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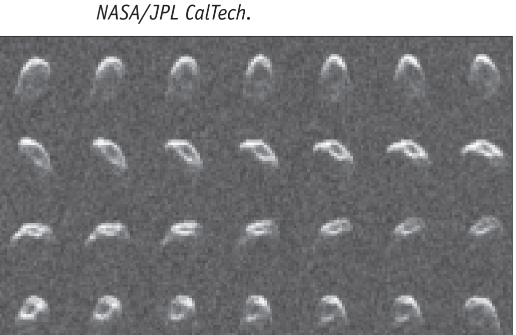
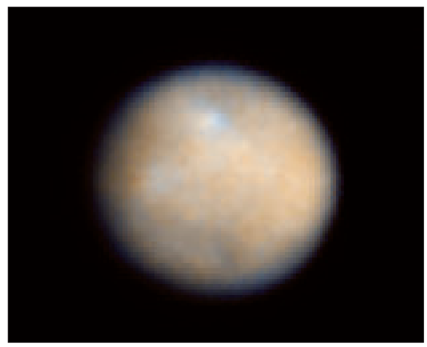
Mapping a course to the asteroids

LAST DECEMBER, TUMBLING SILENTLY in its endless fall around the Sun, asteroid 2010 JL33 swept to within 8.5 million km of Earth, about 22 times the Moon's orbital distance. Discovered by the Catalina Sky Survey in Tucson on May 6, 2010, the 1.8-km-wide JL33 is one of millions of small asteroids and comets that cruise the inner solar system. During its close approach, JL33 came within range of the Goldstone solar system radar, which bounced a tightly focused radar beam off the asteroid. A JPL team recorded a series of images covering nearly a full, 9-hr rotation of JL33's impact-scarred surface, revealing its irregular topography, precise orbit, and axis of rotation.

Ghostly JPL/Goldstone images reveal a prominent impact crater gouged from the pebble-shaped asteroid. The portrait adds to our small but growing body of knowledge of these ancient, enigmatic near-Earth objects (NEOs). Comprised of near-Earth asteroids (NEAs) and the much rarer near-Earth comets, they represent a long-term hazard to Earth, a rich source of scientific information on the solar system's formation, and a source of potentially valuable space materials. And last year they rose to prominence in NASA's plans for future human exploration.

NASA's Goldstone solar system radar captured these images of asteroid 2010 JL33, obtained on December 11 and 12, 2010. The Goldstone and Arecibo radars perform important follow-up investigations of NEOs discovered by other ground-based facilities. Image courtesy NASA/JPL CalTech.





This 2003-2004 Hubble image of asteroid 1 Ceres suggests surface material variations on this 980-km-wide NEO. Ceres probably has a layered interior of rocky inner core, an icy mantle, and a thin, dusty outer crust.

Budget barriers

President Obama declared last April that the U.S. would launch an astronaut expedition toward a near-Earth asteroid by 2025. Specifics were few, however. Now, with the Constellation program effectively ended by the president and Congress, asteroid exploration appears to be the only long-range human deep-space activity NASA has approval to pursue. Yet with the FY11 budget still in limbo, and talk circulating that NASA's exploration office will soon merge with its space operations mission directorate, an 'asteroid program' has yet to take shape.

Although last October's authorization bill terminated Constellation, release of funds to other exploration activities, such as NEA missions, awaits final appropriation action by the Congress. The authorization also directed NASA to develop and fly a heavy-lift rocket by 2016. Such a booster, based on shuttle and Constellation heritage, is a key requirement for human exploration beyond the space station.

The heavy lifter will presumably carry an Orion spacecraft, but neither the White House nor Congress has approved any hardware architecture or schedule for a true deep-space mission capability.

To propose a way forward, NASA's Exploration Systems Mission Directorate (ESMD) has for nearly a year been evaluating possible combinations of technologies, schedules, and budgets that might produce a national capability to reach the asteroids, Moon, and eventually Mars. HEFT, the Human Exploration Framework Team, issued a status report in January, to be followed by a full report this spring.

The January HEFT results were not encouraging, with the NASA team noting that no combination of heavy-lift boosters, deep-space craft, in-space propulsion, and projected technologies enabling beyond-LEO exploration could be produced by the 2016 congressional deadline or within long-term budget projections. At best, NASA could achieve a solution that satisfied only two of the three specified high-level constraints, traded among performance, schedule, or budget.

The agency's sobering assessment echoes the Augustine committee's 2009 conclusion that relatively static funding levels and traditional procurement practices would doom Constellation's lunar return plans.

Senators Bill Nelson (D-Fla.) and Kay Bailey Hutchison (R-Texas) responded quickly that NASA should get on with producing both the heavy lifter and Orion. Nelson told Administrator Charles F. Bolden that "he has to follow the law, which requires a new rocket by 2016," adding, "and NASA has to do it within the budget the law requires." The HEFT stated it will continue to study combinations of vehicle architecture, systems, propulsion, and technology that can deliver a human deep space exploration capability.

Asteroid recon

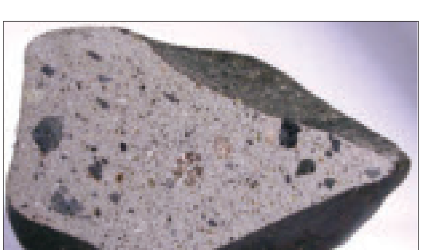
If NASA aims for a human NEA capability, it will need much more information about possible asteroid destinations. To date, just two spacecraft have explored NEAs in detail: NASA's NEAR-

Shoemaker probe landed on 433 Eros in 2001, and Japan's Hayabusa mission returned a microsample of asteroid 25143 Itokawa to Earth last June.

New asteroid data should arrive this summer from NASA's Dawn mission. The ion-driven Dawn spacecraft will visit the two most massive 'protoplanets' in the main asteroid belt between Mars and Jupiter, the source of the Earth-approaching population. The spacecraft will thrust into orbit around asteroid 4 Vesta this August, map its surface in detail, then depart for a rendezvous with the largest asteroid, 1 Ceres, in February 2015.

Spectroscopic observations and meteorite studies suggest that 580-km-wide Vesta is a dry, differentiated body surfaced with lava flows. Mineral composition varies across Vesta's surface, suggesting interior layers are exposed; an apparent impact crater 460 km in diameter lies near the south pole. Fragments excavated by that impact may have arrived on Earth in the form of once-molten igneous meteorites called HED achondrites. Dawn's orbital survey should yield clues about what heat source and style of volcanism produced these impact-welded assemblages of lavas.

Ceres, some 980 km across and only slightly farther from the Sun than Vesta, appears radically different. Its surface exhibits the spectroscopic signature of water-bearing clays. Ceres' north pole may host a thin cap of water frost, fed from a subsurface reservoir of ice incorporated during its formation 4.5 billion years ago.



The Sioux City eucrite meteorite, an amalgam of pulverized silicate fragments and dark basalt lava, is linked to melting, differentiation, and impact processes experienced on Vesta. Image courtesy Arizona State University, J. Kurtzmen.

Large asteroids like Ceres and Vesta are probably the parent bodies of many smaller objects fed into the inner solar system by collisions and gravitational nudges from massive Jupiter. NEAs are objects whose perihelion distances are less than 1.3 AU; a subset with Earth-approaching orbits are potential targets for robotic and human exploration.

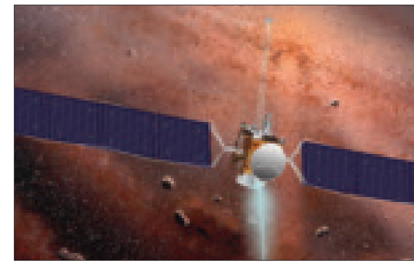
Both NASA's Science Mission Directorate (SMD) and ESMD may pursue missions to NEAs in the coming decade, to learn more about their varied properties, compositions, and origins. NASA is studying the Osiris Regolith Explorer, aimed at returning a 150-g sample from the volatile-rich NEA 1999 RQ36. JAXA's Hayabusa II sample return mission, just approved, will complement NASA efforts.

I serve as principal investigator on a new NEA mission concept called Amor, currently under evaluation for NASA's Discovery robotic exploration program. The Amor mission is designed to address NASA's solar system science priorities and obtain physical measurements vital to human exploration plans and future efforts to deflect a rogue asteroid.

Amor will rendezvous with, land on, and explore a remarkable triple asteroid system. The C-type (carbonaceous) NEA 2001 SN263 is accompanied by two small moonlets. The primary object, Alpha, is 2.8 km wide. Satellites Beta and Gamma are 1.1 and 0.4 km across, respectively. Beta is outermost, its orbit around Alpha spanning some 30-35 km.

The SN263 system's elliptical orbit circles the Sun once every 2.8 years, inclined about 7 deg from the ecliptic. The orbit crosses that of Mars and swings deep into the main asteroid belt. At its inward reach, the system comes as close as 0.06 AU to Earth.

Ground-based spectra classify SN-263 as a C-type asteroid, the dominant type in the main belt; the C-types are thought to be volatile and organic-rich objects relatively unaltered since formation 4.5 billion years ago. Their low



NASA's Dawn will orbit around asteroid 4 Vesta, then depart for a rendezvous with 1 Ceres.

albedo (about 5% reflectivity) makes them difficult to study from Earth, and spacecraft have provided only distant glimpses of two main belt C-types. The Amor spacecraft is designed to study this enigmatic C-type system at extremely close range, taking science to the surface.

Amor will launch aboard an Atlas V booster in January 2017 to begin its nearly five-year journey to SN263. Following an Earth gravity assist and several asteroid flybys, the spacecraft arrives at the triple system in November 2021. Eight months of detailed study follow, including high-resolution mapping and landings on at least two of the asteroid components. Amor will return answers to questions high on NASA's list of science priorities:

- What are C-type asteroids?
- Are these asteroids truly linked to the primitive, carbonaceous chondrite meteorites?
- Are C-types truly rich in water and organic compounds?
- How do multiple asteroid systems form?
- How could we avert an impact from a C-type NEA?
- What resources do C-types offer to future human exploration?

As it stationkeeps with the SN263 system, Amor will use the NEOCam color imager to map the three components, develop a detailed shape model of each body, and choose landing sites on Alpha and one of the two satellites. After several practice approaches enabling a detailed look at the landing terrain, Amor will maneuver onto a trajectory that matches asteroid rotation

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Asteroids

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and brings the spacecraft to a point just 10 m above the surface. The 3-axis-stabilized vehicle, built by Orbital Sciences, then free falls to the surface under the few micro-*g*s of local gravitational acceleration.

Once on the surface, held fast by a set of auger-like anchors, Amor begins a week of intensive surface investigation. Operations and science teams at NASA Ames deploy both the NEONS (neo spectrometer package) for major element composition and the CHAMP (camera hand-lens and microscopic probe) macro/microscopic imager. The articulating, 2-m-long robot arm carries CHAMP into close contact with the surface to characterize surface mineral texture and structure down to submillimeter scales. CHAMP's strobe-lit color images, along with bulk elemental composition from NEONS, will test the suspected link between the C-type surface and carbonaceous chondrite meteorites. If confirmed, the link will enable us to use terrestrial meteorite samples to assess the mineralogy, thermal history, and practical resources of C-type asteroids.

Astronauts to asteroids

Missions like Amor, Hayabusa II, and others would scout the properties of a variety of NEAs and assess techniques for proximity operations, resource prospecting, and anchoring to varied asteroid surfaces. A series of robotic missions over a decade should be sufficient to inform the details of an astronaut expedition. Constellation program studies and industry concepts like Lockheed Martin's Plymouth Rock have outlined how an early NEO mission might be conducted.

A piloted asteroid mission capability would have at its core a heavy launch system and a beyond-LEO spacecraft (Orion). Following a flexible path toward deep space, NASA could add the hardware components needed to enable visits to asteroids, Lagrange points, or the Moon's surface, depending on national priorities.

Asteroid missions could do without the expensive lander or habitats sited on the lunar surface, but they do require more crew consumables and habitation space than sortie-class lunar missions lasting just a few weeks. A hab module, either derived from ISS experience or a TransHab-style inflatable design, would be added to propulsion and crew reentry modules assembled in LEO or at a Lagrange point. Together the reentry, propulsion, and hab components would form a spacecraft capable of multimonth asteroid expeditions.

Lockheed Martin's Plymouth Rock mission concept would use a pair of Orion spacecraft to take an astronaut crew to a nearby asteroid. The vehicle would support a crew for about 6 months, including a two-week exploration phase at the asteroid. Image courtesy Lockheed Martin.

A few known asteroids offer round-trip delta-V requirements equal to or less than a lunar expedition, but propulsion for a crewed NEA mission might call for refueling from an orbital depot or multiple propellant tank launches. Minimizing required propellant costs creates a large incentive to start a thorough search for accessible asteroids as soon as possible.

Last fall, a NASA Advisory Council task force on planetary defense recommended that NASA launch a space-based search telescope into a Venus-like orbit to catalog NEOs. The hundreds of thousands of asteroids and comets discovered would greatly aid NASA's science, exploration, and planetary defense programs.

Encounter

The hab module would house consumables, radiation shielding, exercise gear, and docking ports for EVA suits or small exploration craft. Following Earth departure and several months of cruise, a three- or four-person crew would rendezvous with the chosen asteroid, already scouted by a robotic explorer. Following a few days of surface reconnaissance using a small teleoperated probe, a pair of astronauts would translate to the asteroid surface in personal spacecraft whose handling qualities had been checked out years earlier at the ISS.

These 'multimission exploration vehicles,' or MMEVs, would ease the jobs of surface anchoring and asteroid sampling. Should science requirements or problems on the surface demand it, astronauts could conduct space-suited EVAs, but mobility, productivity, and reduced fatigue favor use of the MMEV, with its shirt-sleeve environment and stationkeeping autopilot. ESMD has been studying MMEV concepts derived from work on its lunar electric rover.

During a two-week exploration phase, the MMEVs should enable more wide-ranging, sustained surface investigations than spacesuits alone. A major activity would be physical properties measurements aimed at developing deflection techniques. After stowing NEA samples totaling tens of kilograms aboard the reentry vehicle, and deploying science packages and resource extraction demonstrators, the crew would prepare the cruise vehicle for Earth return.

Sustained exploration

After a multimonth cruise to Earth, the astronauts would undock their reentry module for a direct entry into the atmosphere, while the deep space vehicle maneuvers into a high Earth orbit for refueling and refurbishment. This concept preserves the hab, personal exploration craft, and propulsion modules for reuse. Later asteroid explorers might return with their cruise vehicle to a Lagrange point, transferring with their samples to a waiting reentry transport.

Although more costly initially than a minimalist approach using, for example, coupled Orion spacecraft, reusable exploration vehicles can be adapted for repeated use throughout the Earth-Moon system, to nearby asteroids, and eventually to the Martian moons. Addition of a lander for lunar surface sorties or descent to Mars itself is a natural evolution of this sustained approach to exploring deep space.

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