

# Science Issues Discussion

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# Science Issues

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- ❑ Overview developed from SBAG-generated Decadal White Papers
  - ❑ Feel free to interrupt with questions/additions but remember I did not create the science issues – the white paper teams did.
  - ❑ For some questions, we learn by looking at ensembles of bodies; for others, we are interested in individual targets.
  - ❑ There is some cross-over between categories. Will have to be handled in a non-confusing way in the roadmap.
  - ❑ The questions posed in the white papers tend to be specific and not generally of a very broad nature.
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# Generic Questions

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- What is the population of any type of body?
  - What are the physical properties of this type of body?
  - What is its composition?
    - Does the surface composition inform us about the interior composition?
  - Where did these bodies form? How did they evolve dynamically?
  - How pristine are these bodies?
  - What interactions did they have with planets? How did this affect them? How did it affect the planet?
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# Small Satellites of the Solar System

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“Many of these objects are believed to be captured asteroids or Kuiper Belt objects: a spacecraft mission to them would thus yield information on an object that came from elsewhere in the Solar System.”

148 objects identified in this class

# Top-Level Scientific Questions

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- What is the compositional and dynamical relationship between the small satellites and other bodies in the Solar System, including the outer main asteroid belt, Hildas, Jupiter and Neptune Trojans, KBOs (including the scattered disk), Centaurs, comets (including those from the Oort cloud), and the main satellite systems?
    - Why do some small satellites appear to resemble P/D-type asteroids and others resemble C-type asteroids (e.g., Phoebe)?
    - Is this an intrinsic difference, an evolutionary difference, or some combination of the two?
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- What mechanism captured the outer irregular satellites, and how does this mechanism constrain planet formation processes in the outer solar system?
    - Were they captured from accretion regions near the giant planets during planet formation, or are they refugees from a massive primordial disk of comets that may have existed beyond the orbits of Uranus/Neptune?
    - Can outer irregular satellites be used to verify or rule out the predictions made by Solar System formation scenarios?
  - What is the relationship between the inner small moons of Saturn and its rings?
    - Are they compositionally related, and do the moons determine the morphology of the rings?
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- What determines the densities of the satellites?
    - Specifically, why is the density of many so low?
    - Are they rubble piles of loosely accreted material or material of a satellite that was broken apart and reaccreted?
  - What are the interior composition and structure of Phobos and Deimos?
    - Is there a dust ring associated with them, and can it reveal their composition?
  - How has the high number of collisions shaped the outer irregular satellites (e.g., can we use these bodies to probe the nature of icy planetesimals?)
  - How have the outer small satellites bombarded the main satellite systems?
    - What is their role in the chronology of the main satellites as derived through crater counts?
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# Note:

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- Physical properties of the satellites is not explicitly mentioned but implied in several of the questions.
    - Need to put this in explicitly in roadmap.
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# Near-Earth Objects

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“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.”

# Top-Level Scientific Questions

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- What is the compositional distribution of NEOs?
    - Need to understand and compensate for discovery selection effects.
    - How does bulk composition relate to surface mineralogy?
    - What is the effect of “space weathering”?
  - What is the range of NEO physical properties and how do they evolve?
    - What are the size-frequency and spin-state distributions?
    - Requires an understanding of impact processes, radiation processes and their timescales
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- What are the specific NEO source regions and sinks?
    - What are the dynamical mechanisms and their efficiencies for transferring objects from different regions in the main asteroid belt and elsewhere to the NEO region?
  - How can NEOs be used as resources?
    - Are the resources of NEOs accessible?
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# Ice Dwarf Planets

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“Our Solar System has many examples of a third type of ‘ice dwarf’ planet.”

# Top-Level Scientific Questions

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- What is the Solar System's inventory of ice dwarfs?
    - What are their gross characteristics: size, albedos, spin rates, shapes, pole orientations, surface compositions?
    - Which have atmospheres?
  - What is their taxonomy?
  - What accounts for their observable features?
    - What features are the result of "nature" and what of "nurture"?
      - What are primordial features and what features come from further evolution?
    - What is the evolution of their heliocentric orbits and spin axes?
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# Interplanetary Dust

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“The interplanetary dust complex is a compositionally and dynamically diverse population stemming from a range of sources.”

“The diverse nature of interplanetary dust makes its study both interesting and complex.”

# Top-Level Scientific Questions

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- What is the detailed composition of interplanetary dust?
    - Identify the compositional differences between interplanetary dust particles of cometary, asteroidal, and Kuiper belt origin. How does the composition vary within each source population and region?
    - What is the composition of interstellar grains sweeping through the solar system?
    - Are the sources of interstellar dust particles single stars or a galactic mixture?
  - What is the global structure of the cloud and how does it compare to exo-zodiacal clouds?
    - Does the Kuiper belt produce a cloud of cold dust similar to that seen around most other main sequence stars (cf. Vega)?
    - What is the structure of this outer zodiacal cloud?
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- How are interplanetary dust particles generated, how do they evolve dynamically, and what are the dominant loss mechanisms?
    - What is the collisional environment in the asteroid and Kuiper planetesimal belts?
    - How does the dynamical evolution of interplanetary dust particles affect their categorization into cometary- or asteroidal-type purely based on their orbits?
    - How important are inter-particle collisions, radiation pressure, and Poynting-Robertson drag, and what is their role in the production of  $\beta$ -meteoroids and nano-particles?
    - Which Near-Earth Objects (NEOs) are the parent bodies of our meteor showers? When were the meteoroid streams created? How did the meteoroid streams evolve to cause the meteor showers we now have at the Earth (and the Moon)?
    - What are the differences and similarities between the characteristics of NEOs and meteoroids?
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- What are the relative contributions of dust particles from each source to the zodiacal cloud as a whole?
    - What is the orbital and velocity distribution of dust particles in the inner solar system and what implications does this have for the impact threat to artificial satellites and the exploration of the lunar environment?
    - Would the collisional breakup of a major asteroid result in a collisional cascade and cause a significant flare in the brightness of the zodiacal cloud?
      - If so, how often does this occur?
    - How does the flux of interstellar dust through the solar system change over time as the Sun moves through the galaxy, the local hot bubble, and nearby molecular clouds?
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# Comets

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“Comets harbor the most primitive Solar System material, were the building blocks for the cores of the giant planets, transport water and organics (the seeds of life) throughout our planetary system, and possibly played a key role in terrestrial planet habitability.”

# Top-Level Scientific Questions

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- How did the Solar System form from the protoplanetary cloud – what were the physical and chemical conditions in the nebula, what was the nature of the solid materials in the nebula, and what role did mixing of material within the nebula play (*e.g.*, transport of material from small to large heliocentric distances and vice-versa)?
    - Were cometary nuclei formed as an agglomeration of amorphous H<sub>2</sub>O ice and dust?
      - Does such ice still exist in the interior of comet nuclei as they enter the inner Solar System?
      - Does it drive cometary activity?
    - Are the layers seen on comets 9P and 81P signs of a primitive formation process or massive internal activity in their later evolution?
    - What roles have fragmentation and collisional processes played in the formation of cometary nuclei?
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- What is the history of Solar System volatile and organic compounds?
    - Did amorphous H<sub>2</sub>O ice play a role in trapping super-volatiles in cometary ices?
  - What was the role of comets in the delivery of water to planets, particularly in the habitable zone and what does the distribution of primordial icy volatile material tell us about the evolution of habitable planets in extrasolar planetary systems?
  - How can measured comet chemistry be related to formation location or evolutionary processing history?
    - What roles do evolutionary processes (collisional, photon and particle irradiation, solar heating, mass loss, radioactivity) play?
  - What is the detailed physical structure of comets, and how does this relate to the mechanisms for cometary activity?
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# Centaur and Trans-Neptunian Objects

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“These small bodies carry dynamical and compositional clues to the history of our Solar System – they are the less-processed (but not pristine) remnants of the icy building blocks that formed the outer planets...”

# Top-Level Scientific Questions

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- What are the Physical Properties of TNOs?
    - What is the size distribution of TNOs , and how does the distribution change at the smaller sizes?
    - What are the masses, densities and tensile strengths of TNOs?
    - What is the interior structure of TNOs and how does that structure change with size?
  - How have major collisions changed the bulk structure and rotation states of these objects?
  - How many objects are in multiple systems? How do physical properties differ between a parent and its satellites?
    - What are the mechanisms for creating multiple systems?
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# Top-Level Scientific Questions

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- How is energy transported through the interior? What are the thermal conductivity, heat capacity, and porosity of these bodies?
    - What are the relative strengths of insolation, endogenic heating, and structural changes (e.g. water-ice crystallization) for determining the interior temperatures?
    - To what depths has significant heating occurred? How and when does cometary activity start in Centaurs (and potentially in all TNOs) and how does it differ from the kind of cometary activity seen in inner Solar System comets?
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- What are the compositions of TNOs?
    - What is the bulk composition of TNOs, and how do the materials seen on their surfaces reflect that composition?
    - What is the relative abundance of volatiles and water ice, and how does the composition vary as a function of other object properties?
    - What are the isotopic abundances, and how do they differ from such abundances in other parts of the Solar System?
    - How are icy and rocky material mixed inside these bodies – and at what length scale? How are different ices mixed?
    - Why are TNOs in the cold, classical population apparently different in observed quantities from the rest of the TNOs?
    - How did compositional gradients in the solar nebula and protoplanetary disk influence the final properties of the forming TNOs?
    - Are there “snow lines” in the protoplanetary disk for multiple volatile species and does that produce observable effects?
    - Are compositional differences driven by formation rate versus dynamical timescale, so objects forming closer to the Sun formed fast enough to get  $^{26}\text{Al}$ , or to have formed in a gassy nebula, while things further out accreted slower and thus had different materials to draw on?
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- What physical and chemical processes affect TNOs, and how?
    - How much does original composition influence the colors and spectra we see today? What are the dominant processes that would have changed these quantities?
    - What do reflectance differences among bodies tell us about their different histories? How important are surface chemistry, cosmic-ray exposure, irradiation, cometary activity, impact gardening, and endogenic heating for objects of various masses? What causes the variation in color between objects in the same dynamical subgroup? Is there a common origin for dark red-colored material in the Solar System?
    - Why do we see organics on some surfaces and not others? Is this variation primordial?
    - What ices exist on the surfaces of TNOs of various sizes? At what layers below the surface do more volatile species still exist?
    - Since crystalline ice is now seen in TNOs, what processes (e.g. irradiation, collisions) determine the crystalline-to-amorphous water ice ratio?
    - What role did liquid water play (if any) in the compositional development of the TNO interiors?
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- What is the dynamical structure of the trans-Neptunian region?
    - What are the relative populations of the resonant objects, the cold and hot classical objects, and the scattered disk objects (including the Centaurs)?
    - How do TNO orbits (in all dynamical classes) evolve on Myr and Gyr time scales?
    - What did planet migration do to the original mass in this region?
    - What are the dynamical pathways for TNOs to become Centaurs and thence inner Solar System Jupiter-family comets, and how efficient are these paths?
    - How often are Centaurs captured by giant planets?
    - How do collisions change the mass and structure of the trans-Neptunian region?
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# Asteroids

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“Even though asteroids represent only a tiny fraction of the total mass of the terrestrial planets, their large numbers, diverse compositions, and orbital distributions provide powerful constraints for planet formation models.”

# Top-Level Scientific Questions

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- What was the compositional gradient of the asteroid belt at the time of initial protoplanetary accretion?
    - What are the physical properties of asteroids?
    - How do surface modification processes affect our ability to determine this structure?
    - What is the population and compositional structure of the main asteroid belt today?
    - What does the composition (mineralogy/chemistry) of asteroids tell us about the redox and thermal state/gradient of the early solar system?
    - How do dynamics and collisions modify this structure over time?
    - The degree of mixing/transport in the asteroid belt offers a glimpse into solar-system wide transport. Were TNOs implanted in the outer asteroid belt and did differentiated asteroids evolve from the inner solar system?
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- 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 asteroidal families are favorably placed in the main asteroid belt (MB) to be represented in meteorite collections? Which are in dynamical proximity for Yarkovsky transfer and MB resonances that serve as likely sources of NEOs?
    - What asteroidal bodies are geochemically linked?
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- What do asteroids tell us about 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 (planetary surfaces and fragments of protoplanets) reveal about the earlier size distribution of objects in the MB?
    - What do meteorites tell us about formation and evolution processes of these bodies? How well do they sample the population of primitive bodies in the solar system?
    - What can primitive meteorites tell us about the first stages of planetesimal accretion?
    - What are the benchmarks for early solar system conditions and processes shaping its evolution?
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- What are the characteristics of asteroids as individual worlds?
    - How do thermal-related processes such as differentiation, magnetism (remnant from an ancient core dynamo), volcanism, and hydrothermal alteration proceed?
    - What are the characteristics of water-rich and/or hydrated asteroids? How do hydrothermal processes drive internal evolution, the development of brines, and formation of organic material? Do the variations of water-rich spectral classes reflect compositional stratification?
    - What are the similarities and differences between small (and difficult to observe) mainbelt asteroids and comparably sized NEOs? Can NEOs serve as surrogates for the properties of small MBAs?
    - What are the densities of the large asteroids and family members?
    - What are the key surface processes (e.g., impact cratering, tectonics, regolith development / movement into "ponds", and space weathering) that act on small bodies?
    - How do these processes vary with composition, gravity, and solar distance?
    - What is the relationship between composition and surface roughness of asteroids as seen in radar polarization data? What are the implications of this for porosity, mineral cleaving and strength of these objects?
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# Enabling Technologies

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There was a set of enabling technologies which were called out in most of the white papers.

# Propulsion

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- Especially for the outer Solar System, low-thrust propulsion will be enabling for lower-cost missions.
    - For outer Solar System, nuclear propulsion is probably needed
    - So far electric propulsion has seen only limited use (DS1 and Dawn) and more work needs to be done for this technology to be routine
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# Navigation

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- Autonomous Guidance, Navigation & Control systems should be developed
    - Targets are of unknown size and shape and the orbit can be very uncertain.
  - Low cost and longer distance LIDAR should be developed
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# Telecommunications

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- Need to be certain there is enough DSN capabilities
    - Either maintain 70m dishes or build more 34m dishes
    - Perhaps can use clusters of 5m dishes – suitable for some things but not good for some navigational issues
  - Need higher bandwidth for larger heliocentric distances
    - Should develop higher bandwidth, low-power transmitters/receivers, such as optical communications
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# Instrumentation

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- Need lighter-weight wide-field imagers, better spectrometers, etc.
    - Landers will require miniature instruments with capabilities similar to or better than current instruments
    - Wide-field will allow for seeing fainter targets
    - Need to develop reliable dust protection for operating in situ on a surface or in a coma.
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# Power Systems

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- More efficient Solar Arrays will allow for smaller, lighter arrays
    - Save mass and size to save  $\Delta V$
    - Easier to maneuver in proximity to a body
  - The outer Solar System will require nuclear power
    - $^{238}\text{Pu}$  supply currently low
    - Need to develop ASRGs to produce more power from less plutonium
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# Sampling mechanisms and return technology

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- Sampling technology needs to be developed and tested
    - Need tools to work with porous fluffy bodies (comets), harder, larger bodies (asteroids, satellites) and extremely fragile, small bodies (dust particles)
  - Once samples are obtained, need to be able to return them to Earth and handle them in a lab without harming the sample
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# Telescopes

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- Need more access to large telescopes and capabilities for working with moving targets
    - PanSTARRS and LSST will be productive for finding targets but will need follow-up
      - Will require large telescope time – need to assure that this is available to the planetary community
    - JWST and ALMA will be excellent tools
      - Need to ensure they can track planetary bodies
      - Need to deal with small solar elongations
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