NEAR-EARTH OBJECTS

Community White Paper to the Planetary Science Decadal Survey, 2013-2022

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Abstract
Because the NEO population is constantly evolving and being replenished from the main asteroid belt and cometary reservoirs, it consists of objects with a variety of compositions and internal structures. These objects present unique opportunities for future planetary science goals and exploration. In order to realize these opportunities for future NASA studies, an expanded program for NEO discovery and characterization should be undertaken, and NEO exploration and sample return spacecraft missions should be developed and implemented over the next decade (2013-2022), both for scientific and exploration considerations.

1 Subdiscipline Overview

1.1 Introduction.

Asteroids and comets with perihelion distances < 1.3 AU are referred to as near-Earth objects (NEOs). Because of encounters primarily with planets in the inner solar system, NEO orbits are fundamentally unstable with an average residence time less than ten million years. NEOs are constantly replenished from the main asteroid belt and cometary reservoirs, primarily as a consequence of gravitational resonances with Jupiter and Saturn. In turn, objects in these resonance source regions are replenished by collisional diffusion of orbits and the consequence of radiation forces (i.e., the Yarkovsky effect). There is compositional variation throughout the asteroid belt, with the inner region dominated by brighter silicate-rich objects and the outer region and Jupiter-family comets dominated by dark carbonaceous objects; however, there is substantial mixing across the belt. Because the NEO source regions span the main belt and Jupiter-family comets (though with widely variable efficiency), they are a diverse population.

1.2 Why study of NEOs is a compelling undertaking

NEOs are important for 4 main reasons:
First, as samples of main-belt asteroids and comets, NEOs provide clues to the nature of the early solar system. These objects are part of the surviving population of planetesimals from the very earliest stages of solar system formation. These bodies thus provide the primary constraints on the processes and conditions that were present during the formation epoch and can be used to test current models and theories describing the late solar nebula, the early solar system, and subsequent planetary accretion. From detailed knowledge of NEO compositions, probable starting materials and thermal histories of their asteroid and comet parent bodies can be inferred. Further, because meteorites and interplanetary dust particles (IDPs) represent the **primary** evidence for the environments and mechanisms of the formation of the Solar System, if specific meteorite and IDP groups can be compositionally associated with NEOs, and the NEOs tied to main-belt asteroids and comets, the interrelations between all these objects can be tested, providing a spatial context for the detailed laboratory studies of meteorites and IDPs.

Secondly, NEOs have the potential to significantly and adversely affect life on Earth. It is now generally accepted that a small (~10 km) extraterrestrial body hit the Earth causing the transition between the Cretaceous and Tertiary periods (K/T) and caused a massive extinction of the existing flora and fauna. NEOs will impact the Earth in the future. Therefore, NEOs have been the focus of ground-based surveys in recent years in order to discover, and to a lesser degree characterize, these bodies. Detailed investigations of these objects would therefore provide an extremely important scientific resource, as well as an invaluable data set on NEO physical characteristics (e.g., physical strength, density, etc.) that would be of vital importance in the development of possible mitigation strategies for any hazardous NEO. This continues to be a major NASA objective; indeed, the NASA Solar System Exploration Roadmap states: "*To understand the impact threat posed by asteroids and comets, as well as the feasibility of potential mitigation strategies, we must assess not only the number of potentially hazardous bodies and the frequency of both small and large impacts, but also the physical characteristics of the objects themselves.*" Mitigation strategies depend in detail on the physical state of the impactor. Density, degree of fragmentation and presence or absence of satellites are all critical information for planning any potential mitigation strategy.

Thirdly, the next step in the human exploration and exploitation of space will be highly dependent on extracting materials (primarily water and minerals) from in-situ sources. NEOs are our nearest neighbors in the solar system after the Moon, and are even nearer in ΔV. Thus, they are potentially the most cost-efficient sources for providing life support and propulsion and for building structures in space. It is highly probable that the success and viability of human expansion into space beyond low-Earth orbit will depend on the ability to exploit these potential NEO resources. Therefore, a detailed physical and compositional assessment of the population will be required during the next decade before human missions are sent to these objects.

Finally, NEOs are also important objects for the simple reason that they are some of the easiest objects to reach in the solar system, both by spacecraft and with ground-based characterization. These objects have relatively lowΔV (5 to 6 km/s) and are prime targets for possible future science and sample return missions. NASA's NEAR Shoemaker spacecraft to (433) Eros, JAXA's Hayabusa probe to (25143) Itokawa, and ESA's Rosetta mission to comet 67P/Churyumov-Gerasimenko are examples of the types of missions that can be sent to NEOs. For the next decade of planetary science research, we need to identify and characterize targets within the NEO population for future spacecraft missions, develop technologies required to interact with these objects, design robotic spacecraft to explore/sample NEOs, and explore the potential for manned exploration.

2 Top-Level Scientific Questions

While much progress has been made in recent years towards answering the following top-level science questions and their more specific sub-questions, our current understanding of these issues is far from complete. These areas demand further investigation through a well-balanced program combining ground-based and space-based NEO observations, targeted spacecraft missions, laboratory research, fireball detection to aid meteorite recoveries, and data analysis activities. These efforts should focus on addressing the following key questions:

A) What is the Compositional Distribution of NEOs?

Answering this question requires understanding and compensating for discovery selection effects, understanding how to relate remote observations with specific mineralogies and how surface mineralogies relate to bulk composition. It requires understanding the nature of "space weathering" on NEOs and how it varies with composition, presence of regolith, and object size. The answers provide insight into their geological diversity, the relationship between NEOs and collected meteorite and IDP samples (which in turn provide more detailed information about

NEO formation and evolution) and the existence and abundance of key resources on NEOs (i.e., water, minerals, metals, organic molecules, etc.).

B) What is the Range of NEO Physical Properties and How do they Evolve?

The important physical properties of NEOs include their size-frequency and spin-state distributions, which provide constraints on their collisional evolution and other processes affecting these distributions. Interior structure can be probed directly by using dedicated instruments on board spacecraft or potentially indirectly via a knowledge of spin states coupled with size and shape, which can provide insights into density, strength, and interior. Understanding evolution requires an understanding of impact processes, radiation processes (e.g., YORP) and their timescales. Recently, the view of most NEOs has undergone some major changes consistent with a) the now widely accepted rubble-pile model for their structure and b) the implications of spin state alteration (or more generally, angular momentum alteration) through YORP and similar effects. YORP-induced spin-up can lead to “landsliding” or redistribution of material to produce surface features. By observing these features, we can constrain the material properties of the rubble pile material such as coefficients of friction. Carried further, YORP spin-up can cause material shedding or even fission to produce a satellite and form a binary system. Binary asteroids represent an in-situ laboratory for studying these processes, where they are actively modifying the system on human-accessible timescales. They are likely to shed mass during their evolution, and may contribute significantly to the meteorite population. The large fraction of NEO binaries suggests that they represent a common part of an asteroid’s “life cycle”.

C) What are the Specific NEO Source Regions and Sinks?

Dynamical mechanisms and their efficiency for transferring objects from different regions in the main asteroid belt and elsewhere must be understood as well as the composition and physical characteristics of the source region population. In this sense, NEO monitoring programs can provide accurate orbital information for meter-sized impactors such as 2008TC3. It would allow better identification of the dynamic resonances delivering meteorites from the main belt, and also identify NEOs producing meteorites. Detailed modeling of dynamical evolution is required to understand NEO interactions with the inner planets, including Earth, resulting in scattering, disruption or accretion. This also provides insights into the role NEOs played in the delivery of water and prebiotic materials to the Earth. A thorough investigation of the NEO population that bears all of these diverse goals in mind will yield the broadest results regarding the scientific, hazard, mitigation, and resource potential of NEOs.

D) How can NEOs be used as resources?

The dynamically closest objects are the most accessible for exploration and/or exploitation, and possess the highest Earth-impact probabilities (Chesley and Spahr, 2002). In particular, the availability of water (for drinking, oxygen, and fuel) is likely to be the limiting factor in extending the human presence in space. There is considerable evidence that many C-class (and some M-class) asteroids contain significant amounts of water in the form of hydrated minerals. Confirmation of this, and identification of NEOs most likely to contain such minerals, is thus a necessary precursor to developing a long-term manned presence in space. Final assessment of the accessibility of these resources on candidate asteroids will require spacecraft reconnaissance. However, the goal of confirming the existence of water and identification of NEOs that contain it can be met using existing techniques and instruments, albeit ultimately on larger telescopes than those now typically available to such programs. Past ground-based studies have provided information to address this issue for numerous main-belt asteroids and for a handful of NEOs.

3 Required Research and Research Facilities

3.1 Discovery and Characterization.

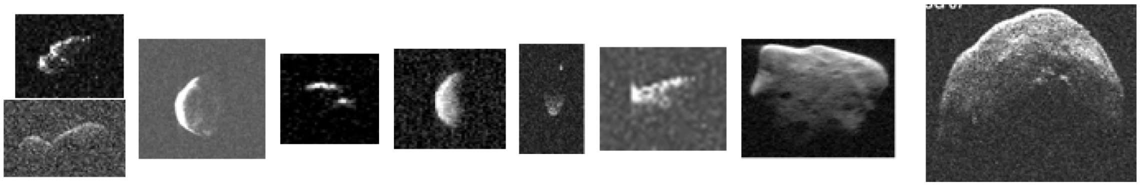
These activities are the foundation of any scientific investigation of NEOs. A general survey of the dynamical and physical characteristics of the NEO population as a whole is a necessary first step towards achieving a more sophisticated understanding of these objects. Once enough data has been acquired from a representative sample of the NEO population, more educated decisions concerning spacecraft target selection can be made. To date most mission targets have been selected primarily on accessibility: How much delta-V and how long will it take to reach the target have been fundamental to target selection. Only by greatly expanding the number of well characterized asteroids can we expand the number of mission opportunities and explore options for multiple NEO targets for a single mission. Maintaining these programs decreases overall mission risk and simplifies spacecraft designs, which corresponds to a reduction in mission cost while still achieving the desired scientific and exploration objectives.

3.1.1 Asteroid Discovery Programs.

We estimate that there are approximately 20,000 NEOs larger than 140 m diameter of which 6292 NEOs (of all sizes) are known (September 4, 2009; http://neo.jpl.nasa.gov/stats/). This number is increasing by several hundred each year, primarily as the result of current NEO search programs. It is vital that these programs continue until next-generation surveys such as Pan-STARRS, LSST and NEOSSat reach operational maturity and **demonstrate** that they are more efficient in the long term. Even after the discovery goals are met, ground-based discovery programs will allow us to discover terminal-discovery impactors like 2008 TC3, which are of enormous scientific and geopolitical importance. 2008 TC3 is the only ureilite parent body we have been able to characterize. Because of its discovery in a routine survey — it was not a fluke discovery — it was well characterized before impact and provides important ground truth.

3.1.2 Characterization.

A robust and ongoing program to obtain physical observations to determine rotation rates, pole directions, sizes, shapes and composition of NEOs is needed. This can most efficiently be done using ground based facilities, which can observe orders of magnitude more objects than spacecraft reconnaissance at orders of magnitude lower cost. Only ground-based spectral and imaging observations can study the population of NEOs in a statistically meaningful manner. In particular, radar observations are a powerful technique for obtaining such data on close-approaching NEOs and providing a unique capability to image them. These images reveal geophysical features, and the variety of physical processes that alter them [see the topical White Paper by Nolan et al.]. In order to meet these requirements, we also need to: expand current programs; provide instrumentation to cover 0.4 to 5 micron spectral coverage at individual telescopes so that spectra covering the entire relevant wavelength range can be obtained in a single night; and make available larger telescopes to enable study of smaller NEOs, improve albedo information, (e.g., via direct imaging, polarization observations or multi-wavelength radiometric data) and better constrain mineralogical identifications.



The variety of NEOs is readily apparent in this montage of radar images of nine different asteroids, showing spheroidal, irregular, and elongated shapes, binary systems, and objects with various surface features, including craters, ridges, boulders and concavities.

3.2 Rendezvous and in situ Physical Characterization

The dynamically closest NEOs are the most accessible for scientific exploration and/or resource exploitation, and also possess the highest Earth-impact probabilities (Chesley and Spahr, 2002). An ongoing program of robotic missions to rendezvous and characterize a number of NEOs is needed to accomplish the overall NEO science goals for the next decade. Since the NEO population is a diverse and complex population of bodies, the overall strategy should be to visit a number of objects of differing compositions and internal structures. Binary NEOs are particularly interesting and present additional challenges and unique opportunities, as discussed in the topical white paper by A.F. Cheng et al. Such a program should be optimized based on a common spacecraft design for this initial reconnaissance, and would ideally deploy spacecraft to, or visit, multiple NEOs with a single launch vehicle to reduce mission cost and program risk. Fly-by missions are desirable from a science return perspective if the ultimate destination is a rendezvous with a NEO. Therefore, *in situ* physical characterization missions would help to discover interesting prospects among the NEO population for further investigation, both via robotic and crewed spacecraft, and identify possible future sample return mission targets.

3.3 Sample Return

Despite considerable progress with composition determination by remote methods, many puzzles remain that are only tractable by sample return. For example, clinopyroxene can be detected spectroscopically and is generally assumed to indicate melts or partial melts, but it is equally diagnostic of unequilibrated ordinary chondrites, the most primitive (unmetamorphosed) ordinary chondrites. Another example is chronology, which is essential for understanding the history of solar system materials, but there is as yet no accurate means to do this remotely or by in situ methods. A third example is physical studies to yield density, porosity, etc. Meteorites are a highly biased (selection during creation, solar system transport, and atmospheric passage) subset of the asteroid population, representing the tough material. They are therefore probably not completely representative of the material observed by asteroid astronomers. Sample return can provide unconsolidated regolith, with its wealth of information about the space environment and the local and distant geology of the asteroid (viz. lunar regolith studies).

4 Technology Needs

New research and technology development programs are needed in order to achieve the goals and objectives of NEO research for the future decade in the following areas:

- Remote sensing and characterization
- Spacecraft systems (e.g., guidance, navigation, propulsion)
- Surface mobility and sample collection

- *In situ* resource utilization

One of the biggest issues in NEO research is the quality and quantity of the data for characterization. In order to maintain pace with the discovery programs, ground-based characterization efforts should be improved. New instrumentation should cover the entire 0.4-5.0 micron spectral range at individual telescopes so that spectra can be obtained in a single night to better constrain NEO compositions. More observing time on larger telescopes will be required to enable the study of smaller NEOs.

In addition to the above needs for augmentation of ground-based observing facilities and improvement of their operation and coordination, specific small body reconnaissance and/or sample return missions require further development of spacecraft technologies. Few of these development programs are unique to the study of NEOs, but the needs for navigation and proximity operations in the vicinity of NEO mission targets are complex due to their small sizes, possible multiplicity of components, and irregular gravity environments. These include propulsion and power, telecommunication, remote sensing (e.g. radar tomography, seismic studies, etc.), surface sampling, guidance navigation and control (GN&C), and autonomy technologies. In addition, spacecraft deployed assets (landers, rovers, penetrators, etc.) interacting with a NEO's surface under microgravity conditions are also needed to maximize the science potential and permit resource utilization and manned exploration.

5 Major Mission Priorities

5.1 No flagship missions to NEOs are proposed over the decade 2013-2022.

5.2 New Frontiers Class mission(s) - Over the decade 2013-2022, New Frontiers-class sample return and grand-tour missions should be developed.

- The highest priority is a sample return from a volatile-rich object not known to be represented in meteorite collections. A P-, D-, or W-class object would be optimal, followed by the other "wet" classes such as B, C and G. For targets that are well-characterized by ground-based spectroscopy and imaging, as well as in-orbit characterization before sampling, existing technologies will be able to return samples.

- The second priority is a Grand Tour mission to rendezvous with a number of NEOs of a variety of classes. Only a spacecraft mission is capable of elucidating the distinctions between the various compositional classes and providing the imaging detail needed to understand the details of formation of difference physical types. Such a spacecraft could have several (perhaps three or four) penetrators, microlanders, or similar low-cost easily-deployed surface exploration modules. This mission could be at a somewhat lower cost than the sample return mission.

6 Discovery Science Goals over the decade 2013-2022.

6.1 Reconnaissance of the population of NEOs.

Asteroid rendezvous (which can include a flyby component) missions with imaging and surface-modification capabilities could study the several NEOs in detail, and should be able to connect asteroid taxonomic types with meteorite classes, as did the NEAR mission. These missions can also examine the small-scale structure inaccessible to ground-based imaging. In addition, the riskiest part of a sample-return mission to an asteroid is the actual sampling step, which necessarily makes assumptions about the physical nature of the surface to be sampled. A less-expensive rendezvous can image the surface at the cm-scale relevant to sampling, and can attempt a collection with microlanders and impactors that assess the surface and demonstrate the most effective methods for sampling and eventual resource extraction.

6.2 NEO Search from a space-based platform.

A space-based discovery platform has clear performance advantages over the same-size ground-based telescope due to the lack of atmospheric absorption (particularly in the IR), weather, continuous operation, and diffraction-limited optical performance. Space-based platforms also have more limited lifetimes, higher costs, and more restricted operating modes than do ground-based systems. Stokes *et al*. (2003) modeled performance of a search telescope in Earth orbit, Earth-Sun Lagrange point L2, and in Venus-trailing orbit from the point of view of speed of retiring impact hazard as a function of cost.

7 Balancing Priorities

Increased support for ground-based observations of NEOs at large telescopes and for analysis of existing data from NEAR Shoemaker, Hayabusa, and related missions (e.g., Deep Impact) will lead to a better foundation for future NEO studies and place their science results in proper context. In addition, in order to provide good foundations for the selection of future NEO missions, and the subsequent interpretation of their data, efforts should be made to include a mix of survey operations, spectral and physical characterization studies, radar observations, laboratory analyses, technology development, and theoretical modeling in well-supported and consistently funded NASA research and data analysis programs. These budgets should be stable.

Ground-based and space-based observations can discover and characterize a significant fraction of the estimated NEO population. These assets can also identify the future mission candidates for investigation, while *in situ* spacecraft reconnaissance will provide answers to the detailed questions that cannot be answered via remote sensing methods. For example, a New Frontiers sample return mission to a volatile-rich NEO could return material not represented in our meteorite collection, which would simultaneously answer questions about solar system formation and if any useful resources be extracted from them. Hence, a NEO research program should incorporate elements of both remote sensing and spacecraft *in situ* physical characterization.

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