

THE GALILEO ENCOUNTERS WITH GASpra AND IDA

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Abstract. The Galileo spacecraft encounters with 951 Gaspra and 243 Ida have provided the first close-up pictures and measurements of asteroids. These two small, S-type asteroids are both irregular in shape, confirming generalized pre-encounter interpretations from groundbased data. Gaspra is lightly cratered by small, fresh craters whereas Ida's surface is heavily covered by craters of all sizes and in all stages of degradation. Unless there are major differences in strength between these two bodies, Ida may be about 10 times older than Gaspra – approaching the age of the solar system. Both asteroids have grooves, although not as prominent as on Phobos. Ida has a population of boulders, particularly near its ends. While Ida seems to have a deep regolith, Gaspra is more nearly in a state of erosion, although there is evidence for an older megaregolith. The data are thus far not conclusive about the geophysical properties of these objects (e.g. whether they are rubble piles) and there are as yet no firm conclusions about how asteroid families are produced by catastrophic collisions. Interesting spectral data relevant to the S-type asteroid controversy (e.g. spatial variations on Gaspra) may lead to some useful generalizations after the remaining Ida data are returned and analyzed in spring 1994. Unexpected magnetic anomalies observed in the vicinities of both asteroids are being studied.

1. Introduction

Until recently, our insights about asteroids came from a very unbalanced set of data. First, there is a great body of astronomical data, obtained from telescopic observations of unresolved, point sources (radar images, which will become more important in the future, are a rare exception to the rule that groundbased data have no spatial resolution). Second, we have a wealth of hand-samples excavated from asteroid surfaces, the meteorites. But until the Galileo spacecraft, enroute to Jupiter, flew past the inner main-belt asteroid 951 Gaspra on 29 October 1991, we had no data at intermediate scales of resolution. For the first time, Galileo provided us with a picture of an asteroid, directly showing its shape, its geological features, and variations in color and other properties across its surface. This encounter thus provided a potential linkage with the other disparate data sources. In addition, the inferences, extrapolations, and theoretical models derived from astronomical data can now be compared with “ground truth,” thus calibrating the confidence with which we can derive valid inferences from astronomical data of the countless asteroids that will never be visited by spacecraft. Also, the speculative “meteorite parent bodies,” derived from cosmochemical inferences from meteoritical data, can be compared for the first time with real asteroids.

Then, on 28 August 1993, Galileo made its second and final encounter with an asteroid, 243 Ida, one of the larger members of the Koronis family. Only a small portion of the Ida data have been returned to Earth at the time of this writing (nearly all of the remainder are planned for playback in spring 1994). Therefore,

this review only briefly comments on some of the preliminary results for Ida. Ida, of course, provides a basis for understanding the degree to which the intermediate-resolution studies of Gaspra represent typical or anomalous aspects of asteroids. Since both Gaspra and Ida are main-belt members of the S spectral type and they are both roughly the same size (Ida is less than three times as large as Gaspra), these fly-by encounters represent only a first step in the close-up study of asteroids. Continuing improvements in groundbased radar and application of cheap, generic spacecraft encounters – like the forthcoming Clementine studies of 1620 Geographos – will provide some additional insights about different kinds of asteroids at these intermediate scales. However, the excellent quality of the Galileo data for Gaspra and Ida provides a strong rationale for the use of state-of-the-art instrumentation specifically designed for small body studies. And the kinds of questions that remain unanswered after the Galileo encounters argue that a dedicated program of asteroid exploration will require rendezvous, in situ measurements, and sample return.

Since part of Galileo's instrument package was designed for the Galilean satellites, some of the instruments are well suited to these first asteroid flyby observations. So far, the important scientific results have come primarily from the Solid State Imaging (SSI) camera, the Near-Infrared Mapping Spectrometer (NIMS), and – surprisingly – the magnetometer. Spacecraft encounters at both asteroids were restricted to distances beyond any expectation for existence of dangerous debris trapped in orbit around the targets. Those distances were nearly optimal for imaging because of uncertainties in target ephemeris and the need to sample large areas of sky to be assured of capturing the asteroids in the mosaics; if Galileo had flown much closer, there would have been inadequate time to take mosaics large enough to guarantee showing the targets at larger phase angles, best for studying geologic features. For both fly-bys, the data were recorded on the spacecraft tape recorder. Due to failure of Galileo's high-gain antenna, data return is complicated and time-consuming. In the case of Gaspra, much of the data was played back shortly before the second Earth-encounter, when the low-gain antenna was sufficient. For Ida, the best SSI image plus associated data from other instruments, were returned at 40 bits per second (bps) in September 1993; it is expected that most of the rest of the recorded data can be played back in spring 1994 (also at 40 bps) prior to planned observations of the impact of fragments of Comet Shoemaker-Levy 9 into Jupiter in July 1994.

Preliminary reports interpreting the images of Gaspra (Belton *et al.*, 1992) and the apparent magnetic anomaly near Gaspra (Kivelson *et al.*, 1993) have appeared in Science. A collection of more detailed reports from the imaging team is scheduled to be published in *Icarus* in early 1994. A preliminary report on the data returned from Ida during September 1993 will be available by the time this review appears.

Briefly, the close-up pictures of Gaspra and Ida did not produce stunningly unexpected revelations. In some ways, the interpretations of groundbased and meteoritical data, and predictions by theorists, had not overlooked anything terribly fundamental. But for the asteroid research community, there were more than enough surprises from both encounters. We now know what asteroids (at least two of them) look like, we have new ideas about the size distribution of smaller objects in the asteroid belt (from the cratering record on Gaspra and Ida), we have in-

formation that begins to constrain heretofore highly speculative models of regolith evolution on small bodies, we have magnetometer evidence of unexpected interactions between asteroids and the interplanetary space environment, and we have interesting hints relevant to the longstanding scientific controversy concerning the nature of S-type asteroids and their relationships to differentiated and undifferentiated meteorites.

2. 951 Gaspra

Gaspra is one of the most irregular bodies ever seen from close range in the solar system, unless Ida proves to be even more irregular (Fig. 1). Gaspra's principal diameters are $18.2 \times 10.5 \times 8.9$ km (Veverka *et al.*, 1993a), with an average diameter of 12.2 ± 0.8 km. In the closest image, it presents a planar surface or facet to the spacecraft, and other facets are visible on the edges. One facet, named Dunne Regio, is 5×7 km and is flat to within 200 m. Subsequent playback of earlier pictures of other sides of Gaspra revealed a lumpy visage, with a smaller lump attached to a larger lump. Gaspra's shape is consistent with ideas that asteroids might be rubble piles, composed of multiple bodies following a size distribution in which the largest component contains most of the mass. It is also consistent with Gaspra being the core fragment from a catastrophically disrupted larger precursor body, in which case each planar surface may mark the locus of spallation of other outer fragments.

Davies *et al.* (1993) have determined that Gaspra's pole is located at RA $9^{\circ}.5 \pm 0.9$, Dec $+26^{\circ}.7 \pm 1.2$ (J2000), similar to the less precise orientation determined from pre-encounter analysis of telescopic lightcurves (Magnusson *et al.*, 1992), and they confirm the groundbased spin period of about 7.04 hours (prograde). No satellite of Gaspra has been found in the 150-image data set; 57 images contained at least a part of Gaspra itself. Helfenstein *et al.* (1993) find Gaspra's geometric albedo to be ~ 0.22 (with regional variations 10% or less), very high for an S-type (but Gaspra was known to be an outlier from typical S types). The bolometric Bond albedo is 0.12 ± 0.03 .

The most prominent characteristic of Gaspra is its smoothed surface, peppered by a sprinkling of small, fresh craters. (I will address the craters in more detail below.) Other features have been recognized including grooves and compressional features (Veverka *et al.*, 1993b), in addition to the more general ridges, facets, and lumps that make up Gaspra's general shape. Thomas *et al.* (1993) argue that there is a continuity of structural elements, or "fabric", suggesting that Gaspra is a monolithic body, rather than a gravitationally-bound assemblage of smaller pieces. I would note, however, that the structural elements have been resolved only for one side of Gaspra, from high-resolution pictures taken under similar lighting geometries; furthermore, such a conclusion is not inconsistent with the expectation (from typical fragment size distributions) that a rubble pile would be dominated by one large piece and only a few significant subordinate pieces.

Images taken through different filters through the visible and near-IR, as well as NIMS spectra of different parts of Gaspra's surface, indicate slight spatial variations in composition. In some places (especially ridges), Gaspra's albedo is slightly brighter, the prominent olivine absorption band is relatively stronger, and the overall

reflection spectrum is slightly less red, while Gaspra's facets tend to be redder

but have lower spectral contrast (perhaps they are slightly more metal-rich). Granahan *et al.* (1993) have intercompared the two data sets and find a spread in the olivine/pyroxene ratio comparable to that separating the H, L, and LL groups of ordinary chondrites – but, in Gaspra's case, even the olivine-poor end-member is more olivine rich than the most olivine-rich ordinary chondrites (the LL's). This evidence supports the idea that Gaspra is a differentiated body. However, large units of substantially differentiated composition are not evident anywhere on Gaspra; the color variations are only about 5%. The smaller differences that are seen may best be attributed to episodic segregation of materials, perhaps by downslope movement following seismic shaking by rare, larger impacts.

Analysis of more than 600 craters (Chapman *et al.*, 1993) from the highest resolution image of Gaspra reveals that most craters are very fresh and follow an unexpectedly (to some) steep size-frequency distribution (see Fig. 2). The crater production function has a differential power-law exponent (population index) of about -4.3 over the range 0.2 to 0.6 km diameter, considerably steeper than the -3.5 characteristic of collisional fragmentation processes (Dohnanyi, 1971) and steeper than the range of possibilities evaluated before encounter by Namiki and Binzel (1991). All craters together, including the modest numbers of shallow, "soft", degraded craters, actually follow a slightly shallower size distribution (slope = ~ 3.8), but the degraded craters appear to represent an earlier generation of larger craters (typically greater than 500 m diameter) that peek through the last episode of general crater erasure.

Although the -4.3 slope for the production function was surprising to some, it is identical to the production function for craters of similar sizes on the lunar surface; the equivalent slope has also been reported (although it remains controversial) for small bodies in Earth-crossing orbits (Rabinowitz, 1993). Recent work on asteroid collisional evolution, reported at the Gubbio Workshop (cf. Campo Bagatin *et al.*, 1993), suggests that the -3.5 slope may not be sacred, and there may be ways to explain the steeper slope on Gaspra without having to invoke such special circumstances as a recent spray of small particles from a catastrophic fragmentation in the Flora family region.

The steeply sloping production function has implications for the small scale structure of Gaspra's surface, such as its putative regolith. Although perhaps half of the ejecta may be retained from larger cratering events on Gaspra (Housen, 1992), the visible craters could have distributed only a few meters of material around Gaspra (Carr *et al.*, 1993; Chapman *et al.*, 1993). The smaller cratering events would excavate and scour the surface very efficiently, since the majority of ejecta would escape Gaspra from each of these events. In fact, Gaspra's surface must be in net erosion and there can be no continuous production of (or reworking of) regolith on its surface (Chapman *et al.*, 1993). Thus there is little opportunity for optical alteration of surface materials on Gaspra analogous to processes on the lunar surface. The indirect arguments for slight alteration and for minor downslope movement of particulates (invoked, for example, to explain the correlation of color differences with topography) probably pertain to occasional episodes, perhaps induced by seismic shaking due to large impacts, during which the ancient megaregolith is briefly



Fig. 1. Galileo images of Gaspra and Ida, showing their approximate relative sizes.

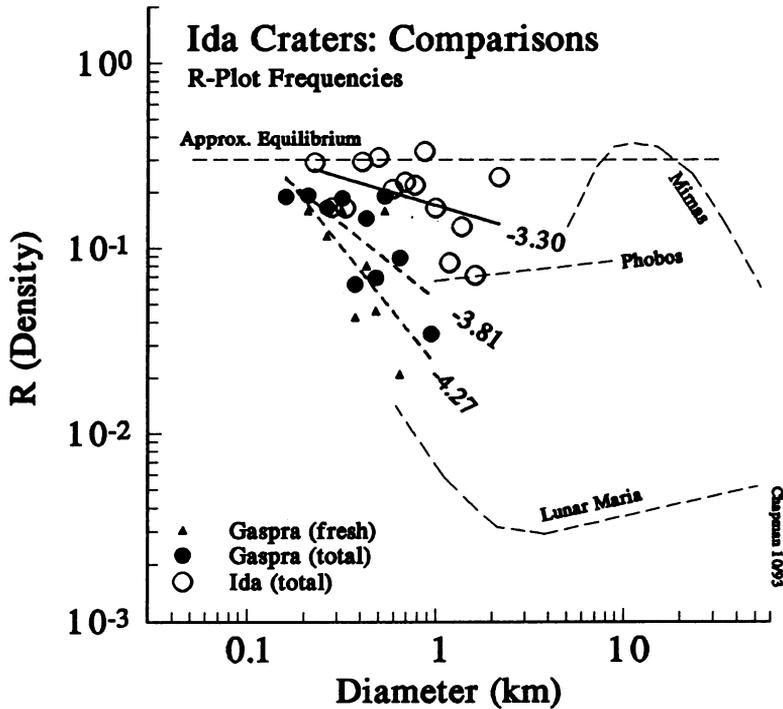


Fig. 2. Crater size-frequency data for Gaspra and Ida, with comparisons. These “R-plot” consists of differential frequency data, normalized by dividing by D^{-3} . Modified from a figure in Chapman *et al.* (1993).

mobilized after which it then remains quiescent for another long duration.

It is plausible that the largest impacts on Gaspra, and on its precursor body, would have developed a poorly consolidated megaregolith. Such megaregolithic structure at depth is probably required to explain the subdued larger craters, the generally softened appearance of Gaspra’s profile and surface, and the grooves. The megaregolith may have been formed, along with the planar facets, when Gaspra was formed by the catastrophic disruption (e.g. by spallation) of a larger precursor body in the Flora family zone of the asteroid belt. Perhaps there have been a few subsequent episodes of shaking and blanketing due to sub-catastrophic impacts, although no craters larger than 3 km diameter have been found on Gaspra. Possibly a large crater remains hidden in the small, unimaged part of Gaspra near its

southern pole.

The cratering age of Gaspra (i.e. the age of exposure of the visible, smoothed surface, to the production function, as represented by the fresh crater population) has been estimated (Belton *et al.*, 1992) as 200 My, assuming that Gaspra responds to cratering impacts as a body with rocky or sandy impact strength. This is a highly model-dependent result, for which the Galileo data provide only some new elements (see Chapman *et al.*, 1993). Compared with a self-consistent estimate for the collisional lifetime of Gaspra (500 My), this result means that Gaspra is relatively youthful. If Gaspra actually has the impact strength associated with ductile metal, which would be possible if it had a stony-iron composition, then it could be much older. A more controversial idea (Greenberg *et al.*, 1993; see also discussion by Chapman *et al.*, 1993) is that Gaspra behaves, ironically, as an exceptionally strong body because it is weakened by large impacts; these arguments, based on hydrocode models of asteroid collisions, would also lengthen Gaspra's lifetime and cratering age.

3. 243 Ida : Preliminary Observations

A single, highest resolution image of Ida, ~ 35 m/pixel, was the first Ida image to be returned, and the only one as of this writing. It presents an appearance similar to Gaspra in some respects, but very different in others. As had been expected from groundbased lightcurves, Ida is also very irregular. (Ida's shape in the single image is consistent with the second of two ambiguous pole solutions derived by Binzel *et al.*, 1993). Ida appears to be somewhat larger than was expected. It is not a contact binary, contrary to some pre-encounter suggestions, but whether it is a monolithic body, a rubble pile, or has some other shape characteristics is speculative until views from its other sides are returned. These will be very important for understanding whatever clues Ida might hold in store for us about how the Koronis family parent body was disrupted.

Ida, unlike Gaspra, is one of the most densely cratered objects in the solar system. The crater density is similar to that attained on surfaces that have been saturated by impacts and are in equilibrium. Theoretical studies of such equilibrium processes (applied to the lunar surface: see Chapman *et al.*, 1970) show that craters will follow a power law size distribution with differential index (slope) of -3, and that crater morphologies will range from fresh to degraded (degraded being the most common) with similar ratios between the morphological classes at all diameters. This is just what is seen on Ida (Fig. 2). The slope of the power-law for Ida's craters is about -3.3 (with error bars wide enough to include -3.0).

It is not always possible to unambiguously determine the underlying production function when the craters are in equilibrium. However, Ida's crater population could be produced by letting the same crater production function that is responsible for Gaspra's fresh craters impact on Ida for about 10 times as long. If this is true, Ida's surface may date back 2 billion years. If these asteroids have higher impact strength, then their corresponding ages are even older, and Ida could date back to the Late Heavy Bombardment.

Unlike Gaspra, Ida shows many suggestions of a deep regolith. There are boulders visible on Ida's surface (particularly near its ends), indications of downslope

movement, and small-scale albedo variations (e.g. dark floored craters), in addition to the range of crater morphologies. There are some very large craters on Ida, so there are sources for the deeper regolith. Other geological features have been recognized on the high-resolution image of Ida, including lineaments that predominate on one part of the asteroid.

Preliminary reports by the NIMS experimenters suggest that Ida is much more spatially uniform in colors (spectral reflectance) than is Gaspra. This seems somewhat inconsistent with preliminary indications from groundbased observations, reported by Barucci *et al.* among others at ACM93, of large color differences on opposite sides of Ida. If the NIMS data hold up once the complete data set is returned in spring 1994, it could indicate either that Ida is compositionally homogeneous (perhaps it is an undifferentiated, chondritic body) or that it has been "painted grey" by global distribution of ejecta from the latest large impact.

Magnetometer observations during fly-bys of both Gaspra and Ida revealed anomalies that the experimenters have interpreted as probably reflecting interactions of these bodies with the solar wind. The original interpretations of the anomaly near Gaspra (Kivelson *et al.*, 1993) considered Gaspra to have remanent magnetization similar to that found in most meteorites (both differentiated and undifferentiated). Although such a net magnetic moment would be inconsistent with a randomized sandbank, it would not be inconsistent with a rubble pile having a size distribution (similar to that of the main-belt asteroid population) dominated volumetrically by the largest component. The magnetic anomaly observed near Ida has caused the investigators to begin rethinking the Gaspra anomaly (Kivelson, personal communication, 1993), so the implications of these unexpected data for either asteroid science or space physics remain to be developed.

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