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Ida and Dactyl: Spectral Reflectance and Color Variations

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Galileo SSI color data between 0.4 and 1.0 μm demonstrate that both Ida and Dactyl are S-type asteroids with similar, but distinct spectra. Small but definite color variations are also observed on Ida itself and involve both the blue part of the spectrum and the depth of the 1-μm pyroxene–olivine band. Ida's surface can be classified into two color terrains: Terrain A has a shallower 1-μm absorption and a steeper visible red slope than does Terrain B. Qualitatively, the color–albedo systematics of these two terrains follow those noted for color units on Gaspra and the variations in 1-μm band depth with weathering described by Gaffey *et al.* (Gaffey, M. J., J. F. Bell, R. H. Brown, T. H. Burbine, J. Piatek, K. L. Reed, and D. A. Chaky 1993. *Icarus* 106, 573–602). Terrain A, with its slightly lower albedo, its shallower 1-μm band, and its slightly steeper visible red slope relative to Terrain B could be interpreted as the "more processed," "more mature," or the "more weathered" of the two terrains. Consistent with this interpretation is that Terrain A appears to be the ubiquitous background on most of Ida, while Terrain B is correlated with some small craters as well as with possible ejecta from the 10-km Azzurra impact structure. Because of these trends, it is less likely that differences between Terrains A and B are caused by an original compositional inhomogeneity within the body of Ida, although they do fall within the range known to occur within the Koronis family.

The spectrum of Dactyl is similar to, but definitely different from, that of Terrain B on Ida. It does not conform to the pattern that obtains between the colors and albedos of Terrains A and B: the satellite's 1-μm band is deeper than that of Terrain B, but its albedo is lower, rather than higher. By itself, the deeper band depth could be interpreted, following Gaffey *et al.*, to mean that Dactyl is a less weathered version of Terrain B on Ida, but such an interpretation is at odds with Dactyl's redder spectral slope. Thus, the explanation for the color difference between Dactyl and Ida is likely to be different from that which accounts for the differences

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between the two terrains on Ida. Given that Dactyl and Ida have very similar photometric properties (Helfenstein, P., J. Veverka, P. C. Thomas, D. P. Simonelli, K. Klassen, T. V. Johnson, F. Fanale, J. Granahan, A. S. McEwen, M. J. S. Belton, and C. R. Chapman 1996 *Icarus* 120, 48–65), thus ruling out any dramatic texture differences between the two surfaces, the most likely explanation is that the satellite has a slightly different composition (more pyroxene?) than Ida. The spectral difference is within the range reported by Binzel *et al.* (Binzel, R. P., S. Xu, and S. J. Bus 1993. *Icarus* 106, 608–611.) for members of the Koronis family, and could be caused by compositional inhomogeneities of the Koronis parent body rather than by post-breakup regolith processes.

1. INTRODUCTION

During its flyby Galileo provided multicolor views of Ida covering a full rotation of the asteroid. From whole-disk data alone it is evident that there are subtle but significant color variations on Ida: for example, the 1-μm absorption is definitely stronger near longitudes 270°E than it is in the opposite hemisphere (Fig. 2 of Helfenstein *et al.* 1996). In this paper, we examine the color variations on Ida in detail, demonstrate that much of Ida's surface can be divided into two types of terrains on the basis of color in the 0.4 to 1.0 μm range, and compare these colors to those of Ida's satellite, Dactyl.

We do not attempt any detailed interpretation of the spectral reflectance data in terms of mineral composition. Such interpretations are best carried out using data which have finer spectral resolution and a broader wavelength range than Galileo SSI data. In particular, such analyses will become possible once a complete reduction of the Galileo NIMS data has been published and these data can be combined with telescopic measurements. As outlined above, our focus in this paper is twofold: first, to characterize the color differences that exist between the two major color units on Ida; and second, to determine the difference in color between these two units and the surface of Dactyl. We investigate briefly to what extent the color variations on Ida can be correlated with structural and geological boundaries identified by Thomas *et al.* (1996) and by Sullivan *et al.* (1996) respectively, and compare the pattern of variations with those observed on asteroid 951 Gaspra, a case in which Helfenstein *et al.* (1994a) demonstrated an intriguing correlation between color and local elevations and topography.

Finally, we speculate to what extent the color variations on Ida and the color differences between Ida and Dactyl can be explained in terms of differences in regolith texture and to what extent they may imply compositional variation within the Koronis family parent body from which both Ida and Dactyl are most likely derived.

TABLE I
SSI Color Data: Filter Definition and Scale Factors[a]

λ_{eff} (μm)	Filter description		Scale factor
0.41	VLT	Violet	1.18 ± 0.03
0.56	GRN	Green	1.00 ± 0.03
0.62	CLR	Clear	1.03 ± 0.04
0.67	RED	Red	1.05 ± 0.04
0.73	MT1	Methane 1	
0.76	NIR	Near-IR	1.02 ± 0.05
0.89	MT2	Methane 2	1.24 ± 0.06
0.99	1MC	1-μm	1.05 ± 0.06

[a] From Helfenstein *et al.* (1995). See text for details.

2. SPECTRAL VARIATIONS ON IDA

As detailed in Helfenstein *et al.* (1996), Galileo images of Ida were calibrated radiometrically, using the GALSOS program developed by JPL. For each image a flat-field correction was made, using inflight data obtained from observations of Galileo's calibration target. Corrections were also applied for scattered light effects by applying a wavelength-dependent modulation transfer function correction. Each image in a particular color sequence was registered at a subpixel level to the corresponding GRN-filter (0.56 μm) image and then divided by it to yield a color ratio image relative to the GRN-filter data. In all cases, color scale factors, reproduced in Table I, obtained by the following procedure were applied.

As described in Helfenstein *et al.* (1996) earthbased spectra from three sources—Zellner *et al.* (1985), Binzel *et al.* (1993), and Tholen (D. J. Tholen, personal communication, 1994)—were combined to yield the composite mean spectrum of Ida between 0.34 and 2.46 μm. It was found that the average colors of Ida observed through Galileo's filters agreed reasonably well with the colors predicted by convolving the Galileo camera filter functions with the average spectrum of Ida (see Fig. 1 of Helfenstein *et al.*, 1996). For four of our six filters, the agreement is within 5% (Table I). As described in Helfenstein *et al.* (1996), we have chosen to rescale the Galileo-determined colors to make them match the average colors determined from the telescopic data: the resulting scale factors are summarized in Table I and have been applied in all subsequent analyses in this paper. The essential point is that having made the average Galileo-derived spectrum match that observed from Earth, the resulting relative colors between units on Ida and between Ida and Dactyl can be determined reliably (certainly to ±5%).

Earth-based observations show Ida to be an S-asteroid of subclass S*IV* (Tholen, 1989; Gaffey *et al.* 1993). Galileo imaging data reveal only small albedo and color variations over its surface. The color variations can be divided conveniently into two major terrain types on the basis of the 1MC/VLT color ratio: with ratios in excess of 1.35 defining Terrain A, and those equal to or less than 1.35, Terrain B (Figs. 1 and 2). While the histogram in Fig. 2 indicates that there actually is a continuum in the 1MC/VLT color ratio between Terrains A and B, the distinction between the two terrains is not entirely arbitrary as they map into spatially distinct units on Ida. The distribution of the two terrains shows a strong longitude dependence (Fig. 1), giving rise to the longitude-dependent color variations in Ida's whole disk light noted by Helfenstein *et al.* (1996) and others.

As is evident from Fig. 1, most of the surface of Ida, and in particular the 60°E hemisphere, is covered by Terrain A (red). A major concentration of Terrain B is seen near 310°E and as noted by Sullivan *et al.* (1996) and Geissler *et al.* (1996) may be associated with the 10-km diameter crater Azzurra and its presumed ejecta. Other, more localized occurrences of Terrain B are found in and around certain smaller craters. A secondary concentration of Terrain B is associated with crater Lechuguilla in Vienna Regio.

The average spectra of Terrains A and B are shown in Fig. 3, where for later discussion we have also included the average spectrum of Ida's satellite, Dactyl. Terrains A and B differ spectrally in two respects: the relative depth of the 1-μm absorption and the slope of the visible red portion of the spectrum. Terrain A has a shallower 1-μm absorption and a steeper visible red slope than does Terrain B (see also Fig. 8). Helfenstein *et al.* (1996) find that both terrains have similar photometric properties but that Terrain A is slightly darker than Terrain B, with p (geometric albedo) $= 0.20$ and $\tilde{\omega}_0$ (single scattering albedo) $= 0.213$ for Terrain A and $p = 0.21$ and $\tilde{\omega}_0 = 0.223$ for Terrain B. The values quoted are for the Galileo GRN filter at 0.56 μm.

Included in Terrain B are small areas of the surface which in a preliminary study (Helfenstein *et al.* 1994b) were designated as Terrain C. The spectrum of this putatively distinct terrain differed from that of Terrain B only in the VLT filter (0.41 μm) (with Terrain B ~10% brighter). Given this very slight difference and the small area on Ida assigned to Terrain C, we have in this paper subsumed this unit into Terrain B.

3. COMPARISON WITH GASPRA AND OTHER S-ASTEROIDS

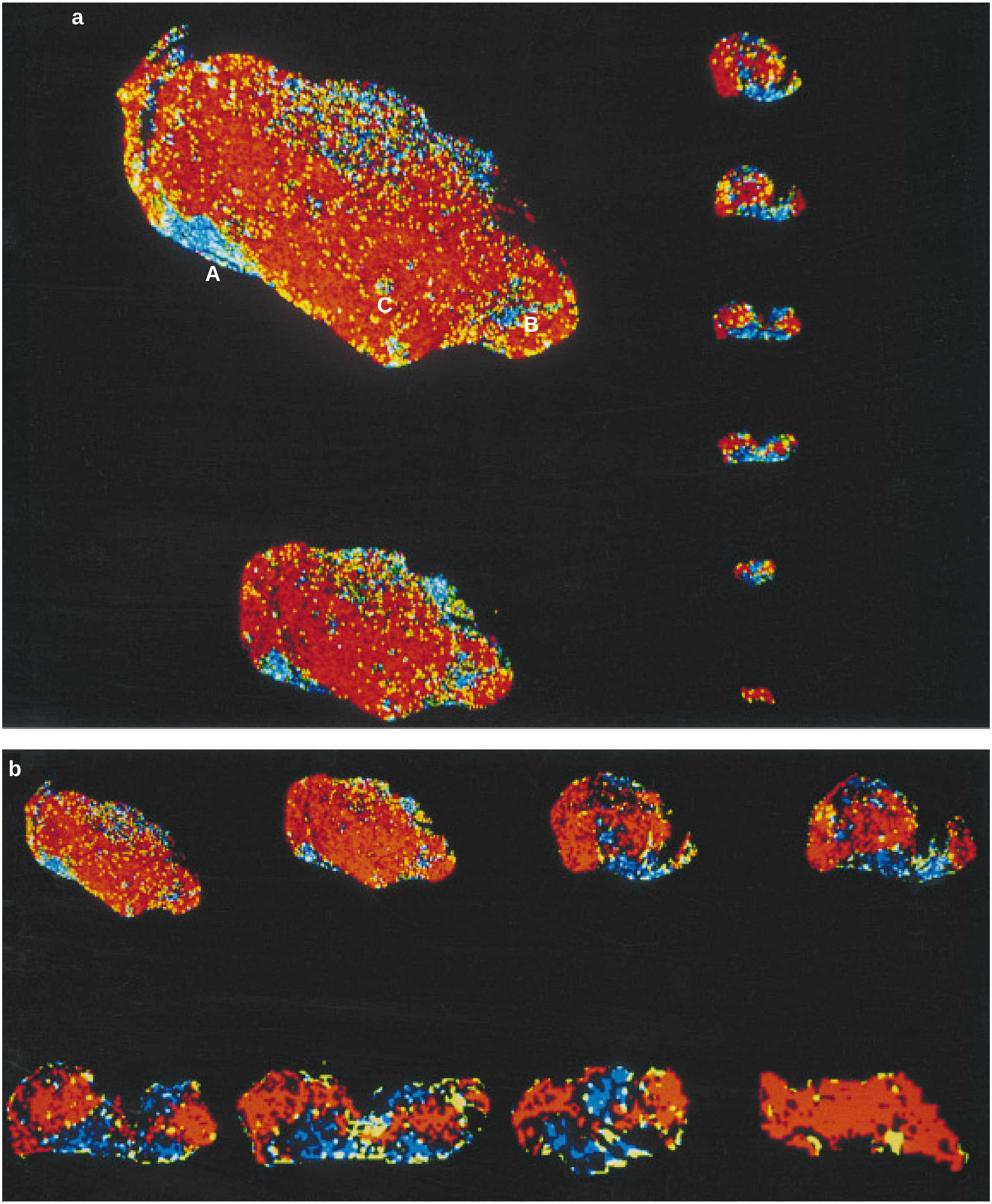
Qualitatively, the color/albedo systematics for the two principal terrains on Ida follow those noted for Gaspra (Helfenstein *et al.* 1994a; Carr *et al.* 1994) and for S-asteroids in general (Gaffey *et al.* 1993). Terrain A, with its slightly lower albedo, its shallower 1-μm band, and its slightly steeper visible-red slope relative to Terrain B can be interpreted as the "more processed," "more mature," and/or the "more weathered" of the two terrains.

On Gaspra, Helfenstein *et al.* (1994a) noted an analogous relationship between Terrains PC2-β and γ (analogs of Terrain A) and Terrain PC2-α (analog of Terrain B). For S-asteroids in general, Gaffey *et al.* (1993) demonstrated a strong correlation between the prominence of the 1-μm band and the asteroid's diameter, a relationship that can be explained in terms of weathering and the increasing ability of large asteroids to retain more regolith. Specifically, Gaffey *et al.* demonstrate that above a diameter of 100 km (larger than either Gaspra or Ida), the 1-μm band depth is shallow and independent of asteroid diameter. However, as the diameter decreases below 100 km, the prominence of the 1-μm band increases linearly with decreasing diameter. The ability of a small asteroid to retain weathered regolith should increase with diameter until an equilibrium is reached (apparently near 100 km). Gaffey *et al.* also note that for S-asteroids, unlike the case for lunar materials (see below), there is little evidence that the decrease in prominence of the 1-μm band is accompanied by a significant decrease in albedo or by a marked increase in spectral slope.

In terms of the Gaffey *et al.* scheme, one would interpret Terrain A to be the older (more mature or more weathered) of the two terrains on Ida, an interpretation which is also consistent with the observed spatial relationship of the two terrains relative to major surface landforms. Significantly, the prominence of the 1-μm band for Terrain A is comparable to that found for large (>100 km) asteroids in Gaffey *et al.*'s sample.

On Gaspra, the analog of Terrain B (PC2-α; Helfenstein *et al.* 1994a) was found to be significantly correlated with "ridges" and other topographic highs and in particular with the least degraded craters in such areas. This correlation on Gaspra led to the interpretation that "fresher" material with a deeper 1-μm band and bluer spectral slope was being exposed along topographic highs and that regolith migration, accompanied by an unspecified "regolith maturation" process was accumulating redder (and darker) materials with a more subdued 1-μm band in topographic lows. One strong indication of this correlation on Gaspra

FIG. 1. False-color images of Ida derived from VLT/GRN, MT2/GRN and IMC/GRN color ratios. Two major units are evident: most of Ida is covered by the red unit (Terrain A), which has a shallower 1-μm absorption and a somewhat steeper red-violet spectral slope than does the blue unit (Terrain B). Most of the contiguous extent of Terrain B may be associated with ejecta from crater Azzurra (A), while minor occurrences are found in the vicinity of the intermediate-sized crater Lechuguilla in Vienna Regio (B) and several smaller craters (e.g., at C). Images are shown at a true relative scale determined by range (a) and at a common intermediate scale (b). In (a) subspacecraft East longitudes are (top to bottom): Left: (47°–48°), (37°–39°). Right: (351°–355°), (337°–340°), (307°–310°), (277°–280°), (217°–220°), and (126°–130°). Resolution ranges from about 0.11 km/pxl to 1.7 km/pxl.


a
A
C
B
b

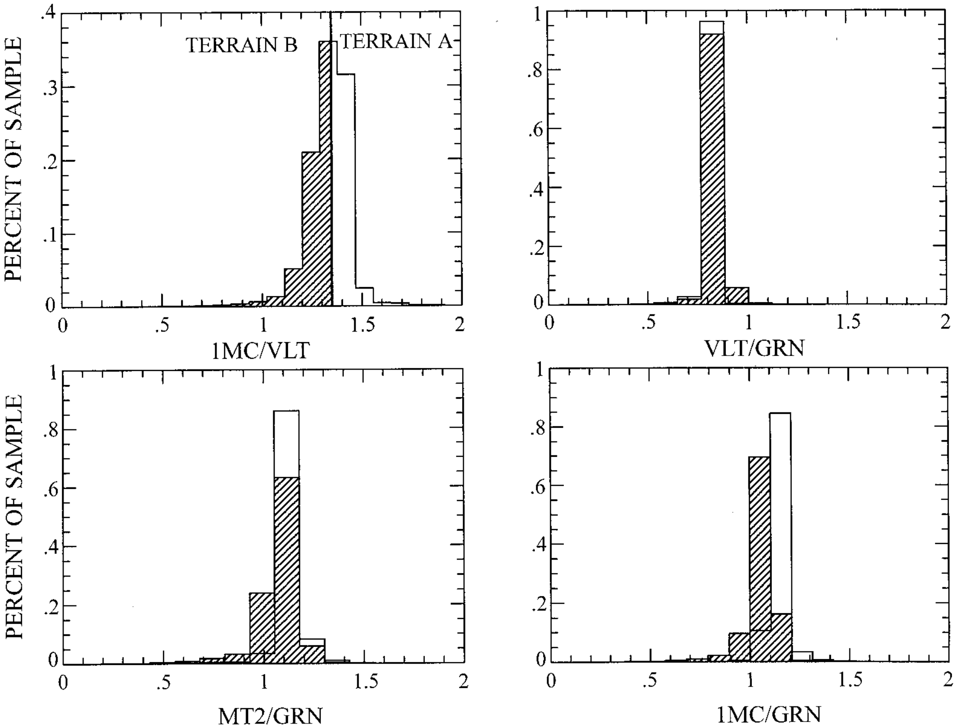


FIG. 2. Histograms of color ratios derived from data mapped in Figs. 1 and 4. Terrains A and B are primarily distinguished by the 1MC/VLT ratio which peaks at 1.35. Values in excess of 1.35 define Terrain A; those less or equal to 1.35 define Terrain B. The effective wavelengths of the filters are: 1MC (0.99 μm), MT2 (0.89 μm), GRN (0.56 μm), and VLT (0.41 μm).

is found in plots such as Fig. 13 of Helfenstein *et al.* (1994a), which shows that the 1MC/VLT color ratio on Gaspra is smaller (deeper band) in relatively high places on Gaspra and is larger (smaller band depths) in relatively low areas.

On Ida, there is also a strong correlation locally between apparently fresher craters and the occurrence of Terrain B. Specific examples are indicated in Figs. 1 and 4 (see also Sullivan *et al.* 1996). The most striking instance is that of the large crater Azzurra. However, in contrast to the case of Gaspra, on Ida one does not find a significant decrease in band strength and a concommitant increase in spectral slope with decreasing elevation *on a global scale.* Also, unlike Gaspra, lower areas on Ida do not systematically exhibit a lower albedo. In Fig. 5 we plot the 1MC/VLT ratio against the dynamic height (Thomas *et al.* 1996). Recalling that the division between Terrains A and B corresponds to a ratio of 1.35, we note that globally on Ida Terrains A and B occur at all dynamic heights. The very slight decrease in the ratio with dynamic height that is seen most clearly in the bin-averaged version of Fig. 5A shown in Fig. 5B can be attributed convincingly to the fact that by area most of Terrain B is associated with the crater Azzurra and its presumed ejecta (Geissler *et al.* 1996) which are concentrated at lower elevations and lower dynamic heights (Fig. 4).

The observed distribution of Terrains A and B on Ida can be understood as a result of two major processes. First, given Ida's larger size, and especially the fact that in terms of crater density Ida's surface is significantly older than that of Gaspra (Belton *et al.* 1992; Chapman *et al.* 1996), we would expect a more uniform cover of older, more processed regolith on this asteroid, consistent with the observation that Ida is covered with Terrain A, irrespective of elevation or dynamic height. This situation has been modified by a second process: the exposure of less processed materials by relatively recent impacts to produce Terrain B. This process has led to the formation of localized patches of Terrain B in association with small craters, and most importantly—as suggested and described in detail by Geissler *et al.* (1996)—to the emplacement of much larger areas of Terrain B by the formation of Azzurra and its ejecta.

The types of boundaries between areas dominated by Terrains A and B vary. In the high southern latitudes (Fig. 1A, two largest images) there is a gradual change from dominance by Terrain A to Terrain B. On the other side of Ida, there is a sharper division of colors along part of Townsend Dorsum which extends from about (-50°E, 0° to 80°E, 40°N). Two lines of evidence indicate these changes are not reflections of underlying structure and compositional variations: first, the gradational change from A to B in a large part of observed areas (Fig. 1A); second,

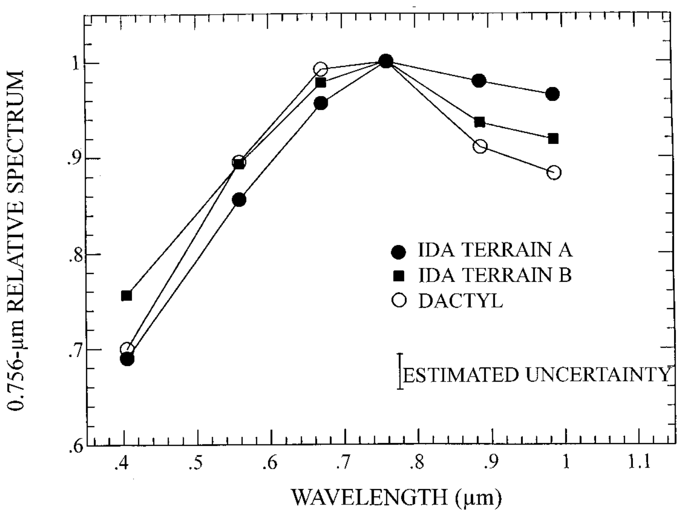


FIG. 3. Spectral reflectance of Terrains A and B on Ida, and of Dactyl, normalized at 0.76 m. Scale factors from Table I have been applied.

the modelling of ejecta from Azzurra by Geissler *et al.* (1996) which shows that the pattern of the area dominated by Terrain B is closely correlated with that expected to be subject to direct infall of ejecta. The sharper boundary across Townsend Dorsum can be explained by topographic shadowing of ejecta from Azzurra (compare to map of ridges in Thomas *et al.*, 1996, and Fig. 1).

We stress that the band depth, spectral slopes, and albedo systematics observed on Ida and Gaspra, summarized in Figs. 6 and 7 are consistent with a scenario in which there are basically two types of materials exposed on the surfaces—the relatively more weathered or processed materials corresponding to Terrains A and PC2-β and γ on Ida and Gaspra, respectively, and the relatively less weathered and less processed materials corresponding to Terrains B on Ida and Terrain PC2-α on Gaspra.

4. DACTYL AND IDA

The data in Fig. 3 demonstrate clearly that color differences exist between Dactyl and Ida. It is essential to realize that whatever causes the color variations observed between Terrains A and B on Ida, something else is involved in explaining the color differences between Dactyl and Ida. It is true that Dactyl has a more prominent 1-μm band, as would be expected for such a small asteroid from the Gaffey *et al.* (1993) correlation discussed above, but the systematics of the visible red spectral slope do not follow those observed for the terrains on Ida. Dactyl has a deeper 1-μm than even Terrain B on Ida, and should therefore have a shallower spectral slope (i.e., be bluer). This is not the case, as seen in the top panel of Fig. 8, where we have plotted the color differences corresponding to the spectral reflectance curves in Fig. 3 relative to the average spectrum of Ida. The same conclusion follows by considering the albedo/color systematics (Fig. 6). Because Dactyl has a deeper 1-μm feature than Terrain B, we would expect Dactyl to have a higher albedo than does Terrain B, whereas the opposite is the case (0.21 compared to 0.22). The conclusion is that the color and albedo systematics of the two terrains on Ida and of Dactyl cannot be reconciled with the same mechanism.

In an attempt to maintain the hypothesis that Dactyl represents a less weathered example of Terrain B on Ida (as proposed by Chapman *et al.* 1995), one must claim that the evidence introduced above is not conclusive. In terms of the albedo-based argument, such a position can be maintained given the facts that no strong changes in albedo with observed changes in 1-μm band strength have been documented for S-asteroids in general (Gaffey *et al.* 1993), and that the Ida/Dactyl differences observed are very small anyway. It is more difficult to claim that the VLT color reported here for Dactyl is in error, because our entire procedure (see Helfenstein *et al.* 1996) is based on deriving accurate *relative* colors for Dactyl and for areas on Ida. Thus, while our absolute measurements of the VLT color could be in error (cf. Table I), there is no reason to believe that we have not measured the relative colors of Dactyl and Ida with sufficient accuracy to support the argument made above.

Realizing that our measurements as shown in Figs. 6 and 7 do not appear consistent with the hypothesis that Dactyl is a less weathered version of Ida's Terrain B, we now consider several alternative explanations of the color differences observed.

First, it is possible that Dactyl differs slightly in mineral composition from either Terrain A or Terrain B on Ida. Qualitatively, the increased band depth near 1 μm can be explained by an increase in the pyroxene/olivine ratio. The compositional differences implied lie within the range of those observed for the Koronis family (Fig. 8) by Binzel *et al.* (1993). Binzel *et al.* argue that the color differences observed among the Koronis family members are most likely due to slight compositional variations of the different fragments of a somewhat compositionally heterogeneous parent body. While plausible, the argument is not conclusive and rests largely on the apparent lack of any evident correlation between asteroid size and spectral signature of the Koronis family members—a correlation that might be expected if the observed variations were due largely to regolith maturation effects on bodies of different size and hence gravity. We have searched for small areas on Ida that might have spectra like that of Dactyl, but have found none.

A second possibility is that Dactyl's increased band depth results from a coarser regolith texture. While it is true that for powdered silicates a decrease in particle size

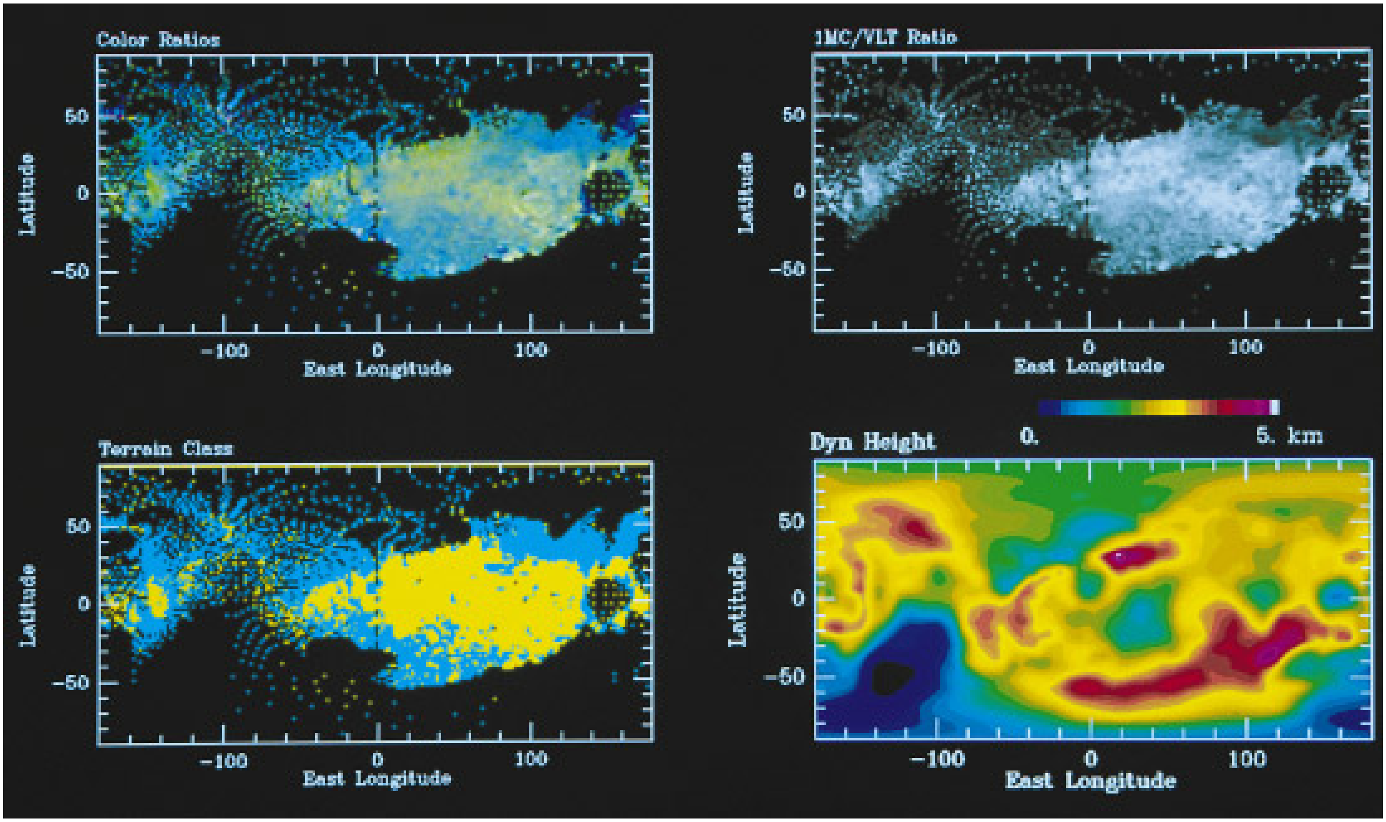


FIG. 4. (a) Simple cylindrical map of Ida created by sampling and averaging color images in two degree bins of latitude and longitude. This three-color composite was constructed by displaying 1MC/GRN ratio map in the red channel, MT2/GRN in the green channel and VLT/GRN in the blue channel. At locations in the map where data were available from more than one image sequence, only the highest resolution data were used. Yellow colored areas represent materials that have a relatively shallow 1 micron spectral absorption feature and slightly redder spectral slope compared to blue colored areas. (b) Map of 1MC/VLT ratios corresponding to (a). Ratios equal to or less than 1.35 correspond to blue colors; those above 1.35 to whitish yellows. (c) Terrain map derived from (b). Terrain A, represented by yellow, is defined by regions that have 1MC/VLT ratios greater than 1.35. Terrain B, blue, has 1MC/VLT ratios less than or equal to 1.35. (d) Dynamic height model of Thomas *et al.* (1996, Fig. 3). Contours of dynamic height correspond to contours of effective gravitational acceleration. The zero point is arbitrary. Crater Azzurra (denoted by the letter A in Fig. 1) is centered near −150°E, +30°N at upper left.

often leads to an increase in the depth of the 1-μm band and to a decrease in visible albedo (e.g., Adams and Filice 1967; Lee *et al.* 1995), such an inverse relationship need not always obtain (e.g., Hapke 1993). Thus, one cannot prove that Dactyl's slightly lower albedo and markedly deeper band depth must mean that Dactyl has a coarser regolith texture than Ida. Nor is it evident how the spectral reflectance curves of either Terrain A or Terrain B material on Ida could be modified to look like Dactyl by simply changing the texture. Furthermore, the generally close photometric similarity between the two bodies noted by Helfenstein *et al.* (1996) is consistent with similar surface textures for the two bodies.

5. DISCUSSION

Spectra of S-asteroids have been interpreted in two very divergent ways. According to one view, the surfaces of S-asteroids consist of primitive materials which have not experienced igneous processes since accretion. An opposing view holds that we are seeing materials that have undergone igneous processes connected to the complete or partial differentiation of a parent body following its accretion (see for example, Bell *et al.* 1989). In both views the minerals involved would be largely olivines, pyroxenes, and nickel–iron metal, but the relative proportions differ according to which of these extreme models is closer to reality. Unfortunately, the metal fraction has proven particularly difficult to derive accurately from spectral reflectance data.

A closely related problem is whether ordinary chondrite meteorites are connected with materials exposed on S-asteroid surfaces. Recently, Gaffey *et al.* (1993) have demonstrated convincingly that the taxonomic S group contains objects of very diverse geochemical histories and that so far only one subgroup (referred to as S*IV*) has olivine

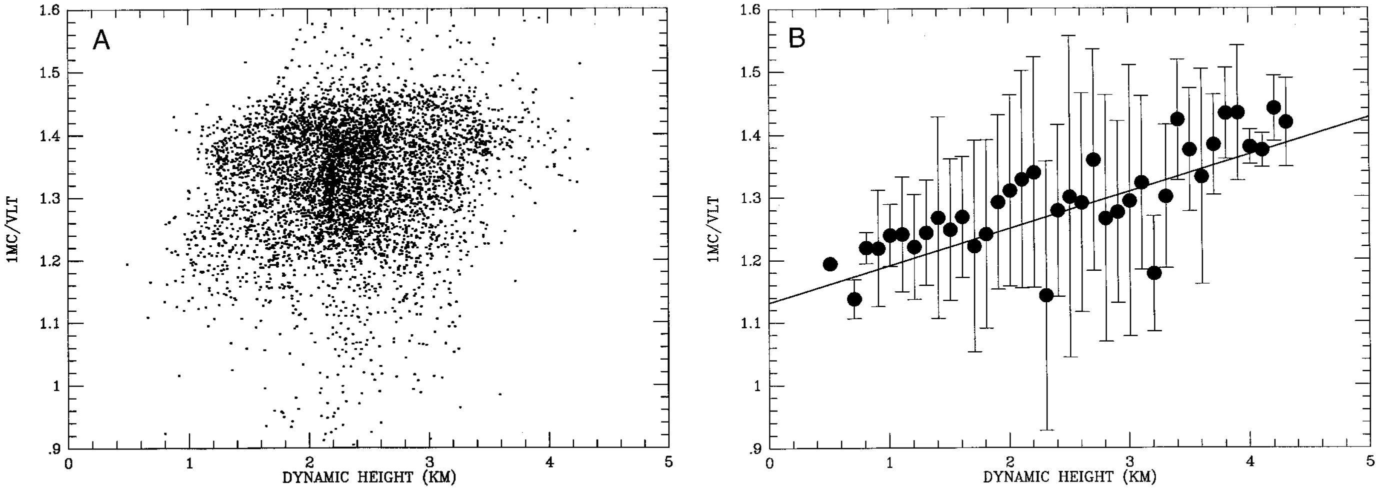


FIG. 5. (A) Scatter diagram of 1MC/VLT ratios versus dynamic height on Ida (from Thomas *et al.* 1996). Note that Terrain A (1MC/VLT > 1.35) occurs at all dynamic heights, as does Terrain B. However, there appears to be a slight tendency for higher average values of 1MC/VLT to occur at higher dynamic heights. (B) Bin-averaged values of 1MC/VLT ratio as a function of dynamic height. Error bars represent the standard deviations of the points (in Fig. 5B) that were averaged.

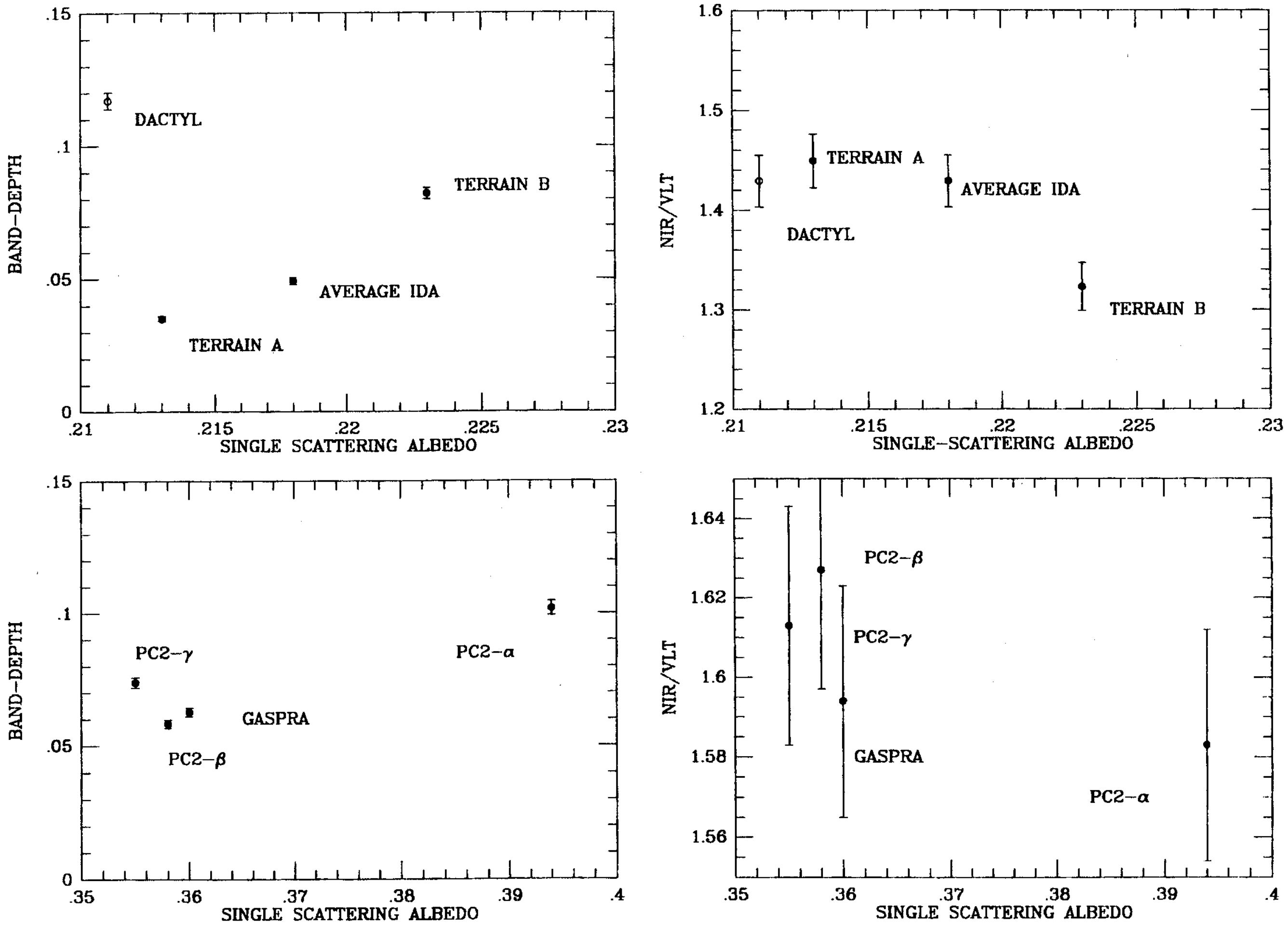


FIG. 6. Color–albedo systematics on Ida and Dactyl compared with those on Gaspra. The Gaspra data are from Helfenstein *et al.* (1994a); the Ida and Dactyl albedos are for the GRN filter and are taken from Helfenstein *et al.* (1996). The band depth is defined by the (NIR − 1MC)/NIR ratio.

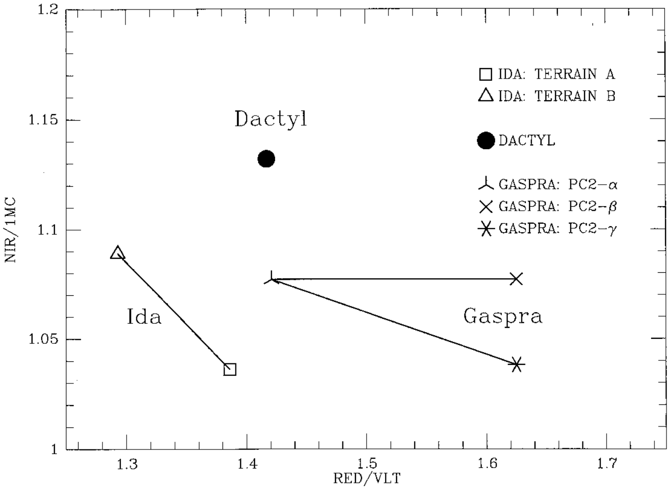


FIG. 7. Effect of supposed weathering on the colors of Ida and Gaspra terrains. The NIR/1MC ratio is an indicator of the depth of the 1 μm mafic absorption band, while the RED/VLT ratio is a proxy for the spectral slope at shorter wavelengths. Weathering on the Moon decreases the band depth and increases the spectral slope significantly. Gaffey *et al.* (1993) report evidence for similar but much less pronounced effects on some S-asteroids. According to these systematics, Terrain A on Ida is more weathered than Terrain B. Nominal data for Dactyl do not fit this presumed weathering trend. See text for details.

to pyroxene ratios compatible with those measured for ordinary chondrites. Interestingly, Ida is a member of this subgroup, but Gaspra is not (Gaffey, personal communication). Even members of the Gaffey *et al.* subgroup S*IV* have spectral slopes which are too red to match those of ordinary chondrites. This fact, that in general S-asteroids have spectral slopes which are much redder (higher red-to-violet color ratios), has been known for almost 30 years, but a generally agreed upon explanation does not exist. One extreme view is that the difference points to a fundamental and geochemically significant difference between the two mineral assemblages and that S-asteroid materials are not connected to ordinary chondrites. The other extreme view is that ordinary chondrites are derived from some S-asteroids, and that the observed spectral differences result from weathering processes which occur in S-asteroid regoliths, but the evidence for which is not preserved in ordinary chondrite samples.

The nature of this weathering process continues to be debated (Bell and Keil 1988; Britt and Pieters 1994; Cassidy and Hapke 1975; Clark *et al.* 1992; Cloutis *et al.* 1990; Gaffey 1986; Horz *et al.* 1994; Keil *et al.* 1992; King *et al.* 1984; Pieters *et al.* 1993; etc.) but there is now definite evidence that some weathering processes that alter spectral reflectances do occur on S-asteroids. Two of the clearest examples are the systematics of color/spectral variations observed on Gaspra by Galileo (Helfenstein *et al.* 1994a), and the increase in the depth of the 1-μm band with decreasing asteroid diameter established by Gaffey *et al.* (1993).

Weathering processes that affect spectral reflectance have long been recognized on the Moon (e.g., Matson *et al.* 1977), although even in this case some debate remains concerning the explanation (e.g., Bell and Mao 1977; Cassidy and Hapke 1975; Pieters *et al.* 1993). The observed trends are very definite and very marked: as a lunar soil matures, the 1-μm band becomes shallower, the spectral slope becomes steeper, and the albedo tends to become lower.

While the trends discussed for S-asteroids by Gaffey *et al.* (1993), for Gaspra by Helfenstein *et al.* (1994a), and for Ida in this paper are qualitatively similar to those observed for the Moon, the strength of these maturation effects is much less for S-asteroid regoliths than it is for the Moon. This difference may in part be due to the explanation advanced by Matson *et al.* (1977), according to which these spectral changes are associated with the retention of impact- altered regolith, particularly the glass-rich fraction presumed to be associated with the highest velocity ejecta. Obviously, the Moon with a gravity much larger than any asteroid would retain a larger fraction of such ejecta. The difference also probably reflects the difference in chemical

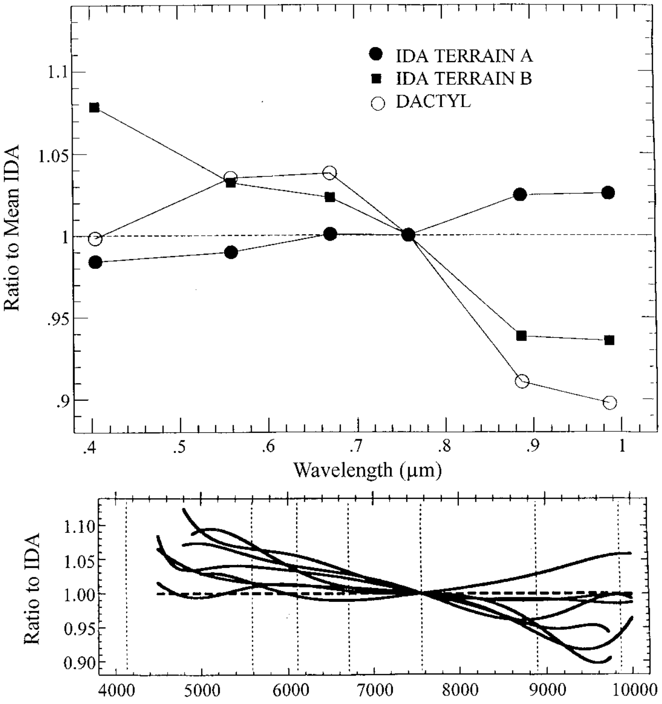


FIG. 8. Spectral differences among Dactyl and Ida's two terrains compared to Ida's average spectrum (top), compared with spectral variations observed by Binzel *et al.* (1993) for other members of the Koronis family (bottom). In the top panel Ida's average spectrum (cf. Fig. 1 of Helfenstein *et al.* 1996) plots as a straight line at unity.

and mineralogical makeup of S-asteroid and lunar regoliths.

6. CONCLUSIONS

The systematic color differences observed between Ida's two major color terrains are consistent with the weathering trends on S-asteroids documented by Gaffey *et al.* (1993) and on Gaspra by Helfenstein *et al.* (1994a). Terrain A, which covers most of Ida (Fig. 4) and which is characterized by a relatively shallower 1-μm band and a somewhat steeper spectral slope in the visible, corresponds to the older, more mature regolith unit. Terrain B, predominantly associated with certain well-defined small craters and with the very large crater Azzurra and its ejecta, corresponds to fresher, less processed material. It is also true that the spectral differences between Terrains A and B fall within the range of those reported by Binzel *et al.* (1993) for members of the Koronis family (Fig. 8). Based on the fact that the spectral differences observed within the Koronis family cannot be correlated convincingly with asteroid size, Binzel *et al.* have argued that these differences are best attributed to slight compositional differences in the Koronis parent body rather than to subsequent alteration by regolith processes.

For Terrains A and B on Ida, we find our explanation of the differences in terms of weathering more convincing for several reasons:

(1) The definite correlation between fresh craters and Terrain B is what would be expected from the weathering model. Such a correlation is not required by the model which ascribes the observed differences to compositional heterogeneity of the Koronis parent body.

(2) There is no evidence that contacts between Terrains A and B are controlled in any significant way by Ida's fundamental geologic structure, as expressed for instance by troughs or ridges. If the differences between Terrains A and B were due to fundamental compositional inhomogeneities within the body of Ida, one might expect that the boundaries between the two terrains would show more structural and geological control than they appear to (Geissler *et al.* 1996; Thomas *et al.* 1996; Sullivan *et al.* 1996).

(3) The depth of the 1-μm band for Terrain A on Ida is comparable to that found for the largest asteroids (diameter >100 km) in the study of Gaffey *et al.* (1993). This agreement is consistent with Terrain A being the mature regolith on this S-asteroid, mature in the sense that all processes that affect the spectral reflectance are closer to equilibrium.

The situation with Dactyl is more complex. There is no question that Dactyl's spectrum differs from those of either Terrain A or B on Ida. It is also true that at the resolution of the SSI color data ($\gtrsim$100 m), there are no locales on Ida with spectra identical to those of Dactyl.

Dactyl's spectrum differs primarily from that of Ida's terrains by having a deeper 1-μm band and a redder slope shortward of 0.56 μm. Note that SSI color data do not have the spectral resolution to compare meaningfully the central wavelengths of the 1-μm bands in the Ida and Dactyl spectra. As already noted by Chapman *et al.* (1995), the deeper 1-μm band for Dactyl is consistent with the weathering trend as a function of asteroid diameter noted by Gaffey *et al.* (1993). In this view, the deeper 1-μm band on Dactyl simply means that Dactyl is made of Ida material which is even less weathered than is Terrain B. Attractive as this hypothesis may be, it does not agree with all available data. Specifically, as already discussed, this view would suggest that Dactyl should have a less red spectral slope than does Terrain B, something which is not observed (Figs. 3, 7, and 8). For this reason, taking all data at face value, we must entertain the possibility that in the case of the Dactyl/Ida difference the Binzel *et al.* scenario is correct and that this difference reflects the fact that Dactyl and Ida are different pieces of a slightly inhomogeneous body, and that Dactyl happens to be a piece with a slightly higher pyroxene to olivine ratio than Ida.

We note that it is unlikely that the deeper band on Dactyl is caused solely by a difference in texture, specifically a coarser texture on Dactyl. There is no evidence in the photometry of the two objects for any marked textural difference (Helfenstein *et al.* 1996), nor is it evident how the spectral reflectances of either Terrain A or B could be modified to look like Dactyl solely by a change in texture.

A significant next step in the resolution of some of the questions that remain will come when the Galileo NIMS spectra of Gaspra and Ida are published and analyzed in a definitive manner. Preliminary NIMS results indicate that olivine/pyroxene ratios on Ida are consistent with those found in LL chondrites (Granahan et al. 1995), whereas Gaspra has a much higher olivine to pyroxene ratio than any known ordinary chondrite (Granahan et al. 1994). These results are consistent with those of Gaffey, which show that Ida falls within the S*IV* subgroup, but Gaspra does not.

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