primordial origin for asteroidal satellites has been suggested\textsuperscript{13}, 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 (for example, from re-accretion of ejecta from a large crater) or else at the same time as 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 the properties of Dactyl and those predicted\textsuperscript{3} for a satellite formed from cratering ejecta (a small object in a prograde orbit around a rapidly spinning asteroid). However, it was also concluded\textsuperscript{14} that ‘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\textsuperscript{15} and proposed more specifically as an outcome of natural ‘jetting’ phenomena studied experimentally by Martelli et al.\textsuperscript{17}. We prefer this explanation for the origin of Dactyl. Although Durda\textsuperscript{18} has found a low rate of formation of binaries (where the two bodies are approximately the same size) by this mechanism, small satellites are more likely to be formed this way. Because Ida itself is saturated with craters\textsuperscript{19}, and because of the shorter collisional lifetimes for smaller bodies, it is somewhat unlikely that Dactyl could have avoided collisional disruption since its formation. It is more likely to be a remnant from a pre-existing, perhaps larger, original satellite that has undergone breakup and re-accumulation 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 breakup and re-accumulation, perhaps augmented by the sweeping up of some other temporary debris ejected from Ida. However, if Dactyl managed to survive breakup, it could well have been smoothed by erosion. The steeply sloping power-law size distribution of asteroidal projectiles found from Gaspra’s crater population\textsuperscript{19}, if it extends to sufficiently small sizes, would result in a ‘sandblasting’ erosional smoothing. Whether Dactyl is solid or composed of rubble, its smooth shape (and Ida’s smoothness at comparable scales) probably reflects, in part, the apparently steep size distribution for heliocentric cratering projectiles \(\sim 10-100 \text{ m in diameter} \) (that is, 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.\textsuperscript{19} 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 breakup 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\textsuperscript{20,21}.

The discovery of Dactyl (which would be difficult to detect from Earth), together with other data (indications from radar that some small asteroids may be contact binaries, studies of double craters, and so on)\textsuperscript{22,23}, has caused reassessment of how common asteroidal satellites may be. Unconfirmed photometric blink-outs associated with asteroidal stellar occultations remain inadequate proof of 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 (for example, the mass of the primary asteroid) and about asteroidal processes.

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**BULK DENSITY OF ASTEROID 243 IDA FROM THE ORBIT OF ITS SATELITE DACTYL**


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**DURING its reconnaissance of the asteroid 243 Ida, the Galileo spacecraft returned images of a second object, 1993(2431) Dactyl—the first confirmed satellite of an asteroid. Sufficient data were obtained on the motion of Dactyl to determine its orbit as a function of Ida’s mass. Here we apply statistical and dynamical arguments to constrain the range of possible orbits, and hence the mass of Ida. Combined with the volume of Ida, this yields a bulk density of \(2.6 \pm 0.5 \text{ g cm}^{-3} \). Allowing for the uncertainty in the porosity of Ida, this density range is consistent with a bulk chondritic composition, and argues against some (but not all) classes of meteoritic igneous rock types that have been suggested as compositionally representative of S-type asteroids like Ida.

Figure 1 shows a selection from 47 independent views of Ida and Dactyl obtained by the Galileo solid-state imaging (SSI)
Ida and Dactyl are spatially resolved in most images. Accurate knowledge of their shapes and orientations was therefore used for precise estimation of the positions of their projected centres of mass. Ida's interior is assumed to be homogeneous. Resolved images of Ida over a full rotation period (4.633 h) allowed detailed shape models to be developed, yielding volumes of 16,100 ± 1,900 km³ for Ida (mean radius, 15.7 km) and 1.4 km³ for Dactyl (mean radius, 0.7 km). Ida's rotation pole was determined from SSI data to be in the direction right ascension 345° 76', declination 87° 10' (J2000).

Figure 2 shows two-body orbits that fit the SSI data. Predicted positions of Dactyl relative to Ida were directly compared with measured positions in the image plane. Weighted root-mean-square (w.r.m.s.) errors of fit to the best-fitting orbit solutions were consistently <0.2 pixels in image coordinates. In Fig. 3 selected orbital elements, periapsis distance (Rₚ), and w.r.m.s. errors are shown as a function of GM, where G is the gravitational constant and M the mass of Ida. (Periapsis is the point in the orbit which is closest to the centre of mass.)

The w.r.m.s. errors show a slight preference for lower values of GM, but do not allow a specific value of GM to be determined with confidence. For GM < 0.0023 km³ s⁻², the orbits are highly elliptical (eccentricity e > 0.98) or hyperbolic with Rₚ decreasing from 78 to 70 km. We estimate the probability of the chance presence of any detectable (radius > 100 m) main-belt asteroid in Ida's entire gravitational sphere of influence (radius ~7,000 km) at only ~10⁻⁷. It is therefore highly unlikely that Dactyl is on a hyperbolic orbit and that GM is less than 0.0023 km³ s⁻².

Beyond a distance Rₚ ≈ a₀ (M/M₀)²/₃, where M₀ is the mass of the Sun and a₀ is the heliocentric distance of the Dactyl–Ida system (that is, ~1,500 km), two-body motion is no longer a good approximation. Hamilton and Burns indicate that circular retrograde (with respect to the orbital motion) orbits with semimajor axes as large as ~445 times the primary's mean radius (~7,000 km) may be long-lived, and the orbits for Dactyl are highly elliptical with their periapsis distance approaching Ida as their apoapsis increases beyond Rₚ. (Apoapsis is the point in the orbit which is farthest from the centre of mass.) This type of orbit should be sensitive to small perturbations and may possibly be chaotic, although regular orbits of this class may exist, locked-in by resonance effects.

As Dactyl could be on a bound orbit that takes it relatively far from Ida, we searched for it in images (from the Wide Field Planetary Camera on the Hubble Space Telescope) that were taken in April 1994 (April 26.2 UT, ~240.5 days after the Galileo encounter. We found no trace of the satellite between projected distances of 400 and 30,000 km from Ida. Dactyl's estimated visual magnitude was 21.6, ~1 mag brighter than the detection limit of our data. A search to lower distances was prevented by scattered light from Ida. This excludes hyperbolic orbits for GM < 0.0020 km³ s⁻² and makes orbits with apoapses > 700 km (that is, GM < 0.0024 km³ s⁻²) unlikely.

Orbits with GM > 0.0030 km³ s⁻² (Fig. 3) become increasingly elliptical, with Rₚ rapidly falling towards distances comparable with the size of Ida (a = 28 km, b = 12 km, c = 10.5 km, where a, b, c are the principal axes of the best-fit ellipsoid). Calculations of the evolution of orbits about a triaxial ellipsoid (used to simulate Ida) show that orbits with GM > 0.0031 km³ s⁻² (that have Rₚ < 75 km) either collide with Ida or are ejected on a hyperbolic orbit. This result is consistent with the work of Chauvineau et al. and Scheeres, who showed that circular prograde orbits could be stable outside a critical distance from the primary (~63 km). For Dactyl to have a stable elliptical prograde orbit with Rₚ < 75 km it would have to be trapped in some special, low-order, resonance with Ida's spin period. In view of the distinctly non-ellipsoidal shape of Ida and the comments of Chauvineau et al. on the effects of deviations from an ellipsoidal shape, we doubt that such special orbits are appropriate for Dactyl. We conclude that, for the range of orbits that satisfy
FIG. 2. Possible orbits of Dactyl. Each orbit is labelled with the value of the assumed gravitation parameter, GM (km$^3$ s$^{-2}$). The outline of Ida is approximated by an ellipsoid and is drawn to scale. The orientation shown for Ida is for the time of closest approach, 1993 August 28.70284 UT. The view directions for several of the images are shown as diagonal lines. Because these directions lie close to both Dactyl’s orbital plane and Ida’s equatorial plane, and because there was little parallactic motion between Ida and Dactyl during the early parts of the sequence, it was not possible to distinguish between the best orbits for different GM. The orbits approximately intersect at ~85 km from the centre of Ida because the final images of the fly-by sequence were taken from a wide range of viewing angles but within a few minutes of each other, thus rendering Dactyl effectively stationary from different view points. These latter data therefore allow accurate triangulation of the position of Dactyl relative to Ida. The motion is prograde with respect to Ida’s spin which is retrograde, that is, the view is from the direction of Ida’s south pole.

the observations and are likely to be stable, GM is in the range 0.0024–0.0031 km$^3$ s$^{-2}$, that is, $GM = 0.0028 \pm 0.0004$ km$^3$ s$^{-2}$. The corresponding mass of Ida is $M = 4.2 \pm 0.6 \times 10^{26}$ g, and the range of possible Dactyl orbital periods is 227.3–247 h. Radio tracking of the spacecraft during the encounter might have yielded an independent estimate of Ida’s mass. However, no systematic Doppler shifts in the radio signal were detected (J.D. Anderson, personal communication).

Ida’s bulk density, $\rho_b = 2.6 \pm 0.5$ g cm$^{-3}$, follows immediately from the above estimates and gives insight into its bulk composition and porosity, $p$. These quantities are related to the grain density, $\rho$, of the rock type by $p = (1 - \rho_b/\rho)$.

S-type asteroids have been proposed$^{11,13}$ as the parent bodies for ordinary chondrites, the most numerous meteorite type$^{14}$. Although there are spectral similarities between the two, there are also strong differences$^{15}$. In the absence of any demonstrated ‘space weathering’ process to transform suitably the spectrum of ordinary chondritic material$^{16,17}$, the current assessment is that most S-type asteroids are closely related to types of stony-iron meteorites that reflect a record of igneous processes in the primitive planetary system. This identification leaves the relatively primitive and abundant material in ordinary chondrites without any well observed parent-body type—a situation sometimes referred to as the ‘ordinary-chondrite mystery’. Meteorite analogues to the S-types that have been suggested$^{19,22}$ include pallasites, olivine-dominated stony iron, lodranites, irons, and, for a small subset of S-types, ordinary chondritic material. In Table 1 we give estimates of Ida’s bulk pyroosity using typical densities and porosities of meteoritic types$^{23}$ assuming that they dominate Ida’s composition.

Bulk porosities for Ida, which may be appreciably fractionated in its interior, are expected to be larger than the porosities seen in meteorite samples. Thus an Ida of stony-iron composition (typically $p < 0.01$) is expected to have a bulk porosity of >1%, whereas a chondritic composition (typically $p \approx 0.11$) is expected to have a bulk porosity >11%. Estimates of the bulk density of other Solar System objects of comparable size to Ida, for example, Janus, Empintheus, Phobos and Dimos, when interpreted in terms of reasonable assumed bulk compositions, suggest that bulk porosities in the range 0.1–0.6 are plausible (we}

FIG. 3 Variation of orbit shape, inclination, and goodness of fit with assumed value of Ida’s gravitational parameter, GM. Plotted variables (top panel to bottom panel) are as follows: Semimajor axis, $a$; for GM < 0.0023 km$^3$ sec$^{-2}$, the orbits are hyperbolic. Eccentricity, $e$. Inclination (with respect to Ida’s equatorial system), $i$. Periapse distance, $R_p$. Bound orbits with $R_p$ below the dashed line at 75 km are found to collide with, or escape from, Ida on very short timescales. Weighted root-mean-square, w.r.m.s., sum of deviations of orbital positions from observed locations.
Magnetic switching in cobalt films by adsorption of copper

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Magnetic storage of information requires the ability to manipulate the magnetization of thin films with high sensitivity and spatial resolution. Non-magnetic overlays are known to affect the characteristics of magnetic films: for example, the direction of magnetization of cobalt and iron films can be altered by deposition of a monolayer of copper and gold, respectively. The magnetic properties of cobalt films seem to be particularly sensitive to copper overlays—deposition of only sub-monolayer amounts of copper will decrease the coercive field required to invert the magnetization direction. Here we show that copper coverages as small as three-thirds of a monolayer are sufficient to rotate by 90° the magnetization of Co films up to 20 atomic layers thick. This implies that the spins of about 500 cobalt atom sites switch direction for each copper atom added. Adding more copper eventually switches the magnetization back to its original direction. This fine tuning of thin-film magnetism might be useful for developing sensitive magnetic-field sensors, as well as for magnetic recording.

We use Co films grown epitaxially on a Cu(100) single crystal with a slight miscut of 1.6° in the [110] direction—this produces a controlled step structure. These steps turn out to play a central part in the magnetic switching. To detect changes in the magnetization, we use spin-polarized scanning electron microscopy (spin-SEM) and measurements of the magneto-optical Kerr effect. Spin-SEM determines the magnetization direction with high precision and spatial resolution, and the Kerr effect records hysteresis loops in the magnetization as a function of applied magnetic field.

To investigate the changes that might take place on Cu deposition, we grew a Cu wedge of 120 μm length onto a Co film and measured the magnetization direction locally by spin-SEM as a function of the Cu coverage dcu. Figure 1 shows a magnetic map of a 2.16-nm-thick Co film (=12 atomic layers, AL) partly covered by such a Cu wedge. The entire image, except one stripe, appears dark. This is direct evidence that the magnetization vector of the uncovered as well as the Cu-covered parts (dcu > 1.2 AL) of the Co film point in the [110] direction, which runs parallel to the steps induced by the miscut of the substrate. In contrast, at low Cu coverages the magnetization direction changes in-plane by 90° from the [110] to the [10] direction, as indicated by the light stripe. A line scan through the magnetic map in Fig. 1 reveals that this transition of the magnetization direction by 90° is discontinuous. This abruptness, and the fact that the original magnetization direction is resumed on further Cu coverage, signifies the elementary features of a magnetic switch: the magnetization switches discontinuously between two discrete states.

To elucidate the mechanism for this behaviour, we investigated the response of the magnetization to a magnetic field. Hysteresis loops were recorded using the Kerr effect on increasing the Cu coverage of a Co film (Fig. 2). Again, the easy magnetization axes of the uncovered and the Cu-covered (dcu > 1.2 AL) Co films point in the [110] direction. This is clear from the very different hysteresis loops observed for the two directions: a rectangular loop typical of the easy magnetization axis for the [110]-direction, and a more complicated one composed of two shifted loops for the [10] direction. Correspondingly, the ratio of the remanent magnetization Mr to the saturation magnetization Ms = M(H = 14 kA m⁻¹) = M/H = 1 for the [110]-direction but Mz/Mx = 0 for the [10]-direction.

The region of interest has a Cu coverage of 0–1.2 AL. Minute amounts of Cu coverage completely change the shape of hysteresis loops. For coverages thicker than 0.03 AL, the role of the two directions is interchanged. The complicated loop of the 110-direction is replaced by the rectangular loop of an easy magnetization axis, whereas the 100-direction loses its easy character, and Mz/Mx < 0.2. An additional 0.1 AL of Cu switches the easy magnetization axis back to the 110-direction, and produces rectangular hysteresis. Most intriguing is the loop at 0.15 AL < dcu < 1.2 AL. Although Mz/Mx = 1, the typical rectangular loop of an easy axis is missing. A compound loop is present, but the shift of the loops is smaller than that of the uncovered Co film in the 110-direction. This means that Mz/Mx = 1 for both

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