tion of the cuff was verified. Two rats were found to have nonfunctioning cuffs; their scores were therefore excluded from the analysis. The analysis of variance and specific comparisons were based on the other eight rats. The rats clearly preferred the nutrient paired flavor [$F(1,7) = 17.35$, $P < .01$] (Table 1).

It seems that the stomach can recognize some components of food and signal their arrival rapidly to the central nervous system, where such messages produce reinforcement. So far, the presence of nutrient sensors in the duodenum, signaling to the brain via the release of cholecystokinin, has been postulated (*4*). The presence of nutrient sensors above the level of the duodenum must also be considered. The mechanism by which the sensors in the stomach transmit their signals to the central nervous system remains to be elucidated.

J. A. DEUTSCH, M.-L. WANG
Department of Psychology, University of California, San Diego La Jolla 92037

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Sea Straits and Glacial Periods in the Red Sea

Deuser *et al.* (*1*) compared oxygen isotopes in tests of foraminifera from sediments of the Gulf of Aden with those from the Red Sea. In glaciated periods they found an ^{18}O enrichment of 2 per mil in the Red Sea tests, which corresponds to an excess salinity of 6 to 7 per mil in the Red Sea over the Gulf of Aden. Today this excess salinity is only 3 per mil. Deuser *et al.* concluded that "during the periods of maximum glaciation the climate in the area of the Red Sea was, on the average, considerably drier than today."

This conclusion seems to be in conflict with what is known about flow through sea straits. Deuser *et al.* stated that lowering sea level would reduce the exchange between the Gulf of Aden and the Red Sea. However, the implication of such a reduction would invalidate their conclusion about the paleoclimate of the Red Sea.

The Red Sea is in a state of frictional overmixing such that the exchange through the Strait of Bab al Mandab is limited by critical Froude conditions (*2*). The salinity difference $\Delta s = s_2 - s_1$ between the discharge from the Red Sea, s_2, and the inflow to the Red Sea from the Gulf of Aden, s_1, is related to the bathymetry of the strait and the excess evaporation over the Red Sea according to

$$\Delta s \,\alpha\, q^{2/3} L^{1/3} Y^{-2/3} D^{-4/3}$$

or

$$\frac{q^*}{q} = \left(\frac{\Delta s^*}{\Delta s}\right)^{3/2} \left(\frac{D^*}{D}\right)^2 \left(\frac{Y^*}{Y}\right) \left(\frac{L}{L^*}\right)^{1/2}$$

Here q is the excess evaporation over the Red Sea, and L, D, and Y are the length, depth, and width of the strait. Quantities with asterisks refer to glacial periods, and those without asterisks refer to the present. The salinity (or ^{18}O) differences are thus more sensitive to changes in depth than to changes in the evaporation rate.

For present-day conditions one may characterize the Strait of Bab al Mandab by the parameters (*2*) $L = 160$ km, $Y = 18$ km, $D = 180$ m, $q = 28000$ m^3/sec, and $\Delta s = 0.003$. The sea level lowering at the maximum of the glacial period was 130 m (*3*), and on the average I will conservatively assume a lowering of 80 m. The glacial parameters in the above equation can then be approximated by $L^* = 160$ km, $Y^* = 12$ km, and $D^* = 100$ m. Adopting the estimate $\Delta s^* = 0.007$ of Deuser *et al.*, I obtain

$$q^*/q = 0.73$$

Thus, it seems more likely that during glacial periods the climate of the Red Sea area was similar to or somewhat more humid than that of today.

GAD ASSAF
Isotope Department, Weizmann Institute of Science, Rehovot, Israel

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6 August 1976

I am grateful to Assaf for applying his model for the water exchange through straits (*1*) to our data in order to check the implications for the Red Sea climate during glacial times (*2*). I am not convinced that the model with its implicit and explicit assumptions and simplifications can do justice to the complexities of nature, but I will not argue about its applicability in this space nor take issue with Assaf's choice of dimensions for the Strait of Bab al Mandab (*3*). However, even if the value of 0.73 for the ratio of glacial to present excess evaporation over the Red Sea were correct, Assaf's conclusion is not valid. An 80-m drop of sea level during glacial times reduced the surface area of the Red Sea by 37 percent (*4*). Therefore, the evaporation had to take place over an area a^* which was only 63 percent of the present surface area a. The climatically significant quantity in the context of our report (*2*) is excess evaporation per unit area of sea surface, e, and not the net influx, q, of water through the Strait of Bab al Mandab. Using Assaf's asterisk notation and his influx ratio of 0.73, I obtain

$$\frac{e^*}{e} = \frac{q^* a}{q a^*} = \frac{0.73}{0.63} = 1.16$$

Thus, whatever the merit of the model calculations, it still seems likely that during glacial periods the climate in the Red Sea was drier than today.

W. G. DEUSER
Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543

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4. I calculated this value by planimetry of the areas within the coastline and the 50- and 100-m depth contours on the map of M. Pfannenstiel and G. Giermann [in S. A. Morcos, *Oceanogr. Mar. Biol. Annu. Rev.* **8**, 73 (1970)] and interpolating the 80-m value.
5. Inasmuch as I was responsible for drawing the conclusion in our jointly authored report (*2*) which was questioned by Assaf, I assume responsibility for this reply. Supported by NSF grant OCE73-06586.

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Galilean Satellites: Anomalous Temperatures Disputed

In a recent report, Gross (*1*) argues that the observed infrared brightness temperatures of the Galilean satellites are significantly higher than temperatures calculated on the assumption that these largest satellites of Jupiter are in equilibrium with the incident sunlight. He therefore suggests that their surfaces are being heated above equilibrium values by energetic atomic particles in the Jovian magnetosphere but notes that the observed particle fluxes are about an order of magnitude too small to account for the apparent heating. Unfortunately, his calculations of equilibrium temperatures are in error, and, when corrected, the theoretical temperatures are in satisfactory agreement with the observations. In fact, this agreement is a cornerstone of the "radiometric method" of determining the diameters of asteroids and other satellites, a technique that is being widely applied today in physical studies of small objects in the solar system.

The equation used by Gross to calculate the equilibrium temperatures of the satellites is useful as a conceptual tool but inadequate for detailed comparison with observations. The "average temperature" it yields is neither a physical temperature nor a brightness temperature; rather, it is a quantity defined such that energy absorbed is balanced by energy radiated for an isothermal sphere [his $T_{eq}(4)$] or isothermal hemisphere [his $T_{eq}(2)$]. Real temperatures vary, and the observer sees preferentially the warmer parts near the subsolar point. The theoretical quantity actually required for comparison with infrared observations is the irradiance, within the region of spectral sensitivity of the measurement, averaged over a model satellite whose physical temperature varies with position on the surface. The disk-averaged brightness temperature, T_B, for a given spectral band, is a shorthand means of expressing this spectral irradiance in terms of an equivalent isothermal blackbody.

The temperature variation over the surface of the satellite depends on rotation and on the optical and thermophysical properties of the surface material. In the case of the Galilean satellites, the rotation is synchronous with the orbital period (*2*), the large-scale distribution of surface reflectivity is known (*3*), and the thermal properties have been ascertained from measurements of eclipse cooling curves (*4, 5*). Therefore, it is possible to calculate with confidence the temperature distribution on the surface. The primary sources of uncertainty in a comparison of calculated T_B values with observed T_B values lie in uncertainties in the diameters of the satellites, in the phase integral q, in the degree of enhancement of infrared emissivity at near-normal emission angles (an effect well known for the moon, which has center-of-disk infrared brightness temperatures significantly higher than the physical temperatures), and finally in the absolute calibration of the infrared flux scales.

Physically realistic thermal models of the sort described above have been computed for the Galilean satellites by Morrison *et al.* (*6*), Morrison and Cruikshank (*4*), Matson (*7*), Jones and Morrison (*8*), Hansen (*9*), and others, and were reviewed in a paper presented at the 1974 International Astronomical Union colloquium (*10*). Table 1, adapted from this review, compares computed and observed temperatures. The computed temperatures are significantly higher than those listed in Gross's table 3. The difference is due entirely to the fact that more realistic thermal modeling is used in Table 1; for these objects, T_B at 10 and 20 μm is 0.90 to 0.93 of the subsolar temperature, whereas Gross's equations give factors of 0.50 for the isothermal sphere model and 0.71 for the isothermal hemisphere model. In all cases the calculated temperatures in Table 1 agree to within realistic estimates of uncertainty with the infrared observations. There is no evidence for additional heating from the Jovian energetic particles.

Table 1. Computed and observed temperatures (in degrees Kelvin) for the Galilean satellites; p_V is the average geometric visual albedo; A is the corresponding Bond or spherical albedo; T_{max} is the calculated subsolar surface temperature; T_B (10 to 20 μm) is the average of the calculated, disk-averaged infrared brightness temperatures for the two wavelengths indicated (the values at 10 and 20 μm agree to within 5°K); the last two columns summarize the observed infrared brightness temperatures.

Satellite	p_V	A	T_{max}	T_B (10 to 20 μm)	Observed T_B (10 μm)	Observed T_B (20 μm)
Io	0.63 ± 0.02	0.56 ± 0.12	141 ± 11	130 ± 10	138 ± 4	129 ± 4
Europa	0.68 ± 0.09	0.58 ± 0.14	139 ± 12	127 ± 10	130 ± 4	121 ± 4
Ganymede	0.43 ± 0.02	0.38 ± 0.11	154 ± 6	141 ± 5	143 ± 4	140 ± 5
Callisto	0.17 ± 0.02	0.13 ± 0.06	167 ± 3	153 ± 3	154 ± 4	152 ± 5

Gross mentions Amalthea, the innermost known Jovian satellite, as probably subject to the greatest heating by particles. However, the infrared (8- to 21-μm) color temperature of this small satellite was found by Rieke (*11*) to be $\simeq$ 155°K, a value consistent with a relatively dark satellite (geometric albedo $p_V \simeq 0.1$) in approximate equilibrium with the sunlight.

Although the conclusion reached by Gross that infrared measurements give evidence for significant heating of the Galilean satellites by Jovian energetic particles is false, there do remain some interesting differences between calculated and observed temperatures for these satellites. The differences between data at 10 and 20 μm, particularly for Io, suggest a wavelength-dependent emissivity (*4, 5*). Still more intriguing is the recent indication of a maximum near 8 μm (*12*) in T_B for Io. We also now know that both light ice and dark rock are exposed on the surfaces of Europa and Ganymede, and Fink and Larson (*13*) have shown that the ice is colder than the average surface temperature; thus it would be appropriate to consider models with mixed light and dark surface elements, each in local equilibrium with the sunlight. Because Io and Europa have high albedos, radiometric observations of these two satellites provide an opportunity to determine directly the Bond albedo and the q values of highly reflective solid surfaces (*10*). Moreover, the degree of enhancement of infrared emissivity normal to the surface of the Galilean satellites and other bodies remains an important parameter in radiometric models being used for the determination of the diameters of many small satellites and asteroids (*8, 10, 14*).

DAVID MORRISON*
Lunar and Planetary Laboratory, University of Arizona, Tucson 85721

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* On leave from the Institute for Astronomy, University of Hawaii, Honolulu 96822.

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Gross states in his report (*1*) that the equilibrium temperatures for the Galilean satellites of Jupiter are lower than the brightness temperatures as reported

Table 1. Satellite temperatures. Data in columns 2 through 4 are from Morrison and Cruikshank (2).

Satellite	Temperature (°K) Calculated	Measured (8 to 14 μm)	Measured (17 to 28 μm)	$T_{eq}(2)$
Io	126 ± 10	138 ± 4	126 ± 6	115.9
Europa	121 ± 10	129 ± 4	121 ± 5	107.9
Ganymede	144 ± 6	144 ± 5	137 ± 10	128.3
Callisto	156 ± 4	153 ± 5	148 ± 12	142
Amalthea	156 ± 4	155 ± 15*		142†

*Based on measurements of the thermal emission curve of Amalthea at several band passes from 8 to 20 μm. †Albedo assumed to be similar to that of Callisto.

by Morrison and Cruikshank in (2). As stated by Morrison and Cruikshank, the brightness temperatures as measured by radiometric techniques are not equilibrium temperatures. These satellites have low thermal conductances and relatively slow rotation rates with respect to the reradiation of absorbed solar energy, and therefore any surface element may be considered thermally insulated from its surroundings.

However, contrary to the statement of Gross (1), all portions of the satellites are illuminated in turn even if they are locked in synchronous rotation. Therefore, the surface will have a temperature distribution that is hotter at the subsolar point and cooler toward the terminators. For a perfectly absorbing body (a blackbody) at the distance of Jupiter, the subsolar temperature will be about 175°K whereas the temperature at a point near the terminator will be less than 100°K. The subsolar temperature is much higher than that of the equilibrium temperature (uniformly heated hemisphere) model of Gross (146°K). The radiated flux observed (and the derived brightness temperature measured) by a ground-based observer originates primarily in the area around the subearth point (since the subearth point for objects in orbit around Jupiter is close to the subsolar point). We estimate that the brightness temperature of a blackbody there would be in excess of 160°K.

Table 1 presents the calculated and measured brightness temperatures for the Galilean satellites [as presented by Morrison and Cruikshank (2)] as well as the equilibrium temperatures, $T_{eq}(2)$, as derived by Gross (1). Data from a more recent observation of Amalthea (JV) have also been included (3). Amalthea is much closer to Jupiter than the Galilean satellites so that any bombardment by Jovian energetic particles will be higher.

As can be seen from Table 1, the calculated and measured brightness temperatures as presented by Morrison and Cruikshank are not in disagreement as has been suggested by Gross. Therefore, no particle heating of the surfaces need be postulated to explain any discrepancies.

LARRY A. LEBOFSKY
Jet Propulsion Laboratory, California Institute of Technology, Pasadena 91103

JAMES A. CUTTS
Planetary Science Institute, Pasadena, California 91101

GLENN J. VEEDER
Jet Propulsion Laboratory, California Institute of Technology

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Because the criticisms of Morrison and of Lebofsky *et al.* are essentially along the same lines, I will respond only to the comments of Morrison.

Before discussing the main issue of the possibility of additional heating caused by impacting particles (1), I believe it is necessary to clear up a point of confusion which appears in the criticism of Morrison concerning the relationship between equilibrium, brightness, and subsolar temperatures, designated here by T_{eq}, T_B, and T_{max}, respectively. Although I agree with Morrison that T_{eq} is not a good representation of the temperature distribution about a satellite, it is not so bad a representation of the disk-averaged T_B, particularly when calculated for a hemisphere. Morrison objects that T_{eq} is too low, being 0.50 of T_{max} when computed for a sphere and 0.71 of T_{max} for a hemisphere, whereas he claims it should be closer to 0.90 to 0.93 for realistic temperatures. Although the latter values may be valid, Morrison does not explicitly state how he computed the values 0.50 and 0.71; it is well known that T_{eq} is $4^{-1/4} \approx 0.71$ for a sphere, not 0.50, and $2^{-1/4} \approx 0.84$ for a hemisphere, not 0.71; T_{eq} for a hemisphere is actually closer to the range preferred by Morrison and may be a more useful approximation than he may admit.

With respect to the key issue of particle heating, there is no question that the Galilean satellites are unique in the solar system because of their locations within the Jovian magnetosphere. Particles undoubtedly interact with these satellites as evidenced by the relationship of Io and possibly Europa to Jovian decametric and hectometric radio emissions (2). It is also very likely that the unusual sodium clouds associated with Io, which appear to be replenished (3), at least as long as we have been observing these clouds, result from energetic surface processes that may entail high-energy particle bombardment. In addition, high-energy particle measurements on the Pioneer 10 and Pioneer 11 missions in the Jovian magnetosphere indicated dips in the particle fluxes at the satellite orbits at positions away from the satellites and particle acceleration along satellite magnetic flux tubes (4). It is as though the particles were being swept up by the satellites.

The important questions are not whether there are particle bombardments but whether the plasma bombardment significantly contributes to the heating of the satellite surfaces and whether such heating is evident from the infrared radiometric data. Morrison and Cruikshank (1) and Morrison in his criticism maintain that there are no significant effects. I believe that the evidence is not conclusive. One can make a case for particle heating, but the measurement errors are too great to permit one to make a positive statement one way or the other.

As an example of the difficulty of making positive deductions regarding heating, consider the problem of uncertainty in the Bond albedo of Europa. In my report (5), based on the value (0.7) assigned by Morrison and Cruikshank in (1), I computed T_{max} and T_{eq}; these calculations suggested the need for additional heat input such as would be available from particle bombardment when these calculated temperatures were compared with measured values. In Morrison's criticism a different value is given (0.58) with a tolerance of ± 0.14, that is, an uncertainty of ± 24 percent of the nominal value. The change from 0.7 to 0.58 also amounts to about the same percentage change. These changes occurred in a relatively short period of time with little differences in experimental data. Nevertheless, since calculated temperatures are highly sensitive to the choice of the Bond albedo, one must know its value with much greater certainty if one is to make positive statements that there are no additional heating effects.

One may utilize the 10-μm temperature and calculated values of T_{max} listed by Morrison in his criticism to obtain the ratio of T_B to T_{max} for comparison with his ratio criterion of 0.90 to 0.93. Using his normal and extreme values (6), one obtains the ratios listed in Table 1. Data in column 2 are based on Morrison's nominal temperatures; the extremes based on incorporation of the tolerances are given in columns 3 and 4. The nominal value for Io is well in excess of Morrison's criterion, implying that the measured temperature exceeds that expected from T_{max} calculated with only solar heating and that other energy sources may be present. Although one may argue that the temperature is higher than predicted because of the nature of Io's surface, can one positively make such a statement? The nominal value for Europa is just a bit higher than Morrison's crtierion, whereas the nominal values for Ganymede and Callisto are at the top of the range. Perhaps there is little or no additional heating for Europa and none for Ganymede and Callisto.

Table 1. The ratios of T_B at 10 μm divided by T_{max}, as calculated on the basis of values and tolerances from Morrison's table 1.

Satellite	Nominal value	Minimum ratio	Maximum ratio
Io	0.979	0.882	1.092
Europa	0.935	0.834	1.055
Ganymede	0.929	0.869	0.993
Callisto	0.922	0.882	0.963

Consideration of only nominal values, however, is not sufficient if the tolerances have any meaning. The maximum ratios, at least for Io and Europa, are well beyond the criterion and would imply that there is much more additional heating than required by the nominal ratio. The minimum ratios for all the satellites, on the other hand, imply no extra heating. The range of values in Table 1 certainly covers all possibilities. Although this is a numbers game, one may state with assurance that the radiometric data do not exclude the possibility of particle heating and may not, if at all, clearly indicate the reality of the situation before measurement errors are considerably reduced. The criterion 0.90 to 0.93 is open to question as well.

In addition to the arguments based on temperature ratios, there is other evidence for plausible explanations based on particle heating. One such situation involves the interpretation of Jovian satellitic eclipse data as listed in (7). Particle heating may explain the variation of T_B as observed in an eclipse, contrary to the explanations of Morrison and Cruikshank (7) and of Hansen (8). They postulate a two-layer surface model to explain the changes in radiometric flux as the satellites are eclipsed. The lower layer in this model acts as a heat sump, or source of energy, that raises the theoretical flux level to that observed during eclipse. Their upper layer is assumed to be of low thermal conductivity, and its thickness is computed to be only a few millimeters. If bombarding particles serve as the source of energy during eclipse, this lower layer is unnecessary. Further, it is not necessary to posit so thin a layer of materials on top of the surface, and so one avoids the attendant problem of explaining its relationship to a real surface of unknown structure.

Another possible indication of particle heating is the observation (7) that the radiometric fluxes from Io and Europa maximize between western elongation and superior conjunction and minimize between superior conjunction and eastern elongation. A corotating magnetospheric plasma would be expected to produce such an effect if the plasma provides heat to the surfaces of these satellites. Although such a rotational phase effect is not necessarily attributable exclusively to particle bombardment, one cannot rule out this explanation simply on the basis of the radiometric observations.

The secular brightening of the Galilean satellites between 1973 and 1974 (9) represents another event that may be associated with particle interactions. It is also not trivial to wonder whether sodium clouds would have been observable before that time.

In another criticism of (5), Morrison suggests that particle effects, if significant, should be even greater for Amalthea because it is deeper in the Jovian magnetosphere than for the other Galilean satellites. Rieke's recent measurement of Amalthea's brightness temperature (10) is referred to by Morrison as indicating no particle heating effects. Rieke found a brightness temperature of 155° ± 15°K. If particle heating effectively contributes only 30 percent over and above the absorbed solar flux, then, everything else being held the same, a nominal temperature due to the sun alone of 155°K would increase roughly by a factor $(1.3)^{1/4}$ $(=1.068)$ to 165.5°K, which is within the tolerance. Rieke's data thus do not clearly indicate that there is no particle heating. Morrison's conclusion on particle heating of Amalthea is even more uncertain in view of the absence of any good determination of Amalthea's albedo. Particle sweeping by Amalthea has been reported as a result of measurements on the Pioneer 10 and Pioneer 11 missions.

In (5) I suggested that particle fluxes ten times those measured on the Pioneer 10 and Pioneer 11 missions were needed. This flux level was not deemed unreasonable, since particles transporting the bulk of the particle energy, those in the kilovolt energy range and below, were not measured. However, if the particle energy fluxes were only two to five times the measured values of the Pioneer missions, amounting to an energy flux of some 5 to 20 percent of the absorbed solar flux, such levels of particle energy fluxes may be sufficient to explain the nominal temperature ratios for Io and Europa in Table 1. However, until particles in the lower energy ranges are measured, the validity of such fluxes is uncertain.

More energetic fluxes within the magnetosphere may not be necessary if mechanisms are at work that enhance the particle influx at the satellites. One such mechanism may involve a sweeping action, due possibly to electric fields and gravity. The particles are focused into the satellite and the interaction is more energetic than expected from measurements of the Jovian magnetospheric particles.

In summary, I believe that, although there certainly are particle effects, analysis of radiometric data to indicate particle heating is still speculative, although the data are not inconsistent with such an interpretation. The treatment of these data has been mostly a numbers game. It is necessary to reduce the measurement errors in order to make a positive determination of what is occurring. In view of all of this, I believe the matter of particle heating is far from closed.

STANLEY H. GROSS
Department of Electrical Engineering and Electrophysics, Polytechnic Institute of New York, Farmingdale 11735

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