Reports

Io: An Intense Brightening Near 5 Micrometers

Abstract. *Spectrophotometric observations of the jovian satellite Io on 20 and 21 February 1978 (Universal Time) were made from 1.2 to 5.4 micrometers. Io's brightness at 4.7 to 5.4 micrometers was found to be three to five times greater at an orbital phase angle of 68° than at orbital phase angles of 23° (5.5 hours before the brightening) and 240° (20 hours after the brightening). Since the 5-micrometer albedo of Io is near unity under ordinary conditions, the observed transient phenomenon must have been the result of an emission mechanism. Although several such mechanisms were examined, the actual choice is not clear.*

Transient brightenings of the jovian satellite Io, especially in blue light, have been reported by numerous observers. They appear to occur intermittently in a short time period (about 15 minutes) after the satellite emerges from the shadow of Jupiter. Such observations were cataloged by Frey (*1*), who tentatively proposed that the brightenings might be due to a nonuniform distribution of blue reflectors on Io's surface. Nelson and Hapke (*2*) described a possible correlation of Io's posteclipse brightening with solar flare activity. They proposed that the increase in trapped jovian particle radiation after a solar flare could cause the brightening by thermoluminescence or by radiation from volatiles released by direct heating from the radiation.

The observations reported here were originally intended to augment earlier measurements (*3*) of Io's reflectivity spectrum from 0.7 to 5 μm with more accurate spectrophotometry between 4.6 and 5.4 μm. Just prior to making our observations, we were advised by L. Lebofsky that he and his associates were looking for transient phenomena in the range from 2 to 4 μm [they had observed such phenomena after Io's emergence from eclipse (*4*)] and that our 4.6- to 5.4-μm spectra might be a useful adjunct to theirs. Consequently, we carried out two series of observations during the first hour after Io's emergence to compare the first 1/2 hour with the second. No significant differences were noted. A third set of observations, made 5.5 hours after emergence, revealed a dramatic and unexpected increase in brightness especially in the 5-μm range. Lebofsky (*5*) observed a lesser brightening in the range from 3 to 4 μm 2 to 4 hours after emergence. Since the brightness increase at 5.4 μm was three times greater than could be accounted for by a reflectivity of 1.0, the physical mechanism must have been associated with the emission of radiation. We describe here the observations and summarize some candidate mechanisms that may be responsible for the 5-μm brightening.

We carried out the observations using the 151-cm Lunar Planetary Laboratory–National Aeronautics and Space Administration (LPL/NASA) telescope at Mount Lemmon, Arizona, with a continuously variable filter wedge (CVF) spectrometer. The CVF provided spectral coverage with 1.7 percent resolution from 1.2 to 2.4 μm and from 3.0 to 5.4 μm, except where prevented by atmospheric absorption. The sensing element was indium antimonide. Details of the instrument and its use for spectrophotometry are given by Strecker *et al.* (*6*). The field of view was 12 arc seconds. We modulated the signal by oscillating the secondary mirror of the telescope to achieve spatial chopping of 30 arc seconds in the plane of Io's orbit. Unfortunately, it was not convenient to rotate the direction of chopping perpendicular to the orbital plane as would be preferred to minimize the possible effects of scattered light from Jupiter. Consequently, when Io was observed close to Jupiter, each observation of Io was followed by a similar observation of a portion of sky just north of Io at the same distance from the jovian disk. Thus, possible gradients in the background could be subtracted. When Io was farther from Jupiter, it was observed alternately in each of the two fields of view determined by the chopper. Both techniques remove gradients in background caused by unequal radiation from warm structure or atmosphere in the two beams. If scattered light from Jupiter contributed significantly to the gradient, it would be much smaller at an orbital phase angle of 68° than at 20°. In fact, the average gradient for all measurements from 4.7 to 5.0 μm was equal for the two orbital phase angles; this result supports the assumption that the background gradient was caused only by warm structure or atmosphere, or both. Furthermore, the background gradient signal was only 22 percent of the total signal at 68°. This low background gradient signal provides an upper limit to the error that could be made if the background gradient were nonlinear instead of linear as implicitly assumed in the two-beam technique. As will be seen, the observed brightening was too large to be accounted for by even a 22 percent error in the total signal from Io in the range from 4.7 to 5.0 μm.

Since both broad spectral coverage (to tie in with previous data) and accurate photometry at longer wavelengths were desired, each set of observations was made in two parts. The first consisted of continuous 1-minute spectral scans from 1.2 to 5.4 μm; the second consisted of 2-minute integrations (including time for the subtraction of the background gradient) at 3.5 μm and at 0.1-μm intervals from 4.6 to 5.4 μm. The first two sets of observations were made consecutively starting at an orbital phase angle of 20°, just after Io emerged from Jupiter's shadow. The third set of observations was made at an orbital phase angle of about 68° and the fourth at 240°. A log of the observations including air mass, orbital phase angle, and System III (1957) longitudes of Jupiter's central meridian and the sub-Io point appears in Table 1.

We used β Geminorum to calibrate the Io measurements; this star was observed with both the scanning and photometric technique. The flux versus wavelength for β Geminorum has been established in the range from 1.2 to 5.4 μm by Strecker *et al.* (*6*).

Corrections for air mass were determined at each wavelength (λ) as follows. The spectra of a star were obtained through two different air masses on the same night. Let the spectrum through air mass A be $S(A,\lambda)$ and that through air

Length Limit for Reports: The average length of individual Reports in *Science* has been steadily increasing. At the same time, the number of pages allotted to Reports has remained constant and cannot be increased. The net result has been that fewer Reports on fewer subjects are being published; many that receive excellent reviews are being rejected for lack of space. The overall rejection rate is more than 80 percent. In order to increase the acceptance rate for Reports in 1979 we plan to enforce the length requirements: one to seven double-spaced manuscript pages of text, including the references and notes, and two items of illustrative material (tables and figures) which together will occupy no more than half of a published page (30 square inches). After Reports are reviewed, those that are being considered for acceptance and that exceed the length limit will be sent back to the authors for shortening before a final decisions is made. Reports that initially meet the length requirements will not be subject to this delay.

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mass B be $S(B,\lambda)$. The absorption per unit air mass, $\tau(\lambda)$, is determined from the relation

$$S(A,\lambda)/S(B,\lambda) = \exp[-A\tau(\lambda)]/\exp[-B\tau(\lambda)]$$

(We assumed that sky moisture conditions did not change with time or azimuth on a given night.) Then, if the object is at an angle θ from the zenith, the observed spectrum must be divided by $\exp[-\tau(\lambda) \sec \theta]$ to correct the absorptions in Earth's atmosphere. Both Io and the calibration objects were corrected in this way.

The spectra of Io at orbital phase angles of 23° (bottom curve), 68° (top curve), and 240° (middle curve) are shown in Fig. 1. Both continuous scan and integrated data are shown. Points near strong terrestrial absorption features have been deleted. Significant differences between the spectrum at 68° and those at 23° and 240° are evident: the most obvious is the large increase in flux beyond 4.5 μm; an absorption feature near 1.58 μm is stronger at 68°. The reflectivity plots in Fig. 2 show that the apparent reflectivity for the 68° observation is two to three times unity in the range from 4.7 to 5.4 μm. The reflectivities at the other phase angles are consistent with earlier measurements (3, 7) made near 5 μm. We obtained the reflectivity by dividing the Io flux by the flux from a perfectly diffusely reflecting disk of radius 1820 km (8) at appropriate distances

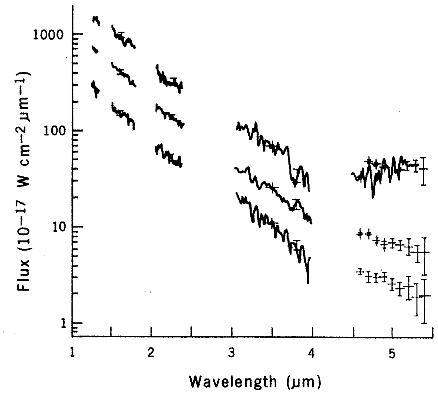

Fig. 1. Spectral flux of Io during (top), after (middle), and before (bottom) brightening. The top spectrum, taken from 7:14 to 7:55, 20 February 1978 U.T., is displaced upward by a factor of 2 from the true value to avoid overlap with the undisplaced middle spectrum taken from 3:12 to 4:03, 21 February 1978 U.T. The lower spectrum is an average of two data sets taken from 1:59 to 3:05, 20 February 1978 U.T., and is displaced downward by a factor of 2.

from the sun and Earth, using the solar flux values of Smith and Gottlieb (9). (No correction was made for the part of Io that was not sunlit as seen from Earth in February 1978. This correction would be only about 1 percent if Io were perfectly round.)

The spectra of the differences between the integrated data at an orbital phase angle of 68° and at the other two phase angles are shown in Fig. 3. Blackbody spectra are shown for comparison. The general character of the increased brightness did not change during the 30 minutes of observation near a phase angle of 68°. Unfortunately, it was not possible to observe at much greater angles the same night because of the rapidly increasing air mass. Spectroscopic observations by Fink and Larson made simultaneously with the photometric observations of Lebofsky were obtained at frequent intervals and may give a time history of the early part of the brightening at shorter wavelengths (4, 5).

The error bars shown in Figs. 1 to 3 are ± 1 standard deviation random errors in the Io data. A further uncertainty of ± 5 percent in the absolute fluxes arises from the quoted uncertainty in the flux values of the calibration star (6). Uncertainties in the air mass correction may arise from changes in atmospheric moisture through the evening. The measured 5-μm flux from Io near a phase angle of 68° through 1.75 air masses was twice as large as it had been earlier in the evening through only 1.02 air masses. Furthermore, at 2800 m the atmospheric transmission at 4.7 μm is 89 percent through 1.75 air masses and 5 mm of precipitable water (we had only 2 mm of water). Thus the total air mass correction, and consequently any possible error in it, is small at a wavelength where the apparent reflectivity rose up to 2. Thus we have little doubt that the observed flux increase was real and not a result of uncertainties in the correction process.

A variety of hypotheses can be offered to explain the nature of the observed excess flux. These include (i) an increase in the amount of reflected sunlight due to a high-albedo feature, (ii) thermal radiation having either an internal or an external origin, and (iii) thermal or ordinary luminescence. We explore below the likelihood of each of these possibilities.

Let us consider first the explanation involving a high-albedo feature. One postulates that a region of the satellite having a very high albedo in the spectral interval from 3.4 to 5.4 μm was within the hemisphere facing Earth at the time the excess was observed but was situated on the other side of Io at the time of the other two observations. According to Fig. 2, the geometric albedo of the high-albedo feature must be at least 3 at wavelengths close to 5.3 μm when the excess was observed. Since the phase integral of objects having high reflectivities is typically about 1 and the lowest known phase integral of any object in the solar system is about 0.6 (10), it would be necessary that the Bond albedo of the hypothesized high-albedo feature exceed unity by a considerable amount in order

Table 1. Summary of observations. The angles and longitudes in the upper half of the table are mid-observation values.

Object	Date (U.T.) in February 1978	Time (U.T.), begin/end	Air mass	Orbital phase angle	System III (1957) longitude*: Sub-Earth point (Jupiter central meridian)	System III (1957) longitude*: Sub-Io point
Integrations at 3.5 μm and at 4.6 to 5.4 μm						
Io	20	2:03/2:24	1.05	23°	49°	206°
Io	20	2:40/3:05	1.02	29°	73°	224°
β Geminorum	20	5:52/6:03	1.01			
Io	20	7:15/7:39	1.75	68°	241°	353°
Io	21	3:32/4:03	1.02	240°	257°	197°
β Geminorum	21	6:32/6:44	1.04			
Continuous scans from 1.2 to 5.4 μm						
Io	20	1:59	1.06	21°	41°	200°
β Geminorum	20	5:43	1.01			
Io	20	7:51	1.99	71°	254°	3°
β Geminorum	20	9:04	1.48			
α Tauri	21	2:22	1.04			
Io	21	3:12	1.01	235°	236°	181°
α Tauri	21	5:18	1.44			
β Geminorum	21	6:24	1.04			

*The north magnetic pole System III (1957) longitude was 238° (21).

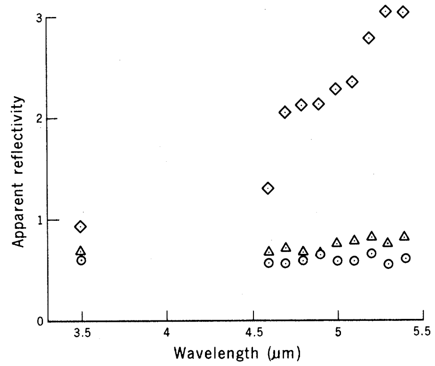

Fig. 2. Apparent reflectivity of Io before, during, and after brightening. Circles denote values obtained before brightening (2:03 to 3:05 U.T.). Diamonds denote values obtained near 7:25 U.T. when Io was bright. Triangles denote values obtained the next evening at 3:32 to 4:03 U.T. when Io had faded.

to match our observations. Such values for the Bond albedo are not possible, and we therefore reject this explanation.

Next, let us suppose that the excess infrared flux is due to thermal emission from a hot portion of Io's surface. As illustrated in Fig. 3, a blackbody temperature of about 600°K would be required to fit the observed wavelength dependence of the excess except for the dip at 4.6 μm which is assumed here to be an absorption feature. In this case, the observed absolute value of the flux excess implies that the extra emission is coming from a surface area equal to about 2×10^{-4} times the total surface area of Io.

A hot local region on Io could be produced by either internal or external factors. One might invoke for an internal origin the rising of hot magma from the satellite's interior to a position quite close to the surface. The postulated thermal radiation could arise either from a heating of the adjacent surface by the magmal pocket, the eruption of the magma onto the surface, or the eruption of hot gases into the atmosphere. Although it is not possible to definitively rule out this explanation, we consider it to be unlikely by analogy with our experience with objects in the inner solar system. No such internally generated hot spot having the approximate size and temperature of the one postulated for Io has ever been observed on global infrared surveys of Earth, the moon, Mercury, or Mars (*11*). This negative result is in part due to the extremely rapid cooling time of an exposed hot surface. For example, a layer 1 cm thick having an initial temperature of 600°K would radiatively cool by 100°K in only several minutes. Thus, a cool crust would rapidly form over any exposed hot magma, although one could conceive of situations in which the hot magma was continually replenished. Similar arguments hold for the alternative scenarios in which local hot spots on Io are created by internal processes.

Bombardment by high-energy particles coming from the jovian magnetosphere might provide an external source of energy for heating a portion of Io's surface. A major difficulty with this hypothesis is finding a mechanism for heating only a minute fraction of Io's surface area and the attendant requirement of focusing the incoming high-energy particles so as to meet the energy budget demands. The difficulty of focusing the particles onto a small area is avoided if the heating of the individual dust particles by the incident protons is sufficient to raise the particle temperature to 600°K. If the surface is composed of a loose dust or fragile, poorly connected material, then the heated portion would radiate most of this energy away before losing it by conduction to adjacent particles. If protons have range R_p in the dust particle and incident energy E_p, then the energy deposited by a single proton during passage through a single dust particle of diameter D is, on the average, DE_p/R_p for $D < R_p$ and simply E_p for $D \geq R_p$. If most of the energy lost by the proton goes into heat, then the temperature rise of the dust particle (assume $D < R_p$) is

$$\Delta T = \frac{D}{R_p} E_p \left(\rho \frac{\pi}{6} D^3 C_p\right)^{-1}$$

where ρ and C_p are the particle density and specific heat, respectively. Protons from the thermal plasma in Jupiter's magnetosphere may be accelerated to several hundred kiloelectron volts by a plasma sheath surrounding Io (*12*). The flux may be as high as 2×10^8 proton $cm^{-2} sec^{-1}$. The flux of electrons accelerated by the plasma sheath is thought to be 30 times as high (*12*), but the range of electrons in solids is much larger than that of protons, so that individual particles are not heated up as much by electrons. We may estimate the range of the protons in material of atomic mass M by using the Bragg-Kleeman rule (*13*)

$$R_p = 3.2 \times 10^{-4} \frac{\sqrt{M}}{\rho} R_p \text{ (in air)}$$

The value of R_p (in air) for 0.3-MeV protons is about 0.5 cm. The ratio $\sqrt{M}/\rho$ is not too different for a variety of candidate materials, so we use here the properties of silicon: $M = 28$ and $\rho = 2.33$ g cm^{-3}. The resulting proton range is 1.8×10^{-4} cm. If a heat capacity of 0.8 J g^{-1} $°K^{-1}$ (typical of granite and many other stony materials) is used, then the diameter must be only 0.0074 μm to produce a ΔT of 500°K. This may not be

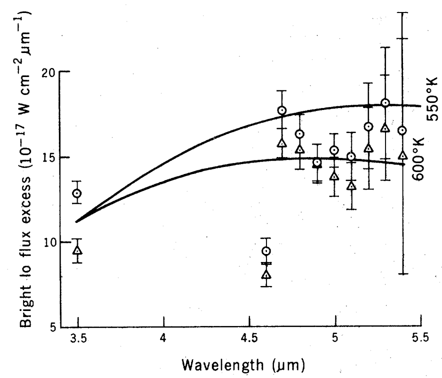

Fig. 3. Comparison of the Io infrared excess during brightening with two blackbody curves (550° and 600°K). The circles denote the difference between the Io flux before and during brightening. The triangles denote the difference between the Io flux during brightening and 20 hours later.

unreasonable for a surface made up of redeposited sputtered material. The fraction of the surface radiating at any time during an incident flux of 0.3-MeV protons of 2×10^8 cm^{-2} sec^{-1} would be on the order of 3×10^{-5} for 0.0074-μm particles. This is nearly ten times lower than our CVF data suggest, but, in view of the uncertainties in the assumptions, is not too small to rule out proton bombardment as the explanation. The spectral shape appropriate for this model would deviate from the assumed blackbody because of the optical properties of the material and the small size of the particles. This deviation affects the temperature estimate and the time required to cool, both of which determine the fraction of surface that is radiating. At this point, it does not appear reasonable to rule out thermal heating by magnetospheric protons as an explanation for the brightening.

The third possible origin of the excess flux is luminescence. In this process energetic particles excite electrons into normally unfilled states in the target material. These states then decay, emitting radiation at wavelengths characteristic of the target material. In the case of Io, the target material may have many defects caused by radiation damage and thus its characteristic radiation may be considerably changed from that of the original material. Such defects may provide low-lying states which could emit in the infrared. Although luminescence has been observed in the infrared at wavelengths beyond 3.2 μm (*14*) in specially doped materials, 5-μm luminescence is not known to be an important mechanism of energy release for stony materials or even for alkali halides, although the latter do have luminescence peaks at shorter infrared wavelengths (*15*).

Thermoluminescence, a two-step process in which electrons are first excited into metastable states in cold materials and later stimulated to decay by heating of the materials, has been proposed by Nelson and Hapke (*2*) to explain Io's posteclipse brightening. They showed that this process would be consistent with the correlation they found between solar flare activity and Io's posteclipse brightening. There were solar flares of importance 2N on 8 February 1978 and of importance 2B on 22 November 1977, both within 10° in heliographic longitude of the sub-Jupiter point (*16*). (Flares of importance 2 cover 5.2 to 12.4 square degrees on the solar disk. Smaller flares are much more common. The term "N" refers to "normal" and "B" to "rather bright" appearance.) Unfortunately, our knowledge of thermoluminescence, like ordinary luminescence, suffers from a lack of data in the 5-μm region. The possible relation of the 5-μm Io brightening to the solar flare could support any of the above explanations based on energetic particle bombardment.

To examine the reasonableness of the luminescence hypotheses, let us carry out a "black box" analysis in which we compare the observed excess amount of emitted energy with likely amounts of energy contained in high-energy particles striking Io's surface. We require then that the energy flux hitting the surface exceeds the energy emitted. If the observed excess flux originates from the entire hemisphere facing Earth, then it corresponds to an energy flux of about 5×10^2 erg cm^{-2} sec^{-1} at Io's surface. The surface of Io is being bombarded by high-energy magnetospheric electrons and protons (*17*) as well as thermal plasma protons and electrons that have been accelerated by a plasma sheath thought to exist about Io (*12*). Of these four possibilities, the highest energy flux would be expected from thermal plasma electrons accelerated through the positive sheath (*12*). Using a typical unidirectional flux of 5×10^9 electron cm^{-2} sec^{-1} and a potential drop of 300 kV across the sheath (*12, 18*), we obtain an energy flux of about 2×10^3 erg cm^{-2} sec^{-1} striking the surface of Io in the region beneath the positive plasma sheath. Thus, accelerated plasma electrons represent a plausible energy source for the postulated luminescence provided that the efficiency of conversion of particle impact energy to luminescence is 0.25. Values for luminescence efficiency for electron impact rarely exceed 0.2, but very few data exist at 5 μm. Typical values of luminescence efficiency in visible wavelengths for lunar materials (*19*) are below 10^{-2} for excitation by ultraviolet light and lower still for excitation by protons.

The occurrence of the postulated luminescence at one rotational phase angle but not at others could be attributed to several factors. First, if thermal luminescence is responsible for the effect observed, the rate of excitation out of metastable states could depend strongly on temperature, so that either nighttime cooling or eclipse cooling might delay the release of the observed photons. Second, only a portion of Io's surface is exposed to bombardment by the accelerated thermal plasma electrons so that the observed excess can be seen only when this portion of Io is facing Earth. Third, the plasma density and therefore the amount of luminescence may depend on Io's position relative to the jovian magnetic equator (*20*). Finally, the surface composition and therefore the efficiency of luminescence may vary with position on Io.

On the basis of the above discussion, we conclude that the observed excess flux near 5 μm was probably the result of emission excited by an interaction with Jupiter's magnetosphere. Further observations will be needed, however, to rule out internal heat sources or to relate the brightening to a specific magnetospheric phenomenon.

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Predator Removal: Effect on Fisheries Yields in Lake Victoria (East Africa)

Abstract. *Lake Victoria's artisanal fishery has an overfishing problem. A possible solution is suggested by records showing that fish catches are best where predator populations have been reduced by fishing. It may be possible to remedy overfishing by increasing fishing effort, provided the additional effort is directed toward predators.*

Harvesting the predator of an exploited animal population should theoretically release more of that population's production for human consumption (*1*). I recently encountered an example of this while analyzing records of the artisanal, inshore fishery of Lake Victoria.

My analysis of Lake Victoria was motivated by symptoms of overfishing such as low catches and reduced fish sizes, which have been particularly conspicuous during the past decade (*2*). It has been proposed that this problem could be solved by (i) reducing the fishing effort and (ii) eliminating fishing gear that captures juvenile fish (*3*). The purpose of my analysis was to evaluate the effectiveness of these two proposed solutions, but it became apparent that an al-