

**A White Paper on Pluto Follow On
Missions:**

**Background, Rationale,
and New Mission Recommendations**

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Signatories In Alphabetical Order:

**Caitlin Ahrens,
Michelle T. Bannister,
Tanguy Bertrand,
Ross Beyer,
Richard Binzel,
Maitrayee Bose,
Paul Byrne,
Robert Chancia,
Dale Cruikshank,
Rajani Dhingra,
Cynthia Dinwiddie,
David Dunham,
Alissa Earle,
Christopher Glein,
Cesare Grava,
Will Grundy,
Aurelie Guilbert,
Doug Hamilton,
Jason Hofgartner,
Brian Holler,
Mihaly Horanyi,
Sona Hosseini,
James Tuttle Keane,
Akos Kereszturi,
Eduard Kuznetsov,
Rosaly Lopes,
Renu Malhotra,
Kathleen Mandt
Jeff Moore,
Cathy Olkin,
Maurizio Pajola,
Lynnae Quick,
Stuart Robbins,**

**Gustavo Benedetti Rossi,
Kirby Runyon,
Pablo Santos Sanz,
Paul Schenk
Jennifer Scully,
Kelsi Singer,
Alan Stern,
Timothy Stubbs,
Mark Sykes,
Laurence Trafton,
Anne Verbiscer,
Larry Wasserman,
and
Amanda Zangari**

Executive Summary

The exploration of the binary Pluto-Charon and its small satellites during the New Horizons flyby in 2015 revealed not only widespread geologic and compositional diversity across Pluto, but surprising complexity, a wide range of surface unit ages, evidence for widespread activity stretching across billion of years to the near-present, as well as numerous atmospheric puzzles, and strong atmospheric coupling with its surface. New Horizons also found an unexpected diversity of landforms on its binary companion, Charon. Pluto's four small satellites yielded surprises as well, including their unexpected rapid and high obliquity rotation states, high albedos, and diverse densities.

Here we briefly review the findings made by New Horizons and the case for a follow up mission to investigate the Pluto system in more detail.

As the next step in the exploration of this spectacular planet-satellite system, we recommend an orbiter to study it in considerably more detail, with new types of instrumentation, and to observe its changes with time. We further call for the in-depth study of Pluto orbiter missions as a precursor to the 2023 Planetary Science Decadal Survey.

Introduction

The first exploration of Pluto was motivated by (i) the many intriguing aspects of this body, its atmosphere, and its giant impact binary-planet formation; as well as (ii) the scientific desire to initiate the reconnaissance of the newly-discovered population of dwarf planets in the Kuiper Belt (e.g., Belton et al. 2003). That exploration took place in the form of a single spacecraft flyby that yielded an impressive array of exciting results that have transformed our understanding of this world and its satellites (Stern et al. 2015), and which opened our eyes to the exciting nature of the dwarf planet population of the Kuiper Belt. From Pluto's five-object satellite system, to its hydrocarbon haze-laden $\text{N}_2\text{-CH}_4\text{-CO}$ atmosphere, to its variegated distribution of surface volatiles, to its wide array of geologic expressions that include extensive glaciation and suspected cryovolcanoes, plus the tantalizing possibility of an interior ocean, the Pluto system has proven to be as complex as larger terrestrial bodies like Mars (e.g., Moore et al. 2016; Gladstone et al. 2016, Grundy et al. 2016; Olkin et al. 2017; Stern et al. 2018), and begs for future exploration.



**The spectacular Pluto-Charon binary in montage
from the New Horizons color imager.**

Owing to Pluto's high obliquity (and consequently, current-epoch southern hemisphere polar winter darkness) and the single spacecraft nature of the New Horizons flyby, only ~40% of Pluto and its binary satellite, Charon, could be mapped at high resolutions (10 km/pixel or less). Additionally, due to their distances from New Horizons at closest approach, none of Pluto's small moons could be studied at high resolution during the flyby. Furthermore, studies of the time variability of atmospheric, geologic, and surface-atmosphere interactions cannot be practically made by additional flybys.

We find that these limitations, combined with Pluto's many important, open scientific questions, strongly motivate a Pluto System Follow On (PFO) orbiter mission.

The Case for a Pluto Follow On Mission

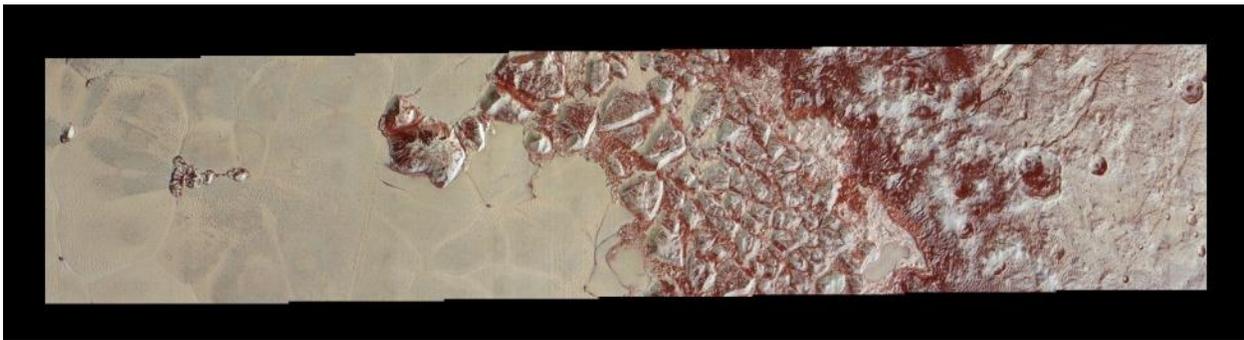
The reasons to return to Pluto are multifold, as we summarize here. We begin with Pluto's surface and interior, then go on to its atmosphere, its satellites, and finally to Pluto's context in the Kuiper Belt.

1. Geological and Compositional Diversity and Geophysical Processes on Pluto. The New Horizons encounter revealed evidence for a world of ongoing, diverse geological activity, similar in extent and variety to Mars (e.g., Moore et al. 2016; Stern et al. 2018). While certain aspects of Pluto's complex geology were predicted (e.g., Moore et al. 2015), the diversity of activity and novel processes were not anticipated. These include: (i) ancient and ongoing N₂-ice glacial activity, (ii) convective overturn in a vast, kilometers-thick, N₂-rich ice sheet contained in an ancient basin, (iii) multiple large, potentially cryovolcanic constructs, (iv) aligned blades of methane ice hundreds of meters tall and stretching across hundreds of kilometers, (v) an extreme range of surface ages based on crater spatial densities, and (vi) evidence for a surviving cold ocean under Pluto's surface (e.g., Howard et al. 2017, McKinnon et al. 2016, Moore et al. 2018, Nimmo et al. 2016). Evidence for these and other features such as regional compositional and color diversity (e.g., Grundy et al. 2016, Protopapa et al. 2017), resulted from the high-resolution observations made by New Horizons during its brief flyby in 2015.



Pluto in enhanced color showing the vast Sputnik Planitia (SP) N₂-dominated glacier and surrounding mountain ranges.

However, New Horizons only studied about 40% of Pluto's surface in detail; the rest was observed either at very low resolution on the anti-encounter hemisphere or obscured by darkness in the southern regions due to winter darkness. Further, New Horizons only studied Pluto at high resolution for a period of <24 hours, and it carried a powerful but limited suite of first reconnaissance instrument capabilities. To understand the surface of Pluto there is a clear need to: (i) map all remaining terrains (e.g., using Charon light or active sensors in polar darkened terrains); (ii) obtain higher resolution geological and compositional maps; (iii) obtain datasets from new kinds of instruments such as ground penetrating radars, mass spectrometers, thermal mappers, and altimeters; (iv) obtain well-resolved gravity measurements; and (v) study time-dependent phenomena.



High-resolution images at the Sputnik Planitia (SP) boundary, with chaotic mountain blocks and possible dunes and wind streaks on the SP glacier.

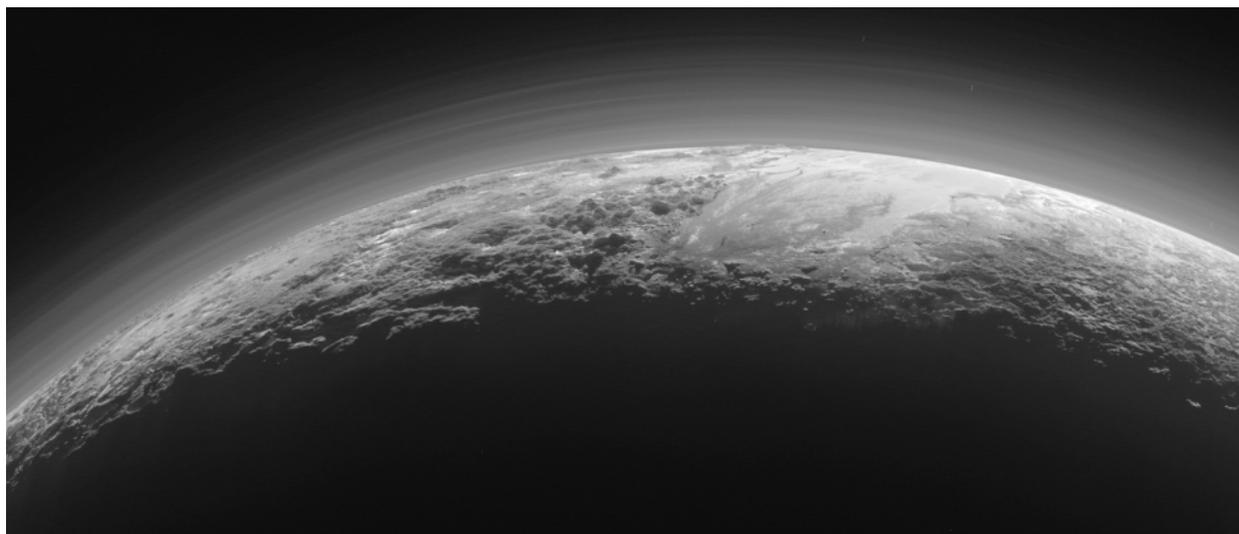
Major questions that must be addressed now include details of Pluto's interior structure, such as whether there exists a liquid subsurface ocean today, which can be constrained by global gravity measurements. And, if there is an ocean, how deep is it and what is its extent and composition? When were Pluto's cryovolcanoes active and to what extent? How were the bladed terrains constructed? What caused the formation of Pluto's giant rift system and other tectonic features? What powers Pluto's ongoing geological activity?

2. Atmosphere, Climate, and Atmospheric Interactions with Pluto's Surface. Pluto's atmosphere and surface function as an interconnected system (e.g., Gladstone et al. 2016; Stern et al. 2018). Surface composition and topography, together, interact with the atmosphere because the atmosphere is supported by vapor pressure equilibrium. Therefore, both the distribution of volatile ices on Pluto's surface and its atmospheric pressure are dynamic and

respond to the received insolation. Clearly, one cannot understand either the distribution of surface volatiles or the atmospheric structure in isolation: they are dependent on each other, and they are also dependent on both short-term (diurnal) and long-term (orbital) factors and timescales.

Observations from groundbased stellar occultations have shown that the atmospheric pressure on Pluto increased by a factor of three between 1988 and 2015 as Pluto receded from the Sun (Sicardy et al. 2016). Now that topography and the distribution of volatiles on Pluto are known—at least for the encounter hemisphere (Grundy et al. 2016)—detailed global circulation models (GCMs) can be run. Bertrand & Forget (2016) have replicated the observations from New Horizons and the increase in atmospheric pressure detected from groundbased stellar occultations. These models predict significant changes in the distribution of volatiles even on timescales of a terrestrial decade (just 4% of Pluto's orbital period), including the disappearance of mid- and high-latitude frost bands.

Another striking atmospheric discovery made by New Horizons was the extent of haze in Pluto's atmosphere. Yet owing to it being a flyby, New Horizons could not study the dynamics or formation of this haze in any real detail, nor could it see responses in haze production and destruction to diurnal, orbital, seasonal, and solar forcing (as, e.g., Cassini was able to do at Titan).



Pluto's steep topography with characteristic 3-5 km amplitudes and laterally organized atmospheric hazes over 200 km in altitude.

New Horizons also lacked the capability to make in-situ atmospheric measurements of composition, haze-size particle frequency distributions, and to study atmospheric dynamics. To accomplish these objectives, and to observe volatile transport and the detailed evolution of the atmosphere (and its escape rate) due to solar cycle and orbital/seasonal effects, requires a new mission with new measurement capabilities, and the ability to remain at Pluto for several terrestrial years. New atmospheric capabilities that are warranted include in-situ mass spectroscopy, nephelometry, and ion/electron density measurements.

3. Charon, Pluto's Large Satellite. Charon is comparable in size to the mid-sized Saturnian and Uranian satellites, and it shares with them a cratered, water-ice rich surface. But, it also stands out in ways that may provide insights into stages of evolution common to icy worlds. Ancient terrains are better preserved at Charon owing to reduced impact, radiation, and thermal damage/processing in the Kuiper Belt relative to the regular satellites near the giant planets.

Therefore, Charon can provide unique insight into the evolution of icy ocean worlds, particularly when compared to icy satellites of the ice and gas giants. Charon can also provide key insights into binary planet and also, importantly, Earth-Moon system, formation—an objective that cannot be accomplished with any closer system.

New Horizons images showed that Charon's surface geology and interior geophysics present important challenges that require future exploration to understand (e.g., Olkin et al. 2017; Stern et al. 2018). For example, one striking feature of Charon's encounter (i.e., sub-Pluto) hemisphere is the dichotomy between Vulcan Planum, the smoother equatorial plains, and the widespread rougher terrains to its north (Moore et al. 2016; Robbins et al. 2017). Perhaps Vulcan Planum represents a large-scale eruption liquid resulting from a freezing internal ocean, forced to the surface by the expansion on freezing (e.g., Beyer et al. 2017). This last melt could have been especially rich in antifreeze substances such as NH_3 that would increase its viscosity (Kargel et al. 1991). A related scenario involves foundering of blocks of an ancient icy crust, as the distinctive morphology of Kubrick, Clarke, and Butler Montes (the mountains in depressions) and that of a similar-scale cavity with no mountain are suggestive of blocks having been submerged into an extremely viscous fluid or slurry.

A striking feature of Charon is, in fact, the clear presence of NH_3 (Dalle Ore et

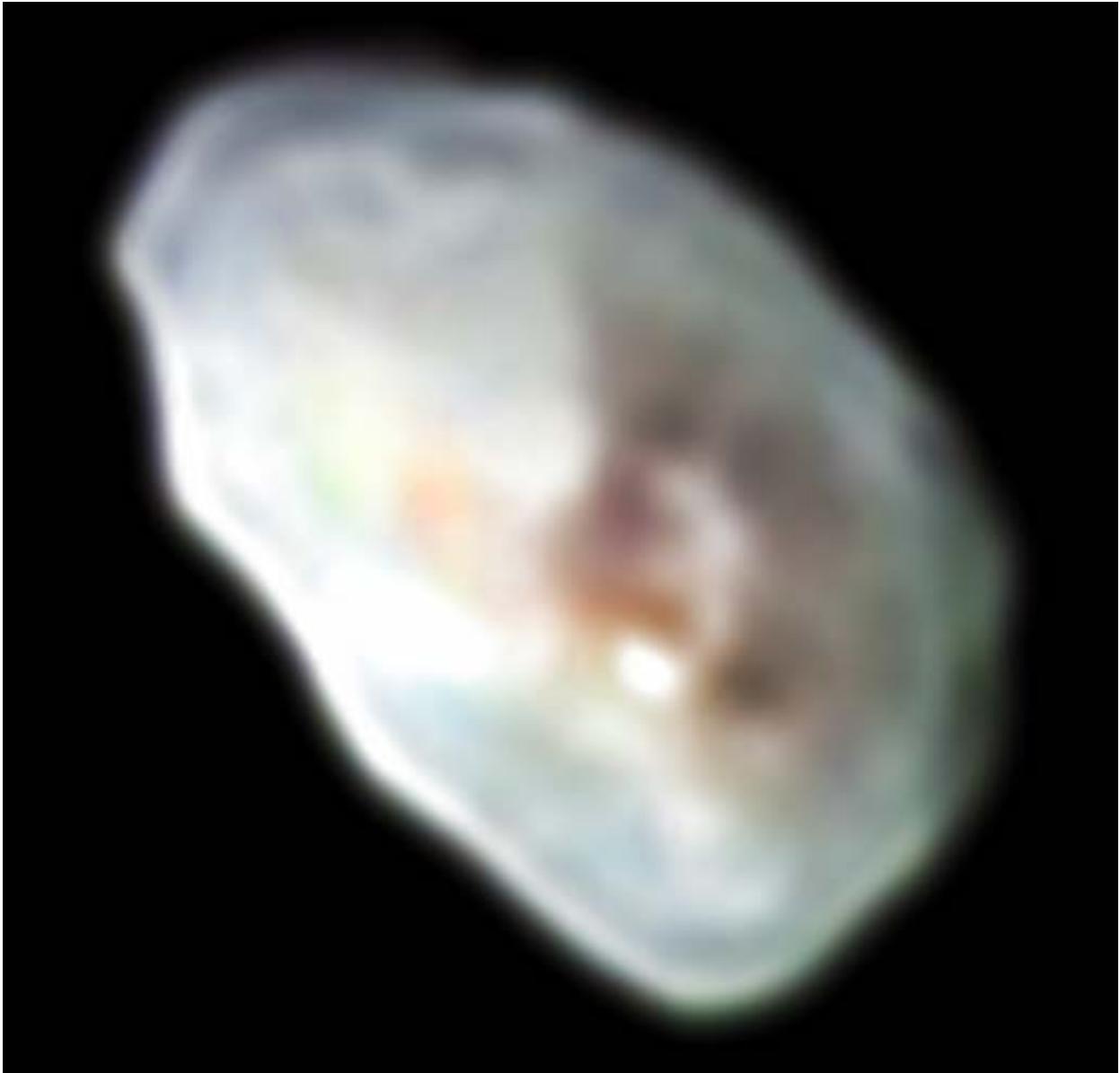
al. 2018) inferred from a weak 2.2 μm band (which could be more effectively mapped at longer wavelengths than New Horizons' instrumentation was designed to reach). Exposed NH_3 is readily destroyed by radiolysis, so its abundance in certain crater ejecta could indicate recently exposed interior material (Grundy et al. 2016). There could be a radiolytic cycle involving a more stable ammoniated molecule, or it could also be diffusing out from Charon's interior, all of which would be important for a future mission to investigate. Additionally, multiple regions of patterned ground in Vulcan Planum—small pits at the $\sim 100\text{s m}$ scale—hint at volatile escape, offering clues to the chemical evolution of Charon's interior.



Charon as seen by New Horizons, featuring its red polar stain, ancient terrains, and clear signs of massive tectonics.

Furthermore, an ancient global expansion is also implied by the large polygonal blocks separated by deep graben in Oz Terra (Beyer et al. 2017; Schenk et al. 2018). These graben appear throughout much of the encounter hemisphere by over 20 km of vertical relief and several multi-kilometer-deep canyons. Why the tectonic and cryovolcanic response differs in Oz Terra and Vulcan Planum is unclear, and whether or not such expressions are also present elsewhere on the 60% of Charon not seen at high resolution by New Horizons compel a revisit.

4. Small Satellites and Satellite System Origin. Pluto's four tiny outer satellites were all discovered from Hubble Space Telescope observations in support of the New Horizons mission (Weaver et al. 2016; Showalter et al 2011, 2012). They present a striking contrast to the giant moon, Charon, each being some 10^6 - 10^8 times less massive than Pluto's binary companion. The satellite system's coplanar, circular orbits indicate that it most likely originated from the Charon-forming giant impact (Stern et al. 2006). Detailed numerical modeling of this process (Ward & Canup 2006, Kenyon & Bromley 2014, Walsh & Levison 2015) has been unsuccessful at reproducing the key orbital characteristics of the system, specifically that the moonlets orbit close to, but not directly in, the N:1 mean-motion resonances with Charon. The moons are also likely influenced by exotic three-body resonances (Showalter & Hamilton 2015), which greatly complicate the orbital and perhaps also their spin/obliquity dynamics. The Pluto system thus presents key standing challenges—as well as opportunities—to understanding giant impact satellite formation and evolutionary dynamics.



Nix in stretched color at best New Horizons resolution.

The discovery of the uniformly high albedo, water-ice surfaces of the four small satellites, compared with similarly sized KBOs and even Charon, was surprising, as was the diversity of their bulk densities. Understanding the origin of these attributes and exploring the detailed geologies of these bodies is something New Horizons could not accomplish but which begs for future exploration. Comparative studies of these bodies to the cold classical KBO flyby target 2014 MU₆₉ is also of extreme interest, but impossible without a revisit to study these small satellites at comparable resolutions to the New Horizons flyby of MU₆₉.

To better understand the small satellites and their origins, the next Pluto mission should include multiple close flybys of all four satellites to make detailed geological and compositional maps, direct measurements of their densities, optical studies of their regolith microphysical properties, and thermal mapping of their surfaces.

5. Pluto's Value to Further Understand the Kuiper Belt and the Kuiper Belt's Many Dwarf Planets is Also Critical. The exploration of the Pluto system by New Horizons was initially predicated on being the first reconnaissance of bodies in the Kuiper Belt, with Pluto being the largest, longest and best known, and most studied world therein (Belton, National Research Council 2003). The dynamical structure of the Kuiper Belt is the primary evidence for and the greatest test of hypotheses for an early dynamical instability/rearrangement of the Solar System (e.g., Levison et al. 2008, Nesvorný et al. 2016, and many others). All of these models share the inference that Pluto, lodged in a 3:2 mean-motion resonance with Neptune, formed in an ancestral planetesimal disk closer to the Sun, likely between 20 and 30 AU (Malhotra 1993).

The Pluto system thus reflects the physical and chemical properties of this key region of the original solar nebula. The Pluto system is made even more valuable by the wide range of phenomena that it offers to teach us relevant to other Kuiper Belt dwarf planets. These include: satellite system formation, binary planet formation, and a wide range of Kuiper Belt planet surface, interior, and atmospheric processes.

The Logical Next Step in Pluto Exploration:

Recommendations to NASA

Despite its size compared with the Earth or Mars, Pluto is a world of extraordinary diversity, complexity and ongoing activity. Keys to its novel and active geology and geophysics, which operates in the absence of tidal heating, seem to include the prominent role of volatile ices, strong atmosphere-surface coupling, widespread tectonism, cryovolcanism, and a possible liquid interior ocean. At the frigid conditions of its surface, endogenic warmth from the decay of radioactive elements in its interior, as well as sunlight, are sufficient to mobilize ices such as N_2 and CH_4 in both vapor and solid form, and possibly

as liquids in Pluto's past. How do such novel and active processes work on bodies whose surfaces are dominated by volatile ices? Pluto thus serves as the archetype for other dwarf planets of the Kuiper Belt, and is the only Kuiper Belt world that is known well enough to justify a second generation mission such as an orbiter or lander. Because none of the vexing problems opened by the New Horizons datasets are likely to be resolved from Earth or Earth orbit in the foreseeable decades, the case for returning to the Pluto system is strong.

As we have described here, the numerous, compelling, open scientific issues surrounding Pluto itself and the Pluto system in general, and the relationship of the Pluto system to the Kuiper Belt strongly motivate calls for follow on Pluto system exploration. Among the various options for that exploration is a second flyby, an orbiter, or a lander. Table 1 below compares these three options.

Evaluating Table 1, we conclude that an orbiter is the best next step. However, many aspects of such a mission remain open and require study in order to properly compare a Pluto orbiter to other choices that the next Planetary Decadal Survey must evaluate. Accordingly, we recommend that in advance of the 2023 Decadal Survey, NASA fund one or more Pluto orbiter studies.

Key factors that such mission studies need to address include:

- ✓ Feasible mission designs with available launch vehicles and in-space propulsion systems.
- ✓ Proof of concept orbital tour designs (e.g., using Charon flybys for orbit change to reconnoiter the small satellites, to make low periapse studies in Pluto's atmosphere, etc.).
- ✓ Science traceability to payload compliment.
- ✓ Spacecraft requirements (communication, propulsion, power, etc.).
- ✓ Substantiated cost estimates.

**Table 1: Possible Pluto Follow On Mission Architectures:
Key Comparative Attributes**

	Flyby	Orbiter	Lander
Pros	Lowest cost (New Frontiers Class)	Intermediate cost (Small Flagship Category)	Enables detailed high resolution surface process studies
	High TRL	High TRL	Enables seismic/heat flow studies and in-situ lower atmospheric and surface studies
	Shortest flight	Allows detailed full-system exploration	Possibly able to respond to new discoveries.
	Map some unseen terrains on all bodies in the system, carry new instruments, look for temporal changes since New Horizons	Map all unseen terrains on all bodies in the system, carry new instruments, study temporal changes on many timescales, make in-situ upper atmospheric studies	Carry new instruments, study temporal changes.
	Could also explore KBOs	Explore KBOs beyond Pluto by leaving orbit?	
		Able to respond to new discoveries.	
Cons	No extensive time variability studies	More expensive than a second flyby mission	Highest cost (Flagship Class)
	Not useful for many needed investigations (e.g., altimetry, gravity)		Cannot go on to explore elsewhere in the Kuiper Belt
			Immature TRL
			Risky given current surface knowledge
			No landing site survey precursor
			Limited global or satellite studies

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