The Dark Side of Iapetus: Additional Evidence for an Exogenous Origin

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ABSTRACT

'l'he Saturnian satellite Iapetus presents one of the most unusual appearances of any object in the Solar System: one hemisphere is about 10 times as bright as the other. The origin of the dark hemisphere - which reflects only a few percent of the solar radiation falling on it - has historically been one of the great puzzles of planetary science. From a map produced from previously unstudied, archived Voyager images obtained in the near ultraviolet. region of the spectrum, we show that the interface between the bright and dark material is gradual. The ultraviolet (0.34 μm) normal reflectance gradually changes from '0.55 to less than 0.03 over a distance of about 1500 km. We present the first color map of Iapetus, showing there is a gradual change in color at the interface between the two hemispheres. 'l'his change is highly correlated with the change in albedo. This result supports a spectral mixing model in which the dark and bright sides are the spectral end members, and the interface represents a progressive enrichment of a dark red chromophore. Our results are most consistent with a model originally proposed by Cruikshank et al. (*Icarus* 53, 90, 1983) and Bell et al. (*Icarus* 61, 192, 1985). In this model, exogenously produced material from Phoebe impacts the leading side of Iapetus and volatizes the icy component to leave a dark red lag deposit consisting of material from Phoebe and a preexisting non-volatile constituent that is similar to the D-type material found on Hyperion and D-type asteroids.

I. Introduction

Shortly after the French astronomer Cassini discovered the Saturnian satellite Iapetus in 1672, he noted that it was moderately bright at one point in its orbit, yet 180 degrees away from this point it nearly disappeared. He understood that if Iapetus kept one side always turned toward Saturn - *as* the Earth's moon does - one hemisphere would need to be composed of highly reflective material and the other of very dark material. Modern telescopic observers confirmed Cassini's view with quantitative measurements showing that Iapetus is over five times as bright on one hemisphere as on the other (Wendell *1909;* Guthnik 1914; Graff 1939; Zellner 1972; Noland et al.1974; Morrison et al. 1975; Minis 1977). The origin of the dark hemisphere of Iapetus has been one of the outstanding problems of planetary science. Was the dark region endogenously created by a geologic event or did it result from the deposit of exogenously produced particles? From an analysis of previously unstudied, archived Voyager images, we show that the dark material was produced by an exogenous process. Although no other object in the Solar System exhibits an albedo dichotomy as extreme as that of Iapetus, an understanding of the origin of its dark region will lead to an understanding of alteration processes relevant. to all planetary surfaces . Figure 1 shows an image of Iapetus obtained in 1982 by the Voyager 2 spacecraft.

Ground-based observations of the lightcurve of Iapetus culminated in the creation of a low resolution visual albedo map in essential agreement with the Voyager images (Morrison et al. 1975). One important aspect of Iapetus's albedo distribution is that the dark side is centered on the leading point of the satellite's orbit around Saturn (the so-called "apex of motion") . Spectra of the two hemispheres of Iapetus reveal marked differences in surface composition (Clark et al. 1984; Bell et al. 1985). The spectrum of the trailing side is typical of that of an icy satellite: broad water ice absorption bands are seen at 1.5 and 2.0 μm (McCord et. al. 1971; Fink et al. 1976), and the spectral reflectance is high even into the near-UV portion of the spectrum. 'l'he dominant surface constituent is water ice, with small amounts of siliceous or carbonaceous contaminants . The dark side of Iapetus shows a broad absorption band into the blue end of the spectrum, and only shallow water ice absorption bands (which may, in fact, be contamination from the bright material). Based on comparisons of laboratory samples, Bell. et al. (1985), suggest that this unusual spectrum indicates a surface composition which is 90% hydrated silicates, 10% organic polymers, and <1% trace 'amounts of elemental carbon. These authors claim that the material found on the dark side is similar to that, present on the D-type primitive asteroids, and it may be akin to the enigmatic non-ice component which seems to be ubiquitous in the outer Solar System.

Two classes of theories have emerged on the origin of the dark side of Iapetus (Morrison et al. 1984). In one, the dark material was placed by an internal (endogenous) geologic process. The existence. of dark-floored craters, where slurries of ice-opaque mixtures presumably were emplaced, is one piece of evidence supporting this theory. The seemingly sudden interface between the dark and bright materials - apparent in Voyager images (see Figure 1) - also supports the model.

'l'he second class of theories entails the impact and accretion of exogenous material onto the leading side of Iapetus, and the associated erosion of the preexisting material. The primary piece of evidence supporting this group of models is the coincidence of the center of the dark side of Iapetus with the satellite's apex of motion. In the first version of this model, proposed by Cook and Franklin (1970), enhanced meteoritic flux on the leading side caused an erosion of a thin (-1 M) layer of ice as ejected particles exceeded the escape velocity. Underneath the removed crust was dark, siliceous material. A later model (Peterson 1975), espoused the preferential *accretion* of bright particles on the trailing side due to the lower velocity of' meteoritic particles impacting that hemisphere.

In another exogenous model, first proposed by Soter (1974), dark material was ejected from Phoebe (the low albedo outer satellite of Saturn) , spiraled into the orbit of Iapetus due to Poynting-Robertson drag, and was accreted onto the leading side, 'I'he inclined, retrograde orbit of Phoebe suggests it has had a violent history, including possibly capture or an incident involving a major collision. However, the visual spectrum of the dark side of Iapetus is much redder than that of Phoebe; Phoebe's flat spectrum is similar to carbonaceous chrondritic material (Tholen and Zellner 1983, Thomas et al. 1983; Buratti and Mosher 1991; Bell et al. 1985).

Another model combining the features of both Cook and Franklin's and Soter's work involves the erosion of ice on Iapetus's 'leading side by dark particles from Phoebe (Cruikshank et al. 1983; Bell et al. 1985). In this model the concentration of preexisting dark, red material on the dark side of Iapetus explains t-he color differences between the two bodies. The impact of high-velocity retrograde particles from Phoebe resulted in impact. volatization of ice on Iapetus's surface and the concomitant enrichment of the low albedo, red, opaque component. In the Cook and Franklin model, the ice was mechanically removed, while in the Cruikshank et al. and Bell et al. models it sublimated away because it is more volatile. In another variation of the impact-accretion model , CH_4-rich ice was preferentially excavated by the enhanced meteoritic erosion on the leading side, where it was subsequently darkened and reddened by UV irradiation (Squyres and Sagan 1984).

The observation of Iapetus at moderate resolution by the Voyager 2 imaging system did little to dispel the controversy surrounding the origin of its dark side. The first analyses of the images was inconclusive (Smith et al. 1982). Later, the creation of a visual albedo contour map suggested the existence of nearly concentric isophotes centered on the satellite's apex of motion (Squyres et al. 1983; Cruikshank et al. 1984). However, an independent photometric analysis suggested that the interface between the dark and bright sides of Iapetus is well-defined and sudden (Goguen et al. 1983; Morrison et al. 1984). Furthermore , the change in color seemed to be abrupt (Cruikshank et al. 1984).

One means of providing new insight into the origin of Iapetus's dark side is to examine disk resolved observations at different wavelengths, Observations by Noland et. al. (1974) showed that the amplitude of the rotational lightcurve of Iapetus is larger towards the blue end of the spectrum. The markedly different composition (and thus color) of the leading and trailing hemispheres, specifically the broad UV-absorption present only on the leading side, means that the contrast between the bright and dark sides is enhanced towards the near-UV region of the spectrum. Albedo maps in this spectral region would thus provide a more sensitive inclination of global albedo patterns on the satellite, particularly in the region of transition between the bright. and dark materials. Another line of investigation is to ratio two wavelengths, in the red and near-UV, to create a map of the distribution and abundance of the dark red material responsible for the absorption band in the UV.

The ultraviolet is an important spectral region that has not been investi.gated for Iapetus, except for a ratio spectrum between the leading and trailing hemispheres showing no measurable differences (Nelson and Lane 1987). The Voyager 2 spacecraft did in fact obtain a significant. collection of near-UV (0.34 μm) images of Iapetus. None of these observations were published or examined quantitatively, because of their relatively low signal-to-noise Advancements in image processing techniques over the past 12 years and an increased knowledge of the behavior of the Voyager camera have made it possible to quantitatively reexamine these images. These improvements include the computation] power to perform many image processing operations rapidly and iteratively on whole images; an improved theoretical foundation for describing the scattering properties of icy satellites (Hapke 1981 , 1983, 1986; Buratti 1985); and an improved knowledge of the Voyager dark current for each pixel. In this paper we present the first analysis of these images, including an ultraviolet map of Iapetus and a map of the ratio of tile spectral reflectance of Iapetus at *0.55* μm ancl *0.34* μm.

II. Data Analysis

Ultraviolet images representing the best resolution and geographical coverage were chosen from those obtained by the Voyager 1 and 2 spacecraft (Table 1). The green (0.55 μm) and clear (0.47 μm) filter images in the same sequence were also chosen to map the disk resolved color of Iapetus. ‘l’he images were geometrically and radiometrically calibrated according to preflight and inflight calibration files maintained at the Multimission Image Processing Subsystem (MIPS) at the Jet Propulsion Laboratory. Additional calibration factors of 1,47 for the UV images, and 1.17 for the clear filter were applied to the images. This correction was derivedby averaging the factor required to bring photometric ground based observations of several icy satellites, including Europa, Ganymede, Rhea , and Dione, in agreement with corresponding Voyager measurements.

It is important to remember that most of the observed variation of specific intensity on the spacecraft images listed in Table 1 is due to changing radiant incidence and emergence angles as a function of position **on the** target’s surface. Furthermore , images obtained at different solar phase angles exhibit decreasing intensity as this angle increases. To derive a map of normal reflectance, which is a representation of the intrinsic albedo variegations on a surface, it is necessary to accurately model these effects. Following the techniques described in Buratti et al . (1990), we fit each image to the function (Buratti 1984)

$$I/F = \frac{f(\alpha)\,A\,\mu_o}{\mu+\mu_o} + (1-A)\,\mu_o$$

where I is the specific intensity, πF is the incident solar flux, f(a) is the solar phase function, which expresses changes in intensity due to changes in the solar phase angle (rigorously it is $wP(\alpha)/4$, where w is the single scattering albedo and $P(\alpha)$ is the single particle phase function; here we use values of f(a) that have been normalized to 00), μ and μ_o are the cosines of the emergence and incidence angles, and A is a parameter such that A = O is a pure Lambert scatterer dominated by multiple scattering, and A = 1 is a pure single scattering surface (like the Moon). We find that A=1 adequately describes all observations, in agreement with previous work on the photometric properties of the Saturnian satellites (Buratti 1984). This function was fit to each image listed in Table 1. ‘I’he resulting fits were applied to each image to obtain normal reflectance, for which both μ and μ_o = O. Ideally, each element of terrain should have a specific $f(\alpha)$ associated with it. In practice, there is not. enough coverage in solar phase angle to constrain this function for most of the surface. We find that a single, average value of f(a) for each image (Table 1) adequately accounts for changes in intensity due to solar phase angle (i .e. , abrupt changes in albedo do not occur when the images are mosaiced). This is because the shapes of the phase curves for the bright and dark terrains are similar (Squyres et al. 1984) , and because (to give away our punchline) albedo changes on Iapetus, particularly when dealing with one image, are in fact. gradual.

A mosaic was constructed from the images (only the best resolution of overlapping regions was included) and degraded to a common resolution. Geographical longitude and latitude for each pixel were computed based on spacecraft pointing information contained in the Voyager Supplemental Experiment Data Record (SEDR), which is maintainedby MIPS at the Jet Propulsion Laboratory. Finally, the images were projected into Mercator coordinates (Figure 2). The equivalent map in the clear filter, which was originally presented in a more rudimentary form by Squyres et al. (1983), is also shown in Figure 2.

Color ratio maps were obtained by dividing each UV image with its corresponding image obtained in the green filter (Table 1). The image ratios were then mosaiced and projected (bottom of Figure 2).

We estimate the errors of our processed images as follows: the internal errors within an image are less than 1%; for images of the same filter they are -l%. The relative calibrations between the UV, clear, and green filters are accurate to ‘3%. Finally, our absolute calibrations are good to +/- 5% in the clear and green filters, and +/- *8%* **in** the UV filter.

III. Results and Discussion

Figure 2 shows clearly that the interface between the dark and bright regions of Iapetus is gradual, Nearly concentric isophotes are centered on the apex of motion, as is the center of the large dark region. The ratio map at the bottom of Figure 2 shows that even the *color* of Iapetus changes gradually as a function of distance from the apex of motion. ‘l’he top of Figure *3* is a scan of albedo extracted across the interface between tile high and low albedo regions. At about the middle of the line (latitude, longitude ?3°, 143°) the shape of the curve becomes sinusoidal. This shape suggests an impact origin to the pattern, from the first-order physical principal that the flux of isotropic impactors onto a sphere will be proportional to the cosine of the angle measured from the direction of impact to the local surface normal. For the case of Europa, impact processes (both meteoritic and magnetospheric) have been shown to cause a global sinusoidal pattern in color, and to a lesser extent in albedo (Nelson et al. 1986; McEwen 1986). For Iapetus, the flat part of the curve in Figure 3, which coincides with the region of most intense bombardment at the apex of motion, is presumably where impact processes and the concomitant alteration of the surface have reached saturation. The bottom of Figure 3 shows a similar line of the color ratio, which is also gradual . Finally, a two dimensional histogram of color and albedo normalized for projected surface area (Figure 4) shows that the distribution of both these quantities is not bimodal. This last result is in disagreement. with a preliminary report by Cruikshank et al. (1984)

that the color change on Iapetus is abrupt, and that no color gradient appears in either hemisphere.

Our results are incompatible with any reasonable model for an endogenous origin for the dark material on Iapetus. Internal processing and the resulting extrusion of dark interior materials would result. in a well-delineated interface between the low andhigh albedo regions, rather than the gradual change in albedo and color illustrated in Figures 2 and 3. For an endogenic origin to the dark material, the histogram would show distinct groupings corresponding to geologic domains. One could imagine an exotic geologic feature, such as a single giant geyser spewing materials onto the surface, but there is no evidence for such an object and it is unlikely it would be so large and located at. the apex of motion.

The flux of meteoritic material as a function of position on Iapetus's surface has been calculated by Cook and Franklin (1970). Their model in Mercator coordinates is shown in Figure 5. The flux patterns illustrated are very similar **to those actually** found on Iapetus. Even the prediction of a high albedo northern polar cap with an indistinct. border is born out. No Voyager ultraviolet images of the southern polar region exist , but ground based observations (Morrison et al. 1975) and low resolution Voyager images suggest a cap may exist there as well (Smith et al. 1982)), Although absolute values of the flux onto the leading versus the trailing side of" Iapetus are difficult to determine, a minimum value of 2 is given by the ratio of the flux of heliocentric particles onto the two hemispheres. Another source of material mustbe impacting the leading side of Iapetus; otherwise, the other Saturnian satellites would show even greater albedo dichotomies, due to the gravitational focussing of meteoritic particles, 'I'he flux of particles resulting from an impact onto the surface of the retrograde satellite Phoebe depends on the physical properties of both the impacting body and Phoebe's surface: given the number of unknowns it is extremely difficult to determine. An upper limit of 100 to the ratio of leading/trailing flux from Phoebe has been estimated by Squyres and Sagan (1984). (The original scenario envisioned by Cook and Franklin, that bright ice was eroded away to reveal a dark mantle, is unlikely because the low density of Iapetus (-1.2 gm/cc) is now known to be too small to support the existence of a large mantle.)

Our results are most consistent with the following scenario, which was first discussed by Cruikshank et al. (1983) , and Bell et al . (1985) . Iapetus originally looked like the other five medium-sized Saturnian satellites (Mimas, Enceladus, Tethys, Dione, and Rhea), with a high albedo and relatively flat spectrum consistent with water ice and some contaminants . 'I'he optical properties of the trailing side of Iapetus are indeed similar to those of these satellites (Buratti and Veverka 1984; Buratti 1984). Phoebe, representing a class of bodies that may be common in the outer Solar System (Stern 1991), was captured by Saturn into a retrograde orbit. After an impact between Phoebe and a comet or asteroid, retrograde particles spiraled in towards Iapetus and were accreted onto the leading side (Soter 1974). Impact volatization of the ice on Iapetus's surface led to the enrichment of the opaque, non-ice, preexisting material, which is redder than that found on Phoebe's surface. This process explains the correlation between the color and albedo variations at the interface: the impact volatization and concomitant enrichment of the dark red lag deposit is most intense at. the apex of motion and drops off as a function of distance from that apex. 'l'he dark material has spectral, and presumably compositional, similarities to the dark, red material that seems to be ubiquitous in the outer Solar System, including that found on the primitive D-type asteroids (Tedesco et al. 1989), the Uranian satellites (Buratti and Mosher 1991), and Hyperion (Tholen and Zellner 1983; Thomas and Veverka 1985). Hyperion is particularly notable because it is the next satellite closest to Saturn after Iapetus. It apparently has been coated in a similar fashion as Iapetus, but because it is in chaotic rotation (Wisdom et al. 1984) the material has not been preferentially placed on one hemisphere.

We can eliminate a single impact as the cause of Iapetus's dark side because the results illust.rated in Figure 2 present none of the morphology expected of a large impact event, such as ejects deposits and secondary impacts.

The joint NASA-ESA Cassini mission to Saturn, which is due to be launched in 1997 and to encounter the Saturnian system in 2004, tentatively includes a flyby of less than 1000 km to the surface of Iapetus. Cassini's complement of instruments includes a narrow and wide angle imaging system, two infrared spectrometers, and one UV spectrometer. This payload will enable the determination and mapping of the composition of Iapetus's surface, and it will obtain images with resolution of a few meters for geologic analyses. Our maps show specific regions to be targeted for the flyby. Observations of the southern region are particularly important to determine the existence of a polar cap of relatively pristine material as predicted by tile exogenous model. The region between longitudes of 0° and 240°, where the albedo changes most rapidly, is another key area for close scrutiny.

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Table 1. Voyager Images used in this study.

FDS No. and Spacecraft UV Filter	Green Filter	Solar Phase Angle	Subspacecraft Longitude	Pixel size (km)	f(a)
3497622 (1)	3497616	12	19	26	0.937
4385151 (2)	4385147	23	179	22	0.879
4387539 (2)	4387531	31	192	15	0.805
4388613 (2)	4388605	3 8	203	13	0.800
4389452 (2)	4389444	47	217	11	0.753
4390704 (2)	4390700	68	257	9.3	0.648
4391359 (2)	4391351	81	289	9.1	0.579
4391839 (2)	4391835	89	302	9.2	0.532
Clear Filter					
3497658 (1)		14	19	26	0.937
3500546 (1)		41	44	25	0.790
3502730 (1)		60	69	28	0.690
4373003 (2)		19	152	53	0.900
4385155 (2)		23	179	22	0.879
4387543 (2)		31	192	15	0.805
4388617 (2)		39	203	13	0.800
4389424 (2)		48	217	11	0.753
4390708 (2)		68	260	9.3	0.648
4391403 (2)		81	289	9.1	0.579
4391843 (2)		90	304	9.3	0.532

FIGURE CAPTIONS

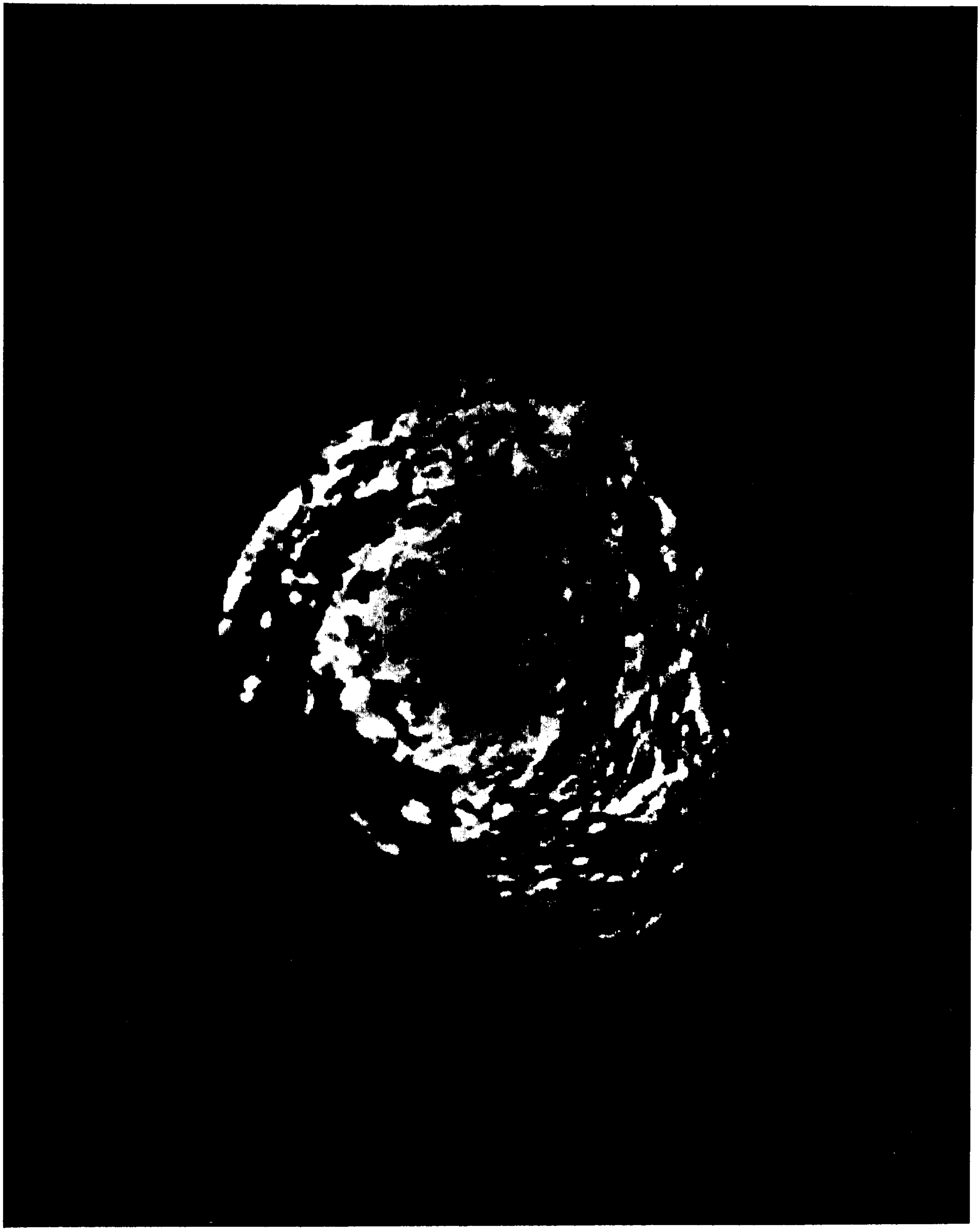
1. A Voyager 2 image obtained in the clear filter of the interface between the dark and bright hemispheres of Iapetus, shown in the upper right region of the satellite. (The demarcation on the left is the terminator). 'I'he resolution is about 22 km. Iapetus revolves around Saturn every 79 days in an orbit which is 3.562 x 10^6 km from the planet and is inclined 14.7 degrees to its equator. The radius of Iapetus is 730 km and its density is 1,2 gm/cc.

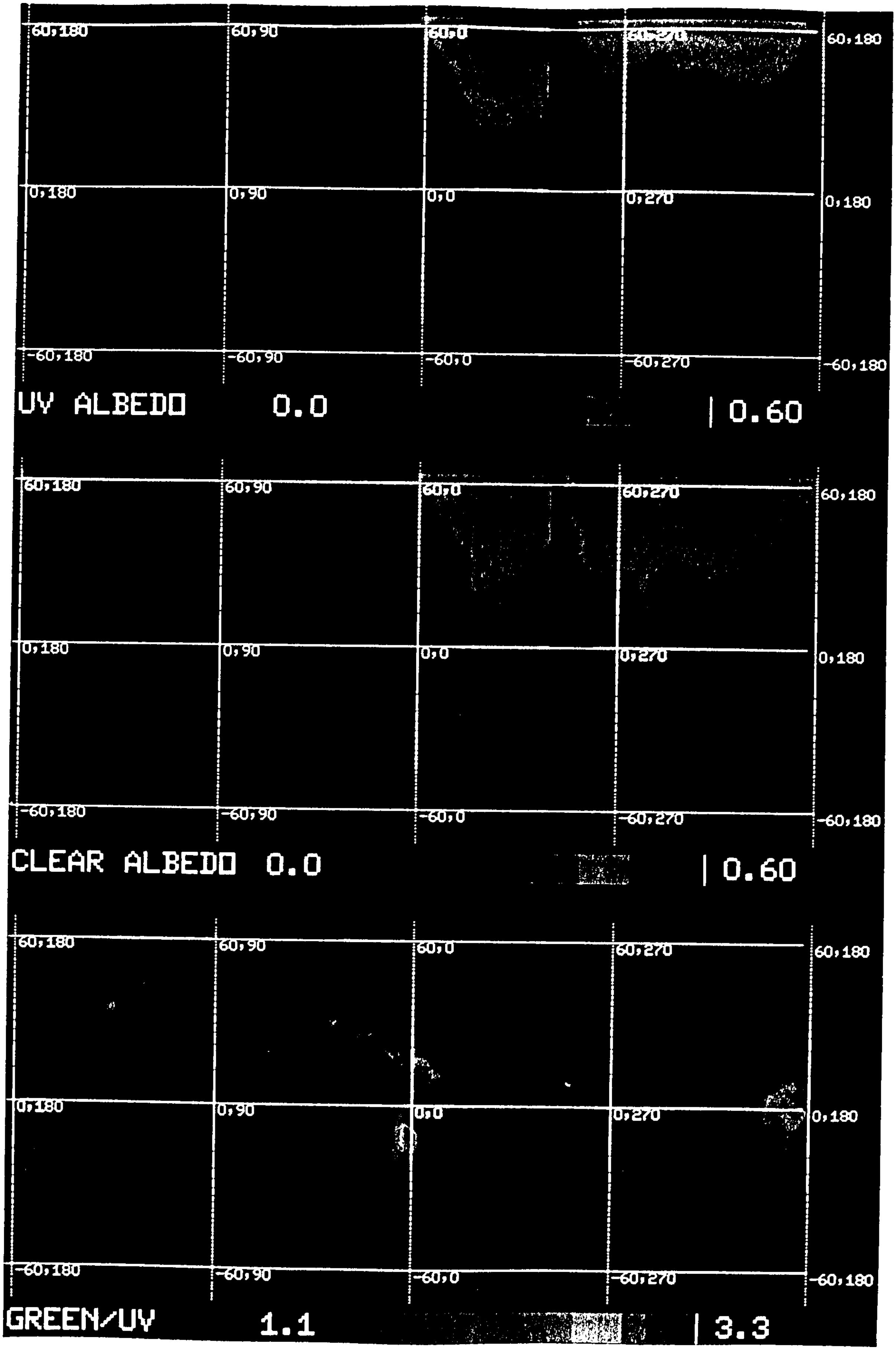
2. (Top) An ultraviolet (0.34 μm) Mercator map of t-he normal reflectance of Iapetus compiled from the Voyager images listed in Table 1. The center of the leading hemisphere **(the apex of motion) is** located **at** geographical **coordinates** of *(0,90),* while the center of the trailing hemisphere is at (0,270). (Middle) A corresponding map created from equivalent images in the clear filter (0.47 μm), showing essential agreement with the previous work of Squyres et al. , 1983. (Bottom) A map of the ratio of inrages in the Voyager green filter (0.55 μm) to the ultraviolet filter. This color map illustrates that the abundance of the red chromophore , responsible for the absorption band seen on the leading side, is more pronounced as a function of position from the antapex of motion (longitude of 2700). (The gores in the upper two maps were causedby the rejection of a few pixels at the limb of one sequence of images for which the albedos blew up to erroneously high values due to edge effects).

3 (Top). A line of normal reflectance extracted from the interface between the two albedo regions clearly shows that the transition is gradual. The line is roughly sinusoidal , which is the expected shape for exogenic particles accreting onto a sphere. The coordinates of the end points are listed below the abscissa. (Bottom), The equivalent line extracted from the color ratio map showing that the dark material becomes gradually redder towards the center of the low albedo region.

4. A two-dimensional histogram of the values for color and albedo from Figure 2. Both parameters are well-distributed. (Much of the distribution in the color ratio for the low-albedo region is due to noise caused by dividing two numbers representing very low signals. Even without this source! of noise, the two-dimensional histogram would show a gradual change in both color and albedo)

5. A Mercator map of the flux contours expected from meteoritic erosion (Cook and Franklin, 1970). The absolute values to the flux from Phoebe depend on many factors and estimates differ by an order of magnitude. The largest flux values are at the apex of motion (corresponding to latitude and longitude of 00,900), and the smallest values are at the poles.

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UV ALBEDO 0.0
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CLEAR ALBEDO 0.0
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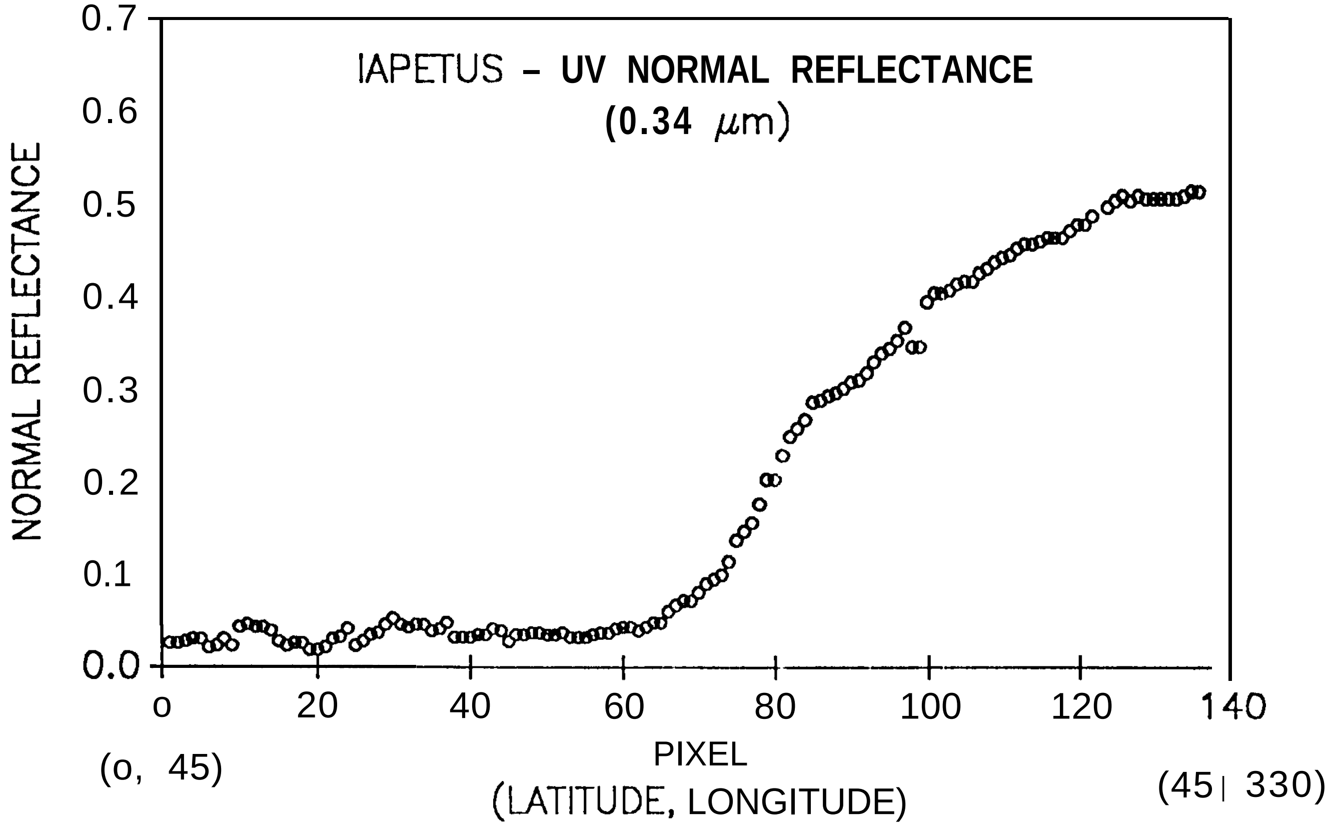
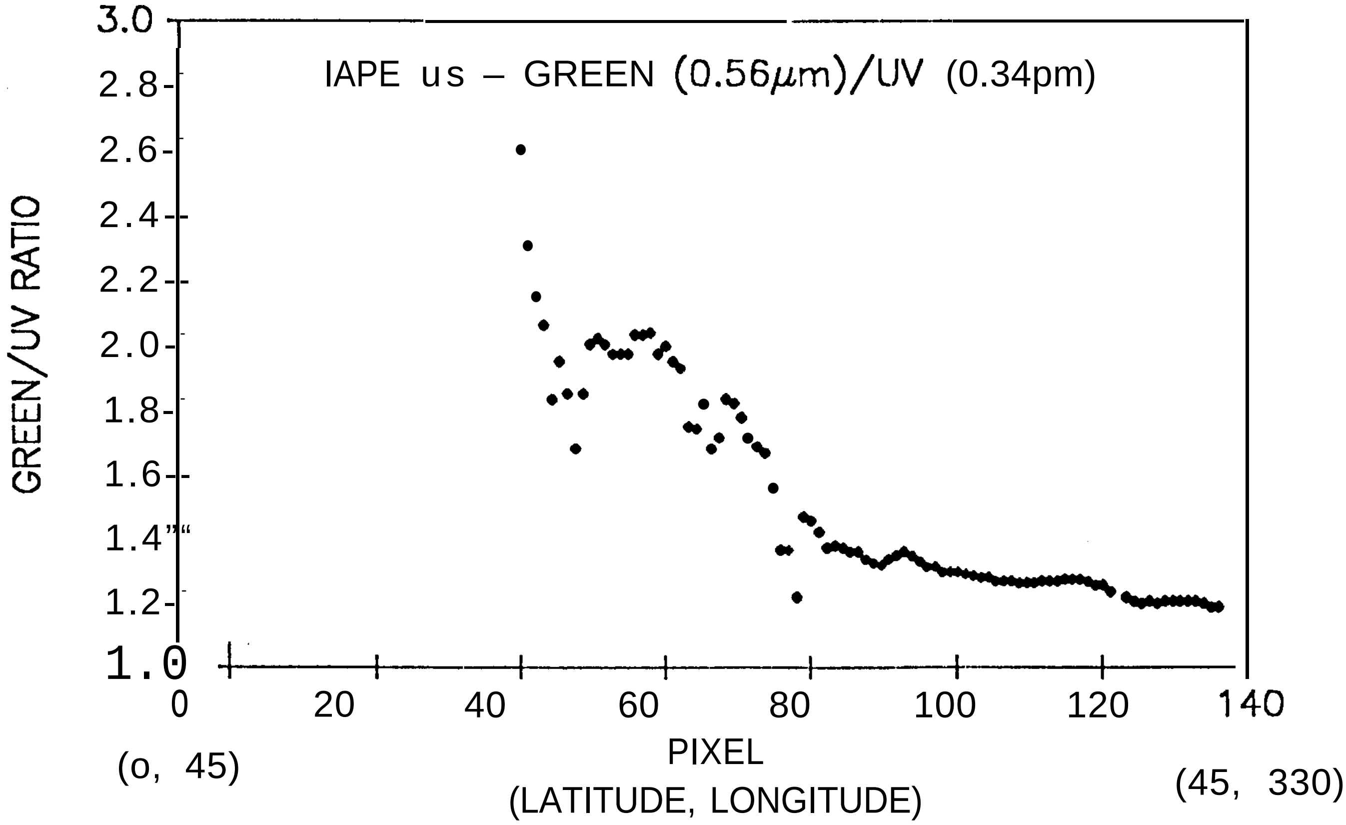
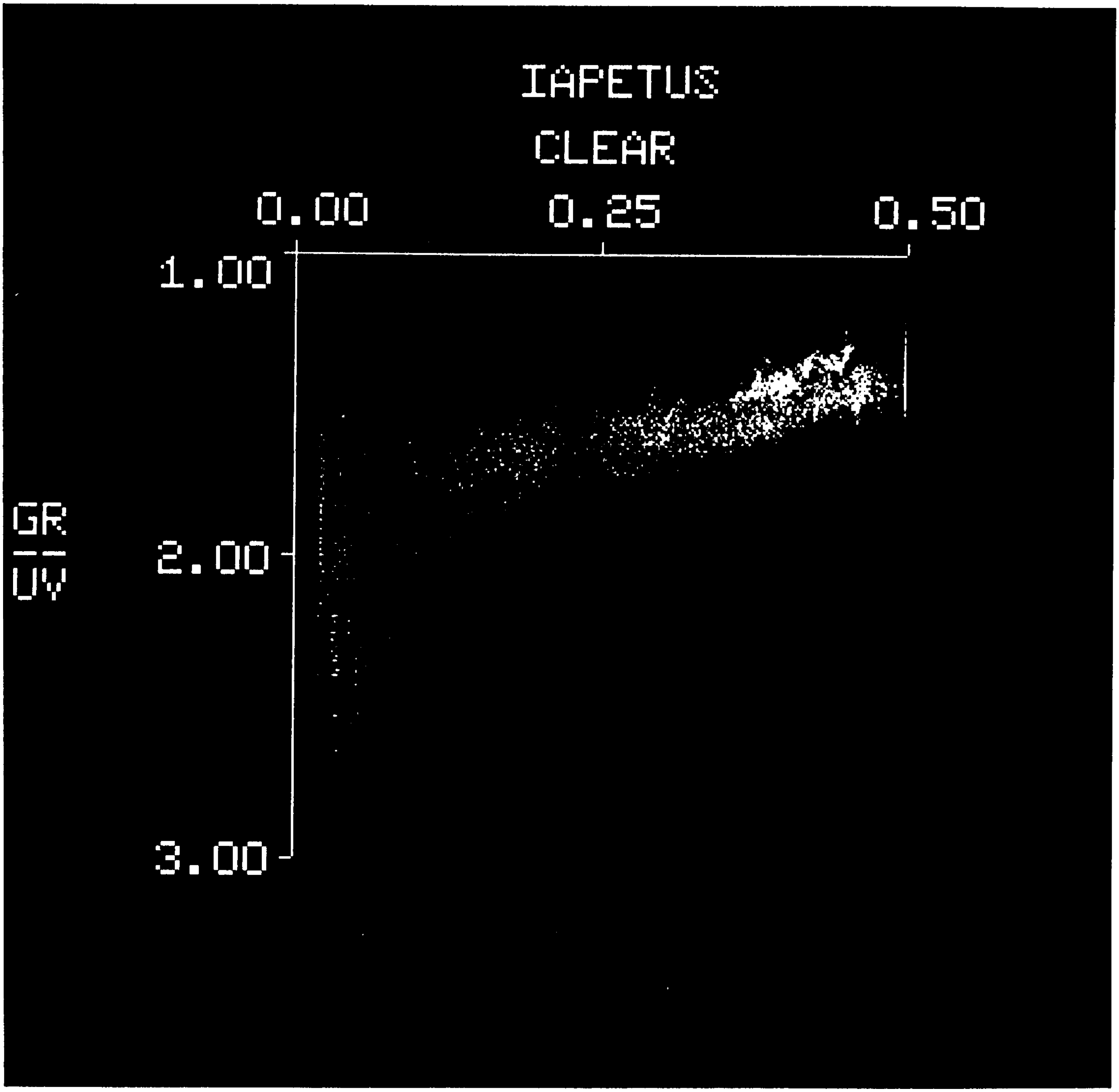
GREEN/UV 1.1
3.3


IAPETUS - UV NORMAL REFLECTANCE
(0.34 µm)
NORMAL REFLECTANCE
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
o
20
40
60
80
100
120
140
(o, 45)
PIXEL
(LATITUDE, LONGITUDE)
(45| 330)


IAPE us – GREEN (0.56µm)/UV (0.34pm)
GREEN/UV RATIO
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0
20
40
60
80
100
120
140
(o, 45)
PIXEL
(LATITUDE, LONGITUDE)
(45, 330)


IAPETUS
CLEAR
0.00
0.25
0.50
1.00
2.00
3.00
GR
--
UV

IAPETUS
METEORITIC EROSION