Imaging of Near-Earth Asteroids.

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Abstract

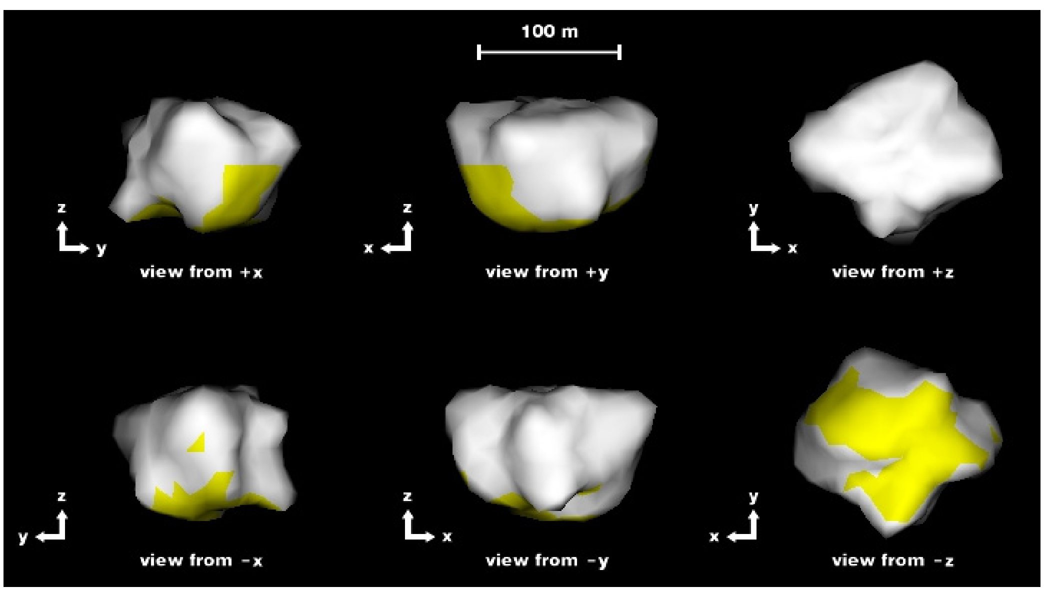
As remnants of accretion, building blocks of planets, space resources and potential impactors, the asteroids offer insights to solar system formation and evolution. Recent results show that this population is extremely diverse, compositionally, texturally and structurally. As a result, spacecraft cannot explore the population of asteroids in a reasonable time or at a reasonable cost without guidance from Earth-based reconnaissance. Compositional variation can be studied using remote-sensing spectroscopic techniques, either ground-based or from general-purpose space-based telescopes such as HST and JWST. Study of the textural and structural properties of asteroids requires imaging and shape determination. In addition, the largest uncertainties in orbit determination arise from non-gravitational forces, such as the Yarkovsky effect, that depend on the detailed shapes of asteroids. This shape determination can be done crudely using visible lightcurves and in detail using direct imaging (generally using adaptive optics), interferometric and radar techniques. Of these, only ground-based radar using the Arecibo and Goldstone radar systems has been routinely used for asteroid imaging, typically yielding shapes with tens to hundreds of pixels across a diameter and an absolute size accuracy of 5% or better. Other groundbased techniques are unlikely to achieve this level of precision in the upcoming decade, and space-based techniques will visit no more than a few targets.

1 Scientific questions

1.1 Orbit Determination and Delivery Processes

The asteroids are believed to be collisionally evolved remnants of the protoplanets that formed the Solar system. Some have been heavily altered thermally and chemically, while others remain relatively pristine. These differences are reflected in the compositions and textures of meteorites, which fall to Earth from (usually) unknown sources, and (usually) are derived from asteroids. Interpretation of meteorite data depends on our understanding of the processes that deliver them to Earth and the sampling biases introduced by those delivery processes.

The primary delivery processes for asteroids and meteorites are the orbital evolution of the asteroids, driven by gravitational and radiation forces and impacts, and the collisional evolution of asteroids as they impact one another. Orbital evolution can be further separated into gravitational and non-gravitational effects. Gravitational forces are largely independent of an asteroid's chemical and physical properties and, with modern computing capabilities, can generally be modeled as well as needed. Non-gravitational forces however, depend on the detailed physical properties of the bodies in question: for example, the magnitude and even sign of the YORP effect depend on asymmetries in the shape of the object [e.g. Taylor et al. 2008, Scheeres et al. 2008]. These effects are large enough that if they are ignored the orbits of asteroids can be followed for only a few thousand years with any degree of accuracy [Giorgini et al. 2002]. Uncertainties in non-gravitational forces dominate the uncertainties in predicting the impact probability of the asteroid 99942 Apophis [Giorgini et al. 2008].



The shape of asteroid 50549 YORP, showing the surface irregularities leading to spinup due to the YORP effect.

Thus, the details of individual object shapes are important for predicting their detailed orbits; and uncertainties in the variety of shapes of objects limits our understanding of the evolution of the population.

1.2 Collisional and textural evolution

The delivery of meteorites from NEOs depends in detail on the material properties of the surface from which they are liberated (either by impact or by spinup). The potential for and methods of resource exploitation and hazard mitigation also depend on surface texture and physical state. In addition, the processes involved are the same ones responsible for accretion during solar system formation.

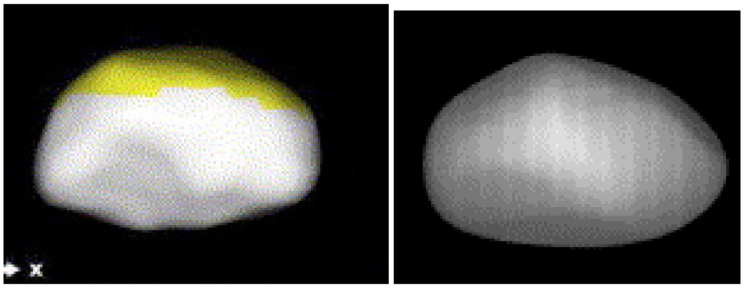
The outcomes of collisions determine the physical state of the surface and interior, and are not easily studied under terrestrial conditions due to the presence of Earth's gravity. Meteorites are derived from the asteroids, so the degree of processing as an asteroid greatly affects the interpretation of meteoritic data, our primary source of information on the chemistry of the solar system. The asteroids represent a laboratory for studying these phenomena.

2 Required research and Equipment

The study of the population of asteroids for understanding accretion, meteorite delivery, and the impact hazard requires the imaging of a wide variety of objects over the gamut of sizes that are involved in those processes. Asteroid physical properties change with object size, for example spin rate and strength against collisional disruption (Pravec and Harris 2007, Holsapple 2007). In some cases, the smallest objects dominate the problem: the most frequent meteorite falls necessarily derive from the smallest objects that can produce meteorites, because of the vastly larger number of objects at the smaller sizes. However, only the larger objects are likely to be imaged by spacecraft in the next decade and beyond. We must be able to understand how to extend the properties of objects at different sizes to both larger and smaller ones to understand the population as a whole. Direct optical imaging of a 1-km object 0.02 AU from the Earth at, for example, 10-m spatial resolution, requires an optical resolution of 10m/ (.02 × 150,000,000,000m) = 3 nanoradians or 0.6 milliarcseconds, requiring a diffraction-limited aperture (or interferometry baseline) of 300m. Adaptive-optics direct imaging of asteroid 2002 NY40 was modestly successful when it was 0.005 AU from Earth (Roberts et al. 2007). However, the challenges of using adaptive optics on very fast-moving NEAs during a close approach to Earth remain substantial. Opportunities of very close approaches are rare, and the target must be very bright for current systems, though this is a promising technique for the future.

2.1 Lightcurve inversion

The impossibility of using a lightcurve to derive a unique asteroid shape has been recognized for over 100 years [Russell, 1906]. However, if no concavities are allowed on the surface, the lightcurve can be inverted to derive a shape for an object with uniform albedo [Kaasalainen et al. 2002]. The resulting "gift-wrapped" shape is a useful approximation for many purposes. Radar observations show that concavities do in fact exist on most asteroids, and may become more prevalent as the object gets smaller and more irregular. Shape models for asteroid 1580 Betulia from both lightcurve and radar models illustrate the similarities and differences (Kaasalainen et al. 2004 and Magri et al. 2007).



The shape of 1580 Betulia from Arecibo radar (left) and lightcurve (right) modeling. The results generally agree, but the lightcurve-only model explicitly excludes concavities (such as craters). It is possible to include both types of data in a model.

The remaining techniques available for this task are spacecraft reconnaissance and radar imaging. These two techniques are complementary, and should be used together to explore the population. They need to be combined with other remote sensing techniques to put the studies in context.

2.2 Spacecraft Imaging

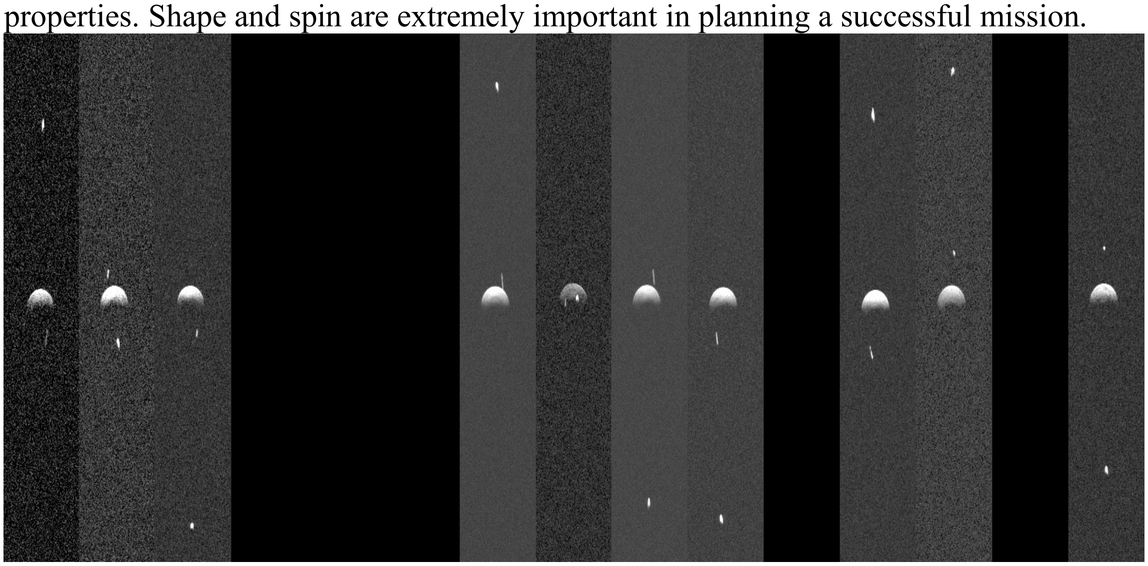
With the success of the NEAR and Hayabusa spacecraft missions, it is clear that Discovery-class missions can produce spectacular asteroid images. Imaging is not the only motivation to visit an asteroid, and the Near-Earth Object Community white paper discusses this question in detail. Recently proposed missions could visit several near-Earth asteroids for moderate-resolution imaging. Spacecraft imaging produces the most detailed images and shapes, with cm-scale global resolution feasible for an orbiting spacecraft. A Discovery-class mission could visit several (3-4) asteroids over a mission life of 3-4 years, increasing the number of high-resolution spacecraft-derived shapes by two or three. A New Horizons-class sample-return mission would certainly obtain detailed imaging of the target, and may be able to obtain flyby images of 1-2 other targets, but spacecraft safety concerns for the sample-return science would likely require more conservative imaging of the flyby targets than would a dedicated imaging mission. A further decision whether to maximize the number of targets or the maximum variety of targets would have to be made, as the number of targets depends on the delta-V between them, and the more requirements placed on the targets, the fewer opportunities are available.

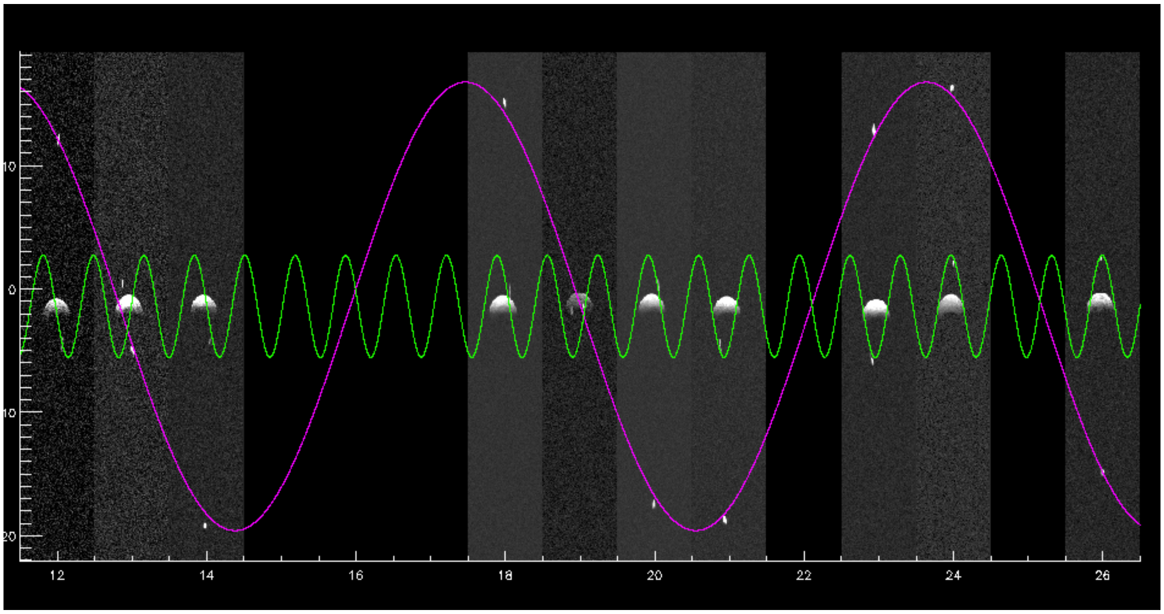
2.3 Ground-Based Radar Imaging

Ground-based radar provides routine imaging (and simultaneously, astrometry) at 10-m scales for targets within about 0.06 AU of the Earth using the Arecibo Planetary Radar system, a part of the National Astronomy and Ionosphere Center in Arecibo, Puerto Rico, and about 0.03 AU using the Goldstone Radar, a part of the Goldstone Deep Space

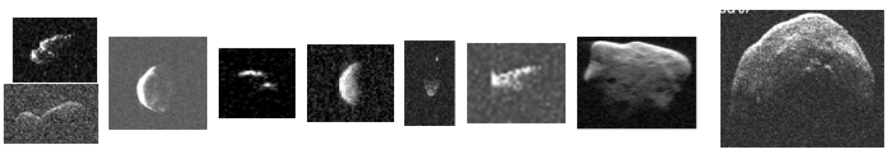
Communications Complex located in the Mojave desert in California. Arecibo is approximately 20 times as sensitive as Goldstone and is capable of imaging ~50 near-Earth objects per year at sizes spanning meters to kilometers, and 1-2 main-belt asteroids per year at ~100-m resolution, though financial limitations reduce the number by about a factor of 2 in practice. Planned funding cuts may reduce that by a further factor of about 3 if Arecibo Observatory's budget is reduced as scheduled in FY2011 [Blandford et al., 2006], which would require closure of that facility for radar observations. Goldstone has less flexibility in scheduling science targets due to extreme competition with that antenna's first priority, spacecraft communications. The combined cost of obtaining 10-m resolution images of 50 objects in one year at Arecibo and Goldstone is less than 0.4% of the cost of a single Discovery-class mission. Advance knowledge of the shape and existence of satellites (present in 1/6 of NEOs larger than 200 m), clearly contribute

tremendously to mission planning and safety, as well as improved target selection to achieve specific science goals. The diversity of NEAs is so large that choosing a target solely on the basis of orbit accessibility leaves a lot to chance. While it is true in our current state of ignorance that *any* object visited will be of great scientific interest, the third and fourth mission targets must be chosen more carefully in order to be representative, and to be complementary to the previous ones. NEAs are being discovered at a far faster rate than they can be characterized for their physical and chemical properties. Shape and spin are extremely important in planning a successful mission.





Arecibo radar images of triple-asteroid system 2001 SN263. Each vertical strip is the sum of data from one day in February 2008. Two satellites are visible orbiting in 147 and 16 hours (respectively). Below is the same mosaic with the orbits overlain.



Mosaic of Arecibo radar images of nine different near-Earth asteroids showing the diversity of the population.

3 Summary

Our understanding of the accretion of the Solar System, delivery of meteorites, and the impact hazard can best be improved by understanding the ***population*** of asteroids, which requires that a large number of targets be observed. Achieving this large number at a manageable cost requires an emphasis on ground-based imaging of many objects combined with detailed spacecraft reconnaissance of a few representative targets selected from the population based on their properties as determined by Earth-based studies. For the upcoming decade, Earth-based imaging will be dominated by radar imaging at Arecibo if that facility is kept operating. If the ground-based observing program is carried out at the “Scout-class” level for the existing radar facilities, a sufficient number of targets can be imaged to characterize the population of targets and choose the best candidates for further spacecraft-based investigation. Radar imaging has known costs using mature facilities. Some (factor of 2-3 in sensitivity and resolution) improvements to the systems are possible following clear upgrade paths. Vey high resolution adaptive optics and interferometric techniques are promising and should be developed over the next decade. Because of the vastly larger number of objects that be observed using ground-based observations, new discoveries are likely and continue to be made (e.g. Nolan et al. 2008, other IAUCs). Spacecraft missions will be required to obtain detailed imaging of targets selected based on ground-based characterization. Future manned explorations programs require an understanding of the asteroid population only achievable with ground-based imaging. Radar imaging from Arecibo and Goldstone are currently the best way to study the population.

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