Discovery of a Satellite of the Asteroid 243 Ida and its Physical Properties

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Submitted to *Nature* 30 January 1995, revised 30 March 1995

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Key words: Asteroids, satellites

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The possibility that satellites of asteroids exist has been debated since the 1970's when several mostly unconfirmed observations of stellar occultations indicated possible satellites[1]. After a decade of negative attempts to find such satellites, the consensus of theorists was[2] that they should be uncommon but some probably exist. The first confirmed asteroidal satellite has now been found by Galileo during the spacecraft's recent encounter with 243 Ida. The discovery, in preliminary engineering data from the Solid State Imaging camera and from the Near-Infrared Mapping Spectrometer, was announced in March 1994[3]. The International Astronomical Union named the satellite Dactyl. It is the smallest solar system object imaged with sufficient resolution for geological analysis. Here we discuss its notably smooth shape, its crater population (including a chain), and its photometric properties. In color, Dactyl resembles its parent, Ida, and other members of the Koronis asteroid family, implying similar composition; small differences may reflect a space weathering process that slightly alters surface colors with time. We infer that Dactyl originated during the break-up of the Koronis precursor body; hence, satellites could be common around other asteroids, especially family members.

Dactyl was found in one of the final 6-color sequence of Ida images, taken at 16:38 UTC on 28 August 1993 through a green filter from a distance of 10927 km. Dactyl is seen on 46 additional images, taken at 18 different times during 5.39 hrs. All have been measured for position and brightness (and colors from color sequences). One image, part of the high-resolution Ida mosaic[4], has a resolution of 39m/pixel at 48^{o} phase and provides the most detailed view for analysis of Dactyl's surface geology (Fig. 1a). An even higher resolution partial picture, taken near encounter, primarily shows Dactyl's shadowed side (Fig. 1b) which is sufficiently illuminated by Ida ("Ida shine") to define its profile.

The remaining Ida imaging data have been examined for additional satellites. We searched much of the inner portion of Ida's gravitational sphere of influence, particularly along Ida's equatorial plane. The chief uncertainties are confusion by sporadic cosmic ray hits on the CCD detector, requiring satellites to be revealed by motion in successive frames. Several interesting features appear to be anomalous cosmic ray hits, but no other satellite has yet been found. It is very unlikely we have missed another object approaching Dactyl's size in the volume searched. The detection threshold diameter within 10,000 km of Ida is roughly 50 m.

Dactyl's size and shape have been determined using the Spud shape-modelling program[5]. Dactyl is approximated by an ellipsoid with axes of 1.6 (±0.1) x 1.4 (±0.14) x 1.2 (±0.24) km, or a total volume of 1.4 (±0.5) km^3. The longest axis pointed toward Ida (to ±15^{o}) at the time it was spatially resolved, and the shortest axis was perpendicular to its orbital plane.

Dactyl does not look like an unmodified, angular rock fragment (Fig. 1,a,b). Instead, despite a slight concavity indicated by the trend of its terminator in Fig. 1a, Dactyl has a rather smooth, regular shape, especially compared with the angularity of Ida and Gaspra and many other small bodies (e.g. Comet Halley, Toutatis, and Castalia). Yet Phobos and Deimos present some aspects with comparable (even smaller) limb roughnesses[6], so Dactyl's shape is not wholly unprecedented. Local parts of the surfaces of Ida and Gaspra, comparable in scale to Dactyl, may be similarly smooth.

Dactyl was observed for a duration exceeding a full Ida rotation but only a modest fraction of even the shortest of Dactyl's allowed orbital periods (~25 hrs)[7]. Its brightness hardly varied. Nor is there any other evidence for rotation, so we conclude that Dactyl's spin period is ≥8 hrs., consistent with the dynamical expectation that Dactyl should have decayed rapidly to tidal lock.

Images of Dactyl over phase angles 20° - 96° permit determinations of its albedo and photometric properties. Within error bars, Dactyl's geometric albedo is identical to Ida's (0.20 ±0.02 at 0.56μm) as is its phase function (it brightens 0.028 ±0.002 mag/deg of decreasing phase angle), consistent with Dactyl's surface having a texture similar to average Ida. Specifically, the data seem inconsistent with the hypothesis that, due to Dactyl's tiny size, its immediate surface might be regolith-free bare rock.

There is a gross similarity of the visible and near-infrared reflectance spectra of Dactyl and Ida (Fig. 2), implying that they have similar compositions; Ida itself is in the S(IV) subgroup defined by Gaffey[8]. This is consistent with the hypothesis that Dactyl and Ida were both originally derived from the precursor body of the Koronis family. Koronis family members are known to have similar colors[9] implying rather homogeneous composition of the precursor body.

Dactyl shows real minor spectral differences from Ida, however, including its slightly less red color. The differences are of similar magnitude to variations among various Koronis family members[10]. However, Dactyl's spectrum tends to differ from other well observed Koronis members in an intriguing way. Dactyl has a significantly deeper 1μm absorption band than Ida (and nearly all other Koronis members) and it shows slightly greater spectral curvature than all observed Koronis members (i.e. its relative reflectance is lower in the violet and infrared than at intermediate wavelengths). These differences, which should be verified by further spectrophotometry of Koronis members, are generally in the same sense that smaller S-type asteroids at smaller heliocentric distances differ from their larger, more distant siblings[11,8].

The spectral differences between Dactyl and Ida (and other Koronis members) could arise from slight compositional differences and/or from a "space weathering" process on Ida's surface that slightly modifies colors with time. (Another explanation, differences in particle sizes, seems unlikely given the identical photometric properties of Ida and Dactyl.) Real compositional differences would mean that Dactyl could not have been derived directly from Ida or that there was real heterogeneity in the Koronis parent body, whereas a weathering process could make identical material look different.

A space weathering process, like that operating on the Moon but much weaker[12], which would "redden" and linearize spectra and weaken absorption bands, is just what would convert a Dactyl-like spectrum to be Ida-like. That just such a process actually operates on Ida (even though we do not know how it works) is indicated by the fact that fresh, young craters on Ida (called Terrain B) are spectrally intermediate between Dactyl and most of Ida (Terrain A)[13,14]. Thus Dactyl could represent an intermediate stage in weathering between an initial mineral assemblage resembling, for example, ordinary chondritic meteorites, and progressing to a "mature" Ida. Small S-types, like Dactyl, may be less weathered because they are younger or their surface layers are more frequently jolted and rearranged by impacts; or they may be less subject to a weathering process dependent on gravity (e.g. regolith maturation).

The most notable geological features on Dactyl are craters. We have identified up to 29 possible craters, of which 15 are definite. From a region of favourable lighting and visibility (basically the half of the image in Fig. 1a closest to the terminator), we have plotted the cumulative diameter frequency relation for the definite craters. It is consistent (in both overall crater density and -2 slope) with the small end of Ida's crater population, which reflects equilibrium with saturation cratering[4].

Dactyl's craters may not be simply due to impacts by heliocentric projectiles. At least 3 sizable craters (and up to 7, including "possible" craters) lie in a well-defined crater chain. It could be produced from an aligned jet of secondary ejecta, from a cratering event on Ida, which immediately struck Dactyl. Some crater chains on larger bodies are of internal origin, which seems unlikely for a body as small as Dactyl.

There is a positive relief feature within the most prominent, large crater. The gestalt of a "central peak" may be misleading, since peaks form only in much larger craters. Possibly, the feature is the wall of a smaller crater nestled within the larger crater. The most intriguing interpretation is that the feature is the remnant of the projectile that formed the crater, but at very low velocity. The ratio of projectile-to-crater size is consistent with sub-escape velocities within the Ida system.

We see no evidence of grooves, ridges, sharp edges, or other geological features in our best images.

It is highly improbable that Dactyl was captured from an independent heliocentric orbit by Ida, since there is no plausible source of dissipation (collision with a pre-existing satellite begs the question; how could *that* satellite have formed?). A primordial origin for asteroidal satellites has been suggested[15], but an object as small as Dactyl is very unlikely to survive over the age of the solar system. Almost certainly Dactyl was formed either from Ida (e.g. from reaccretion of ejecta from a large crater) or else contemporaneously with Ida during the catastrophic collision that formed the Koronis family. Both ideas are compatible with the compositional similarity between Ida and Dactyl.

There are intriguing similarities between Dactyl and properties predicted by Weidenschilling *et al.*[2] for a satellite formed from cratering ejecta (small object in prograde orbit around a rapidly spinning asteroid). However, they themselves conclude "satellites formed by this mechanism may be rare or nonexistent" and large harmonics in Ida's gravitational potential due to its irregular shape further mitigate against orbital stability of an object formed so close to Ida.

The formation of binary asteroids or asteroidal satellites during a catastrophic collision was originally suggested by Hartmann[16] and proposed more specifically as an outcome of natural "jetting" phenomena studied experimentally by Martelli *et al.*[17]. We prefer this explanation for the origin of Dactyl. While Durda[18] has found a low rate of formation of binaries by this mechanism, small satellites are more likely to be formed this way. Because Ida itself is saturated with craters[4] and because of the shorter collisional lifetimes for smaller bodies, it is somewhat unlikely that Dactyl could have avoided collisional disruption since its formation. More likely it is a remnant from a pre-existing, perhaps larger original satellite that has undergone break-up and reaccumulation from orbiting debris. Therefore, Dactyl could well have a rubble pile structure even if it formed originally as a solid Koronis fragment.

Dactyl's relatively smooth shape could reflect several generations of break-up and reaccumulation, perhaps augmented by sweep-up of some other temporary debris ejected from Ida. However, if Dactyl managed to survive break up, it could well have been smoothed by erosion. The steeply sloping power-law size distribution of asteroidal projectiles found from Gaspra's crater population[19], if it extends to sufficiently small sizes, would result in a "sandblasting" erosional smoothing. Whether Dactyl is solid or rubblized, its smooth shape (and Ida's smoothness at comparable scales) probably reflects, in part, the apparently steep size distribution for heliocentric cratering projectiles ~10 m - 100 m in diameter (i.e. there is a relative lack of projectiles capable of making large gouges in Dactyl).

As we noted, some of Dactyl's craters may be locally derived and one may be from a low-velocity impact. If true, the assumption of Belton *et al.*[4] that Ida has been struck solely by heliocentric projectiles from the same population that cratered Gaspra may be too simplistic. If cratering projectiles are derived from within the Ida system, or if the Koronis precursor break-up produced a high flux of Koronis-derived projectiles, then Gaspra-based calculations of Ida's age may be upper limits, and Ida could be younger, more in accord with other age estimates for the Koronis family[20,21].

The discovery of Dactyl (which would be difficult to detect from Earth), plus other data (indications from radar that some small asteroids may be contact binaries, studies of double craters, etc.), has caused reassessment of how common asteroidal satellites may be. Unconfirmed photometric blink-outs associated with asteroidal stellar occultations remain inadequate proof for the existence of any particular satellites. Nevertheless, Dactyl's existence suggests that asteroidal satellites may be more common (especially for family members) than had been thought. Discovery of additional asteroidal satellites would provide important clues about the nature of asteroids (e.g. the mass of the primary asteroid) and about asteroidal processes.

FIGURE CAPTIONS

Figure 1. (a) High resolution image of Dactyl, showing craters and other surface topography discussed in the text. (b) Dactyl image on the edge of one frame from the partial mosaic taken near the time of Ida encounter. Except for the horns of Dactyl's crescent, the sun-illuminated part of Dactyl is beyond the edge of the frame. The shadowed side of Dactyl can be seen illuminated by "Ida-shine".

Figure 2. Comparison of the spectral reflectances of Dactyl and Ida, measured from the final 6-color imaging sequence. Two major color units (terrains A and B) have been identified on Ida. Much of the face of Ida seen in the higher resolution views is dominated by Terrain A. The data are normalized to unity at 0.756µm. The typical uncertainty (±1.9%) of these relative colors represents the accuracy to which the color ratio of a single feature on Ida can be duplicated from one image sequence to another, determined from a series of features tracked in several Ida color sequences.

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ACKNOWLEDGEMENTS. We thank referees R. Binzel and M. Gaffey, colleagues including S. Weidenschilling and J. Gradie, and other members of the Galileo Project for their help. This is Contribution #329 of the Planetary Science Institute, a division of San Juan Capistrano Research Institute. The Galileo Project is managed by the Jet Propulsion Laboratory, California Inst. of Technology, under a contract with the National Aeronautics and Space Administration.