Figure 1: Artist’s rendition of New Horizons at Pluto (JHU APL/SwRI). Cryovolcanism, as proposed by Hussmann et al. (2006), is visible on the right limb of surface.
1 Introduction

Once thought to be a remote oddball of our outer Solar System, Pluto is now known to be one of many objects in the Kuiper Belt. Its three moons—previously thought to be unique for such a small, remote body—make Pluto one of the numerous binary or multiple-body KBOs that have been discovered in the last 16 years. Up to 20% of KBOs in various dynamical classes are multiple systems (Noll et al., 2008), implying that it is not uncommon for a body residing in this region of the Solar System to have multiple moons or be a binary object.

Pluto’s largest moon Charon was discovered in 1978 (Christy & Harrington, 1978), making Pluto a double planet until the 2005 discovery of Pluto’s smallest moons, Nix and Hydra (Weaver et al., 2005). Nix and Hydra not only make Pluto part of a quadruple system, but also present new constraints on the formation of the Pluto system. The satellites’ circular orbits, coplanar with the orbit of Charon, suggest that these moons all formed from material ejected into orbit around Pluto by a giant impact event.

In this paper I review the current literature on the dynamics, formation, and evolution of the Pluto system, including its moons and their surfaces.

2 Pluto

2.1 Formation and Dynamics

It is widely accepted that the Pluto system was formed in a giant impact collision (Canup, 2005; Stern et al., 2006) with little or no exchange of heat or heating of the bodies’ materials occurring, resulting in the formation of not only Pluto but also Charon, Hydra, and Nix. This assumption is valid because of the high angular momentum of the Pluto system is quite high (see references 9-12 in Stern et al., 2006), thus Charon must have formed from a collision
with Pluto and was therefore likely not captured into orbit. The largest body in the 3:2 mean-motion resonance with Neptune (Brown, 2008), Pluto is part of the only quadruple system known to date in the Kuiper Belt. (2003 EL61, the only known triple system, has two small companions, and also has a collisional family.)

### 2.2 Rings?

Binzel (2006) and Stern et al. (2006) propose the possibility of rings, or ring arcs, in the Pluto system, of time-varying optical depth of approximately $\tau = 5 \times 10^{-6}$ (unitless), of the same order of magnitude as the optical depth of the tenuous rings around Jupiter (Showalter et al., 1987; Throop et al., 2004). As Pluto is far away from the perturbing forces of the Sun, the possibility of there existing rings of collisional ejecta from Nix and Hydra in the Pluto system is high, though the arrival of New Horizons will ultimately confirm or deny the presence of rings.

### 2.3 Physical Properties

Smaller than Eris and red, Pluto has a surfaced varied in both color and albedo (Brown, 2008). The largest KBOs, including Pluto, have methane ice on their surfaces, in addition to N$_2$, CO, ethane, and maybe water ice (McKinnon et al., 2008). The density of the Pluto-Charon-Nix-Hydra quaternary system ($2.01$ g cm$^{-3}$, Tholen et al., 2008) implies that the impactors that formed this system were initially accreted (McKinnon et al., 2008). These impactors were differentiated by accretion and radiogenic heating, which resulted in a differentiated Pluto. Taking the argument for Pluto’s being differentiated even further, Hussmann et al. (2006) suggest the presence of a sub-surface ocean below Pluto’s low-density ice. Although formation simulations that result in differentiation are accepted, scenarios that result in subsurface oceans or cryovolcanism are not as widely considered to be as valid.
3 Charon

3.1 Formation

Charon formed from mantle material leftover from the collision that formed the entire Pluto system. As this collision resulted in little or no melting of the impactors’ material, there was little heat exchange, and thus a good deal of the impactors’ icy mantles remained water ice and became the major constituents of Charon (Stern et al., 2006).

3.2 Mutual Events

The discovery of Charon allowed for more precise mass determination for Pluto. Soon after the discovery of Charon, its orbit plane was oriented such that it was edge-on as seen from Earth, resulting in mutual events of Pluto and Charon being visible for approximately five years (Binzel & Hubbard, 1997), allowing for more precise measurements of color and albedo of both bodies (Figure 2 shows a color map of Pluto’s surface). While we will not experience another “season” of Pluto-Charon mutual events again in our lifetimes, improvements in telescope technology and size have allowed us to study the bodies individually and also through occultations (Noll et al., 2008). The discovery of additional binary or multiple KBOs showcases the diversity of the Kuiper Belt, and allows us to apply what has been learned from Pluto to other systems.

3.3 Mutual Events

Charon’s surface is dominated by water ice, in addition to a bit of ammonia (see McKinnon et al., 2008, and references therein); quite a different surface from Pluto. Both Pluto and Charon are tidally locked, the same faces of these two bodies always facing the companion, making these two objects part of what is occasionally called a “double planet”.

4
4 Nix & Hydra

4.1 Formation and Orbits

Nix and Hydra likely formed in the same collision that produced Charon, probably originating as debris from this giant impact between two large, differentiated bodies (Stern et al., 2006). Their coplanar orbits with Charon also suggest that they formed in the same impact from which formed Charon. Combining their coplanar orbits with their neutral colors, it can be assumed that Nix and Hydra are similar in composition to Charon, i.e. that their constituents are mostly water ice.

Another argument for Nix and Hydra forming at the same time as Charon is that they are larger than the critical size boundary for catastrophic breakup over the age of the solar system (Durda & Stern, 2000; Stern et al., 2006). Forming along with Pluto and Charon, Nix and Hydra are likely the same age as the former two bodies and have withstood disruption forces that would have torn apart smaller bodies.

Even if Nix and Hydra have resisted disruption by impacts or tidal forces, they may have lost up to 10% of their masses due to impact erosion. Material ejected from their surfaces by collisions with other KBO fragments could help feed the hypothetical, tenuous rings or ring arcs in the Pluto system (see section 2.2).

The proximity of Nix and Hydra to the corotation (more literally, co-orbital) resonances also implies a common impact origin for these smaller moons, meaning that Nix and Hydra were driven outward by Charon’s migration (Ward & Canup, 2006). At some point, the outward migration of Nix and Hydra ceased, most likely due to the end of Charon’s outward migration. Nix likely escaped from its corotation resonance with Charon first, before the end of Charon’s outward semi-major axis migration due to tidal expansion.

Ward & Canup (2006) also show that these particular corotation resonances (4:1 and 6:1) are the most conducive to moon formation around Pluto, as other corotation resonances are
close to the Hill sphere and other dynamically unstable regions. Nix and Hydra’s probable initial locations in the 4:1 and 6:1 corotation resonances could have lead to the aggregation of material at these points and thus helped contribute to the long-term survival of these moons over the age of the Solar System.

Formation of these moons alongside Pluto and Charon was likely, as they are presently in highly circular orbits \( e = 0.01504 \) for Nix and \( e = 0.00870 \) for Hydra (Tholen et al., 2008), implying that they were not dynamically captured, as the circularization timescales are greater than the age of the Solar System (Stern et al., 2006).

Though the orbits of these two small moons are relatively well known (Tholen et al., 2008), not much is known about either the exact dimensions of Nix and Hydra or their rotation rates. Stern et al. (2006) assume minimal masses for Nix and Hydra and calculate that these moons are likely not in synchronous rotation with Pluto, unless they formed much closer to Pluto and migrated outward (Ward & Canup, 2006).

### 4.2 Binaries

Because up to a fifth of Kuiper Belt objects are binary or have multiple satellites (Stephens & Noll, 2006), studying the multiple system of Pluto allows us to better understand the evolution and current states of other multiple Kuiper Belt objects. Although there are plenty of binary KBOs, it is significantly harder to observe smaller satellites of 100-km class TNOs (Noll et al., 2008), especially for narrowly-separated objects. Comparing the frequencies of nearly equal-sized binaries with objects with smaller companions is difficult, due to observational limits from seeing, telescope size, differences in detectors, etc. Pluto, being one of the brightest KBOs, allows us to most readily study its multiple satellites, making it an ideal target for New Horizons (Section 5).
5 New Horizons

A collaboration between the John Hopkins Applied Physics Laboratory and the Southwest Research Institute, New Horizons (see Figure 1) was launched in January 2006 and is expected to fly by Pluto on Bastille Day in 2015. New Horizons’ science goals include imaging the surfaces and thus mapping the compositions of the four main bodies in the Pluto system, studying Pluto’s atmosphere, searching for an atmosphere around Charon, along with imaging the entire Pluto Hill sphere, searching for presently undiscovered moons and probable rings (Young et al., 2007).

The recent discovery of Nix and Hydra is very timely in allowing target planning and new science goals for the New Horizons mission. Once the rotation rates of these moons are verified, New Horizons will be able to optimally image their surfaces. Knowing the rotation rates of these moons will help verify whether they are in any sort of spin-orbit resonances with Pluto, and place important constraints on the rotation rates of moons of other KBOs.

Nix and Hydra’s recent discovery and their importance in understanding of the Pluto system make them an important and timely mission goal for New Horizons. Until New Horizons arrives at Pluto, a good deal will remain uncertain about the Pluto system, including the absolute radius of Pluto, the height of its atmosphere, the rotation rates of Nix and Hydra, and the masses and composition of these moons.

After visiting Pluto New Horizons will swing by at least one yet-to-be-determined KBO to further study the other icy bodies of the outer Solar System, linking them with other dynamical populations such as Centaurs and comets. Hopefully in the process, New Horizons will begin to answer our questions about the origins and compositions of the cold leftovers of our Solar System’s formation and evolution.
6 Discussion

Almost 30 years after the realization that Pluto was a double planet, the discovery of 1998 WW$_{31}$ demonstrated that Pluto was no longer unique in its binary status (Veillet et al., 2001). According to the frequency predictions of Noll et al. (2008), there could be up to tens of thousands of Kuiper Belt objects with satellites or that are binaries (Stephens & Noll, 2006). Though we know of only three moons in orbit around Pluto, there could have been more moons that were disrupted or destabilized throughout the dynamical history of the Pluto system. In addition to moons that once were, more satellites could be lurking below the detection thresholds of current telescopes, along with rings or ring arcs, not just around the tightly-bound Pluto system but around other KBOs. Maybe there exist KBO systems less tightly-bound than Pluto, such as ones with captured satellites in highly eccentric orbits.

The arrival of New Horizons in the Kuiper Belt will answer numerous questions about the history of this region, but will likely also raise new ones as the spacecraft’s science instruments begin to probe the chilly remnants of planet formation. The objects that compose Pluto’s cohort beyond Neptune should continue to be mysterious and wondrous, for as Hal Levison says, “. . . the Kuiper belt is very strange.”
References


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Figure 2: Surface map of Pluto from Young et al. (1999).