# Exploration Strategy for the Ice Dwarf Planets 2013-2022

SBAG Community White Paper


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## Executive Summary

The past decade saw the discovery of many ice dwarf planets, a new category distinct from terrestrial and giant planets. We propose this strategy for their investigation during 2013-2022:

1. NASA should encourage and support ground- and space-based observations along with associated theoretical and laboratory work to investigate the ice dwarfs as a population, to motivate missions to individual objects and to provide context for mission results.
2. A New Frontiers class mission to an unexplored ice dwarf should be a candidate for NASA AOs during the next decade. The Haumea system could be a particularly compelling target.
3. NASA should flight-qualify ASRG power systems, secure an adequate supply of $^{238}$Pu, and develop the long-lived, low-mass, low-power instruments and flight systems necessary to enable new missions to the edge of the solar system.


## I. Subdiscipline Overview

Our solar system has 4 rocky, terrestrial planets, plus, further from the Sun, 4 gas-rich giant planets. All have been visited by spacecraft, providing a wealth of detailed information. The multiple examples of each type enable comparative planetology techniques to advance our knowledge of these 2 classes of planets. But these 2 are not the only classes. Our outer solar system has many examples of a third type of "ice dwarf" planet*, the focus of this white paper. Spacecraft have visited none, so our understanding lags far behind what is known about the other types. For decades, Pluto was seen as an isolated instance, frustrating comparative studies. Recent discoveries of many more (Table 1), open the door to comparative planetology of a new planet class, with a distinct suite of interior, surface, and atmospheric processes, and the ability to offer new insights into the history of our solar system and the workings of planetary systems in general.

**Table 1.** Likely Outer Solar System Ice Dwarf Planets ($H_V < 4$).

| Object | <*a*> (AU) | <*e*> | <*i*> (°) | $r_{2020}$ (AU) | Radius (km) | Reported satellites | Surface ices |
|---|---|---|---|---|---|---|---|
| Eris | 67.9 | 0.45 | 43 | 96 | 1300 | 1 | $CH_4$+ |
| Pluto | 39.5 | 0.24 | 16 | 34 | 1190 | 3 | $CH_4$, $N_2$, CO |
| Charon | " | " | " | " | 600 | | $H_2O$, $NH_3$ |
| Makemake | 45.6 | 0.16 | 28 | 53 | 750 | | $CH_4$+, $C_2H_6$ |
| Haumea | 43.1 | 0.21 | 26 | 50 | 580 | 2 | $H_2O$ |
| Sedna | 508 | 0.85 | 11 | 84 | <900 | | $CH_4$, $N_2$ |
| 2007 $OR_{10}$ | 67.2 | 0.47 | 34 | 88 | | | |
| Orcus | 39.5 | 0.25 | 21 | 48 | 470 | 1 | $H_2O$ |
| Quaoar | 43.4 | 0.04 | 9 | 43 | 450 | 1 | $H_2O$, $CH_4$? |
| (55636) 2002 $TX_{300}$ | 43.3 | 0.13 | 27 | 43 | <350 | | $H_2O$ |
| (55565) 2002 $AW_{197}$ | 47.3 | 0.13 | 26 | 45 | 370 | | $H_2O$ |
| (202421) 2005 $UQ_{513}$ | 43.4 | 0.15 | 27 | 48 | | | |
| (208996) 2003 $AZ_{84}$ | 39.5 | 0.17 | 16 | 44 | 340 | 1 | $H_2O$ |
| 2007 $UK_{126}$ | 73.8 | 0.50 | 21 | 42 | | 1 | |
| Ixion | 39.5 | 0.25 | 17 | 39 | 330 | | |
| (145452) 2005 $RN_{43}$ | 41.6 | 0.03 | 19 | 41 | | | |
| (55637) 2002 $UX_{25}$ | 42.7 | 0.14 | 20 | 40 | 340 | 1 | $H_2O$ |
| (174567) 2003 $MW_{12}$ | 45.8 | 0.15 | 21 | 46 | | | |
| Varuna | 43.0 | 0.05 | 15 | 44 | 250 | | |

**Table notes:** <*a*>, <*e*>, and <*i*> are mean semimajor axis, eccentricity, and inclination with respect to the invariable plane over a 10 Myr integration. Distance from the Sun during 2020 is $r_{2020}$. Radius estimates are mostly from Stansberry et al. (2008). "$CH_4$+" indicates a contaminant, possibly $N_2$, implied by $CH_4$ band shifts.

NASA's New Horizons spacecraft will fly through the Pluto system in 2015 (Young et al. 2008). This first up-close reconnaissance will propel the field forward dramatically, revealing as-yet unanticipated processes, raising a host of new questions, and attracting new researchers to investigate this type of planet. However, New Horizons will only provide a snapshot of one such system at one point in its 2.5 century seasonal cycle. The real advances in understanding ice dwarfs as a class will come from long term remote sensing of, and ultimately spacecraft exploration of many more examples, to

*The IAU proposes calling these "plutoids" but the term is not widely accepted by the scientific community.

understand their diversity, their shared features, and the processes which act on them. The scientific community studying ice dwarfs is currently small, but it will grow much larger over the next decade as a result of the New Horizons encounter, missions to related objects, and new observational facilities.

*Related Populations*

Related populations provide indispensable context for understanding ice dwarfs, in particular icy satellites of giant planets, Triton, Ceres, smaller transneptunian objects, Centaurs, comets, and asteroids. Scientific boundaries between ice dwarfs and these other populations can be nebulous and even contentious. Lacking space to address these populations in adequate detail, we briefly summarize their connections to ice dwarfs and list relevant white paper leads [in red].

Icy satellites share many features with ice dwarfs, such as sizes, bulk compositions and interior structures, differentiation into rocky cores and convecting ice mantles, cryovolcanism, photolytic/radiolytic ice chemistry, as well as possibilities of interior oceans, hydrothermal systems, and astrobiologically interesting environments (Hussmann et al. 2006). Exploration of icy satellites by spacecraft such as Voyager, Galileo, and Cassini has shaped our thinking about processes likely to be at work on ice dwarfs. [Phillips, Collins, Lunine, Hofstadter].

Triton is thought to be a former ice dwarf, now orbiting Neptune (e.g., Agnor & Hamilton 2006). Like Pluto, Eris, and Makemake,Triton has seasonally-mobile surface deposits of volatile ices, specifically $N_2$, $CH_4$, and CO (Cruikshank et al. 1993). Their sublimation supports a thin atmosphere, like that of Pluto (e.g., Elliot et al. 2000; Lellouch et al. 2009). Voyager images of Triton's distinctive, youthful surface (e.g., Croft et al. 1995; Schenk & Zahnle 2007) inspire expectations of comparably active geology on other ice dwarfs. [Hansen].

Ceres inhabits the asteroid belt, unlike ice dwarfs orbiting beyond Neptune. Its surface is largely devolatilized from proximity to the Sun, but it is thought to have an ice-rich mantle and rocky core (Thomas et al. 2005), and perhaps a seasonal atmosphere (A'Hearn & Feldman 1992). Its proximity offers a far more accessible setting to study interior processes which may be shared by other ice dwarfs. NASA's Dawn spacecraft will begin orbiting Ceres in 2015. [Rivkin].

Ice dwarfs are clearly related to smaller transneptunian bodies, and by extension, Centaurs and ecliptic comets. They formed in similar regions, from similar materials, and experienced similar dynamical, collisional, and thermal evolution environments. In much the same way, Ceres shares kinship with asteroids. Study of these populations is crucial for understanding formation circumstances and histories of ice dwarfs, as well as their present-day environments. [Fernández, Weaver, Britt].

## II. Top-Level Scientific Questions

Three major questions need to be addressed to understand ice dwarf planets as a class. The methods of comparative planetology involve assessing observable differences and similarities and linking them to formation and/or environmental conditions. Prerequisites are discovery and characterization of the objects themselves, identification of correlations and boundaries between observable characteristics, and linking these to specific initial conditions or to the action of specific processes. Ultimately, spacecraft must explore enough examples to encompass their diversity. This last step will take many decades, but progress can still be made on these questions:

*Question 1. What is the solar system's inventory of ice dwarfs?*

Brown (2008) estimates some 2 to 5 large ice dwarfs remain undiscovered, owing to substantial survey coverage gaps, especially in the southern sky and in the galactic plane. The holdouts must be discovered to be available for study. Wide-area survey facilities will play a valuable role in finding them and determining their heliocentric orbits. With its southern hemisphere site and large aperture, LSST will be especially well-suited for this job (e.g., Ivezić et al. 2008).

A variety of observational techniques can reveal the gross characteristics of ice dwarfs, such as sizes, albedos, spin rates, shapes, pole orientations, surface compositions, and the presence of atmospheres. Satellites can be discovered, their orbits determined, and the resulting system masses used to constrain bulk densities. Masses can also be estimated from the assumption of fluid body equilibrium shapes and photometric lightcurves. As will be discussed in Section III, access to world-class observing capabilities is key to obtaining this information.

*Question 2. What is their taxonomy?*

As we characterize ice dwarfs, it is natural to sort them accordingly, looking for patterns, correlations, and break points. For example, there seem to be size and thermal thresholds for retention of surface volatile ices (e.g., Schaller & Brown 2007). Size thresholds are also anticipated for differentiation (e.g., McKinnon et al. 2008) and for ongoing geological activity. More such patterns (and exceptions) will emerge, possibly involving the presence of atmospheres or satellites, rotation rates, obliquities, bulk densities, compositions and phase states of surface ices, dynamical history, albedo/compositional heterogeneity, etc. Classifications may change. For instance, Triton, Pluto, Eris, and Makemake, with abundant $CH_4$ ice on their surfaces, are currently seen as a logical set. But with detailed data from space probes, other aspects could become more salient. Terms like “ice dwarf” and “dwarf planet” could even become obsolete.

*Question 3. What accounts for their observable features?*

The field needs to mature from descriptive exploration to understanding the causes of observable properties, teasing apart the effects of “nature” and “nurture”, and unfolding the actions of processes over time to reconstruct history. Early events with potentially observable consequences include differences in initial composition, rate of accretion, early heating by short-lived radionuclides like $^{26}$Al, giant impacts, tidal damping of satellite orbits (and possible coalescence), early evolution of heliocentric orbits (including possible close encounters with giant planets), convection, partial melting, and differentiation. Ongoing processes can produce diversity as well. Sun-driven loss of volatiles and photolysis are among the most obvious of these. Effects of dust and larger impactors call for a better understanding of the Kuiper belt environment. Proximity to the heliopause and associated exposure to energetic charged particle radiation can also play a role, through radiolysis and sputtering [Cooper]. Better understanding of long term solar output, cosmic ray fluxes, and the local interstellar medium will all help.

Seasonal sublimation and condensation of volatile ices is a key process shaping the surfaces of some larger ice dwarfs. To understand volatile transport cycles we need to understand the evolution of heliocentric orbits and spin axes, along with possible re-supply of volatiles from interiors or other sources. We also need to know more about the thermodynamic and mechanical behaviors of volatile ice mixtures.

What constitutes an observable feature of an ice dwarf needs to mature as well. Spacecraft exploration is crucial, enabling us to study things like crater statistics and surface ages, global or regional tectonic systems (i.e., extensional versus compressional evolution, faulting patterns indicative of tidal spin-down, or evidence of solid state convection), stratigraphy exposed by impacts, relict deposits evidencing polar wander, aeolian landforms indicating past thicker atmospheres, and cryovolcanism (a mechanism for re-supply of surface volatiles and a clue to the nature of subsurface activity). Ideas of what spacecraft should be looking for at ice dwarfs are likely to evolve dramatically in the wake of discoveries by New Horizons and Dawn. The possibility of liquid water in ice dwarf interiors, potentially detectable by magnetic induction, may turn them into important sites for future astrobiological exploration.

## III. Required Research and Research Facilities

Comparative planetology of the rich sample of ice dwarfs provided by nature is our top priority. Spacecraft will visit Pluto and Ceres in 2015. Voyager 2 encountered Triton in 1989. This tiny "explored" sample needs to grow, but considering spacecraft development and travel times, no more will be explored before 2022, so remote observation is crucial in the interim.

The small sizes (~1000 km diameters) and great distances (30+ AU) of the unexplored ice dwarfs make them challenging targets. Brightnesses at *V* band are typically 17$^{th}$ to 21$^{st}$ magnitude. Photometric/lightcurve studies can be done at smaller telescopes, but many observational techniques require access to top-tier facilities in the league of HST, Keck, and VLT. Sensitive systems are needed to record visible and near-infrared spectra of reflected sunlight to study surface compositions. High spatial resolution is needed to detect and monitor satellites, to constrain sizes and shapes, and to map surface albedo features. High resolution infrared spectroscopy can monitor methane in μbar atmospheres. Thermal infrared emission fluxes in the μJy range can constrain sizes, surface temperatures, albedos, and thermal inertias. At present, only Herschel can do this, although ALMA and JWST will eventually provide valuable capabilities for observing thermal emission. A Space Interferometer Mission (SIM) could measure ice dwarf sizes and shapes directly. In its current design, NASA's "SIM Lite" mission could do this down to about 20$^{th}$ magnitude (Li et al. 2009). If NASA selects this potentially valuable mission, it should ensure the flight software is capable of tracking moving solar system targets.

Many observational needs are beyond the capabilities of IRTF, yet call for sampling at temporal cadences not easily accommodated elsewhere. We endorse upgrades or improvements to the IRTF to enable it to do more types of observations on more ice dwarfs. Shorter term cadences include rotational periods to assess longitudinal variability and satellite orbital periods to determine orbits and tidal locking. Longer term cadences are needed to detect precession, assess latitudinal surface variations, monitor seasonal volatile transport and atmospheric evolution, and search for transient phenomena. Mutual events between objects and satellites call for campaigns of observations at specific times: Pluto had mutual events during the 1980s and will have them next around 2100; Haumea is having them now. Stellar occultations are valuable for determining accurate sizes, and to search for and monitor atmospheres. They call not just for observations at specific times, but also from specific locations. SOFIA will be immensely valuable for occultation work. Ideally, many telescopes could be deployed to get multiple occultation chords to better constrain a body's shape and size, and also to allow for ephemeris uncertainties. These examples show that access to a variety of telescope facilities is needed on a range of timescales.

In addition to telescope access, funding is needed for data acquisition and analysis and for related research. Examples include laboratory work on the thermodynamic, chemical, mechanical, and optical properties of outer solar system materials and mixtures at appropriate temperatures and pressures, and of the effects of energetic radiation. Theoretical studies of ice dwarf interiors and thermal evolution are also a priority to refine conditions for liquid water beneath their surfaces, and to assess the astrobiological potential of those environments.

## IV. Technology Needs

Flyby missions to dwarf planets in the Kuiper belt can be conducted under New Frontiers. Future larger-class missions such as tours with multiple flybys or orbiters, or even Discovery-class fast flybys, all await enabling technologies. Such technologies will be applicable across a wide spectrum of robotic mission categories, not just ice dwarfs. Technological development work during the next decade is essential.

Radioisotope decay is the only way to power long-duration missions far from the Sun, but $^{238}$Pu is in critically short supply (Hoover et al. 2009). The Advanced Sterling Radioisotope Generator (ASRG) design offers ~29% efficiency, almost a five-fold increase in power per kg of $^{238}$Pu fuel used compared with existing Radioisotope Thermoelectric Generators. ASRGs need to be tested and flight qualified. Production of $^{238}$Pu also needs to be restarted.

Ice dwarfs orbits have substantial uncertainties, especially in range. At rendezvous, the correspondingly elongated positional error ellipses can consume valuable spacecraft resources, as shown by New Horizons Pluto encounter planning. It would be valuable if long distance ranging could be achieved via RADAR or other techniques. Similar benefits could be realized by advanced guidance, navigation, and control (GN&C) systems to autonomously acquire targets, update knowledge, and adjust instrument pointing/sequence timing. Orbiters will require even more sophisticated autonomous GN&C. Two multiple-rendezvous SEP missions flown in the inner solar system, DS1 and Dawn, show the need for improved mission and trajectory planning. Nuclear electric propulsion would be required for similar tours in the outer solar system [Noble].

Long-lived instrumentation and flight systems with even lower mass, cost, and power requirements are needed, especially if Discovery class missions to the outer solar system are to ever become viable. Gimbaled sensors could greatly enhance science return by decoupling the image planning process from the engineering needs of spacecraft body pointing.

Deep space communication is essential for returning data from distant encounters. More or less technology development will be needed, depending on NASA's chosen solution. Extending the life of the Deep Space Network 70 m antennas is a simple but costly way to support deep space missions. Concepts such as arrays of micro-antennas (e.g. 5 m) are attractive from a cost and data return standpoint but provide less navigational capability, necessitating greater investment in interferometric or optical methods. Optical communications offer tremendous bandwidth and possibly navigational capability, but are as yet unproven, and might not even be feasible beyond Mars. With a New Horizons Kuiper belt encounter anticipated in the late 2010s, the radio capabilities of the Deep Space Network must be maintained for the time being.

# V. Major Mission Priorities

## *Flagship Class Missions*

It is premature to propose Flagship class ice dwarf missions. Visiting most ice dwarfs will take many decades, even using technologies not yet developed. A Flagship class tour of many ice dwarfs and smaller transneptunian objects (or an orbiter or lander in a particularly interesting system) could yield a spectacular scientific bounty, but is not yet feasible. NASA should identify the impediments to such missions and develop promising technologies to overcome them.

## *New Frontiers Class Missions*

A New Frontiers mission using already-proven technology is capable of visiting a small number of transneptunian bodies, as well as doing valuable science during giant planet flybys on the way. We recommend that NASA launch such a “New Horizons 2” type mission to an unexplored ice dwarf during the coming decade, to arrive the following decade.

The Haumea system could be a particularly compelling target for such a mission. It is very different from Pluto, having a rapid spin, elongated shape, high density, unique satellite system, unusually uncontaminated crystalline $H_2O$ ice surface (without volatile ices), and being the center of a collisional family (Brown et al. 2007; Ragozzine & Brown 2009; Lacerda 2009; Pinilla Alonso et al. 2009). With its extreme properties, the Haumea system offers a high potential knowledge gain with insights perhaps not available from more ordinary ice dwarfs.

Other ice dwarfs are also worth exploring, especially if they can be coupled with other interesting Kuiper belt or giant planet targets. For instance, $CH_4$-rich Makemake offers a Pluto-like body near aphelion instead of near perihelion, with corresponding insights into seasonal cycles. It has also perhaps not suffered a giant impact, unlike Pluto and Haumea. Objects intermediate in size between small, relatively pristine transneptunian objects, and large, presumably differentiated ice dwarfs could illuminate conditions for differentiation and geological activity. A mission to such an object using a Neptune flyby would be particularly attractive, since Triton is probably a former ice dwarf, and its surface is likely to have changed since 1989.

## VI. Discovery Science Goals

With currently available technology, a Discovery class mission cannot add another ice dwarf to the “explored” tally. Advances which could enable such a thing would be of great value and we support their development (see Section IV).

A Discovery class space-based telescope could make a valuable contribution to addressing ice dwarf characteristics and taxonomy, if it was sensitive enough to study them. Monitoring spectral reflectance at wavelengths inaccessible from the ground, such as in the ultraviolet and just beyond 2.5 μm, would expand our knowledge of surface compositions, spatial heterogeneities, and seasonal behaviors. High spatial resolution imaging could map albedo features and track satellites, leading to spin axes, system masses, bulk densities, and predictions for mutual events. Observations of stellar appulses could yield primary/satellite mass ratios. [Wong].

## VII. Balancing Priorities

Future ice dwarf missions depend on increasing our knowledge of these objects as a class. Competing needs to broaden the sample and to explore individual objects in greater detail must be balanced so that neither is excluded. A balance also needs to be struck between development of enabling technologies and making use of those available today. Top priorities are:

1. Access to a range of telescope capabilities is essential to complete the inventory of ice dwarfs, determine their gross characteristics, and monitor their seasonal behavior. NASA's best course of action is to ensure adequate community access to facilities such as HST, Keck, VLT, Herschel, etc., to work for access to and ensure moving target tracking capabilities in future projects such as JWST, ALMA, SIM, and future large aperture ground-based telescopes still on the drawing board, and to support improvements to the IRTF. Funding support is needed for observational, laboratory, and theoretical studies to inform mission development activities and ensure availability of researchers, whether or not there is a new mission start for ice dwarfs. Additional increments are needed for analysis of New Horizons and Dawn data.
2. A New Frontiers class mission to an unexplored ice dwarf is worth pursuing using existing, proven technology. In particular, the Haumea system could significantly advance understanding of the diversity and the role of collisions in ice dwarf formation and evolution.
3. New technologies need to be developed to enable more ambitious spacecraft exploration. Development and demonstration of these capabilities, including radioisotope power systems and low mass avionics and instruments, is given a higher priority during this decade than Flagship or Discovery class missions.

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