would not provide efficient combination rates as opposed to atomic diffusion through the surface. First-order adsorption theory requires a heat of adsorption of 1.2×10^4 °K/atom to provide a 1-s lifetime for an atom with a short transport length to the surface. A desorption rate for a 1-s lifetime equaling solar wind influx on the moon requires only a coverage of 2×10^8 cm^{-2} atoms. This density is clearly many orders of magnitude too low to provide efficient combination. The required binding energy is approaching chemical bond strengths and implies that an activation energy would have to be overcome in order for H$_2$ formation to take place [cf. *Hollenbach and Salpeter*, 1971]. We have certainly oversimplified the physics of subsurface reactions, but there is clearly a problem in assuming subsurface production of H$_2$. The formation of H$_2$ as a surface reaction presents an equally difficult problem. The required heat of adsorption in this case can be approximated by the equation

$$D = T \ln [(\tau_0)^{-1}(2f' \phi)^{-1/2}] \qquad (4)$$

where f' is the adsorbed flux of thermal atomic hydrogen and ϕ is the rate coefficient for recombination. If we set the adsorbed atomic hydrogen flux on the moon to an upper limit determined by the observed upper limit of subsolar surface number density, 10 cm^{-3}, and an efficiency of 1 for adsorption collisions, $f' \leq 2.7 \times 10^7$ cm^{-2} s^{-1}, we obtain $D = 10^4$°K using a reasonable value for the rate coefficient, $\phi = 5 \times 10^{-3}$ cm^2/s. We again require chemical bond strengths, which imply surface immobility. The high value of D also implies an unreasonably high concentration of surface defects if we assume physical adsorption, since we cannot expect heats of adsorption this large on unbroken surfaces [cf. *Hollenbach and Salpeter*, 1970]. The value of ϕ applied to the calculation is based on a high degree of surface mobility.

The hydrogen atmosphere on Mercury presents a somewhat different problem. In this case we do not necessarily expect a high efficiency in solar wind collection due to the presence of a weak magnetosphere. Even if we assume that Jeans escape determines the loss rate, we require a solar wind collection efficiency of only 10^{-4} for atomic hydrogen, a factor of 30 less than the required efficiency for helium. The formation of H_2 on Mercury presents the same problem as the formation of H_2 on the moon; we again require $D = 1.4 \times 10^4$°K. The most uncertain factor in the production of H_2 is the efficiency of the direct interaction of solar wind protons with subsurface adsorbed hydrogen. Most of the proton energy must be dissipated before encounter with a bound hydrogen atom in order to obtain recombination with a reasonable probability. The bond with the solid lattice must be broken in order to form H_2, and the ideal proton energy at encounter is probably of the order of 10^4°K. The hydrogen content of lunar surface material is deficient in relation to helium [*Stoenner et al.*, 1970] in comparison with solar wind content. We assume that this mode of H_2 production is not significant because of the energy constraint on the reaction and because hydrogen content of the surface material is of the order of 100 ppm. The photolysis of H_2 in the atmosphere does not result in efficient production of thermal atomic hydrogen. The photolysis product has an energy of several electron volts per atom and will not thermalize on a single encounter with the surface unless there is chemisorption. The presence of a thermal atomic hydrogen atmosphere on Mercury suggests that the atoms must undergo many physical encounters with the surface relative to chemical events because of the predicted inefficient energy accommodation of a Van der Waals interaction.

Thus in the case of both Mercury and the moon there appears to be a substantial deficiency in hydrogen abundance in relation to what one would expect as a result of collection of solar wind particles. The problem is aggravated if we accept the energy accommodation theory discussed above. If thermal loss of hydrogen on the moon is reduced substantially by the nature of the surface interaction, we are in the position of requiring very much less efficient collection of solar wind protons. The upper limit to atomic hydrogen thermal escape is about 3×10^{22} atoms s^{-1} on the moon, representing a collection efficiency of about 1×10^{-3}. If thermal escape is reduced by the nature of the surface reaction, the requirement for collection of solar wind protons could be reduced to a negligible quantity. The possible collection rate of neutral atomic hydrogen from the interstellar wind alone is about 10^{22} s^{-1}. The helium data present a similar situation. Present estimates assuming a Jeans escape mechanism require only 60% of average solar α particle flux for maintenance of the atmosphere [*Hodges,* 1975]. However, note the recent work of *Hodges* [1977], in which the presence of a helium corona is suggested. It is not clear how the surface interaction discussed here would affect the relative population of the corona. The corona population could go up or down depending on the details of the energy distribution. An order of magnitude reduction in thermal escape reduces the loss rate to the order of the radiogenic source rate [*Hodges*, 1975]. However, it is not clear how much of the radiogenic source is lost to the atmosphere.

The suggestion in the above discussion that Mercury and the moon may be very inefficient collectors of at least the light solar wind particles does not necessarily present serious problems with the physics of the surface interaction. The nature of the reaction of keV ions with saturated subsurfaces is not clear either experimentally or theoretically. We do know, however, that the abundance of subsurface adsorbed gas does not increase beyond the point of saturation. The question of the disposition of the ion beam particles beyond the point of saturation has not been investigated in detail as far as we are aware. Neutral or ion particles must reflect or diffuse or sputter from the surface. How the ion energy is distributed in the process is unknown. It is not clear why one should expect thermal particles under these circumstances as has been assumed in the past. *Hodges* [1975] has suggested a superthermal or ionized component of helium released by surface weathering as a process required for inefficient solar wind collection. A related difficulty discussed by *Hodges* [1975] is the apparent serious deficiency of carbon and carbon compounds in relation to solar wind input. The enigma that this presents under the assumption relating to solar wind collection and neutral thermal escape involved in Hodges' discussion disappears under the conditions suggested here. A shortage of carbon would be consistent with inefficient collection of solar wind helium and hydrogen as discussed above.

CONCLUSIONS

1. Observations of the helium and hydrogen atmospheres of Mercury and theoretical considerations suggest that energy accommodation at the gas-surface interface is an inefficient process. This has a tendency to make the global atmospheric distribution more uniform than thermally accommodated models, and it alters the details of altitude distribution. Atmospheric modeling is complicated considerably by the details of the surface interaction, and an adequate theoretical formulation for the process has not yet been developed. The number of adjustable parameters such as variability in heats of adsorption, the nature of surface roughness, and magnitude of accommodation probability may make a unique solution rather difficult to obtain. Crude estimates of energy accommodation coefficients at the lunar and Mercury subsolar points are $\alpha_3 = 0.25$ for helium and $\alpha_3 = 0.1$ for atomic hydrogen. The observed substantial cold component of the Mercury subsolar hydrogen atmosphere may have its most plausible explanation in a low energy accommodation coefficient.

2. Statistical equilibrium of the exospheres with the surface does not necessarily result in a Maxwell-Boltzmann flux leaving the surface. Light atom-surface interaction is dominated by single-phonon events, which produce order of magnitude reductions in the predicted population of the gas in the high-energy thermal loss tail. The resulting reductions in atmospheric loss rates suggest that collection of solar wind helium and hydrogen may be a minor source of atmospheric particles on both the moon and Mercury. A deficiency of carbon and carbon compounds on the moon is consistent with this conclusion.

3. First-order adsorption theory suggests that the production of molecular hydrogen in surface and subsurface reactions may not be an efficient process and that the hydrogen atmospheres of the moon and Mercury are consequently dominated by atomic hydrogen. If this is correct, the required solar wind proton collection efficiency on both the moon and Mercury will be of the order of 10^{-4} and 10^{-5}

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