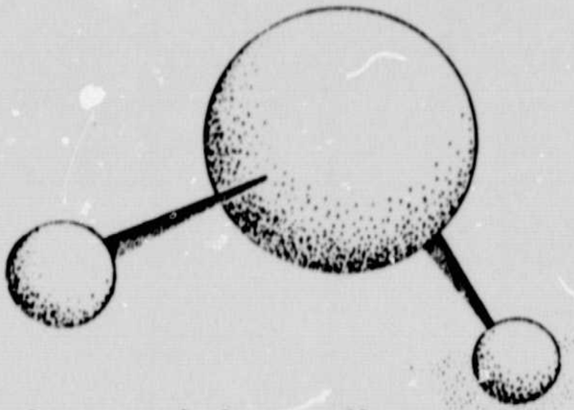

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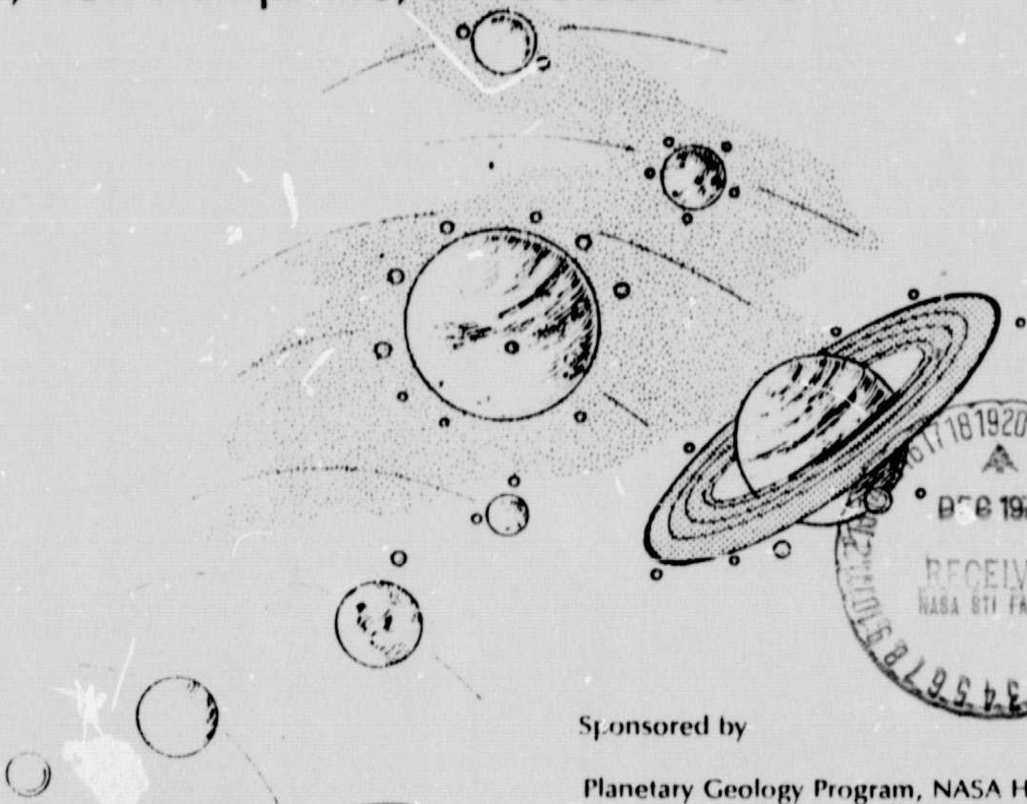

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STABILITY OF WATER ON THE
GALILEAN SATELLITES

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Previous studies of this topic have failed to take into account the physical conditions prevailing on the satellites. In particular, the effects of the magnetospheric environment of Io (J1) have been dealt with only qualitatively or not at all. An early study that is often cited is that of Watson et al. (1963 Icarus 1, 317). They showed that a rapidly rotating 1 km sphere of water ice would have a lifetime of $>10^{10}$ years at Jupiter's heliocentric distance. There are, however, several factors that make this result inapplicable to the Galilean satellites. First, the ice temperatures used by Watson et al. were those for a rapidly rotating (i.e., isothermal) body in equilibrium with the insolation, and are substantially lower than those that may be attained during the day on the surfaces of the slowly rotating satellites. Since the vapor pressure of ice increases by more than an order of magnitude with each 10K rise in temperature in the relevant temperature range. the evaporation rates derived by Watson et al. may be many orders of magnitude lower than the actual local rate at a particular point on a satellite's surface at a particular solar zenith angle. Partially countering this criticism are observations by Fink and Larson (1975 Icarus 24, 411) that indicate that the mean ice temperatures on Europa (J2) and Ganymede (J3) are 95 ± 10K and 103 ± 10K, respectively, values comparable to those used by Watson et al.. Second, since the gravitational field of a 1 km ice sphere is negligible, evaporation is an irreversible process. The calculated lifetime tends to be lengthened, however, by the decrease in surface area as the sphere evaporates. Molecules that evaporate from the surface of a Galilean satellite, on the other hand, will either diffuse through the satellite's atmosphere or follow a ballistic trajectory which, in the absence of other processes, will result in the reimpact of the molecule on the satellite's surface. Last, none of the other gas- or solid-phase processes that may be important on the Galilean satellites--such as photolysis, sputtering, and charged-particle interactions--were considered by Watson et al..

Lebofsky (1975 Icarus 25, 205) conducted an analysis similar to that of Watson et al., but included the effects of slow rotation. He also found that water ice would be stable on the Galilean satellites. His analysis, however, suffers from all of the other limitations described above. Dennefeld (unpublished) did not consider variable surface temperatures due to slow rotation, but did include the effects of the satellites' gravitational fields. He too found the total loss rate of water to be very small.

The determination of the actual water loss rate possible under conditions prevailing on the satellites became particularly important with the introduction of a model of Io's surface (1974 Fanale et al., Science 186, 922) that requires the loss of a large amount of water during the satellite's history. Fanale et al. suggested that Io is covered by evaporite salts of the type found in the carbonaceous chondrite meteorites. They assumed the satellite's interior to be largely of carbonaceous chondritic composition. Water bound in the material will then be devolatilized by radioactive heating. They proposed that this water would percolate to the surface, in the process becoming saturated with salts, and would eventually be lost to space leaving behind a salt surface. They estimated, on the basis of the Watson et al. evaporation rates, that as much as 2 km of ice may be lost over the age of the solar system.

The Fanale et al. model is particularly attractive, because it provides a source for the sodium observed in emission around Io (cf. 1975 Macy and Trafton, Astrophys. J. 200, 510 and references cited therein). (The salts should be rich in sodium, potassium, calcium, and magnesium.) Tests of the model are therefore of great importance to our understanding of Io and the Jovian system in general.

In this paper, the selective loss of water from Io under present day conditions is considered. The main object is to determine whether a large quantity of water can be lost from Io over the age of the solar system (5b.y.). The loss processes considered are thermal escape, photolysis, sputtering, and gas-phase charged particle interactions. These are discussed sequentially below.

For all processes, an ice reflectance of 0.6 has been assumed. This value is probably in the middle of the range of reflectances that might be expected for an ice mixed with dark material on a Galilean satellite. Since the ice is assumed to be in thermal equilibrium with the insolation (charged-particle heating contributes less than 1% of the solar input), the assumption of a lower albedo would result in higher calculated vapor pressures and more rapid loss rates. However, for reflectances appreciably lower than 0.6, ice will tend to migrate rapidly (on a geological time scale) toward the poles, with a consequent reduction in both temperature and vapor pressure. The effect of a lower albedo on the overall water loss rates may thus not be extremely large.

The maximum thermal escape rate was calculated using the treatment of Jeans as discussed by Hunten (1973 J. Atmos. Sci. 30, 1481). Since the thermal escape rate from the atmosphere cannot be larger than the evaporation rate from the surface, thermal escape is unimportant for surface temperatures much below 130K. For an albedo of 0.6, the subsolar temperature is 137K, while the temperature 45° from the subsolar point is 125K. Thermal escape can thus be important only in the vicinity of the subsolar point. The escape rate as a function of atmospheric temperature is as follows:

T atm (K)	Escape Rate (cm^{-2} sec^{-1})
137	1.8×10^{-7}
500	1.3×10^{7}
1000	3.7×10^{9}

The first entry corresponds to an atmosphere at the same temperature as the subsolar surface. The second and third entries correspond to atmospheres heated by the absorption of solar radiation. Taking into account diurnal rotation, the escape rate for 500K, approximately the present day temperature of the atmosphere of Io, corresponds to a loss of about 0.1m of ice over the age of the solar system.

Water can absorb solar ultraviolet radiation at wavelengths shortward of 1850A. If it is assumed that every water molecule that absorbs a photon is lost from the satellite, then the photolytic loss rate R is given by

$$R = JN = N \int \Phi(\lambda)\ \sigma(\lambda)\ d\lambda$$

where J is the rate constant, N is number column density of water molecules, $\Phi(\lambda)$ is the solar flux and $\sigma(\lambda)$ is the absorption cross-section, both functions of wavelength λ. From the absorption cross-sections of Watanabe as tabulated by Schultz et al. (1963 NASA Contractor Report CR-15), and the solar flux measurements of Rottman (private communication), the value of the rate constant J is 2.6×10^{-7} sec^{-1}. For a column density of 2.2×10^{14}, corresponding to the subsolar temperature of 137K, the maximum water loss rate due to photolysis is 5.7×10^{7} cm^{-2} sec^{-1} or about 0.6m of ice over the age of the solar system.

Sputtering by protons can remove a substantial amount of material from Io's surface. The rate of sputtering of sodium from Io is about 10^{7} cm^{-2} sec^{-1} (1974 Macy and Trafton op.cit., also

Icarus 25, 432). If the concentration of sodium in Io's surface is 10%, then the total sputtering rate is 10^8 cm^{-2} sec^{-1}. If the concentration is 1%, then the total rate is 10^9 cm^{-2} sec^{-1}. Since water loss by this mechanism is not limited to the region of the subsolar point, these rates correspond to losses of 10-100m of ice over the age of the solar system. However, this mechanism is not effective in forming an evaporite surface, since it does not remove water selectively.

The water loss rates due to interactions between charged particles and water vapor can be estimated using models for Io's interaction with the Jovian magnetosphere (1976 Shawhan, in Jupiter, ed. T. Gehrels, U. of Ariz. Press, in press; 1973 Shawhan et al., in Photon and Particle Interactions with Surfaces in Space, Reidel, pg. 405; 1973 Shawhan et al., Science 182, 1348; 1974 Shawhan et al., in The Magnetospheres of Earth and Jupiter, Reidel, pg. 375; 1974 Hubbard et al., J. Geophys. Res. 79, 920). These models suggest that charged particles will be accelerated into Io, attaining energies that may be as high as a few hundred KeV for protons. Maximum loss rates were derived under the assumption that all the energy transferred from the charged particles to the water contributes to ionization or dissociation, and that every molecule so affected is lost from Io. The deposition of energy by protons and electrons in water vapor has been studied by Olivero et al. (1972 J. Geophys. Res. 77, 4797) and by Miller and Green (1973 Rad. Res. 54, 343). Their energy deposition rates were used with the fluxes and maximum energies shown in the table below to derive the equatorial water loss rates, averaged over one satellite rotation, shown in the last line of the table.

	Protons	Electrons
E_{max} (KeV)	100	10
Flux (cm^{-2} sec^{-1})	2×10^8	10^{10}
Average H_2O loss rate (cm^{-2} sec^{-1})	10^7 (1m in 5b.y.)	2×10^7 (2m in 5 b.y.)

The conclusion reached is that the selective loss of water from Io, were it present as a surface constituent, would probably not be rapid under present day conditions, amounting to no more than a few meters of ice over the age of the solar system. If the salt surface is present today on Io, then there are at least two possible explanations. First, the conditions of the past need not have been the same as present day conditions. Large quantities of water might have been lost from Io during the period, early in the history of the solar system, when Jupiter was as bright as .01 times the present solar luminosity (1974 Pollack and Reynolds Icarus 21, 248; Cameron and Pollack, in Jupiter, ed. T. Gehrels, U. of Ariz. Press, in press).

Second, an evaporite salt surface might be formed on Io even at very low water loss rates if the loss rate is fast compared to the rate of overturn of the surface material by impacting objects. Under these circumstances, a physically thin, but optically thick, crust of salt could form over the satellite, accounting for its observed optical properties.

COMMENTS:

Zeller: The sputtering potential of elements is really fairly strongly dependent upon their atomic number. Hydrogen sputters off surfaces much more easily than does sodium. It seems to me that you actually can use sputtering to concentrate the heavier elements on the satellite surface. Water loss by sputtering should be rapid enough that an "evaporite" might in fact develop. Particles carrying enough energy to cause sputtering would probably cause dissociation as well, resulting in a total loss of the molecule.

Pilcher: You're right; I shouldn't have given the impression that it's nonselective, it's not. It's just that it's not as selective as evaporation processes where you lose water solely and you don't lose sodium. I haven't thought quantitatively about whether it's selective enough.

Huguenin: Sputtering rates are mass-dependent, and the loss of H and O atoms from Io may be an order-of-magnitude or more higher than the rate of Na^+ loss by sputtering, not the same, as you assumed in your calculation.

Brass: There's an implication in the first part of your model about ice evaporating and leaving salt behind: Salts aren't soluble in the ice - they may be associated with the ice, but even then it requires liquid water as the salt-transporting medium.

Parker: The effect of meteorite plowing coupled with the microscopic heating of the proton irradiation, which will cause ice to melt in a microscopic level, may be a source of NA large enough on Io to be the observed Na torus around Jupiter.