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5. The theoretical expressions used to model the observables contained the standard descriptions for the motions of the sites with respect to an inertial reference frame [see, for example, M. E. Ash, *Lincoln Lab. Tech. Note 1972-5* (1972)]. We intend to refine this model by incorporating the small diurnal effects usually omitted; however, their omission does not significantly affect the interpretation of the data discussed herein.
6. Here we refer only to variations in the speed of the earth's rotation and to shifts in the orientation of the earth with respect to its spin axis, the latter's direction in inertial space being characterized with sufficient accuracy for the present purposes (*4*). For the first published discussion of the determination of the earth's rotation via VLBI, see T. Gold [*Science* **157**, 302 (1967)] and G. J. F. MacDonald (*ibid.*, p. 304).
7. For the separate baseline determinations, we used the smoothed values for polar motion as determined by the BIH and the smoothed values for the variation of universal time (UT.1) with respect to atomic time as determined by the USNO. Both sets of data are tabulated at 10-day intervals in the *U.S. Nav. Observ. Time Service Announce. (Ser. 11) No. 221* (30 July 1973) and *No. 222* (22 Aug. 1974). A four-point Everett formula was used to interpolate between the tabular values. These same smoothed values were used in the comparison with the results from the simultaneous solution; in addition, for the comparison of the UT.1 values with the corresponding BIH values, we used the smoothed values of the latter as tabulated at 5-day intervals in the *Bur. Int. Heure Circ. D65–D68* (1972–1973), and interpolated with the four-point formula.
8. Our baseline is sensitive to only one component of polar motion, almost precisely the conventional "*x*-component."
9. We modeled the solid-earth tides using the constants given in table 3a in P. Melchoir, *Earth Tides* (Pergamon, Oxford, 1966), p. 33. The resultant computer program used to calculate these tides was found to be in reasonably good agreement with one provided by J. C. Harrison (University of Colorado, Boulder): The maximum difference was less than 10 percent of the maximum effect on the delay observable.
10. The smallest postfit residuals, obtained on 29 August 1972, were 0.25 nsec and 0.2 psec sec^{-1} rms for the delays and delay rates, respectively. The largest corresponding rms values, 1.4 nsec and 0.4 psec sec^{-1}, accompanied the 27 June 1972 experiment.
11. Several attempts were made in the analysis to isolate these various contributions. (i) The postfit residuals were studied as a function of elevation angle to separate errors introduced by the propagation medium, but no clear-cut pattern was found. (ii) New observables were formed from pairs of the original observables by taking the differences and sums of adjacent observations. By "down weighting" in a new analysis the "sum" observables, which would be affected by the long-term (> 30 minutes) relative drifts in the clocks at the two sites, with respect to the "difference" observables, which would be sensitive mainly to the short-term (10 to 20 minutes) relative drifts, we hoped to uncover inadequacies in our model of the long-term behavior of the clocks used at the two sites. However, the postfit residuals for the difference observables were not sufficiently small with respect to those for the sum observables to allow us to draw any reliable conclusions about the contribution of clock errors to our results.
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Io: A Surface Evaporite Deposit?

Abstract. *A model is suggested for Io's surface composition involving evaporite salt deposits, rich in sodium and sulfur. According to this model, these deposits were produced as a result of the migration of salt-saturated aqueous solutions to Io's surface from a warm or hot interior followed by loss of the water to space. This model satisfies cosmochemical constraints based on Io's initial composition, current density, and thermal history. Salt-rich assemblages are easily derivable from the leaching of carbonaceous chondritic material; the chemical and optical properties of such deposits, after modification by irradiation, can be used to explain Io's overall albedo and spectral reflectance, its dark reddish poles, and the observed sodium emission as well as or better than other currently suggested materials.*

Any hypothesis for Io's surface composition must explain the spectral curves of Io and the other Galilean satellites in a manner consistent with what is known of their cosmochemical setting in the solar system. Io has long been noted for its unusual optical properties, particularly its high visual albedo and its very low blue and ultraviolet reflectance (*1, 2*). The high albedo, polarimetric evidence (*3*), and the high derived value for the phase integral ($q \sim 0.7$) (*1, 4*) all suggest that Io's surface is covered by low-opacity, multiply scattering material. We hypothesize that the surface of Io is largely covered with an evaporite salt deposit, produced by the migration to the surface of salt-rich aqueous solutions from Io's interior with subsequent water loss to space from the surface. First, we will discuss relevant data from mineralogical and chemical studies of meteorites which suggested our (evaporite) hypothesis. Then we will compare the visible and near-infrared spectrum of Io with our spectra for laboratory samples that seem appropriate for testing our hypothesis. Finally, we will show that our hypothesis is consistent with what is known of the cosmochemical history of the Galilean satellites.

Studies of the mineralogy and chemistry of carbonaceous chondritic meteorites would appear to be pertinent to Io since models for temperature and pressure gradients in the preplanetary nebula (*5*) and derivative chemical models for the initial condensation of solid material (*6*) suggest that carbonaceous chondritic material condensed in the asteroid belt and beyond. Supportive evidence from a comparison of asteroid and meteorite spectra has recently been reported (*7*).

Meteoritical studies are supportive of our hypothesis in that they provide direct evidence of salt production in the parent bodies of carbonaceous chondrites (*8*). In the type I carbonaceous chondrites, epsomite ($MgSO_4 \cdot XH_2O$), bloedite ($MgSO_4 \cdot Na_2SO_4 \cdot XH_2O$), and gypsum ($CaSO_4 \cdot 2H_2O$) have been identified (*8*). In some specimens salt deposits virtually fill the pores, and in some specimens of the Orgueil meteorite up to 15 percent by weight of epsomite is present (*8*). Moreover, studies by Edwards and Urey of the alkali metals in the various types of chondrites suggested to them that the carbonaceous chondrites had been subjected to an aqueous leaching process, resulting in extensive alkali metal migration (*9*).

With this background in mind, we will now compare the optical properties of Io with those of several salts, including an Orgueil leach evaporite we prepared in the laboratory, and with the spectra of previously suggested candidate surface materials. Figure 1 shows the spectral spherical albedo of Io (heavy line) (*10*) reduced from the geometric albedo with the use of a phase integral of 0.7 (*1*). The spectral albedos of three evaporite samples are shown (curves a–c), along with those for sulfur (curve d) (*11*), NH_4SH (curve e) (*11*), ammonium polysulfide (curve f) (*11*), and NH_3 frost (curve g) (*12*).

The curve we obtained for natural halite (NaCl) (curve a) indicates a fairly uniform high albedo from 0.3 to 2.5 μm. Thus, although the albedo of halite matches Io's albedo in the near-infrared reasonably well, it does not match in the ultraviolet and visible. Natural terrestrial evaporites are frequently more highly colored by impurities than the halite sample. The leached evaporite from Orgueil (curve b) shows such coloration and is a better match to Io's curve. We obtained this sample by leaching a 70-mg sample of Orgueil in 40 ml of near-boiling distilled water for 1 hour, filtering the leach solution, and evaporating it to dryness. The evaporite salt resulting from this exceedingly mild leaching weighed 3.4 mg, or 5 percent by weight of the original sample. Wet chemical analysis showed 34 percent $SO_4{}^{2-}$ and 0.8 percent Cl^-. Emission spectrographic analysis gave, in the order of decreasing enrichment over bulk Orgueil concentrations, the following results: sodium, 11 percent; calcium, 6.8 percent; manganese, 0.7 percent; potassium, < 2 percent; nickel, 2.9 percent; magnesium, 25 percent; aluminum, 0.25 percent; silicon, 3.7 percent; and iron, 0.08 percent. Note that this mild leaching procedure concentrated virtually all the sodium in the meteorite sample in the resulting evaporite. A similar experiment was carried out by Nagy *et al.* (*13*), who reported that x-ray diffraction analysis of a leach evaporite from Orgueil gave $MgSO_4 \cdot XH_2O$ peaks plus "other minor peaks."

In addition to changes in optical properties caused by chemical impurities, the high-energy-particle environment of Jupiter's magnetosphere (*14*) could also cause alterations in the optical properties of Io's surface materials. Most earlier suggestions concerning irradiation-produced colors focused on the production of free radicals, polymers, or organic compounds (*15*). Many of these possibilities can probably be eliminated on the basis of the near-infrared reflectance spectra of these materials, as with frosts (*1*). However, color center production does not necessarily suffer from this problem. Salts are particularly susceptible to color center formation under irradiation (*16*). Curve c shows the reflectance of a proton-irradiated sample of halite immediately after irradiation (*17*). The deep absorption centered near 0.48 μm is due to *F* color centers in the NaCl lattice. The depth of absorption decreased rapidly with time as the color centers annealed out at room temperature. In the low-temperature, constant-irradiation environment of Io, however, color center formation would be expected to play a major role. This mechanism may also explain Io's dark reddish polar regions (*18*) since the incident radiation per unit area is highest at the poles and the temperature lowest. The temperature dependence of color center formation and retention may also play a role in eclipse phenomena such as the post-eclipse brightening (*1*). In addition to color center production, it is quite possible that preferential oxygen sputtering or proton-induced reduction, and consequent sulfur production in a sulfate-rich matrix such as our Orgueil leach evaporite, may be important in producing coloration. If so, this process may also have operated more effectively at the poles, again possibly explaining Io's dark reddish polar regions. Finally, the possibility of a relatively high sodium abundance in a surface evaporite deposit may also help explain the presence of sodium–D-line emission from the region around Io (*19*).

Several alternative suggestions regarding candidate surface materials for Io have previously been made, and the spectra of these materials are shown in Fig. 1 as well. One frequently mentioned possibility is that some variety of frost or ice is present. There are several problems with the frost hypothesis, however:

1) Io's near-infrared spectrum does not show any strong absorption bands (Fig. 1), in contrast to those of Europa and Ganymede wherein infrared absorptions have been identified as resulting from H_2O frost (*20, 21*). Also NH_3 frost (curve g) shows deep infrared absorptions.

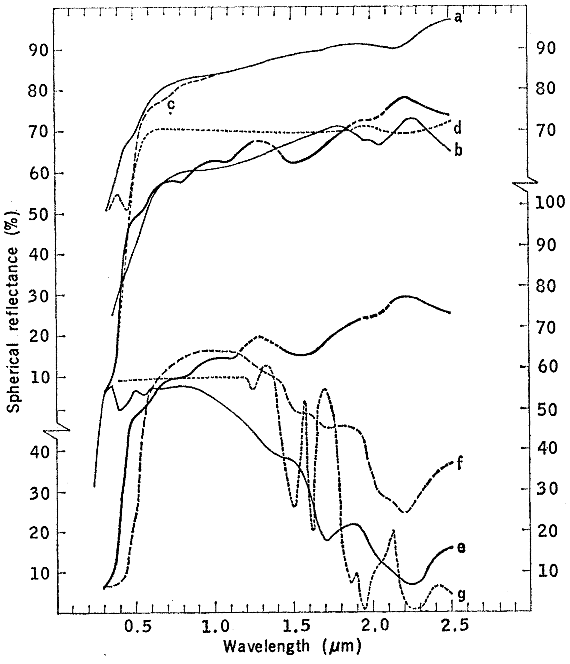

Fig. 1. The spectral reflectance of Io is shown as a heavy solid line in both the upper and lower portions of the figure; dashed areas in the infrared part of this curve indicate areas of high telluric water absorption. The other curves are taken from laboratory spectra, and the comparison on a spherical albedo scale is not exact. Laboratory data taken with an integrating sphere were plotted versus percent reflectance relative to MgO. Data from (*11*) are normal reflectances relative to LiF with an illumination angle of 45°; these data are arbitrarily reduced to spherical reflectance by the use of a phase factor of 0.7 (similar to Io's phase integral). Thus, absolute reflectance comparisons are probably good only to ~10 percent. The upper portion of the figure shows laboratory data for natural halite (NaCl) (curve a), Orgueil leach evaporite (curve b), a sample of natural halite irradiated by protons (curve c), and selensulfur (curve d) (*11*). The lower portion shows: NH_4SH (curve e) (*11*), ammonium polysulfide (curve f) (*11*), and NH_3 frost (curve g) (*12*) (for which the visible portion is extrapolated).

2) Io's visual (0.3 to 1.1 μm) reflectance spectrum is not white as would be expected for pure frosts. A number of possible chromophores to account for this color have been suggested (*1*).

3) Io has dark reddish polar regions (*18*), in contrast to the bright polar caps of Europa (*22, 23*).

Materials other than frosts which have been discussed as candidate surface materials include NH_4SH and pure sulfur, possibly derived from H_2S (*22, 24*), and ammonium hydrosulfides (*25*). Unlike NaCl and the Orgueil evaporite, the ammonia compounds in general have absorption features in the near-infrared which are not observed on Io (*11*); for example, see the spectra for NH_4SH (curve e) and ammonium polysulfide (curve f). The spectrum of selensulfur (curve d) matches the ultraviolet reflectance of Io well. Reflectance curves for pure sulfur are similar (*11*). Sulfur might conceivably be derived from the outgassing of H_2S or by the irradiation of a sulfate salt, as discussed above.

Our hypothesis is also quite compatible with recently published hypotheses concerning the pre- and post-accretion thermal history of the Galilean satellites. As indicated above, solid material in the preplanetary nebula at Jupiter's heliocentric distance is considered to have consisted of a mixture of carbonaceous chondritic material and ices. Differences in density between the Jovian satellites may be due to an initially high surface luminosity for Jupiter (*26*). This would prevent the incorporation of large amounts of H_2O ice in the innermost major Jovian satellite, Io, which has a density of $\sim$3.5 g/cm^3 (*27*); Europa, by comparison, has a lower density of $\sim$2.9 g/cm^3 (*27*) and strong H_2O ice bands in its reflectance spectrum (*20, 21*). Ganymede clearly contains a very large proportion of H_2O ice, as shown by its density of $\sim$1.9 g/cm^3 (*27*). If Io accreted essentially free of H_2O ice, then it might be expected that the degassing of any chemically bound water, such as is present in all forms of carbonaceous chondrites (*28*), is virtually certain to have occurred throughout Io's interior (*29*). Water percolating to the surface of Io is also certain to have become saturated with salts, and eventually the loss of water initially supplied to the surface or near subsurface would result in the retention of salts, regardless of whether evaporation or sublimation was the mechanism of loss (*30*).

It is difficult to judge on theoretical grounds what the composition of the resulting exposed evaporite salts on Io might be. However, we expect that the proposed method of formation would be likely to result in a chemically complex mixture of salts, like our leach evaporite, rather than in a single pure salt such as the epsomite that occurs so conspicuously in Orgueil.

We interpret the high density of Io (*27*) and the absence of H_2O ice bands in its surface spectrum (*1*) as signifying that the above process has proceeded essentially to completion. In contrast, both the lower density of Europa (*27*) and the presence of strong H_2O ice bands in its surface spectrum (*20, 21*) seem to suggest a less advanced state of dehydration than for Io and to indicate that H_2O ice has lately been supplied to Europa's surface at a rate comparable to or greater than that at which it has been lost. The next satellite, Ganymede, shows weaker H_2O ice bands (*20, 21*). But Ganymede must contain much more H_2O ice in bulk (*27, 29*). This may suggest that the separation of H_2O ice and silicates has not yet reached the surface of Ganymede.

In summary, our data suggest that an irradiation-altered evaporite salt assemblage could provide at least as good a match to Io's reflectance spectrum as any other previously suggested materials. At the same time, the presence of surface evaporite salts seems compatible with cosmochemical and meteoritical evidence. Finally, our hypothesis may help to explain some otherwise perplexing properties of Io such as its dark poles and the sodium-D-line emission from the region around Io.

F. P. FANALE
T. V. JOHNSON
D. L. MATSON

Jet Propulsion Laboratory,
California Institute of Technology,
4800 Oak Grove Drive,
Pasadena 91103

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19. Recently, sodium line emission from Io was reported [R. A. Brown, *Int. Astron. Union Symp. 65* (Torun, Poland, 5–8 September 1973), in press]. We offered an explanation for the production mechanism based on a sputtering–resonant scattering hypothesis [D. L. Matson, T. V. Johnson, F. P. Fanale, *Astrophys. J. Lett.* **192**, L43 (1974)]. The arguments and conclusions presented in this report were formulated in February 1973 in an effort to explain the spectral reflectance of Io on the basis of the meteoritical and cosmochemical arguments. The first formal presentation of the evaporite hypothesis was made by F. P. Fanale, T. V. Johnson, D. L. Matson at the American Astronomical Society, Division of Planetary Sciences, 5th annual meeting, Palo Alto, California, 2–5 April 1974 [*Bull. Am. Astron. Soc.* (abstr.) **6**, 384 (1974)]. On the basis of the results of Nash *et al.* (D. B. Nash, D. L. Matson, T. V. Johnson, F. P. Fanale, in preparation), we believe that the evaporite hypothesis allows for much greater sodium production from the surface. A surface material containing 10 percent or more sodium, such as our Orgueil leach evaporite, would offer advantages over other candidate materials which would contain at best only trace amounts of sodium. Eventually, emission measurements may provide severe compositional constraints. As an extreme example, it already appears that materials with a calcium/sodium abundance ratio of > 5 can be eliminated, including most achondrites, because the calcium line intensity at 4227 Å expected [J. Greenstein and R. Arpigny, *Astrophys. J.* **135**, 892 (1962)] would be as great as or greater than that of the sodium line. On the basis of our hypothesis, a strong magnesium line at 2852 Å would be expected. This would have to be observed from above the earth's atmosphere.
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30. On the basis of the relationship between sublimation rates and temperatures given by K. Watson, B. C. Murray, H. Brown [*Icarus* **1**, 317 (1963)] and temperatures for Io's surface (*1*), about 2 km of H_2O ice could have sublimed from Io's surface in 4.5×10^9 years, so long as sublimation was the rate-limiting process. This might be so if the surface pressure was $\leq 10^{-11}$ bar. If the surface pressure is found to be as high as 10^{-8} bar (the Pioneer 10 upper limit) [A. Kliore, D. L. Cain, G. Fjeldbo, B. L. Seidel, S. I. Rasool, *Science* **183**, 323 (1974)], then ion production by megaelectron volt magnetospheric protons together with ion sweeping by the Jovian magnetosphere would cause the atmospheric mean residence time of H_2O ice to be on the order of ~ 4 years [Matson *et al.* (*19*)]. In the case of the "thick" atmosphere, up to a kilometer of ice could still be removed, since actual temperatures as high as 200 to 250 K may be inferred earlier in Io's history from the early luminosity history of Jupiter (*26*). These temperatures are above the H_2O ice–NH_3 ice eutectic (173 K).
31. This report presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract NAS 7-100, sponsored by the National Aeronautics and Space Administration. One of the authors (D.L.M.) was supported by a National Research Council resident research associateship during the period of this study. We thank J. S. Lewis, C. B. Pilcher, and D. B. Nash for helpful discussions.

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Modeling Periodically Surging Glaciers

Abstract. *A numerical model has been developed which produces periodic surging as a characteristic of some glaciers for a certain accumulation and bedrock distribution in contrast to the normal steady state for nonsurging glaciers. Results are presented to illustrate how the magnitude of changes in the length, thickness, and velocity of surging glaciers can be simulated by the model.*

The sudden advance or "surge" of a glacier or ice cap after years of apparent stagnation or retreat remains one of the most fascinating and puzzling phenomena associated with these large ice masses. Such surges [in which the glacier moves forward often many kilometers over periods of months to years at speeds one or two orders of magnitude faster than normal (*1*)] occur in most glaciated regions of the world, and it has been suggested (*2*) that their occurrence in the Antarctic or Greenland ice sheets could have catastrophic consequences on a global scale (*3*).

Numerical models already developed for glaciers (*4*) give a reasonable approximation to their normal flow behavior but cannot be considered satisfactory unless they take into account the surging mode as well. Our aim in the work presented here was to develop a simple model which simulates the most important aspects of surging glaciers and which can be made more sophisticated to match their detailed features as further information on these becomes available. We present here preliminary results showing how the model reproduces various surge phenomena. The detailed theory of the model and its application to specific surging glaciers will be described elsewhere (*5*).

For maximum simplicity we have used a two-dimensional model representing the central flow line of a glacier or a general flow line of an ice sheet. Techniques for determining the parameters of the central flow line for a given glacier have been described by Budd and Jenssen (*4*). The main principles upon which the surge model is constructed are as follows:

1) The average velocity V of a vertical ice column is composed of the average internal deformation through horizontal shear V_i plus the basal sliding velocity V_b:

$$V = V_i + V_b \qquad (1)$$

2) One can obtain the average internal velocity of the column from the flow properties of the ice, for example, using a power law for flow

$$V_i = k\,\tau_b{}^n Z \qquad (2)$$

where τ_b is the base stress, Z is the ice thickness, and k and n are flow law parameters of the ice.

3) The quantity V_b at a point is not directly related to other properties of the glacier at that point but is determined by the integral of the longitudinal strain rates along the glacier. This principle ensures that V_b and τ_b for the glacier as a whole are solved simultaneously to allow feedback and interaction so that their values at any one point interact with the values at other points.

4) The mean longitudinal strain rate through a column is governed by the equation of longitudinal stress equilibrium for scales large by comparison with Z and for small surface slopes α ($\sin\alpha \approx \alpha$) (*6*):

$$-2\,\frac{\partial Z\,\bar{\sigma}_x'}{\partial x} = \tau_c - \tau_b \qquad (3)$$

where $\bar{\sigma}_x'$ is the mean longitudinal stress deviator through the column at position x along the glacier and τ_c is the central downslope stress of the column given by

$$\tau_c = s\rho g\alpha Z \qquad (4)$$

where s is the shape factor for the glacier cross section (varying typically from 0.5 to 1 for symmetric shapes varying from semicircular to infinitely wide), ρ is the density of ice, and g is the gravitational acceleration.

Equation 3 expresses the large-scale balance between the three main forces on a longitudinal section element of the glacier, namely, the gravitational force downslope, the basal friction force of the bed upslope, and the difference between these forces over its ends.

5) The mean longitudinal strain rate through a column $\bar{\epsilon}_x$ is proportional to $\bar{\sigma}_x'$, that is

$$\bar{\epsilon}_x = \frac{\bar{\sigma}_x'}{2\eta} \qquad (5)$$

Equation 5 provides for the extension or compression of the section of the glacier according to whether the longitudinal stress is greater or less than the overburden averaged through the thickness. The resultant strain rate is dependent on the flow properties of the ice.

For the simplest model we have taken the "generalized viscosity" η as a constant to show that a nonlinear flow law is not an essential requirement for surging. More general flow law relations can be used as required, such as a power law or a hyperbolic sine law. For development purposes Eqs. 2 and 5 allow the flow properties of the ice in horizontal shear and in longitudinal tension or compression to be studied independently. This is important for nonlinear flow laws for