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Exploring Main Belt Asteroids

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Abstract. The asteroid belt is filled with fragments of disrupted protoplanets, of which only a few survive. It has been dynamically stirred and suffered substantial mass loss. Samples exist on the Earth as meteorites. Putting these pieces back together provides a window into an early chapter of solar system history, during and after its formation, capturing the earliest epoch of planet formation. Groundbased observations, laboratory analyses of meteorites, and theoretical studies, in addition to flyby and rendezvous missions are all required to progress in this area.

EXECUTIVE SUMMARY

The asteroid belt is a site of interrupted terrestrial planet formation and of complex collisional and dynamical activity. Our investigations of this region of the solar system can be reduced to three key questions:

A. What was the compositional gradient of the asteroid belt at the time of initial protoplanetary accretion?

   Addressing this question requires an understanding of the population and compositional structure of the main asteroid belt today, how surface modification processes affect our ability to determine this structure, how dynamics and collisions modify this structure over time, as well as the physical properties of asteroids.

B. What fragments originated from the same primordial parent bodies, and what was the original distribution of those parent bodies?

   This requires an understanding of what asteroid fragments are associated dynamically, and what objects are geochemically linked (suggesting a common origin).

C. What are the early steps in planet formation and evolution?

   This problem requires knowledge of the compositions and structures of the surviving protoplanets. The cratering records on their ancient surfaces combined with the cratering record of younger surfaces provide insights into the primordial size distribution of objects in the asteroid belt. In addition, available hand samples - meteorites - provide detailed information about the formation and evolution processes of their parent bodies, though we need to improve our understanding of the extent to which meteorites sample the asteroid belt.

These questions cannot be addressed by a single spacecraft mission. Asteroids are characterized by their diversity. Consequently, the most important priority for the next decade is healthy funding support for NASA Research and Analysis programs supporting groundbased observations, meteorite studies, and theory programs. In particular, there should be support for studies using modest aperture telescopes. Asteroid missions addressing the key science questions cannot be planned nor provide a maximum return without a credible and continuing investment in earthbased remote observation programs, meteorite studies, and theory programs. These programs have suffered at NASA in recent years as funding has shrunk, particularly for physical studies of main belt asteroids.

Our recommendations for more expensive facilities/missions include the Large Synoptic Survey Telescope (designed and operated in a manner allowing for the detection of all small mainbelt asteroids), a rendezvous mission to Vesta or Vesta and Ceres, and a Solar System Infrared Survey mission (to survey all mainbelt asteroids having diameters > 1 km). In parallel, a modest technology development program should be supported to investigate the potential for large number of multiple asteroid flybys using microsatellites and possible advanced propulsion systems such as solar sails that would allow for multiple flybys per spacecraft.

REPORT

1. Perspective

Planet formation in our solar system followed a variety of paths, leading in most cases to finished planets: rocky bodies in the inner solar system, gas giants in the middle region, and icy planets in the outer solar system. However, the planet-forming process was interrupted in two regions - the Kuiper Belt (with the exception of Pluto) and the asteroid belt - leaving a vast population of small bodies instead of a single planet or planets. Accretion formed numerous protoplanets in the region between Mars and Jupiter, certainly Ceres-sized bodies formed, and perhaps even Mars-sized bodies. These large bodies would have gravitationally perturbed the local population, increasing collision speeds, and terminating the planetary formation process. Fragmentation and disruption commenced. Jupiter was also forming, accreting (in addition to rocky material) great amounts of ices and gases that were unable to condense in the warmer region of the inner solar system. Jupiter's large mass and orbital location created strong resonances in the asteroid belt that quickly removed any body unlucky enough to move into those resonances. This depletion mechanism removed most of the primordial mass in the asteroid belt and finally cut off the material needed there for further planetary growth.

Today, main belt asteroids (Figure 1) consist of a few unshattered protoplanets (e.g., Ceres, Pallas, Vesta) and the remains of smaller, disrupted primordial bodies whose pieces were shattered and dispersed, then further shattered and dispersed leaving the hundreds of thousands of fragments that dominate the main asteroid belt today (e.g., Gaspra, Ida) as well as feed into the Near-Earth asteroid population (e.g., Eros). While the boundary between the two populations may have some fuzziness (containing perhaps small shattered protoplanets that were not dispersed), the smaller of these fragments (d<50km) tend to be relatively homogeneous, while the surviving protoplanets are more complex (e.g., preserving basaltic eruptions on Vesta and the geological context of ancient water mobilization on Ceres).

The pot has been stirred dynamically and collisionally over the age of the solar system, yet it retains evidence of initial conditions and planet formation

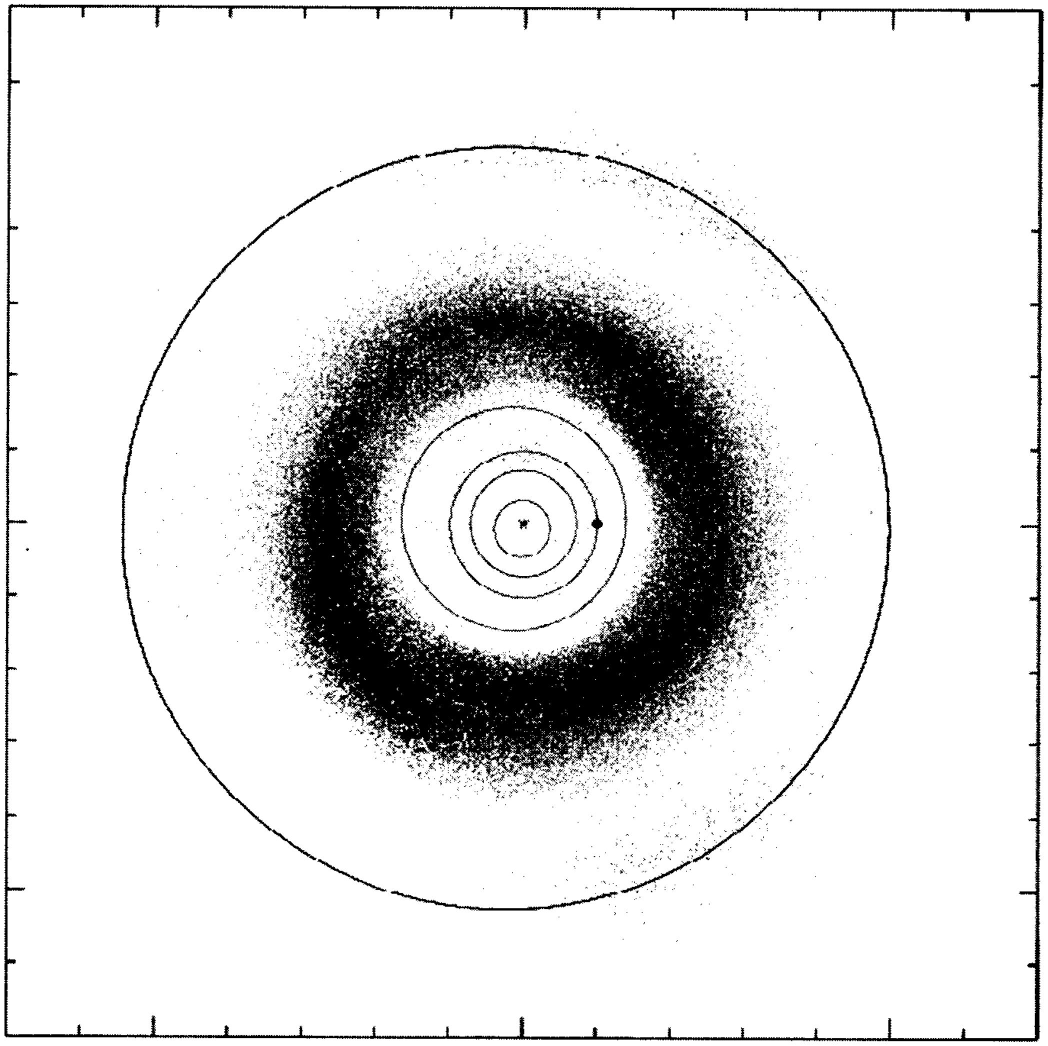

Figure 1. Instantaneous positions of more than 125,000 known asteroids are shown. The orbits of Mercury, Venus, Earth, Mars, and Jupiter are shown for scale. The main asteroid belt resides between Mars and Jupiter. Asteroids are gravitationally perturbed into orbits interior to Mars and the Trojan clouds are observed at the Jovian Lagrange points.

and evolution. Some asteroids have shifted into Earth-crossing orbits, causing concerns about the hazard of impact and interest in their potential as resources for human activity in space. The primordial outer main belt may have been the source of Earth's water (Morbidelli et al. 2000), thus critical to the existence of life on Earth. Destructive asteroid collisions have also been a source of interplanetary dust, generating much of our zodiacal cloud. The detection of non-primordial dust disks around other stars suggests that asteroids and the collisional processes we observe in our solar system occurs elsewhere in the universe.

2. Key Science Questions

There is a hierarchy of questions that motivate almost all of asteroid science which are rooted in our knowledge of the present. In earlier decades asteroid science focused primarily on the gathering of basic data from which derives our modern understanding of the processes operating in the asteroid belt at present and in the past. This is a never-ending process. Our continuously expanding capabilities to gather a wider range of more detailed data over a larger number of objects allows for more sophisticated, detailed, and overarching models, as well as more challenges to them. Asteroid science is dynamic.

On the basis of what we know today, the asteroid belt is a site of interrupted terrestrial planet formation and complex collisional and dynamical activity. There are three fundamental questions that we consider to be key. They are listed below along with the next level of questions that derive from them:

A. What was the compositional gradient of the asteroid belt at the time of initial protoplanetary accretion?

- What is the population and compositional structure of the main asteroid belt today?
- How do surface modification processes affect our ability to determine this structure?
- How do dynamics and collisions modify this structure over time?
- What are the physical properties of asteroids?

B. What fragments originated from the same primordial parent bodies, and what was the original distribution of those parent bodies?

- What asteroid fragments are associated dynamically, suggesting a common origin?
- What objects are geochemically linked?

C. What are the early steps in planet formation and evolution?

- What are the compositions and structures of surviving protoplanets?
- What does their cratering record combined with the cratering record of younger surfaces reveal about the primordial size distribution of objects in the asteroid belt?
- What do meteorites tell us about formation and evolution processes of these bodies? How well do they sample the asteroid belt?

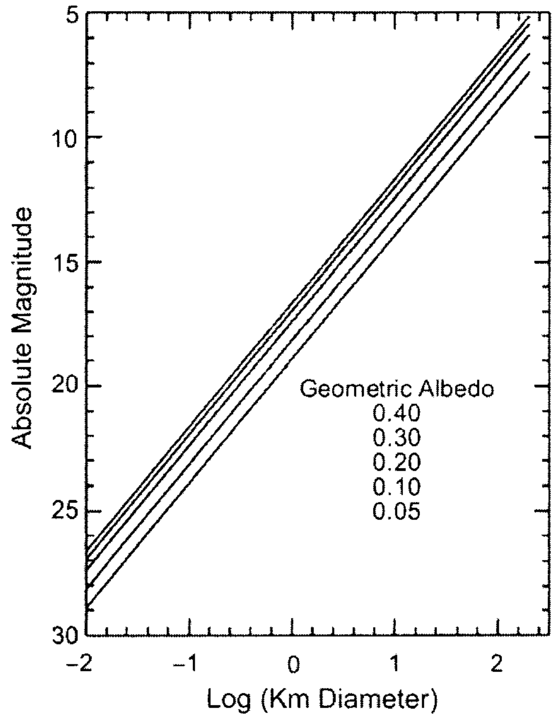

Figure 2. Relating absolute magnitude to diameter and geometric albedo.

2.1. How Can the Science Questions be Addressed?

Discovering Asteroids Basic to main belt asteroid studies is the ongoing discovery of more and more asteroids. The discrete material in the main asteroid belt extends from objects many hundreds of kilometers in radius down to the size of dust particles. Mass is continuously being redistributed from larger to smaller sizes through collisions, then ultimately lost via resonances or radiation forces. Because of their much greater numbers, smaller asteroids provide better tracers of dynamical and collisional processes. Smaller asteroids also differ in their distribution of compositions compared to large asteroids (e.g., Tedesco et al. 1989). In general, asteroids of all sizes are characterized as much by their compositional and physical diversity as their similarities, addressing our key science questions requires the study of objects from the largest (surviving protoplanets) to fragmented rubble piles to objects small enough to have retained physical coherence (tens to possibly hundreds of meters - Pravec and Harris 2000).

Current programs designed to discover Near-Earth objects (e.g., LINEAR) are discovering many main belt asteroids in the process (more than 100 times more). Such programs covering large areas of sky trade off sensitivity (V 19.5) for area. This significantly limits the population of small main belt asteroids that can be discovered. The brightness of an asteroid is a function of its size and albedo (Figure 2).

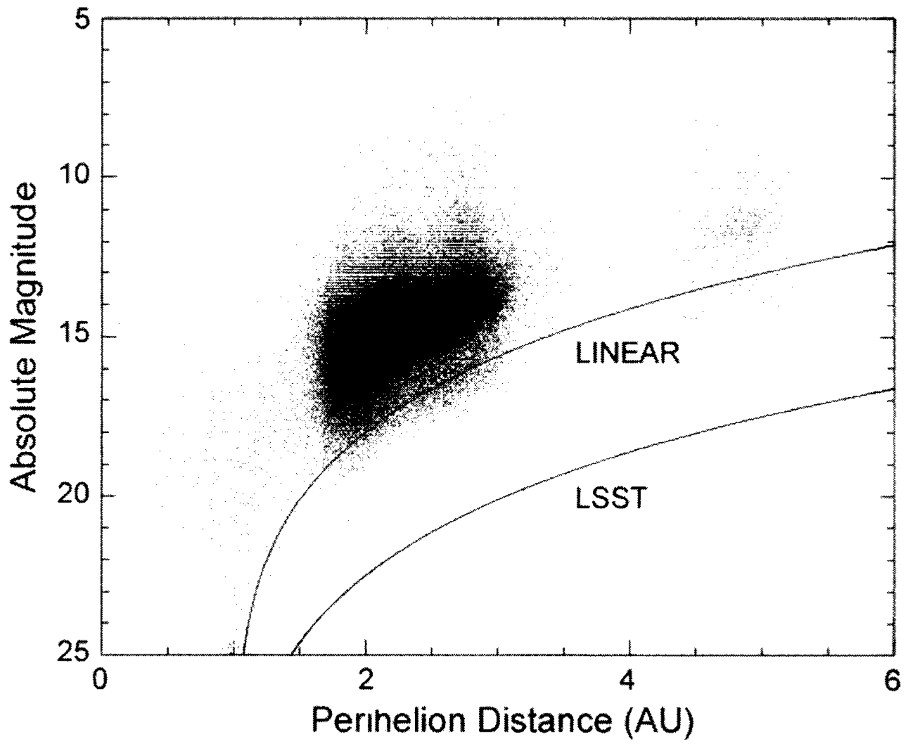

Figure 3. The sensitivity of LINEAR and LSST for discovering asteroids.

The proposed Large Synoptic Survey Telescope (LSST) covers the entire available sky to V=24 in one week. The sensitivity of an LSST survey is compared to LINEAR in Figure 3. The smallest asteroids are most likely to be discovered when they are brightest - at perihelion - as demonstrated in the plot. Most main belt asteroids for which there are orbits were discovered by LINEAR. Through the main belt, LSST would be far more sensitive than LINEAR, detecting asteroids having diameters between 125 and 250 meters. In the Trojan population, asteroids having diameters of 2 km would be detected.

Albedos and Diameters (Addressing A and B) Diameter is a fundamental physical characteristic of all asteroids. Albedo is indicative of bulk composition (e.g., dark carbonaceous, or bright and rocky). Together they determine the absolute magnitude of an asteroid (Figure 2). They are traditionally obtained through occultation studies and radiometric observations, as well as via polarimetry. Occultations require accurate predictions of when the line of sight to a background star is intercepted by an asteroid. These observations are useful because they are the most accurate measure of a specific dimension along the occultation path and they offer an opportunity to acquire the projected shape of an asteroid normal to the line of sight if a number of appropriately separated chords can be obtained. These are target of opportunity measurements. Once a diameter

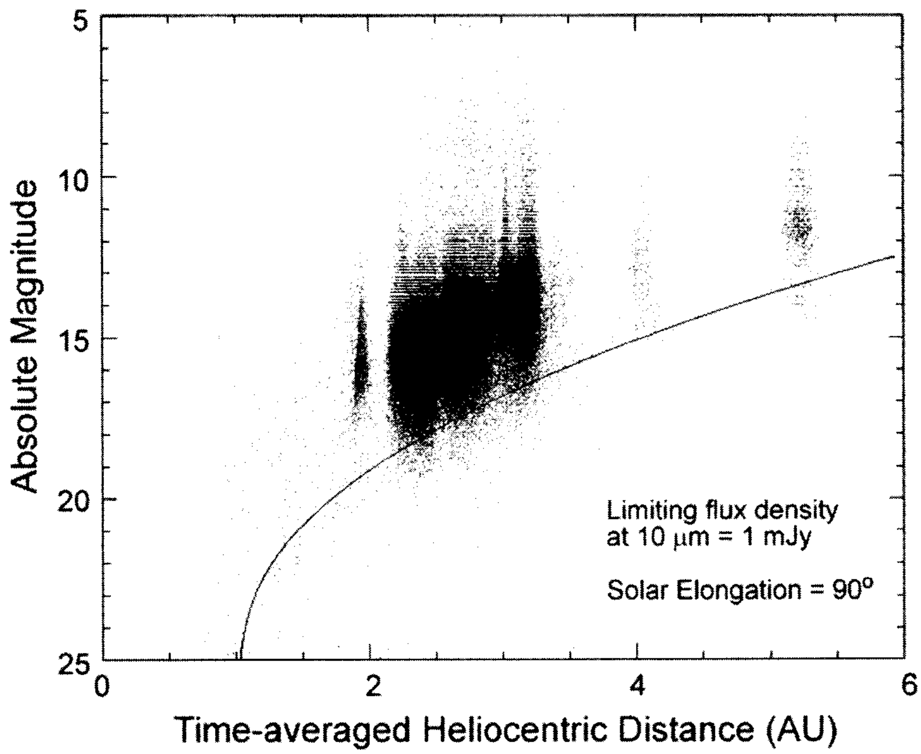

Figure 4. Detecting main belt asteroids at 10 μm using a polar orbiting space-based system at a limit of 1 mJy.

is obtained, geometric albedo can also be determined from the absolute magnitude of the asteroid. Polarimetric studies require a number of observations spread over different phase angles in order to determine albedo from the polarization phase curve and then diameter (as above) (e.g., Dollfus and Zellner, 1979). Radiometry combined with visual magnitude provide perhaps the most efficient means of determining albedo and diameter for an asteroid, requiring only a single observation of the former and knowledge of the latter at that time (e.g., Lebofsky and Spencer 1989). The difficulty of making such observations from the ground is that one must remove the significant contribution to the thermal flux of the atmosphere and telescope itself. Making such observations from space allows all such sources to be removed. The Infrared Astronomical Satellite made the largest number of asteroid radiometric observations in 1983, providing diameters and albedos for 1884 of 7309 numbered or multi-apparition asteroids (Tedesco et al. 1992). Today the number of available asteroid orbits has increased by more than an order of magnitude and the increased sensitivity of thermal detectors make most of these detectable. A thermal detector with SIRTF-like sensitivity (1 mJy at 10 μm) in an IRAS-like polar orbit and scanning the celestial sphere with a 0.5 degree FOV at a constant solar elongation of 90 degrees as the Earth orbits the Sun, would after one year would have scanned 96% of main belt asteroids and detect almost all asteroids for whom orbits have

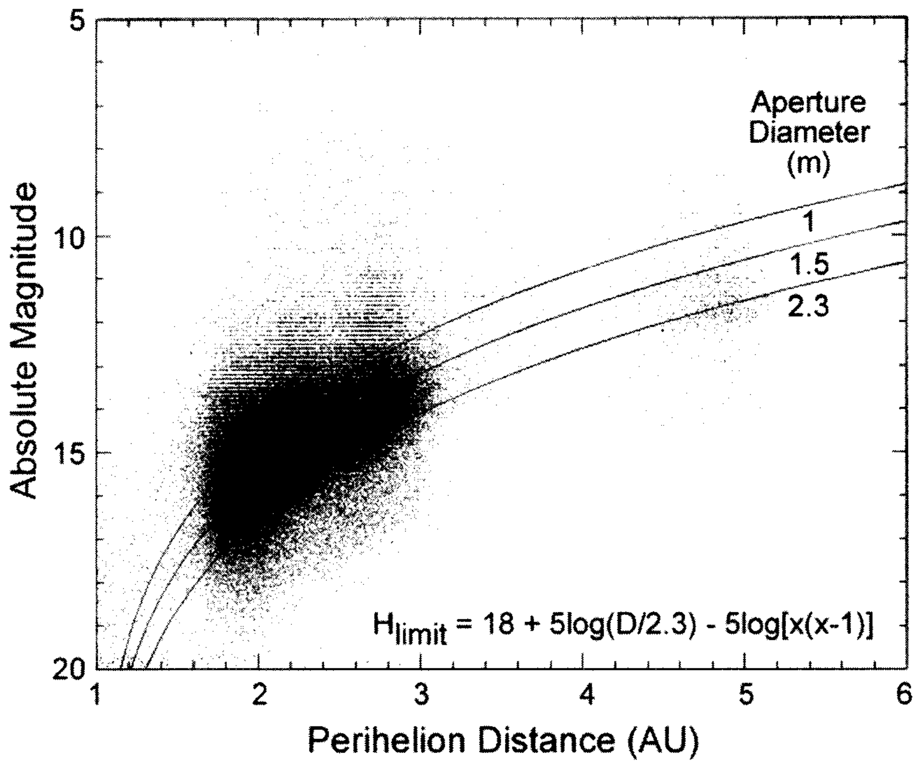

Figure 5. An assessment of modest aperture telescopes for doing lightcurve and CCD spectral studies of asteroids at opposition. For lightcurve studies, SNR=50 in ten minutes is required, for spectral studies, SNR=20 in one hour is required.

been determined (Figure 4), increasing the IRAS database by more than an order of magnitude and providing virtually complete coverage down to km diameters throughout the main asteroid belt and down to around 15 km in the Trojan population. If a visible wavelength channel were added to a spacebased thermal system, relative motions compared to the scan pattern would allow for simultaneous, if partial, thermal and visible lightcurve studies from which would be derivable other physical properties such as thermal inertia. Another byproduct might be detection of debris trails associated with asteroids, which would be directly related to modern collisional activity and dust production from crater ejecta.

Lightcurves (Addressing A and B) Asteroid lightcurves give insight into collision processes by providing information on shape and rotation state. As a consequence of apparent motions, lightcurves for asteroids must be obtained one at a time. The rate at which such information can be acquired is self-limiting. There are relatively few large-aperture and spacebased facilities that may provide the highest signal-to-noise data or data on the faintest objects -

and there is fierce competition for those resources. Acquiring lightcurves for large numbers of objects in a reasonable period of time requires the devotion of a number of facilities operating in parallel. As with asteroids, the smaller the telescope the greater their number.

Even modest aperture telescopes are capable of doing lightcurve studies of tens of thousands of asteroids (Figure 5). This suggests an opportunity for small institutions to engage in such studies, perhaps leveraging basic science education opportunities for students while contributing to very basic knowledge about asteroids.

Asteroids having a diameter greater than 0.5 km are seen to have rotation periods greater than two hours (Pravec and Harris 2000), hence a ten-minute sampling frequency should provide sufficient points to get a baseline lightcurve. However, several small asteroids tens of meters in diameter have been discovered having periods ~10 minutes. In these cases, their intrinsic faintness exclude their observation in the main asteroid belt even by existing large aperture facilities, requiring their study in the closer Near-Earth asteroid population by those facilities.

Spectroscopy and Colorimetry (Addressing A and B) At present, our ability to reconstruct the compositional gradient of the primordial asteroid belt is limited. We have only the coarsest models of the compositional structure of the main asteroid belt today. The 2000 or so asteroid spectra that exist in the literature in 2001 are very inhomogeneous in orbital element space, tending to focus on specific regions. There is significant compositional diversity in the asteroid belt, ranging from primitive carbonaceous objects dominating the outer belt and Trojans to basaltic and metallic fragments in the inner region of the main belt. The "dew" line across which water becomes stable transects the outer main belt (around 3 AU). The composition of all these fragments suggest a significant primordial gradient, an early heating event affecting some but not all asteroids, processes involving differentiation and volcanism, processes involving water mobilization, and significant dynamical processes. For the richness of the key science to be addressed in the main asteroid belt, we are extremely data poor.

As with lightcurves, asteroid spectra must be obtained one at a time. The largest apertures may be utilized to obtained spectral information on a relatively small number of fainter objects of interest, but as with lightcurve studies, modest aperture telescopes are shown in Figure 5, to be capable of acquiring data on tens of thousands of asteroids.

Broadband filter observations allow for more colorimetry obtained much more quickly than CCD spectra - spectral resolution and degraded compositional information is sacrificed for greater signal to noise. However, such information can play a useful role in that it allows for large numbers of asteroid colors to be obtained in a survey, such as the Sloan Digital Sky Survey and (in the near-infrared) the Two-Micron All Sky Survey. This allows for a coarse but relatively unbiased sampling of the compositional structure of the asteroid belt to the magnitude limits of the given survey. Unfortunately, existing such surveys have filters selected for addressing astrophysical issues and are not optimized for asteroidal research, thereby limiting their potential usefulness. Furthermore, lightcurve variations as mentioned above can potentially complicate the trans-

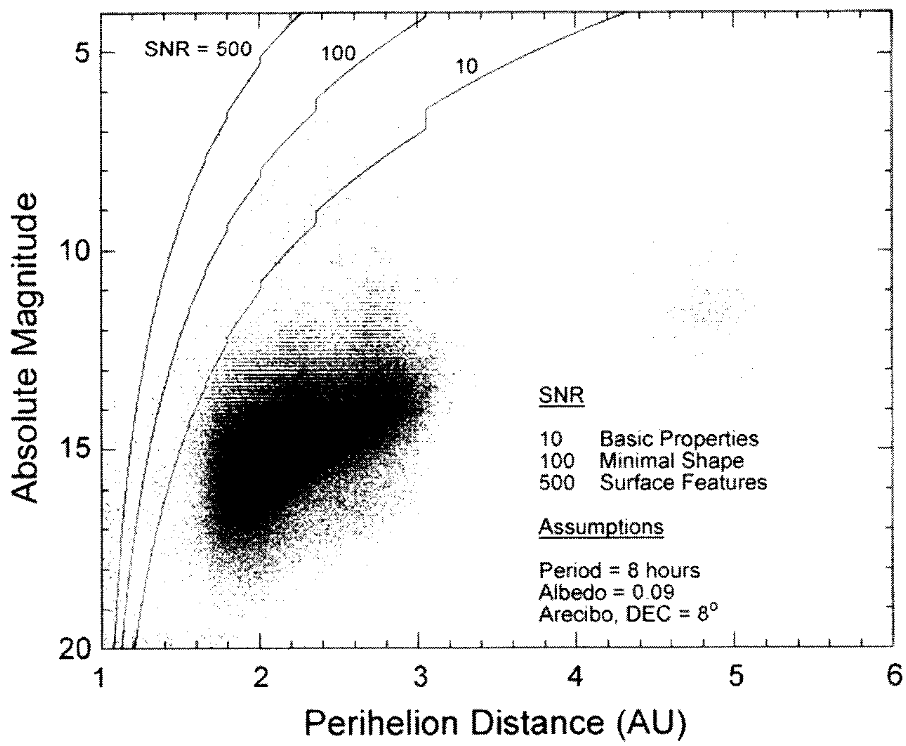

Figure 6. Radar preferentially detects nearby and large asteroids, just sampling the main asteroid belt.

formation of serendipitous but nonsimultaneous color data to taxonomic types. Nevertheless, the use of colorimetry in classifying asteroids is a long-established practice, and the major asteroid classes separate relatively well in both UBV and JHK color diagrams (Zellner et al. 1975, Bowell et al. 1978, Hahn and Lagerkvist 1986).

Relating observations to compositions requires an understanding of how spectra relate to specific mineralogies and how surface scattering properties effect that relationship. In addition, the effects of surface impacts and space weathering over time must be understood. This requires laboratory studies of meteorites and terrestrial analogs of other interplanetary materials.

Radar Studies (Addressing A and B) Radar can provide information on surface properties, reflectivity, surface roughness, spin state, and morphology. It can help to distinguish between degenerate spectral M type asteroids, some of which are metallic and others composed of some hydrated, possibly carbonaceous material.

The recent upgrades at Arecibo allow for the use of this technique to improve our knowledge of main belt asteroids. Figure 6 shows that radar can probe the larger asteroids of the main belt and Figure 7 shows that these targets are

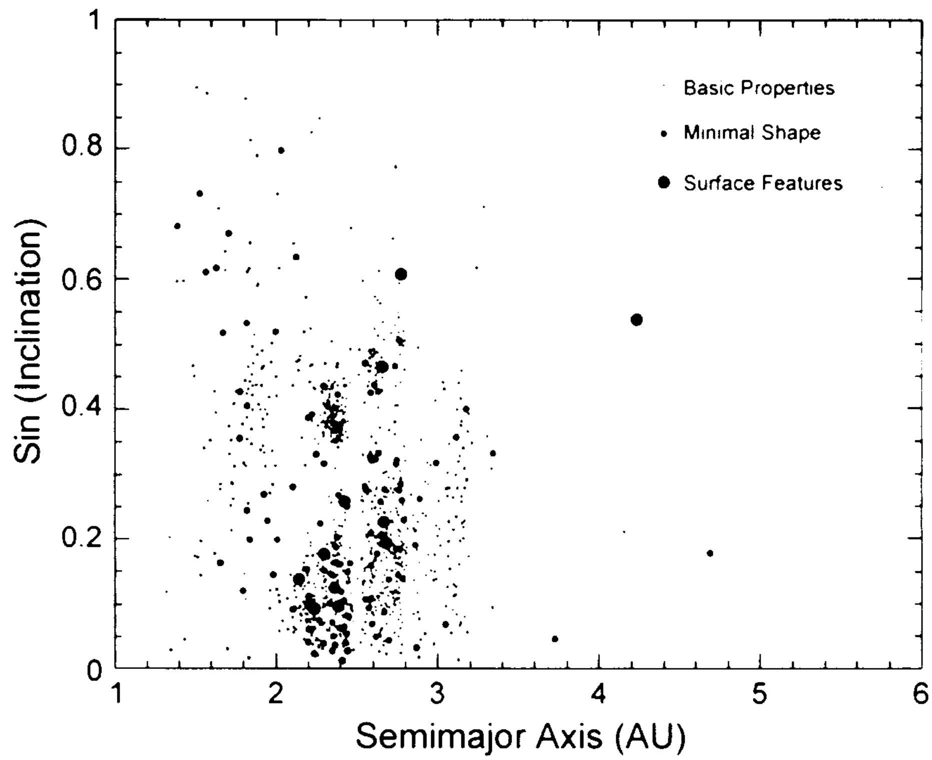

Figure 7. Radar is able to detect asteroids in all dynamical regions of the main belt.

distributed throughout the major regions of the main belt, though not as far as the Trojans.

Dynamical Studies (Addressing A and B) Even given detailed information on the modern compositional structure of the asteroid belt, inferring its primordial structure requires an understanding of the various dynamical processes acting on asteroid orbits, such as gravitational perturbations, chaotic scattering, Yarkovsky effects, collisions, etc. It also requires an understanding of collision mechanics and the preferential erosion of some compositions with their associated physical properties from the modern population of objects.

Such studies also serve to identify asteroids having discernable dynamical relationships (families), targeting them for followup physical and spectral studies to determine whether a common origin makes cosmochemical sense.

Sometimes the identification of asteroids that seem to be spectrally related, such as the Vestoids which lead from Vesta to resonance regions allowing for transport of such material into Earth-crossing orbits and explaining the HED meteorites, calls for more dynamical studies to understand how in detail this actually occurred and if that interpretation of apparent transport is correct.

High Resolution Observations (Addressing A, B, and C) Adaptive optics (AO) and speckle interferometry are now able to discover binary asteroid systems and directly measure asteroid sizes and shapes (at least for the large end of the size distribution. This allows for the determination of mass (from the binary orbit) and density (from the size and shape information combined with mass).

Collision Mechanics (Addressing A and B) Understanding how collisions affect the internal structure and physical properties of asteroids over time requires sustained support for experimental and theoretical work. Challenges for the near future include:

- A better understanding of the response of low-density, high-porosity objects to cratering and catastrophic impacts. NEAR/Shoemaker images of several extremely large craters on 253 Mathilde and the existence of asteroid satellites predominantly around primitive asteroids (i.e., dark taxonomic types like C, D, etc.) indicate the importance of understanding the response of such bodies to collisions. We believe laboratory experiments and hydrocode modeling involving impacts into low-density, high-porosity targets should be given high priority in this area.

- A merger of collisional and dynamical models allowing simultaneous treatment of both mechanisms on asteroid populations. To understand the cratering history of individual objects (e.g., Eros) as well as the collisional evolution of the main belt population, we need to create increasingly sophisticated models that include physical mechanisms like collisions, Poynting-Robertson drag, Yarkovsky thermal drag, resonances, and other related phenomena.

- A link between accretional, dynamical, and collision models in order to produce a seamless, self-consistent model of main belt evolution. The current main belt is but a tiny remnant of the primordial main belt, which may have contained several Earth masses of material and possibly multiple Vesta-like bodies. The sudden disappearance of these bodies, the existence of unusual meteorites like pallesites and mesosiderites, and the overall orbital structure of the main belt are all intimately tied to collisional and dynamical events which took place in the first few tens of Myr of solar system history. Until we understand this epoch better, we will be unable to set the context for interpreting modern-day asteroids.

Meteorite Studies (Addressing A, B, and C) Samples of asteroids are present on the Earth in the form of (the non-lunar/non-Martian) meteorites. Both the absolute number of meteorites and the number of different types of meteorites have grown in recent years as meteorite concentration areas like Antarctic glaciers and deflation surfaces in deserts have been systematically searched by groups like ANSMET. Through study of meteorites, knowledge of asteroidal properties such as compositions, density/porosity, and thermal and aqueous alteration histories can be either directly measured or inferred in a straightforward manner. However, the only current way of linking specific asteroids or asteroid classes with specific meteorites or meteorite classes is through the interpretation and comparison of meteorite and asteroid spectral properties.

Leveraging composition from spectra may be limited when the bulk composition of an asteroid are not optically active minerals or their spectra is masked (e.g., by low-albedo carbonaceous material). Furthermore, regolith processes may change asteroid spectra so that it no longer has a close resemblance to its best meteorite analog. Unfortunately, not all asteroid compositions are thought to be represented in meteorite collections due to biases introduced at every stage of meteorite delivery from impact and fragmentation to survival through the Earth's atmosphere to likelihood of being discovered on the ground. This situation might be improved with samples from dozens of targetted asteroids. which may be a goal beyond this next decade.

The association of specific asteroids or asteroid families with specific meteorite groups remains a high priority for asteroid spectroscopists. This will allow those asteroids to be analyzed as though they were the targets of a sample return, and allow a large store of meteoritical data to be applied directly to asteroidal problems. While great progress has been made in the last decade toward this goal (Gaffey and Gilbert 1998), new findings pertaining to temperature effects on mineral spectra and spectral maturity ("space weathering") effects need to be fully understood and considered.

The Role of Flyby Missions (Addressing A, B, and C) Flybys provide information on shape, density, compositional heterogeneity, and cratering records. Flybys of many members of a particular family would reveal cratering records that could be used to determine relative ages of family members, identifying multi-generational collisional fragmentation histories. Flybys can also help determine whether densities obtained are primordial or arise from collision processes. Similarly, flybys of protoplanetary survivors would reveal cratering records extending back to the earliest epoch of the solar system. Unfortunately, such observations are primarily target of opportunities for spacecraft having other principal targets (e.g., Jupiter for Galileo), and even in the rich target environment of the main belt even a spacecraft dedicated to asteroid flybys would make few observations per year. It is also a limited science return for the expense of the kinds of missions (e.g., Discovery class) that are being sent to or through the main belt, even considering the cost of a launch vehicle (>\$40M for Delta class launcher).

Technology innovation may increase the role for flyby missions by making them substantially cheaper. The "Cube-sat" program is currently building 1 kg satellites of dimension 10 cm^3 having a power of several Watts. The cost of such a satellite is approximately US\$50,000. Two are currently being built for launch: Ffize, which has 6 retroreflectors on board to be used for laser ranging and a test of the theory of relativity, and Rincon, a fully functional but miniaturized standard satellite, having solar cells, a power and battery charge regulator board, a microprocessor board, a transmitter board and a receiver board. They are to be launched from a Russian SS18 rocket in May of 2002.

These Cube-sats are designed and built by teams of faculty mentors and students under the University of Arizona student satellite program. The next generation satellites will study the effects of radiation on electronic components (supported by Alcatel), the development of micro-reaction wheels (supported by Honeywell), a low power 1Kx1K CMOS camera, a small CCD spectrometer with a mass of about 150g a spectral range from 200-1000 nm and a resolution of about 1nm, and a more powerful microprocessor capable of handling and processing spectra and images (all University of Arizona student developments). They are also looking into a joint industry development of ion engine propulsion to be coupled to the small satellites.

Another program being explored is ANTS (Autonomous Nan-Technology Spacecraft) at NASA Goddard Space Flight Center. These are 1 to 10 kg spacecraft utilizing solar sail propulsion to explore the asteroid belt. Most ANTS would contain single instruments and the idea is to launch hundreds to thousands of these to individual or numerous targets. When a large number target a single object, a smaller number would be manager/supervisors whose job would be to schedule/supervise small groups of ANTS taking observations. A few ANTS would analyse measurements and select targets.

It may be possible to launch a large number of such Cube-sats or ANTS containing simple instrument sets - perhaps a single imager - from a single vehicle and provide them with enough Δv capability to make a targeted swath through the main belt, obtaining basic information on at least as many asteroids as their are satellites launched. Many issues regarding data rates and operations have yet to be contemplated, but the possibilities are intriguing.

Rendezvous missions (Addressing B and C) Surviving protoplanets such as Ceres, Pallas, and Vesta are obvious targets for rendezvous missions. The utilization of solar electric propulsion technology allows for missions to any individually (e.g., Binzel and Clark 1999) or even a multiple rendezvous mission to Vesta and Ceres within a Discovery class cost envelope (Russell, private communication).

Only a rendezvous mission can provide detailed information on surface composition, morphology, surface structures, interior structure, magnetic fields, and core formation (or not) needed to probe the earliest stages of planetary formation.

Rendezvous missions to asteroidal fragments can provide important information about the primordial parent bodies and the processes they experienced prior to disruption, but in order to maximize the scientific return from such missions, target selection must be based on an understanding based on a large amount of groundbased data and theoretical studies.

Sample return missions (Addressing A, B, and C) Our principal source of asteroid samples are meteorites. However, meteorites are not thought to sample all regions of the main asteroid belt. They provide extremely detailed information about processes experienced by a particular portion of a single parent body over a range of time. A sample return from a single main belt object would not tell us anything about the asteroid belt as a whole. However, they might serve to provide important information regarding objects or classes of objects for which there are no meteorite samples and allow us to better make mineralogical interpretations from our spectroscopic data.

Multiple sample returns from family fragments showing spectral variations may provide important detailed geochemical information about the formation and internal evolution of the parent body prior to disruption. These might be accomplished to a more limited extent by multiple rendezvous to family fragments.

3. Maintaining Capabilities for the Future

The Key Scientific Questions for main belt asteroid studies are not going to be conclusively answered over the next decade. To ensure that the capacity to address these questions is maintained, strong and steady support for the underlying NASA Research and Analysis programs is required. These programs address these questions directly while creating the necessary bases for future asteroid missions.

4. Data Archive and Access Issues

Data associated with asteroid studies is archived by the NASA Planetary Data System. The data is peer reviewed as part of the ingestion process to ensure quality, consistency, and adequate documentation. To maximize usefulness of this data requires the creation of an interface that would allow researchers to find desired data. This might include a listing of all holdings regarding a particular object, or the identification of those objects meeting SQL criterion across all asteroid data sets.

While the PDS was designed to archive data sets from spacecraft missions, it has growing groundbased data holdings as well, particularly for small bodies. Challenges:

- All groundbased as well as spacebased asteroid data should be captured.
- Relevant laboratory data on meteorites should be captured
- All archive products should be available to remote query

5. Utilization Potential

The pursuit of basic science in the main asteroid belt may provide information that is useful to the utilization of asteroids in near-earth orbits to support future human space activity. For instance, the efficiency at which asteroids of given sizes from given (compositional) regions are removed from the main belt into near-earth orbits is useful as is the growth and physical properties of regolith of carbonaceous to metallic objects. See Jones et al. (this volume, pg. 141).

6. Advanced Technology

The continued improvement of solar panels and electric propulsion thrusters create the capability for multiple rendezvous and flyby missions that are not practical with chemical-based propulsion systems. For multiple flyby missions, solar sail technology may be ideal.

7. Education and Public Outreach

The advent of remote observational facilities coupled with the large numbers of asteroids, make asteroids a wonderful target for seasonally independent education. Programs could be designed in part to acquire data needed to address the key scientific questions - such as spectra and lightcurves. For instance, a student (high school or college) could acquire a spectrum or lightcurve on an asteroid (most might have been previously unobserved), and then fit a simple spectral model (2 or 3 component) to the spectrum, or triaxial ellipsoid to the lightcurve. By comparing the final result to the data, students could learn that science is an iterative process - and that there are no final answers, just better understanding.

8. Recommendations

Our top priority for the next decade is to ensure healthy funding support for NASA Research and Analysis programs supporting groundbased observations of asteroids, meteorite studies, and theory programs. In particular, there should be support for studies using modest aperture telescopes.

Asteroid missions addressing the key science questions cannot be planned nor provide a maximum return without a credible and continuing investment in earthbased remote observation programs, meteorite studies, and theory programs. These programs have suffered at NASA in recent years as funding has shrunk, particularly for physical studies of main belt asteroids. While programs to steadily increase our database of asteroid spectra and lightcurves may not garner headlines, they are critical to our ability to design cost effective missions that maximize the science returned for dollar spent. Success should be measured by the number and distribution (in orbital element space) of asteroids for which such observations are obtained and the rate at which it is obtained. This includes radar observations of main belt asteroids.

8.1. Discovery/Midex class and larger missions

- We endorse the Large Synoptic Survey Telescope provided it is designed and operated in a manner which allows for a determination of all main belt asteroids referred to in Figure 3 and that such a survey is supported. We note that this will place a large burden on the IAU Minor Planet Center (at Harvard) and that funding should be made available to MPC in the event that it processes LSST observations for orbits and links with prior observations.
- A rendezvous mission to Vesta or Vesta and Ceres.
- Solar System Infrared Survey - nominally, a polar orbiting, IRAS-like mission to determine albedos and diameters for all main belt asteroids having D>1 km. Must have non-thermal visible channel, may limit thermal channels to 10 and 20 μm (with a limiting flux density of 1 mJy), simplifying the experiment relative to IRAS. Broadband visible channels may allow for coarse taxonomic determination of the main belt.

8.2. Technology development - modest cost

Investigate the potential for large number of multiple asteroid flybys using microsatellites and possible advanced propulsion systems such as solar sails that would allow for multiple flybys per spacecraft.

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