Small Bodies Perspective on the progress toward *Vision and Voyages*

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Presented to the
Committee on the Review of Progress Toward Implementing the Decadal Survey Vision and Voyages for Planetary Sciences

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What does SBAG represent?

- “Other” bodies
  - Grouped into a single AG in part because they have the common property of being smaller than the bodies claimed by the other AGs
- Variety of types of bodies in a variety of locations
  - Main-belt asteroids, comets, KBOs, Jupiter Trojans, Martian moons, Near-Earth objects, meteorites, Solar System dust
  - Vast majority of cataloged objects in the Solar System
    - Even without meteorites, collected dust
  - Large diversity in processes experienced
    - Many, but not all, processed little since early Solar System

Why were small bodies ignored* for NASA's first 40 years?

- Not the planets, not the Sun, so not obvious first choices, and not understood well enough to understand why they are interesting
- Difficult
  - KBOs are the most distant objects we know of, so they're hard to get to with spacecraft or to study with telescopes
    - Not counting Pluto, the first was discovered 25 years ago
  - Difficult to target
    - Orbits often poorly known
      - Changing with Arecibo
    - Small, so can be hard for spacecraft to acquire
- Nearly 40 years after our first mission beyond low-Earth orbit before we had a mission dedicated to studying any small bodies

*Except for R&A funding of telescopic studies of many small bodies, laboratory studies of meteorites, and ICEE-3

Why have small bodies gotten more attention in the last two decades?

Scientific interest

- Many prized because they have been less processed than their larger kin, retain clues about the material and processes that went into the formation of the planets and large moons
  - Comets, many asteroids, most meteorites, probably Jupiter Trojans
- Others show the processes that occurred on larger bodies, but scaled to different sizes, different parts of the process exposed
  - Differentiation on Vesta, Pluto
  - Core formation and Psyche

Left, volatile-rich Orgueil meteorite (Encyclopedia of Meteorites). Below, artist's conception of asteroid 16 Psyche (Arizona State University)

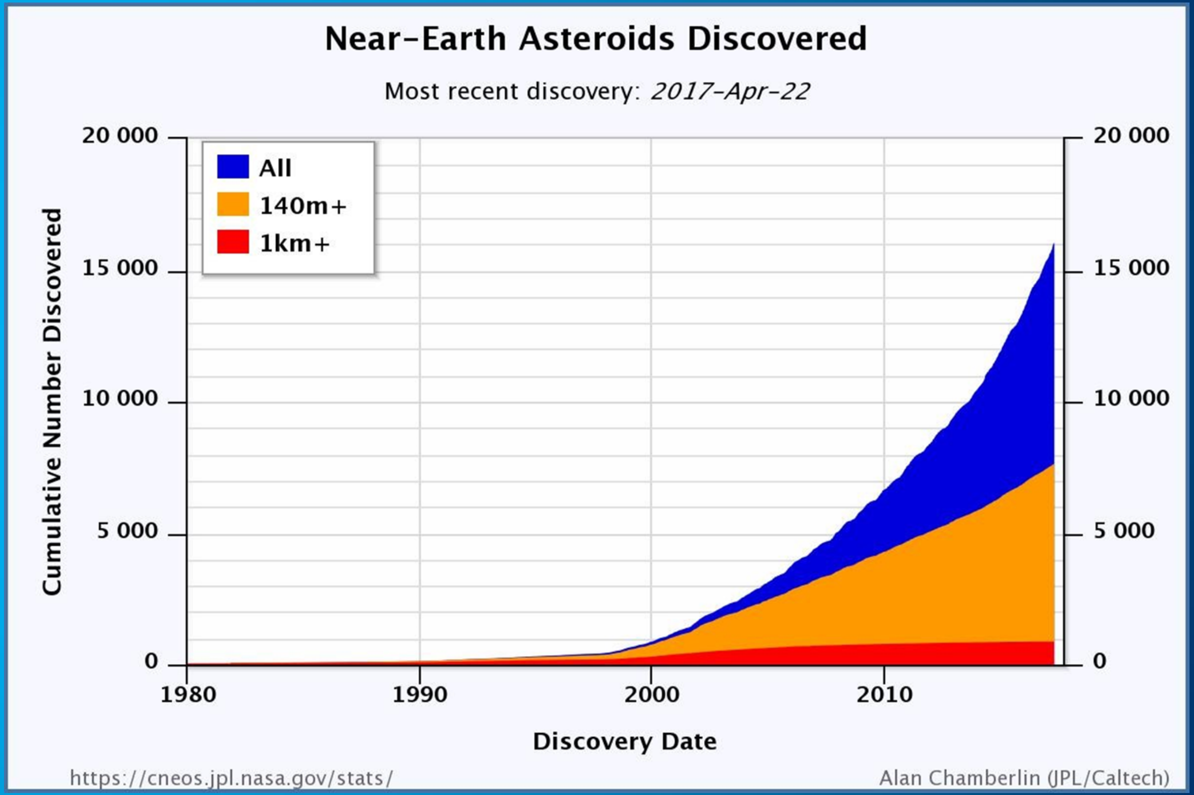
Why have small bodies gotten more attention in the last two decades? Scientific interest (continued)

- Tracers of the dynamical processes that formed the planets
  - How did the Martian moons form?
  - How did the Jupiter Trojans get there?
  - What does the distribution of Main Belt asteroids say about early Solar System dynamics?
  - Prevalence of volatile-rich double-lobed comets like 67P/Churyumov-Gerasimenko (right) suggests gentle accretion

ESA

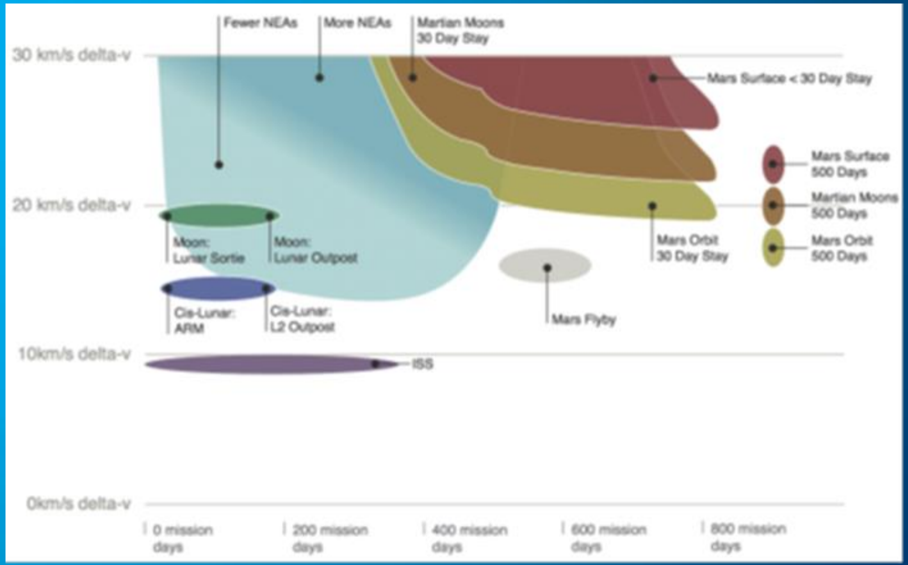
Why have small bodies gotten more attention in the last two decades? More targets

- New Horizons' second target wasn't discovered until shortly before Pluto encounter
- Numbers in most categories have increased significantly
  - First KBO other than Pluto discovered 1992, now more than 2000
  - Number of known Near-Earth Objects a few hundred in mid-1990s, now >15,000
    - NEO surveys have increased numbers in other categories as by-product



Why have small bodies gotten more attention in the last two decades? Ease of access

- Primarily possible because of increased number of targets
- Easiest objects to reach in terms of fuel are NEOs, so can try things for which cost of fuel or communications would currently be prohibitive
  - CubeSat missions
  - Sample return
  - Crewed missions (none currently planned)
  - Arguments apply for lunar missions as well
    - Time is shorter to the Moon
    - Fuel costs lower for many NEOs



Many NEOs (light green) require less fuel (vertical axis, in delta-V) than a trip to the surface of the Moon (dark green), although the trip time (horizontal axis) can be longer (from Near-Earth Object Human Space Flight Accessible Targets Study (NHATS)

Why have small bodies gotten more attention in the last two decades?
Resources, planetary defense

- It’s NEOs that are being consider as resource utilization targets
  - Ease of access
  - Availability of resources
- NEOs are the only objects for which planetary defense is a concern
  - Possibly comets

Artist’s conception of a major asteroid impact on Earth (University of California Observatories)

Goals from “Visions and Voyages”

- Represented by “Primitive Bodies Panel”
  - Chapter 4

Science goals

- Decipher the record in primitive bodies of epochs and processes not obtainable elsewhere, and
- Understand the role of primitive bodies as building blocks for planets and life.

Specific objectives

Understand presolar processes recorded in the materials of primitive bodies

- Questions
  - How do the presolar solids found in chondrites relate to astronomical observations of solids disposed around young stars?
  - How abundant are presolar silicates and oxides? Most of the presolar grains recognized so far are carbon (diamond, graphite) phases or carbides.
  - How do the compositions of presolar grains and organic molecules vary among different comets?
- Targets
  - Meteorites
  - Comet samples, interplanetary dust

Specific objectives

Study condensation, accretion, and other formative processes in the solar nebula

- Questions
  - How much time elapsed between the formation of the various chondrite components, and what do those differences mean?
  - Did evaporation and condensation of solids from hot gas occur only in localized areas of the nebula, or was that process widespread?
  - What are the isotopic compositions of the important elements in the Sun?
  - Which classes of meteorites come from which classes of asteroids, and how diverse were the components from which asteroids were assembled?
  - How variable are comet compositions, and how heterogeneous are individual comets?
  - What are the abundances and distributions of different classes of asteroids, comets, and KBOs?
  - How do the compositions of Oort cloud comets differ from those derived from the Kuiper belt?
- Targets
  - Meteorites and asteroid samples
  - Solar wind samples
  - Comet samples
  - KBOs

Specific objectives

Determine the effects and timing of secondary processes on the evolution of primitive bodies

- Questions
  - To what degree have comets been affected by thermal and aqueous alteration processes?
  - How well can we read the nebular record in extraterrestrial samples through the haze of secondary processes?
  - What is the relationship between large and small KBOs? Is the population of small KBOs derived by impact disruption of the large KBOs?
  - How do the impact histories of asteroids compare to those of comets and KBOs?
  - How do physical secondary processes such as spin-up result from non-gravitational forces, the creation and destruction of binary objects, and space weathering?
- Targets
  - Comets and KBOs
  - Better thermal models of asteroid and comets

Specific objectives

Assess the nature and chronology of planetesimal differentiation

- Questions
  - Did asteroid differentiation involve near-complete melting to form magma oceans, or modest partial melting?
  - How did differentiation vary on bodies with large proportions of metal or ices?
  - Were there radial or planetesimal-size limits on differentiation, and were KBOs and comets formed too late to have included significant amounts of live aluminum-26 as a heat source?
  - What are the internal structures of Trojans and KBOs?
- Targets
  - Large asteroids (Dawn at Vesta, Ceres; Psyche)
  - KBOs (New Horizons), Trojans (Lucy)

Science goals

- Decipher the record in primitive bodies of epochs and processes not obtainable elsewhere, and
- Understand the role of primitive bodies as building blocks for planets and life.

Specific objectives

Determine the composition, origin, and primordial distribution of volatiles and organic matter in the solar system

- Questions
  - What are the chemical routes leading to complex organic molecules in regions of star and planet formation?
  - What was the proportion of surviving presolar organic matter in the solar nebula, relative to the organic compounds produced locally?
  - What roles did secondary processes and mineral interactions play in the formation of organic molecules?
  - How stable are organic molecules in different space environments?
  - What caused the depletions in volatile elements, relative to chondrites, observed in differentiated asteroids and planets?
  - What kinds of surface evolution, radiation chemistry, and surface-atmosphere interactions occur on distant icy primitive bodies?
  - How is the surface composition of comets modified by thermal radiation and impact processes?

Specific objectives

Determine the composition, origin, and primordial distribution of volatiles and organic matter in the solar system

- Targets
  - KBOs (New Horizons)
  - Organic material in primitive asteroids (OSIRIS-REx, Hayabusa-2)
  - Organic material in comet samples (cryogenic?)

Specific objectives

Understand how and when planetesimals were assembled to form planets

- Questions
  - Are there systematic chemical or isotopic gradients in the solar system, and if so, what do they reveal about accretion?
  - Do we have meteoritic samples of the objects that formed the dominant feeding zones for the innermost planets?
  - How did Earth get its water and other volatiles? What role did icy objects play in the accretion of various planets?
  - What is the mechanical process of accretion up to and through the formation of meter-size bodies?
- Targets
  - KBOs (New Horizons)
  - D/H in multiple comets (Rosetta, telescope studies)
  - Studies of multiple asteroids (Dawn, Lucy)

Specific objectives

Constrain the dynamical evolution of planets by their effects on the distribution of primitive bodies

- Questions
  - Which classes of asteroids participated in the late heavy bombardment of the inner planets and the Moon, and how did the current population of asteroids evolve in time and space?
  - What are the sources of asteroid groups (Trojans and Centaurs) that remain to be explored by spacecraft?
  - How are objects delivered from the Kuiper belt to the inner solar system? Specifically, by what mechanisms are Jupiter family comets resupplied to the inner solar system?
- Targets
  - KBOs (New Horizons, surveys)
  - Orbital surveys of asteroids (NEOWISE)
  - Missions to Trojans (Lucy), Centaurs

Six of 10 questions generated by “cross-cutting themes” (Table S.1) call out small bodies missions

Building new worlds

1. What were the initial stages, conditions, and processes of solar system formation and the nature of the interstellar matter that was incorporated?

2. How did the giant planets and their satellite systems accrete, and is there evidence that they migrated to new orbital positions?

3. What governed the accretion, supply of water, chemistry, and internal differentiation of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large projectiles play?

Six of 10 questions generated by “cross-cutting themes” (Table S.1) call out small bodies missions

Planetary habitats

4. What were the primordial sources of organic matter, and where does organic synthesis continue today?

Workings of solar systems

8. What solar system bodies endanger Earth’s biosphere, and what mechanisms shield it?

10. How have the myriad chemical and physical processes that shaped the solar system operated, interacted, and evolved over time?

A seventh question didn’t call out small bodies missions, but probably would if written today

Planetary habitats

6. Beyond Earth, are there contemporary habitats elsewhere in the solar system with necessary conditions, organic matter, water, energy, and nutrients to sustain life, and do organisms live there now?

Exploration of Ceres, Pluto suggest that the largest of the “minor planets’ might also be ocean worlds

Proposed small bodies missions

- No flagship missions considered
- New Frontiers
  - Comet surface sample return (part of current call)
  - Trojan tour and rendezvous
    - Lucy (Discovery class) is Trojan tour
- Stressed regular Discovery, New Frontiers cadence

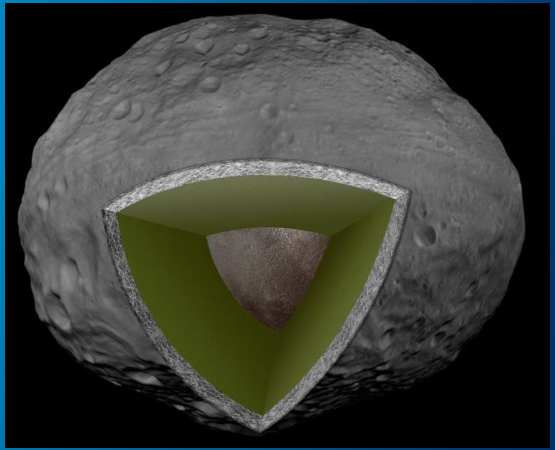
Small bodies missions flying, 2013-present

- New Horizons (New Frontiers)
  - Pluto as an incredibly active world
  - Pluto satellites as a diverse and interesting collection
  - Flying on to a second KBO, 2014 MU_{69}

Small bodies missions flying, 2013-present

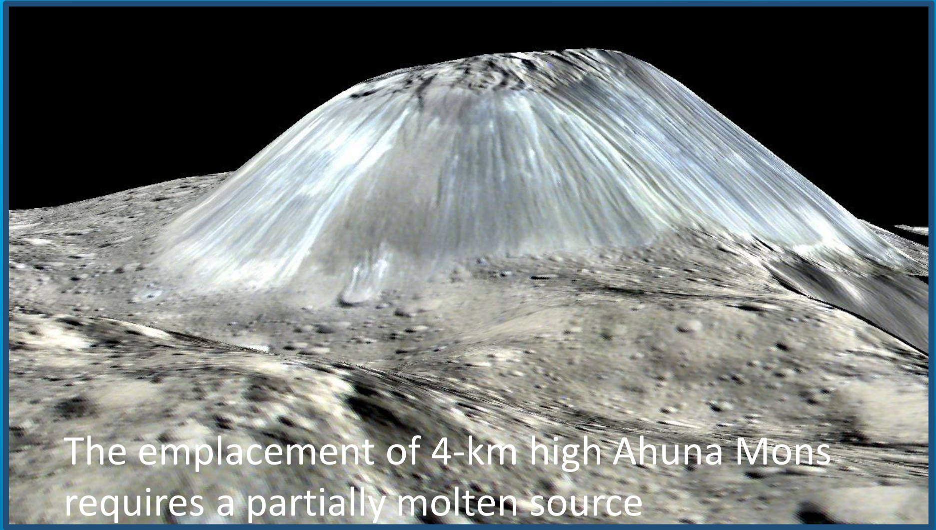
- Dawn (Discovery)
  - Vesta: Ground-truth for HED meteorites
    - Provided geological context for the Vesta asteroid family
    - Also revealed significant surface contamination by carbonaceous material
  - Ceres: First observation of a dwarf planet
    - Confirmed Ceres is large enough to preserve liquid until present
    - Ceres Displays brine-driven cryovolcanic features whose origin (active vs. passive) is under study

Eucrite meteorite



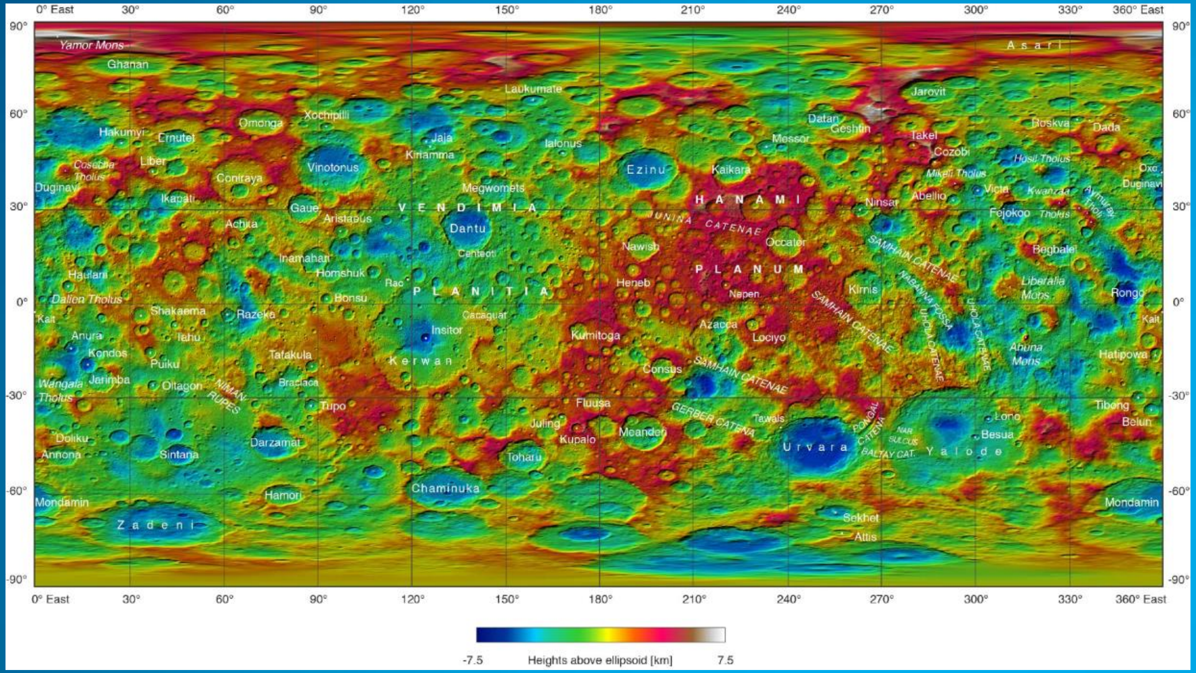
Dawn at Vesta yielded new insights into planetary differentiation and early solar system accretion chronology

Dawn revealed Ceres' rich chemistry, evidence for advanced past and recent hydrothermal activity

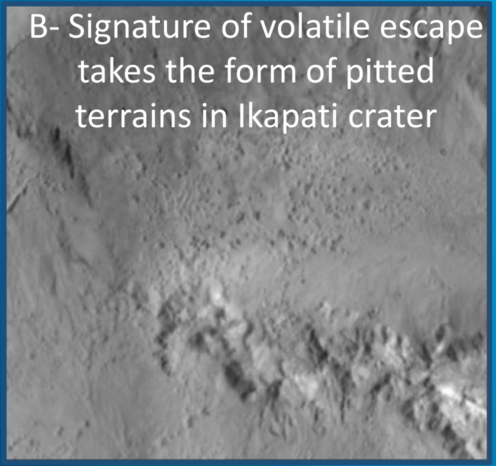


The emplacement of 4-km high Ahuna Mons requires a partially molten source

Dawn revealed Ceres is Geologically Rich World

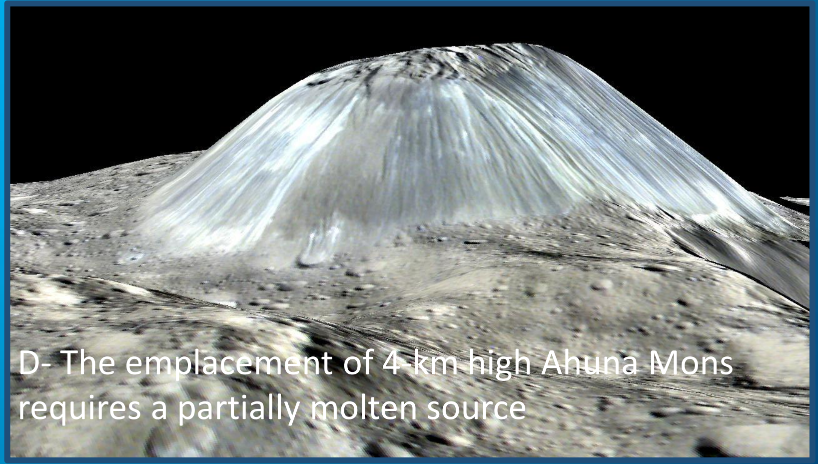


A- Fluidized extrusions formed bright deposits in Occator crater



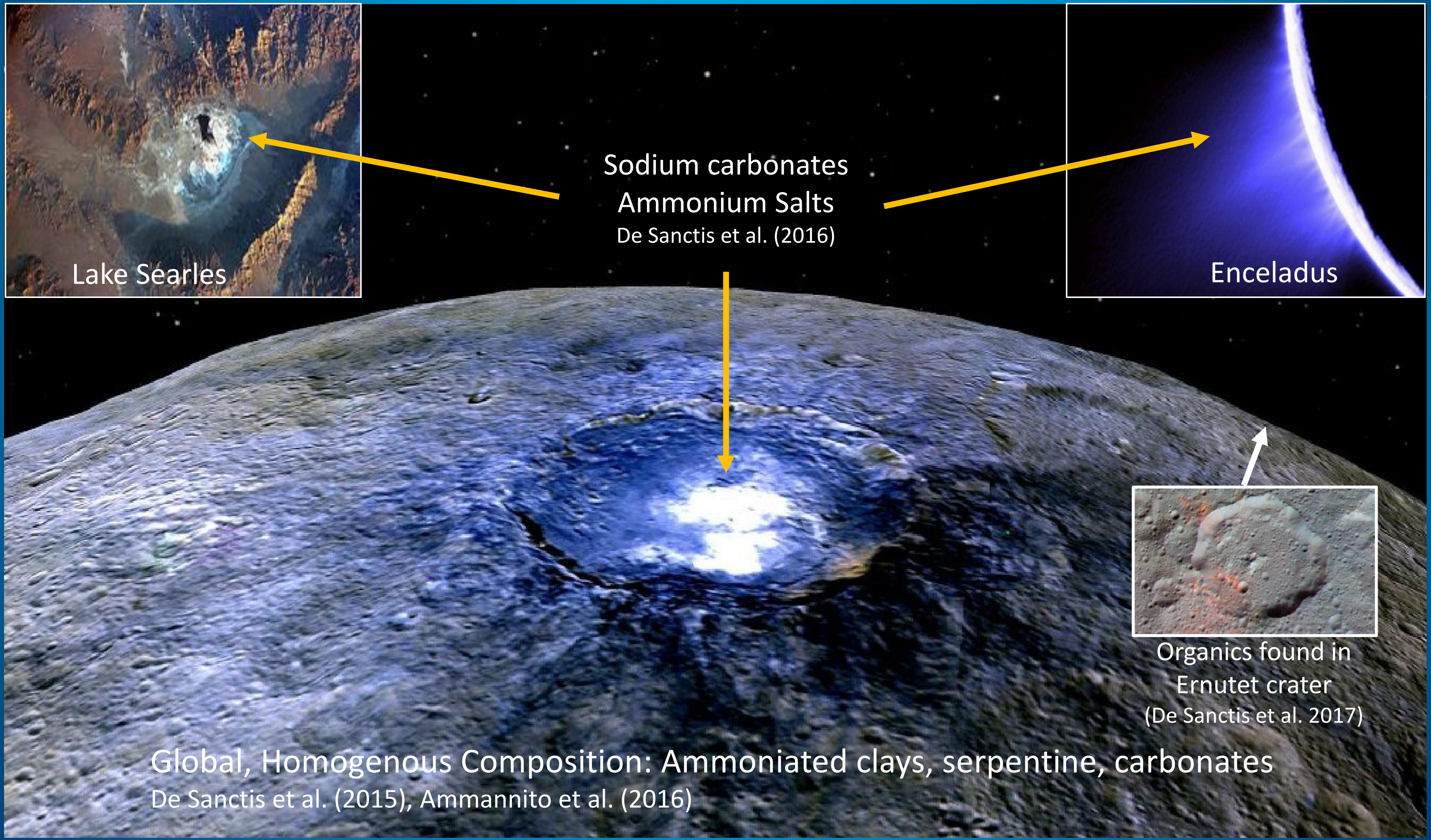
B- Signature of volatile escape takes the form of pitted terrains in Ikapati crater

C- A large landslide reveals water ice at Oxo crater



D- The emplacement of 4-km-high Ahuna Mons requires a partially molten source

Ceres' Surface Shows Mineralogy Found only on Earth and Enceladus

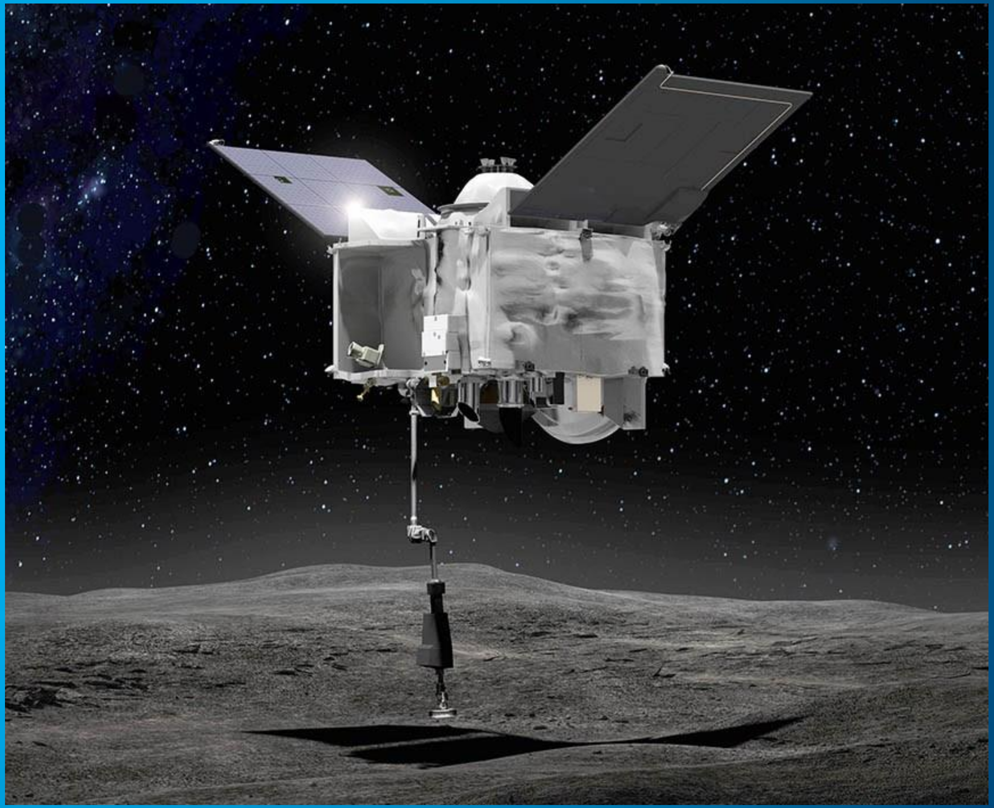


Small bodies missions flying, 2013-present

- NEOWISE
  - Reactivation of WISE (Wide-field Infrared Survey Explorer)
  - Detection of Near-Earth asteroids
  - Infrared, so most effective for dark asteroids, for which ground-based surveys least effective

Small bodies missions flying, 2013-present

- OSIRIS-REx (New Frontiers)
  - Asteroid sample return, called out by previous Decadal Survey
  - Currently en route to Bennu
    - Launched 2016
    - Asteroid arrival 2018
    - In situ study, then sampling
    - Return in 2023
  - Detailed study of asteroid expected to be primitive, volatile-rich



Artist's conception of touch-and-go sampling (NASA GSFC)

Small bodies missions flying, 2013-present

- Rosetta (ESA)
  - Mission concluded September 2016
  - Comet 67P/Churyumov-Gerasimenko as fascinating world
  - Detailed measurements of volatiles
    - More hypervolatiles (e.g., O_2) than expected
  - Radar sounding of interior showed no large cavities
  - Observed active processes through perihelion

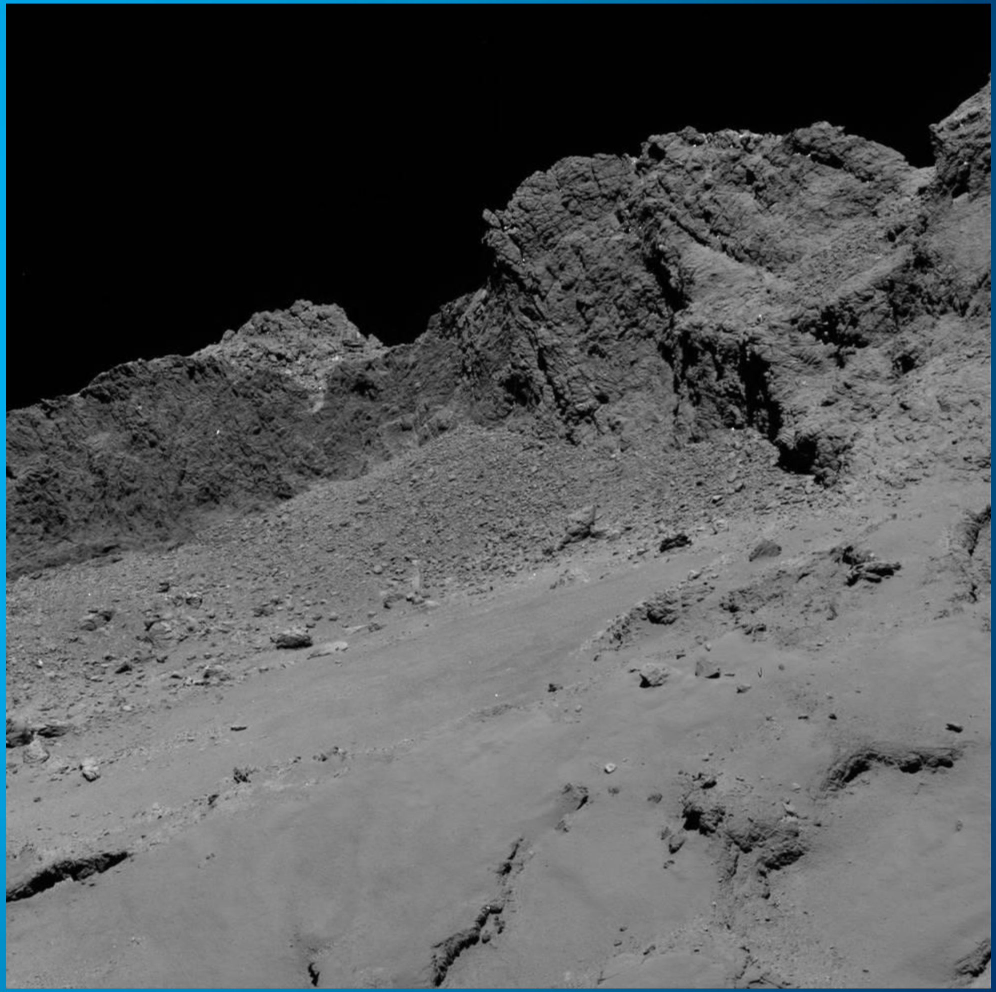


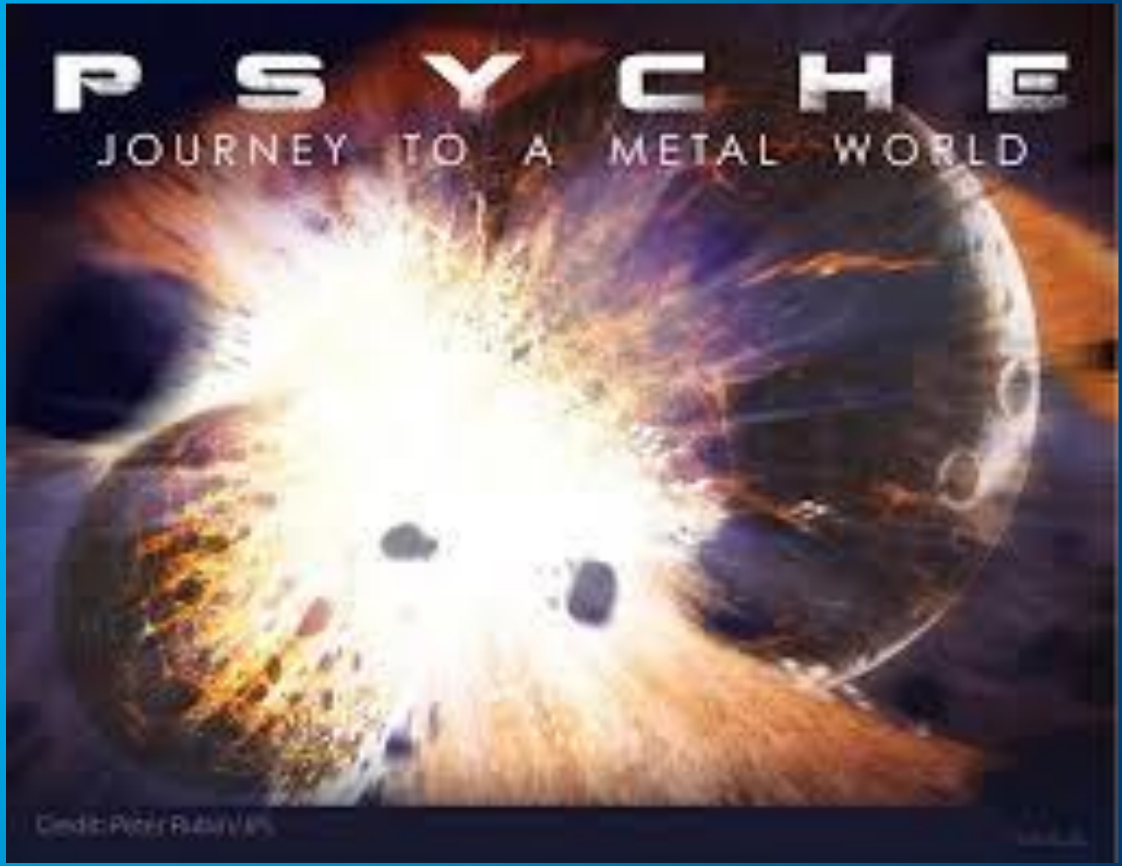
Image of surface (2 km width) taken during final descent (ESA)

Small bodies missions flying, 2013-present

- Hayabusa-2 (JAXA)
  - Asteroid sample return to Ryugu
  - Similar to Bennu (dark, carbon-rich?)
  - Unprecedented opportunity to study two similar asteroids simultaneously

Approved missions

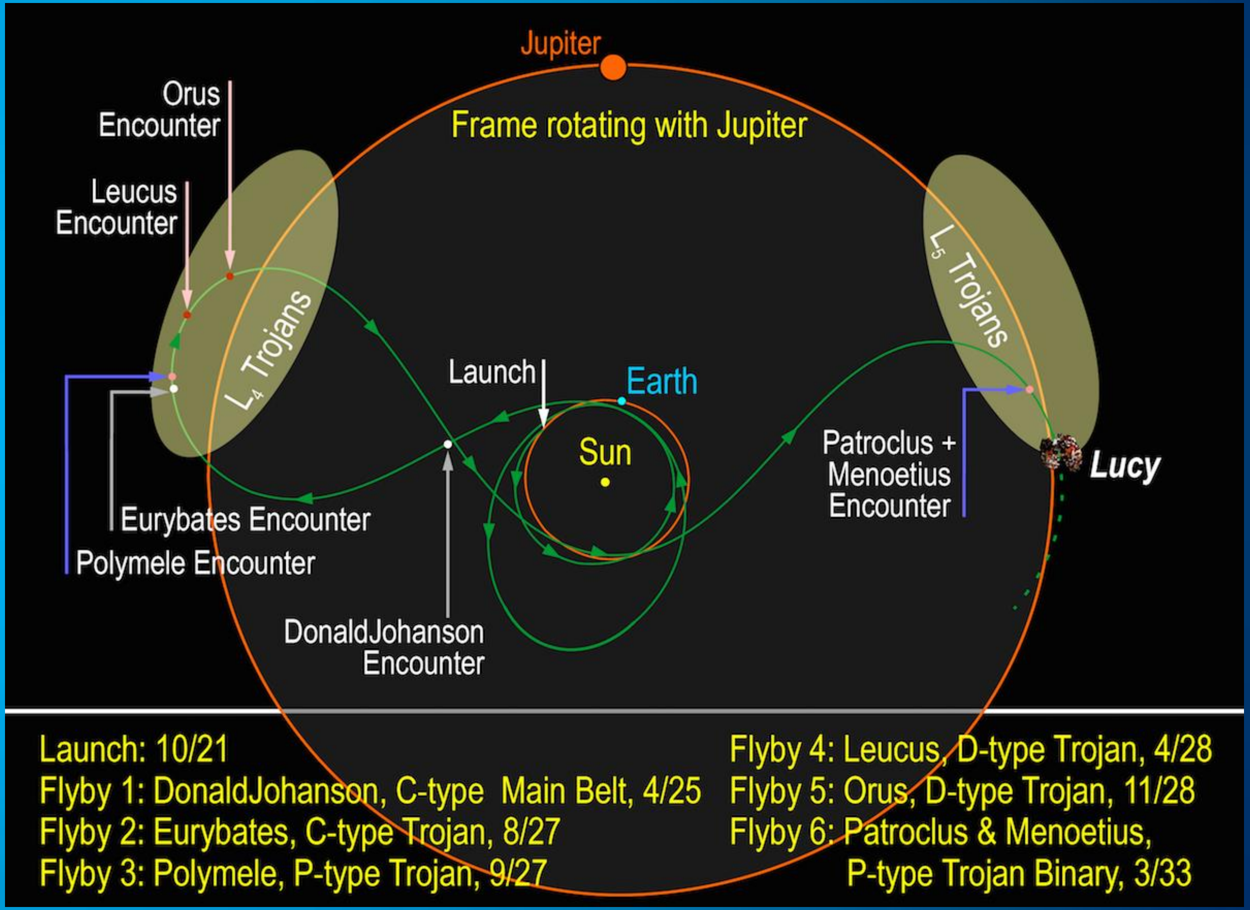
- Psyche (Discovery)
  - Density, spectrum suggest it's metal
  - Largest metallic asteroid
  - Disrupted core?



Proposal cover (ASU)

Approved missions

- Lucy (Discovery)
  - Tour of Jupiter Trojans
  - Five Trojans, one Main-Belt Asteroid
    - Three spectral types
    - Largest member of confirmed collisional family
    - Binary



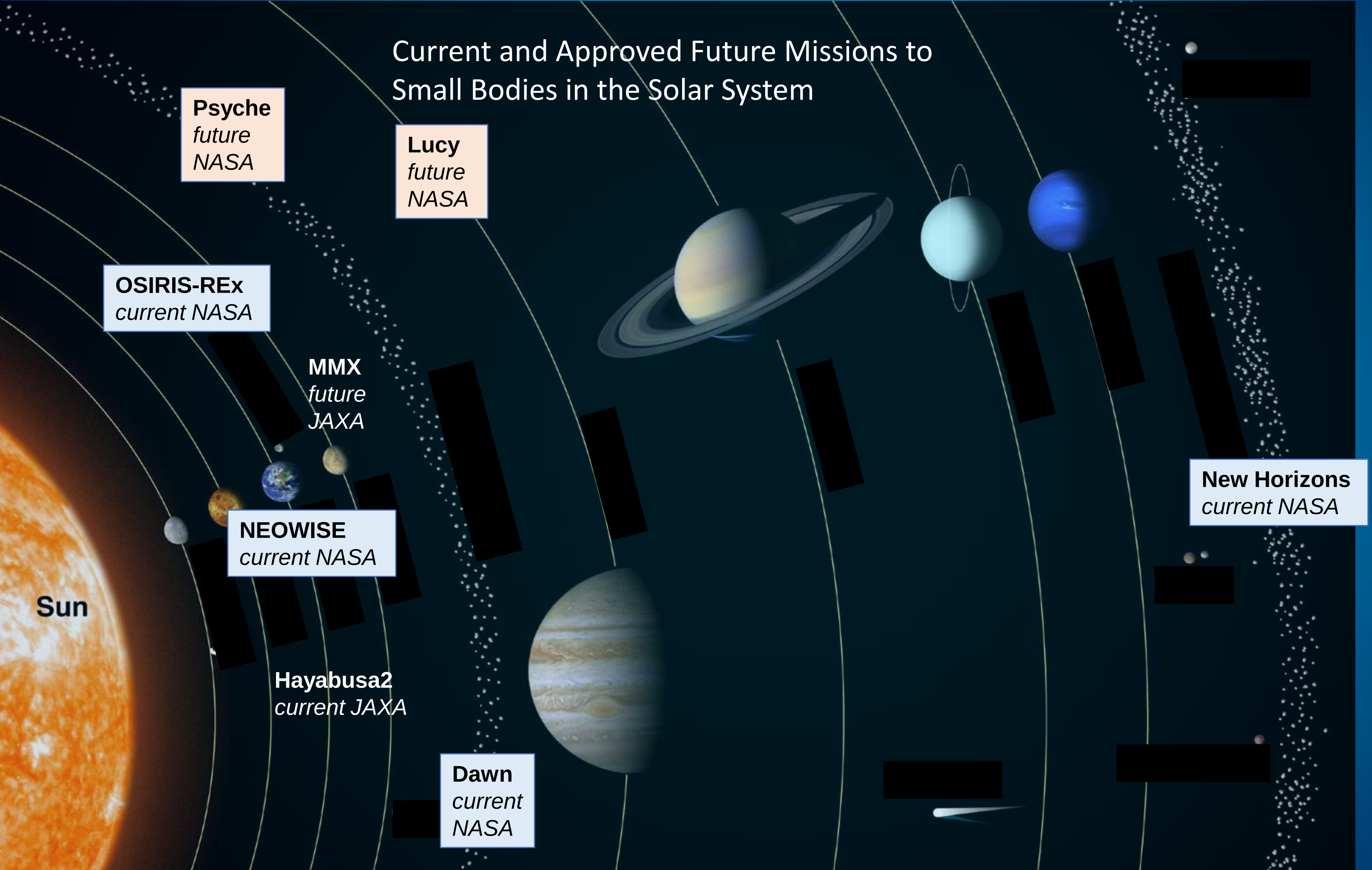
SWRI

Approved missions

- Martian Moons Explorer (JAXA)
  - Study Phobos, Deimos
  - Return sample of Phobos
  - Primary goal – determine origin of moons
    - Implications for formation, evolution of Mars

MRO false-color image of Phobos

Current and Approved Future Missions to Small Bodies in the Solar System



Summary

- Nine missions (including Rosetta) to 17 targets
  - NEOWISE doesn’t have specific targets, per se
- Only two of the nine (OSIRIS-REx and Hayabusa-2) are targeting similar bodies
- **This decade, we are beginning to study the available diversity**

Highlights from small bodies missions

- Pluto is a far more dynamic world than anticipated
- Ceres shows signs of cryovolcanism
- Rosetta measured composition of volatiles escaping from Comet 67P/C-G, new insight into interior structure of a comet

Supporting research and related activities

“The study of primitive bodies is also aided by ground-based telescopes and radar, which are highly useful in this field because the number of objects is so great that only a tiny fraction can be visited by spacecraft, and space missions are aided substantially by prior observation. Indeed, ground-based telescopes continue to discover unusual and puzzling objects in the Kuiper belt and elsewhere, and those objects might serve as the targets for future missions.”*

One of several areas where small bodies science has more need of non-mission funding than other areas -- not counting comments on Research & Analysis and Technology, the Primitive Bodies chapter devoted more attention to this than any other

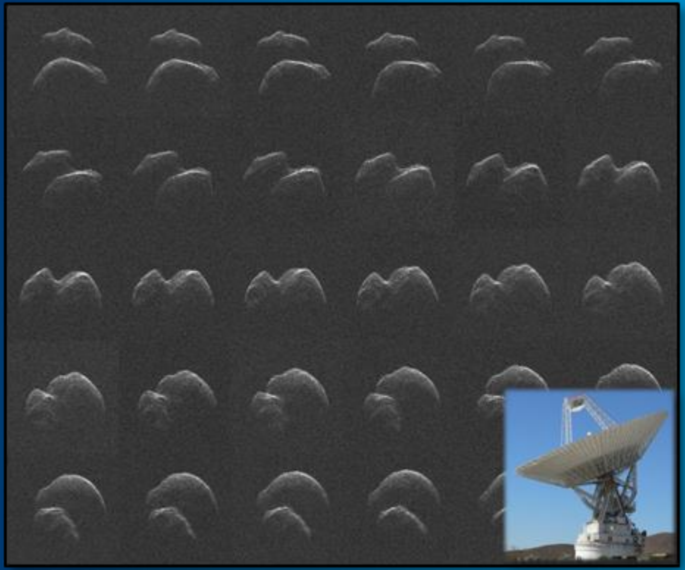
*Vision and Voyages, p. 87

Supporting research and related activities

- Field collection of meteorites
- Ground-based telescopes (including Arecibo)
- Sample curation facilities
- Laboratory facilities
- Research and analysis funding
- Technology development
  - ASRG
  - High-power electric propulsion

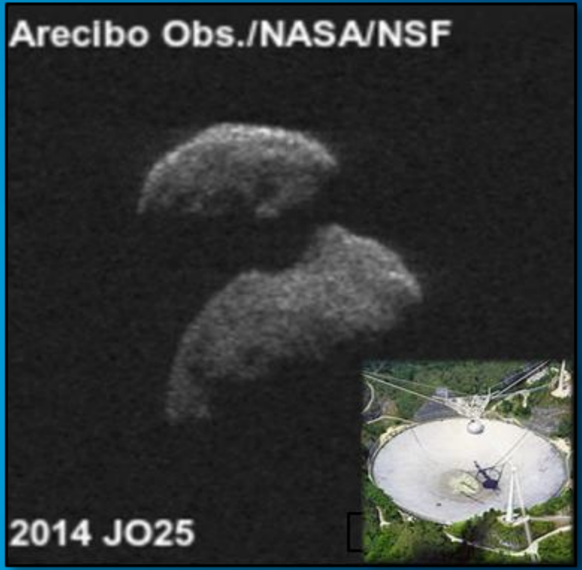
Collecting meteorites in Antarctica (ANSMET/K. Joy)

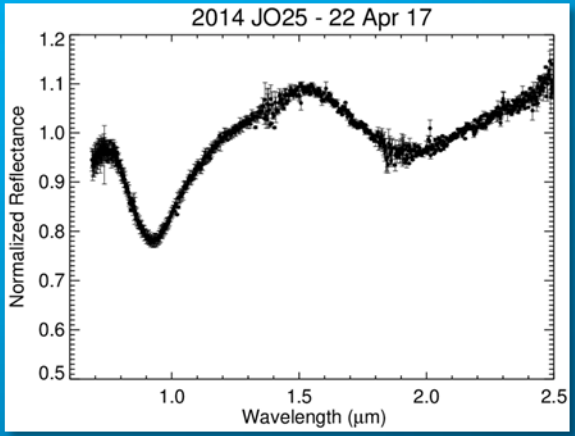
Recent example of coordinated use of ground-based assets



Goldstone Solar System Radar

- Asteroid 2014 JO_{25}
  - April 19, 2017
  - 1 km object, 4.6 lunar distances
- Detailed shape from radar
- Detailed spectroscopy from IRTF
  - Spectrum matches most common meteorites





NASA Infrared Telescope Facility

Concerns of the community

- Concerns about R&A
  - In particular, concerns about retaining the laboratory infrastructure needed to analyze returned samples
- Arecibo
- Concerns about how decisions are made to deviate from the Decadal Survey recommendations
  - Examples: extended cadence for Discovery and New Frontiers*, addition of Ocean Worlds to New Frontiers
  - Previous survey called for a formal decision-making process (p. 314)

***"If cuts to the program are necessary, the committee recommends that the first approach should be descoping or delaying flagship missions. Changes to the New Frontiers or Discovery programs should be considered only if adjustments to flagship missions cannot solve the problem." (Vision and Voyages, p. 275)**

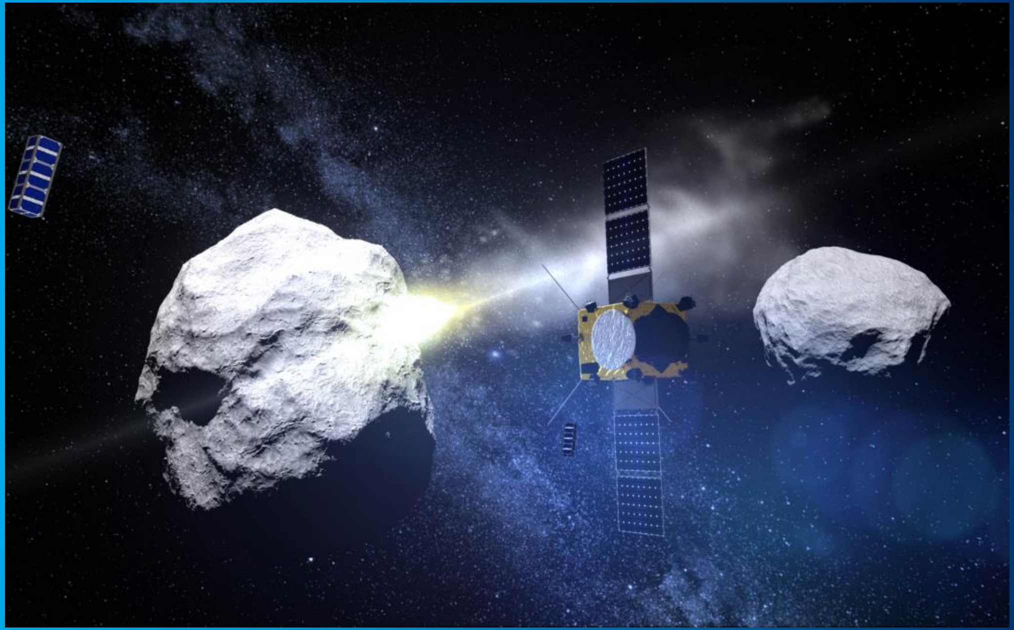
Planetary Defense

- Part of NASA Authorization Act
- Funded through SMD, but explicitly not considered by the Decadal Survey
  - Survey calls out 2010 NRC report on Planetary Defense*
  - While that report sets priorities for Planetary Defense, nothing equivalent to that or *Vision and Voyages* to establish relative priorities within SMD of Science and Planetary Defense goals

**Defending Planet Earth: Near-Earth-Object Surveys and Hazard Mitigation Strategies*

Planetary Defense missions

- NEO surveys address hazard detection, but also have science merit
  - An SBAG Science Objective is to characterize the architecture of the small bodies in the Solar System
  - Several ground-based surveys
  - NEOWISE only survey mission flown, but is reactivation of prior mission, not optimized
  - NEOCam in Extended Phase A for Discovery
- Hazard mitigation missions also provide science value
  - DART (and ESA counterpart AIM), under discussion, results depend on internal structure of target
  - OSIRIS-REx has mitigation as part of its rationale, studying details of Yarkovsky effect



Artist’s conception of ESA’s AIM mission watching NASA’s DART impact asteroid Didymos (ESA)

Planetary resources

- Mentioned, but not explicitly prioritized
- Resource exploration has strong scientific component to it
- Resources to be used for human exploration of interest to HEOMD, commercial entities interested in those and other resources
  - Long discussed, but increased private interest since 2013
- Issue for lunar, Mars exploration as well

Artist's conception (by Denise Watts) of asteroid mining from 1977 NASA study on asteroid mining (NASA)