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Early Pluto Science, the Imperative for Exploration, and New Horizons

Jonathan I. Lunine
Cornell University

S. Alan Stern and Leslie A. Young
Southwest Research Institute

Michael J. Neufeld
National Air and Space Museum

and

Richard P. Binzel
Massachusetts Institute of Technology

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Like a number of other great discoveries, that of distant Pluto was based upon a misconception, in this case that the orbital motion of Neptune was being influenced by a large, more distant, "Planet X". Nevertheless, Clyde Tombaugh's remarkable discovery launched decades of efforts to push telescopic techniques to the limit, and theoretical speculations as to why the solar system's last planetary outpost should be so small. Those speculations were answered beginning in 1992 with the discovery of the Kuiper Belt, of which Pluto is a part. The idea of Pluto as the last planetary frontier galvanized the space science community into pushing for a mission to explore what would turn out to be a body with a wealth of geologic and atmospheric processes and a rich system of satellites. The long odyssey to make the New Horizons mission a reality was the capstone to an era in which the mode of planning planetary exploration was transformed.

1. BEFORE 1930: THE HISTORICAL ASTRONOMICAL CONTEXT OF PLUTO'S DISCOVERY

By the end of the 1920's the United States had become preeminent in the field of observational cosmology, with names such as Milton Humason, Edwin Hubble, Henrietta Leavitt and Vesto M. Slipher demonstrating the true scale of the cosmos and establishing empirically the relationship between distance and recessional velocities of galaxies. One of those pioneering American astronomers, Slipher, did his work at Lowell Observatory, whose founder Percival Lowell began the first—and only systematic—search for a planet beyond Neptune in 1905 (Reaves, 1997, and references therein). Lowell's multiyear search, and briefer searches by others, were stimulated by the conclusions of Herschel that the residuals in the orbital elements of Uranus could not be accounted for entirely by Neptune (Herschel, 1867), and then by the analyses of Pickering (1909) and ultimately of Lowell himself (1915). Because such a planet was expected to be massive and hence bright, much fainter Pluto escaped detection, although it was later "precovered" in Lowell's archival photographic plates of 1915 (Lampland, 1933), and those of Humason in 1919 (Nicholson and Mayall, 1931). Clyde Tombaugh was the first to identify it, in his inexhaustibly diligent blink comparator analysis of plates taken in1930 at Lowell (Slipher, 1930).

Although the discovery of Pluto was celebrated at the time as another triumph of American astronomy, it was much fainter than expected and—thanks to the discovery of Charon four decades later (Christy and Harrington, 1978)—eventually shown to have a mass much too small to have been responsible for the perturbations of Uranus's orbit that began the hunt decades before. With the analysis by Standish (1993) that the apparent residuals in Uranus' orbit were the result of the use of an erroneous mass for Neptune, it became clear that the discovery of the ninth planet was due to hard work by Tombaugh and Lowell's persistence (including bequeathing funds for a new telescope after his passing), but not due to Lowell's theoretical prediction.

One might ask how the history of solar system astronomy might have changed had the search for Pluto failed, or if the search were not mounted in the first place (if, e.g., spurious residuals for Uranus's position had not been obtained). Pluto would very likely have been discovered serendipitously before the 1992 discovery of the first small Kuiper Belt Object (KBO), labelled 1992 QB_1 (and now called 15760 Albion) (Jewitt and Luu 1993), but plausibly after the first paper predicting a belt of material beyond Neptune (Edgeworth, 1943).

In his model for the origin of the solar system, Edgeworth (1949) regarded Pluto as an escaped satellite of Neptune, and hence not a constraint on the distribution of material in his planet-forming “annulus”. Kuiper (1951), on the other hand, explicitly considered Pluto’s eccentric orbit in proposing that the solar nebula (and proto-Neptune’s orbit) extended out to 50 AU. However, his nebular model is today only of historical interest. Perhaps the best answer to whether planetary astronomy might have changed in the absence of Pluto’s discovery until decades later is “not much in the long run,” because the need to explain the injection of long period comets into the Oort Cloud (Oort 1950) and the planar distribution of short period comets (Duncan et al. 1987) would each have spurred on searches for objects in a belt beyond Neptune in any case, and would have eventually resulted in Pluto’s discovery as well as the discovery of the KB and Pluto’s cohort of KB dwarf planets.

2. 1930-1992: THE NINTH PLANET BEFORE THE KUIPER BELT:

2.1 Speculations and Science

The history of Pluto studies prior to the discovery of the next discovered Kuiper Belt object, 1992 QB1, is long and complex (e.g., Marcialis, 1997; Stern and Mitton, 1998, DeVorkin, 2013). Some of the scientific breakthroughs up to the discovery of the Kuiper Belt are tabulated in Table 1 and are briefly described below.

Soon after Pluto’s discovery (see the chapter by Binzel and Schindler), its orbit was determined to be unusually eccentric and inclined relative to that of the other planets (Leonard, 1930). Pluto’s dip inward of Neptune led to the idea that the ninth planet might be an escaped moon of Neptune (cf. Marcialis, 1997 for the complex story of who proposed this first), but some 35 years after the orbit of Pluto was determined, Cohen and Hubbard (1965) established by numerical integrations that Pluto and Neptune were locked in a precise 2:3 mean motion resonance that librates about a center point relative to Neptune. The longitudinal phasing of these two bodies in resonance is such that the two objects can never approach closely and the escaped moon idea is implausible. The libration of the resonance angle prohibits close approaches between Neptune and Pluto; the conjunctions occur near Pluto’s aphelion and the strength of the resonance stabilizes Pluto’s orbit (cf. Malhotra and Williams, 1997). The properties of this resonance would eventually lead to the realization that Pluto was almost certainly formed, and remained in, a belt of primordial bodies beyond the realm of the giant planets.

The physical properties of Pluto, and after its discovery, of Pluto's large satellite Charon, were an active area of research in the decades up to 1990. By mid-century photometric observations determined the rotation period of Pluto (Walker and Hardie, 1955), but it was not until the 1970's that Pluto's large obliquity was inferred from improved and extended photometry (Andersson and Fix, 1973). With the discovery of Charon (Christy and Harrington, 1978), the system mass of just over 10^{25} gm was roughly determined. This was crucial, because it established that Pluto was not a massive object. Although its faintness in discovery images had ruled out Pluto as the source of the apparent (and ultimately artefactual) residuals in Uranus' orbital motion, considerable controversy remained for decades over just exactly how small Pluto might be. .

Duncombe and Seidelman (1980) tabulated estimates of Pluto's mass, and one can identify three 'epochs" between each which the mass declines by an order of magnitude. Pre-discovery, planet "X" was of order 10 Earth masses; from 1930-1955, Pluto is of order an Earth mass, and from 1968 to 1978, Pluto steadily declines from 0.1 Earth masses to a final value, given by Charon's discovery, some 50 times smaller. Indeed, a tongue-in-cheek treatment of this history by Dessler and Russell (1980) predicted a massless Pluto by 1984, by drawing a best-fit line through all the points. However, it is the clustering of the data points, in contrast to a smooth trend, that reveals the underlying cause of the decline: the pre-discovery mass was required to explain the residuals in Uranus' motion, while in the two decades after Pluto's discovery, improved measurements of the motion of Uranus and Neptune reduced the required mass of Pluto assuming it was the perturber. Even more precise measurements in the 60's and 70's further reduced Pluto's mass, but were overtaken by the definitive mass given by the orbital periods and separations of Pluto and Charon. That mass eliminated Pluto once and for all as the cause of any residuals in the ice giant orbital motions, which finally were proved erroneous as noted above with the analysis of Standish (1993).

As ultimately incorrect as they were, the inflated masses of Pluto up through the mid-1960's combined with imprecise estimates of radii contributed to a science-fictionesque mystique of the ninth planet. Typical values of the density obtained were as large or much larger than Earth (Marcialis, 1997). Was this a new kind of ultradense planet, Mars-sized but made of exotic material? Might it be larger, perhaps Earth-sized after all? G.P. Kuiper instead dismissed the masses as overestimates, and on the basis of B-V colors presciently imagined a smaller body with an ice-covered surface (Kuiper, 1950), confirmed a quarter century later in a paper led by one of his former students (Cruikshank et al., 1976). However, it would not be until the fortuitous set of "mutual events" (transits of Charon in front of Pluto and occultations of Charon behind Pluto, first detected by Binzel et al. (1985) that highly accurate radii could be obtained (Buie et al. 1992; Young and Binzel, 1993), showing Pluto to be 70% the radius of Earth's moon. Together with the mass given by the orbital separation with Charon and the orbit period, Pluto turned out to have a density approximately close to twice that of water ice—and to be a small rock/ice world at the edge of the solar system.

An interesting perspective on the problem of Pluto's bulk properties comes from the history of observations of Neptune's moon, Triton, which orbits the Sun roughly as far as Pluto's perihelion and is just 14% larger in diameter. Discovered in 1846 by William Lassell, Triton is difficult to observe because it is small and close in angle to a larger brighter object, Neptune. Early observations suggested Triton was massive enough to perturb Neptune, and Alden (1940) obtained a value of 1.3×10^{26} g—almost twice the mass of Earth's Moon and six times Triton's accurate Voyager 2 mass determination in 1989. Visible and infrared observations led to an upper limit for the radius of 2600 km (Cruikshank et al., 1979). Combining the two leads to a density of 1.8 g/cm^3, fortuitously close to Triton's actually density and perfectly reasonable for a body with roughly equal amounts of rock and ice. However, subsequent observations shrank Triton until speckle studies produced a radius between 1037-1250 km (Bonneau and Foy, 1986). Such a value threw the mass determination out, because it led to an unphysical density, and it also caused considerable angst among planners for the Voyager 2 encounter with Neptune, because the ability to obtain both a UV solar and Earth radio occultation from a possible atmosphere required a larger size for the moon. In the end, as Voyager 2 sped toward Neptune, it became clear that the speckle observations were seeing a bright polar cap and not the darker annulus around it. Triton's numbers from Voyager 2 were a radius of 1353 km, a mass of 2.1×10^{25} kg, and a density of 2.05 g/cm^3 (Lodders and Fegley, 1998).

Although the details are different, the parallels between these Pluto and Triton stories are striking: both bodies had incorrect bulk parameters thanks to inaccurate observations of Uranus and/or Neptune; both bodies were initially thought to be much bigger than they are, and then began to shrink. However, while Pluto's mass and radius values were settled thanks to the discovery of Charon, Triton's required a spacecraft mission—Voyager—a mission that would presage a remarkable voyage of exploration through the Pluto-Charon system by New Horizons a quarter of a century later.

Crucial to the eventual interest in Pluto as a target of spacecraft exploration was its multiple -component icy surface and the presence of an atmosphere. Cruikshank and colleagues discovered methane by carefully selecting two narrow band filters in the 1-2 micron wavelength region (Cruikshank et al., 1976), concluding it was a surface ice based in part on the absence of a water ice signature. A decade later, water ice was discovered—but on Pluto's companion Charon (Marcialis et al. 1987, Buie et al. 1987). The conclusion that the methane signature was from the surface (Buie and Fink 1987; Spencer et al. 1990) would be confirmed years later (Stern et al., 1993) A stellar occultation by Pluto was observed in 1988, definitively establishing the presence of an atmosphere (Elliot et al.1989, Hubbard et al. 1988). Analysis of airborne and ground-based occultation data combined with consideration of the energy balance in the tenuous atmosphere led to the conclusion that this atmosphere could not be mostly methane, but rather dominated by a heavier molecule (Yelle and Lunine 1989), as suggested some years earlier (Trafton,1981). A few years later, nitrogen and carbon monoxide ices were detected in the 2.1-2.4 micron part of the near infrared spectrum of Pluto, with N_2 dominating over CO (Owen et al., 1993). Thus, because N_2 is also the most volatile of the three detected ices, Pluto's atmosphere—like that of Earth, Titan and Triton—turns out to be mostly molecular nitrogen. The main differences of Pluto from Triton known by 1992 were the absence of CO_2 and detectable H_2O ice from Pluto's surface (Brown et al., 1995; Cruikshank et al., 1997) and different insolation patterns thanks to Pluto's large obliquity and orbital eccentricity. Indeed, as Pluto retreats from the Sun, its atmosphere may begin to thin or even collapse [not settled, evne today!], with uncertain timing thanks to the inertial effects of surface ices (Stern and Trafton, 1984; see also the chapter by Young, et al.). Because chemical and physical processes in an ultracold atmosphere are of keen scientific interest, this in turn, would provide another imperative for exploring Pluto before its orbit took it too far from the Sun.

Mapping of what would turn out to be a compositionally and spatially complex surface began with the 1985 mutual events (Buie et al 1992; Young and Binzel 1993), which showed stark albedo contrasts later confirmed by Hubble imaging (Stern et al, 1997). These contrasts, combined with the knowledge that Pluto has an atmosphere, made it clear that Pluto could be a very dynamic world for volatile transport (Hansen and Paige 1992). By the early 1990's Pluto had become known as an intriguing ice-rich world much like its slightly larger cousin Triton—with volatile ices and a thin atmosphere, bound not to a giant planet but rather to a moon within an order of magnitude the same mass. Like Earth and Venus, Uranus and Neptune, or Ganymede and Callisto, Triton appeared to have a near twin in terms of bulk properties and surface composition, but in a very different dynamical configuration. The scientific impetus for spacecraft exploration of Pluto became strong. The discovery of the KB dwarf planet cohort a few years later made that strong impetus become compelling (National Research Council, 2003).

2.2 Missed Opportunities to Explore Pluto by Spacecraft

Just four years after the first successful planetary flyby by Mariner 2 at Venus, Gary Flandro of Caltech's Jet Propulsion Laboratory (JPL) showed that an upcoming alignment of all the giant planets would allow a spacecraft launched in the 1975-1980 timeframe to use Jupiter's gravitational field to explore them all (Flandro 1966). Among the sample missions he calculated were a 1978 launch to fly past Jupiter, Saturn, Uranus and Neptune, and a 1977 launch to visit Jupiter and Pluto. JPL quickly proposed a "grand tour" robotic mission to exploit Flandro's trajectories. In the years after Apollo, steeply declining space program budgets doomed this and other ambitious robotic missions, but did allow for a scaled back "Mariner Jupiter-Saturn" twin-spacecraft mission to be launched in 1977 as Voyagers 1 and 2 (Schurmeier, 1977). (Earlier, NASA had launched a scientifically less ambitious pair of Ames Research Center probes, Pioneers 10 and 11, to Jupiter in 1972 and 1973.) Of the four spacecraft, two went beyond their original targets: after its 1974 Jupiter flyby, Pioneer 11 also encountered Saturn in 1979; after its 1981 Saturn flyby, Voyager 2 completed the giant planet part of the grand tour by also visiting Uranus in 1986 and Neptune in 1989.

However, in all of this, Pluto was missing. The Pioneer remote sensing payload was not built to operate at Pluto's distance from the Sun, although in the end the two spacecraft did send back space plasma physics data from distances even beyond Pluto's orbit. Pioneer 10's trajectory was designed conservatively to avoid excessive radiation during the Jupiter flyby, preventing a Pluto flyby, and Pioneer 11's was designed to get it to Saturn, which also precluded going onward to Pluto. So neither trajectory allowed a trip to the vicinity of Pluto. Once Voyager 1 was successful, Voyager 2's trajectory was reshaped to allow it to reach Uranus and then Neptune from Saturn, again precluding a trip to Pluto. Voyager 1's trajectory through the Saturn system could have been redirected to allow a Pluto encounter, completing the original grand tour goals. However, one of the most important moons of Saturn, Titan, was known since the 1940's to have an atmosphere with methane as a minor or major component, and a 1978 conference on the Saturn system made the case for Titan as a scientifically important target in its own right (Hunten and Morrison, 1978). Further, the haziness of the atmosphere made it impossible to determine its true size, but the extent of the haze layers suggested it might well be the largest moon in the solar system.

Thus, the decision was made to direct Voyager 1 toward an extremely close flyby of Titan, allowing a radio occultation measurement of its atmosphere and physical size, and potentially detailed views of the surface from the TV cameras. While the high optical thickness of the atmosphere precluded such views, the other measurements were successful—revealing a body just slightly smaller than Ganymede (which earned the title of largest moon), with a dense and mostly nitrogen atmosphere that at Titan's surface is four times denser than sea level air on Earth. The greenhouse-warmed surface temperature of 94 K and presence in the atmosphere of methane suggested methane seas, or even a global ocean of liquid ethane and methane (cf. Coustenis and Taylor, 2008). The scientific interest generated by Titan's bulk and nitrogen atmosphere, with the possibility of surface seas, helped to propel NASA and the European Space Agency to jointly agree to a Saturn orbiter with Titan probe, a mission that would come to be called Cassini-Huygens when it was authorized in 1989. The most ambitious planetary mission to date, Cassini-Huygens discovered over 13 years of flying within the Saturn system, a methane hydrologic cycle on Titan's variegated surface, with lakes, seas and methane rivers, and convincingly established the presence of a liquid water ocean beneath Titan's crust (Hayes et al, 2018).

While the scientific payoff of the decision to send Voyager 1 to Titan was inarguably stupendous, it prevented Voyager 1 from being sent to Pluto, and ultimately delayed a mission to Pluto by roughly a quarter of a century. It also necessitated a heroic effort on the part of a dedicated group of planetary scientists to make such a mission—New Horizons—ultimately happen. It is quite possible, as we show below, that the effort might have failed. However, improvement in instrument technology between the 1970's and the late 1990's (instrument technologies are frozen a decade before launch) allowed a much richer data set at Pluto than Voyager could have provided, as (in just one example of many) one can see by comparing the Voyager 2 vidicon images of Triton with the New Horizons solid-state detector images of Pluto and Charon.

3. 1992-2006: UPHEAVAL: KUIPER BELT, PLUTONIAN RECLASSIFICATION, NEW HORIZONS

3.1 Discovery of the Kuiper Belt, and implications for Pluto

With the demise of the escaped satellite model for Pluto's origin, the ninth planet became an enigmatic outpost, in a solar system which had otherwise seemed so well organized into an inner realm of rocky planets and a much vaster outer solar system of giant planets and their extensive satellite systems. It was perhaps surprising, then, that more attention was not paid to the possibility that Pluto might not be unique. Edgeworth's (1949) and Kuiper's (1950) papers were considered highly speculative, while Oort (1950) and Whipple (1951, 1964) focused more on the question of the source region of comets. However, spurred by dynamical considerations, searches for a trans-Neptunian belt of material became more frequent and more sensitive through the 1980's, culminating in the discovery of a 100-km sized body, 1992 QB1 (Jewitt and Luu, 1993). From there, the pace of discoveries picked up, with tens then hundreds, then even more bodies found in the Kuiper Belt (see the review by Jewitt, 1999 and the chapter here by Barucchi et al.). Further in the period 2002-2005, a number of bodies with diameters between 1000 km and 2300 km were discovered (Brown et al., 2005). The last of these, Eris, is practically the same size as Pluto and, based on the orbit of its moon Dysnomia, is about 25% more massive than Pluto (and 29% less massive than Triton).

Because of both its retrograde orbit and Neptune's lack of a regular satellite system, even before the discovery of other large objects in the Kuiper Belt, Triton was shown to be a captured body formerly in heliocentric orbit (e.g., Goldreich et al., 1989). While Pluto is in a 2:3 orbital resonance with Neptune, Eris is part of the "scattered disk" of Kuiper Belt objects without any dynamical relationship to Neptune. Triton, Pluto and Eris all have surface ices more volatile than water ice (Tegler et al. 2010, 2012), at least the first two have atmospheres continuously around their orbit, and all are the same size and (within a factor of 1.6) the same mass. Remarkably, these seem to be versions of the same type of body sitting in dynamically distinct environments. Numerous workers made arguments for declaring a third solar system class of "ice dwarf" planets (beginning with Stern 1991), like the terrestrial and giant planets, some of which (e.g. Triton) have been lost from solar orbit due to interactions with Neptune. However, rather than accommodate this, the International Astronomical Union (IAU) voted in August 2006 to move Pluto from the category of planet to that of dwarf planet, which it shares in the view of the IAU with the asteroid Ceres, with Eris, and with several other large Kuiper Belt dwarf planets. The ill-wisdom of such a designation, and its somewhat awkward definition (dwarf planets are round but not massive enough to fully clear planetesimals from their vicinity) has been and will continue to be debated (DeVorkin, 2013). The reassignment, however, was irrelevant to the success of the New Horizons mission, which had launched to its target eight months before. In the end, Pluto by itself and with its system of satellites would turn out to be every bit as interesting as any larger planet, and the discovery of the Kuiper Belt provided the cosmogonic context that made its exploration of fundamental importance.

3.2 The 1990's: Attempts to Explore Pluto and the Kuiper Belt

Much of what is described in this section comes from the excellent accounts by Stern (2008) and Neufeld (2014a; 2016). The story of the first mission to Pluto really begins at the end of the grand tour mission—with Voyager 2's flyby of Neptune and Triton in 1989. One of the authors of this review, SAS, then completing his doctorate at the University of Colorado Boulder, had already become an advocate for a Pluto mission, proposing it on behalf of an informal scientific interest group (aka the "Pluto Underground") in a May 4 meeting that year to the NASA Solar System Exploration Director at the time, Geoffrey Briggs.

The context then for planetary exploration was grim. Voyager 2 was a legacy of the program of the 1960's, when large missions such as Viking were thought to be the only mode of business. These missions, costing hundreds of millions in then-year dollars (which today well exceeds $1 billion), have come to be known as Flagships (although they were not called so at the time). However, the declining space budgets of the 1970's, and the delays to the Galileo mission caused by the 1986 loss of the Space Shuttle *Challenger* had put the planetary program in crisis. At the time of the August 1989 Voyager 2 flyby of Neptune, NASA had launched only one planetary mission in the preceding 11 years—Magellan to Venus that same May. In that year, however, Briggs initiated studies within the Solar System Exploration Division on smaller, cheaper missions, akin to NASA's Astrophysics Explorers. Stamatios "Tom" Krimigis of the Applied Physics Laboratory (APL) of the Johns Hopkins University was a strong advocate for smaller spacecraft, and APL had developed a rendezvous mission to an asteroid under the short-lived Planetary Observer program. In late 1989 Briggs proposed a Discovery program for small planetary missions. His successor, Wesley Huntress, ultimately succeeded in getting Discovery funded in 1993 (Neufeld, 2014b).

Under the then-nascent 1990 Discovery program, Briggs asked Robert Farquhar of Goddard Spaceflight Center, an expert in celestial mechanics, to conduct a study of an inexpensive mission to Pluto; Stern was appointed study scientist. Called Pluto350 for the proposed spacecraft dry mass in kilograms, the intent was to fly past Pluto and Charon with a minimal payload. Meanwhile, since the early 1980's JPL had been advancing a concept for a new class of outer solar system Flagship missions called Mariner Mark II (Neugebauer, 1983). These would be highly capable spacecraft, larger and heavier than the Voyagers, and capable of executing a number of different missions in the outer solar system, including the potential exploration of Pluto-Charon. Ultimately, only one of these would be built and flown—the Cassini Saturn orbiter—by which point the concept of a series of spacecraft had evaporated. But in application to Pluto, the Mariner Mark II would require a very heavy and expensive launch vehicle, the Air Force's Titan IV Centaur, which NASA would have to pay for. In this incarnation, which NASA favored in 1991, a Pluto mission would have a major impact on the agency's solar system exploration budget.

Another issue also reared its head at the time. If the nation were to send a highly capable and complex spacecraft all the way across the solar system, why not send it to a giant planet system? Triton—as large and chemically complex as Pluto—was only briefly explored by Voyager 2. And detailed exploration of Neptune could be part of the package. But this would leave Pluto out in the cold—again. The Pluto Underground lobbied for Pluto based not only on the novelty of the science—Pluto was to be the last planet to be explored—but also because of the progressive loss of surface illumination over the southern hemisphere and the possible dramatic loss of the atmosphere as Pluto retreated from the Sun (the latter turned out not to happen, probably due to nitrogen-ice-covered Sputnik Planitia; Meza et al., 2019). In other words, time was believed of the essence.

The idea of sending a Mariner Mark II to the outermost solar system was short-lived, however, as the first two planned missions of that line, Cassini and Comet Rendezvous/Asteroid Flyby (CRAF), proved to be too expensive in the budget environment of the early 1990s. NASA soon cancelled CRAF and ordered Cassini descoped by removing a scan platform and making other cuts.

Pluto advocates shifted their attention back to a Pluto350-like mission, but this was displaced by an even more radical concept that JPL engineers Robert Staehle and Stacy Weinstein called Pluto Fast Flyby (PFF). Conceived to have a spacecraft wet mass (with propellant) of only 160 kg, the design required an extremely limited scientific payload, but piqued the interest of new NASA Administrator Dan Goldin. By mid-1992, this JPL concept included two spacecraft for redundancy and to provide complete coverage of both hemispheres of Pluto and Charon. Although the mission cost was less than half the billion dollars proposed for a single Mariner Mark II, the added launch costs for two spacecraft were too formidable to afford.

Several events in 1993 conspired to doom a PFF new start. First, Mars Observer was lost to a propellant line explosion as it neared Mars in August. Then that same month Goldin told the PFF team that he could not afford to budget for two Titan IV Centaur launch vehicles, which were required because the lack of Jupiter gravity-assist opportunities in the later 1990s necessitated a direct launch to Pluto. That fall, Congress provided money for two Discovery missions, APL's Near Earth Asteroid Rendezvous (NEAR) mission and JPL's Mars Pathfinder, but did so over the wishes of Goldin. Caught between a fatally expensive dual heavy lift launch for PFF, the need for a replacement Mars orbiter for Observer, and Goldin's very negative reaction to the extra Discovery mission, Huntress—by then Associate Administrator for Space Science-- terminated the idea of bringing forward PFF as a new start.

Efforts by the Pluto Underground then shifted to the possibility of an international launch provider, to remove the substantial costs of a US vehicle. One of us (SAS) took advantage of a major new initiative in 1993 between the US and Russia to cooperate in space, and met with the director of the Russian Academy of Sciences' Space Research Institute (IKI), Albert Galeev, to gauge interest in providing the launch vehicles. As a scientist, Galeev was interested, if IKI could have a significant scientific role in the mission. This led to a proposed Russian-built atmospheric probe for Pluto. The advocacy group the Planetary Society delivered its own version of a Pluto collaboration with Russia to Huntress in early 1994, which helped to force an initially reluctant NASA Headquarters to pursue the possibility.

But momentum was diffused yet again when Huntress went to Moscow with a much broader palette of cooperation—Mars exploration, a close-approach solar mission (Solar Probe), and the Pluto Fast Flyby. The Russian scientists seemed more interested in Solar Probe, but by drawing on Farquhar's earlier proposal to use similar spacecraft and Jupiter flyby trajectories, the two missions could be packaged as a "Fire and Ice" program. But after multiple scientific and technical meetings and conferences in Russia, Germany and the US, it was clear that these missions would go ahead depended ultimately on the Russian Space Agency's willingness to provide Proton launch vehicles for free. By 1996 it was evident they were not. This and the upper stage failure of a Russian Proton rocket in late 1996, leading to the complete loss of the IKI-led Mars 96 mission, made Russian collaboration in a Pluto launch no longer viable.

Meanwhile, PFF went through multiple design changes and iterations as NASA Administrator Goldin kept moving the goalposts on cost and mass as he sought to make the mission a poster child for his "better, faster, cheaper" (BFC) approach. The failure of two BFC Mars missions in 1999 would ultimately hobble Goldin's campaign, but that was years in the future. The scientific community, JPL, and Huntress at NASA Headquarters all thought they were ready to end trade studies for PFF in 1994, but Goldin insisted on another two years of technology work. At the end of the year, PFF became Pluto Express, the novelty of which was to design the spacecraft architecture around the science. This "sciencecraft" concept was small enough to allow launch on a single large booster, but the low overall spacecraft weight was extremely demanding technologically.

Although a well-attended scientific workshop took place in July 1993 in Flagstaff, leading to the previous Pluto system book in this Space Science Series (Stern and Tholen, 1997), NASA's Pluto mission did not then have the universal support of the science community. The National Academy of Science's Committee on Lunar and Planetary Exploration (COMPLEX) gave short shrift to Pluto in a 1994 report, and without an overarching once-a-decade strategy like the Academy's Decadal Survey in Astronomy and Astrophysics, the planetary community had a difficult time arriving at a consensus set of priorities. Nevertheless, after community urging, NASA convened a Pluto Express Science Definition Team (SDT) in 1995 under the chairmanship of one of us (JIL) in an effort to pull together the science case for the mission, both in the context of what was known of Pluto and the increasing pace of discoveries of Kuiper Belt Objects (KBOs) and Pluto's relationship to them.

By that point, the following was known about the Kuiper Belt:

(1) The count of trans-Neptunian bodies exceeding 100 kms diameter that had been directly observed from ground-based telescopes had reached 28.(Jewitt and Luu, 1995);

(2) Like Pluto-Charon, the orbits of many KBOs cluster near the 2:3 mean-motion resonance with Neptune at a = 39 AU, with these orbits stabilized by the resonance. Other objects were found in other mean motion resonant relationships with Neptune, such as the 3:4 resonance.

(3) The idea that the Kuiper Belt is likely a remnant of the much more extensive (and long gone) protoplanetary disk of gas and dust from which the solid objects of the solar system formed, was strengthened by then-new dynamical simulations (Duncan et al., 1995).

(4) The inferred spatial density of KBOs was known to be sufficiently high to make it highly likely that Pluto Express could be redirected to pass by at least one other KBO after flying through the Pluto-Charon system.

The SDT report (Lunine et al., 1995) cited the uniqueness of several aspects of Pluto, including: its atmospheric energy balance, a possible comet-like interaction with the solar wind, and binary planet nature of Pluto and Charon. The data at hand then also hinted that overall the physical and chemical processes on Pluto are complex and hence demand close up exploration. The SDT report concluded that the opportunity to visit one or more KBO's beyond Pluto, in context with the exploration of the Pluto/Charon system itself, would be of keen scientific interest and exciting to the public. In sum, the presentations to the SDT and consequently the ensuing SDT report, made a compelling case that a mission to Pluto and beyond could be done at low cost and yet have extremely high scientific and public interest value.

As compelling as the Pluto and Kuiper Belt science were, events once again conspired to overtake the mission. In 1995, Mayor and Queloz (1995) detected the first extrasolar planet and the following year, NASA announced evidence of former biologic activity in a meteorite from Mars (McKay et al., 1996). Although the latter discovery was soon rejected by most in the scientific community, the two events stimulated a presidential statement and repackaging of NASA funds into the newly named Origins program. Over the next two years, the magnetometer aboard the Galileo spacecraft provided compelling evidence for a salty, liquid-water ocean beneath the ice crust of Jupiter's moon Europa (Kivelson et al., 2000). The close juxtaposition of these events boosted interest in the search for life, and as a result suddenly Europa was competing with Pluto for a new mission opportunity.

Capitalizing on public excitement and Congressional interest, Goldin and Huntress got a new start in 1998 for an Outer Planets/Solar Probe program, wrapping together a Europa orbiter with the now renamed Pluto-Kuiper Express (PKE), plus a Solar Probe. The project office was placed at JPL (Neufeld, 2014a). Like Fire and Ice, a common spacecraft was planned, ostensibly because all three missions had to go to Jupiter, but the other requirements for each were quite different. A harsh radiation environment was the huge challenge for Europa Orbiter, which had to remain deep within the Jovian magnetosphere, while PKE and Solar Probe simply did fast flybys through the Jupiter system. Nonetheless, all three missions were saddled with the radiation-hardening requirements of Europa Orbiter, and JPL tied the missions to an effort to develop radiation-hard electronics in a program called X-2000. Further, it was stipulated that Europa Orbiter would go first in 2003, followed by PKE in 2004 and then Solar Probe in 2007, to the significant dismay of both Pluto supporters and the space physics community.

The requirements imposed by the environment around Europa, plus difficulties reaching the radiation-hardening goals set by the X-2000 program, led to significant mass and hence cost growth in all three spacecraft. Complicating matters further was the departure from NASA Headquarters of Associate Administrator Huntress, who had been so intimately involved in and supportive of the discussions surrounding international cooperation on a Pluto mission. In his place as Associate Administrator stepped Edward Weiler, an astronomer who had been chief scientist of Hubble Space Telescope before ascending the ranks at NASA Headquarters. Much of Weiler's career had been spent at NASA Goddard Spaceflight Center, in contrast to Huntress who had been at JPL before moving to NASA headquarters in Washington DC. Further, Weiler's first years as Associate Administrator saw the in-flight loss of two JPL Mars probes, victims of Goldin's "better, faster, cheaper" philosophy, to which Weiler had not been party to. Thus, he had every reason to be suspicious of JPL, and was also wary of programs that might be exceeding the funding available.

As the combined costs of Europa Orbiter and PKE exceeded $1.4 billion and continued to climb, Weiler's relationship with JPL became adversarial as he pressured the Laboratory to reign in costs. A positive development was the formation of a science definition teams and

Announcements of Opportunity for Europa Orbiter and PKE instruments. Regardless, the concept of a common spacecraft was unraveling through 1999 owing to the cost increases it resulted in, as well as delays in the availability of radioisotopic power, and uncertainties in launch vehicle costs. Moreover, NASA's space science program was now under pressure from the Office of Management and Budget (OMB), which saw the program as out of control. With the growth of astrobiology research at NASA, Congress and the OMB saw the science that might be done at Europa to assess its ocean's suitability for life as the higher priority. PKE's planetary formation focus, plus its "last planet yet to be explored" public appeal, were seen as less important. On September 12, 2000, Weiler, with OMB backing, told JPL to stop work on PKE—effectively cancelling the mission.

PKE's cancellation fractured the outer planets community. Anticipating cancellation, the Planetary Society began a campaign in July to highlight Pluto as a key planetary target. Nine days after cancellation, the Division for Planetary Sciences of the American Astronomical Society (DPS), the professional organization of planetary scientists, issued a press release highlighting the imperative of reaching Pluto before the collapse of the atmosphere. NASA's Solar System Exploration Subcommittee (SSES), then chaired by the University of Arizona's Michael Drake, met in Pasadena at the end of October 2000, with the Pluto cancellation as a centerpiece topic on its agenda. Two of the authors of this chapter (SAS and JIL) gave presentations on the value of Pluto science, based on the findings of the 1995 Science Definition Team report, and subsequent research developments. The importance of the Kuiper Belt for understanding planet formation was emphasized, specifically that the presence of large numbers of icy bodies created in the outer regions of new systems, subsequently disturbed by the migration of the orbits of the major planets, presented a new picture of planet formation that begged for investigation by spacecraft. JPL's presentation to the committee made it clear that, by stipulating a common spacecraft bus, the design of PKE had been compromised and its costs driven up in order to satisfy the radiation parts selection and heavy shielding requirements of Europa Orbiter.

The net result of the meeting was a letter of strong SSES support to NASA for a Pluto mission and skepticism about the Europa Orbiter. As the costs of the latter soared due to the technological challenge of Jupiter's harsh radiation environment, Weiler cancelled it in 2003, in part because Congress kept appropriating funds for Pluto. That in turn set off a twelve-year-long odyssey through a variety of mission concepts until Congress stipulated a new start for Europa Clipper.[1] The rancor of the Pluto-Europa debate would be reflected in conflicts between astrobiology and planetary science goals in the outer solar system, some up to the present. But at the close of the millennium, as Cassini-Huygens was sailing toward Saturn, the immediate effect was that the US planetary program had no follow-on mission anywhere in the outer solar system.

3.3 After the millennium: Origin and development of New Horizons

In the wake of DPS, Planetary Society, public, and SSES protests against the cancellation of PKE, Weiler approached space scientist Tom Krimigis, then head of the APL Space Department, about the feasibility of a competitive, relatively low-cost Pluto program. With the success of APL's low-cost NEAR Discovery-class spacecraft, now orbiting the asteroid Eros, Krimigis was in a position to do a quick study showing how such a spacecraft could be based on NEAR and another APL Discovery spacecraft then in development, the ill-fated CONTOUR (Comet Nucleus Tour). Following optimism resulting from the APL study Krimigis led, and with Goldin's assent, Weiler had his Solar System Exploration Division Director Colleen Hartman quickly put together an Announcement of Opportunity (AO) for a competitively bid Pluto mission, similar to but on a larger scale than the PI-led Discovery missions.

NASA released the AO on the last day of the Clinton administration, January 19, 2001. Several teams formed to respond with proposals, but the Bush administration's OMB cancelled the Pluto mission the next month —forcing NASA to suspend the AO. The issue was not only budgetary; OMB still favored Europa Orbiter. APL was, however, in Maryland, and Krimigis called upon the powerful NASA appropriations committee chair Senator Barbara Mikulski to intervene. The resulting letter from her office instructed NASA to restart the AO process. Ultimately, five proposals were received in early April 2001. NASA ranked and downselected to two proposals in June 2001: the APL New Horizons proposal, with one of the authors as PI

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[1] Although this Outer Planets/Solar Probe program never came to fruition, New Horizons did launch to Pluto in 2006. Parker Solar Probe followed in 2018; and Europa Clipper is planned for launch by the mid 2020's. .

(SAS), and a JPL proposal called POSSE led by Larry Esposito of the University of Colorado. Each submitted second step proposals in September 2001; on November 29, NASA selected New Horizons for development.

Details of the differences between the proposals are left to the other reviews cited in this chapter, but the innovative payload, low-cost approach, and the PI's community leadership in pushing for a Pluto mission for over a decade were surely positive factors. However, despite their win, the odds remained against New Horizons—the budget profile provided by NASA and the overall budget cap were extremely challenging, the availability of nuclear fuel for the radioisotopic power sources was extremely limited thanks to the cessation of its production by the Federal government, the timetable to make the necessary Jupiter gravity assist flyby was very tight, and the lower-cost booster that would launch the mission was only just becoming available. Within the new administration, the mission was politically radioactive; having had the mission rammed down its throat by a powerful senator, the OMB eventually threatened publicly to withdraw support for the planetary program in general, and then left the mission out of the 2003 President's budget.

While Senator Mikulski worked to get the project funded again through the Congress, the prospect of year-to-year political heroics to sustain it cast a deep shadow over its viability. Two events pushed the mission back from its abyss to reality. First, the inaugural planetary Decadal Survey came out in 2003 with its community consensus prioritization, ranking a Pluto mission at the very top of the medium-class (0.5-1 billion dollars) mission list, specifically emphasizing the value of the mission as a Kuiper Belt explorer as the Pluto Express SDT had done eight years before. This was especially pivotal to the resuscitation of the mission, because it gave Mikulski a powerful scientific rationale for her efforts to get the mission funded. And second, Hartmann had crafted within her Solar System Exploration Division and successfully sold to upper management at NASA a proposed new line of PI-led missions, with a cap twice that of Discovery, called New Frontiers. Unlike Discovery's wide-open landscape for proposing any mission within its cost cap, New Frontiers PIs would be given a limited list of high-priority targets; this program and the Decadal's Pluto Kuiper Belt recommendation made it natural to combine PKB on the list and designate New Horizons as the first New Frontiers mission. The only remaining political hurdle was to convince Weiler and Hartmann that the APL team could bring the mission to launch readiness by the beginning of 2006, when the next Jupiter gravity assist was possible. This having been accomplished—though not without many interesting wrinkles and numerous developmental challenges (Neufeld, 2014a; see also Stern & Grinspoon 2018)—the mission was finally put on solid political and programmatic ground. That enabled a very challenging but ultimately successful spacecraft development, leading to a successful launch on January 19, 2006.

4. 2006-PRESENT: THE SUCCESS OF NEW HORIZONS AND THE FUTURE

4.1 New Horizons in flight

After its launch, New Horizons made a 9.5-year crossing of the solar system, which included a gravity assist, flight test, and scientific flyby of Jupiter in February and March 2007. It then explored the Pluto system early and mid-2015, reaching closest approach to the planet and all of its satellites on July 14, 2015; data transmission from that flyby was completed in October 2016. Meanwhile, in late 2015, New Horizons targeted its first KBO flyby, to explore a small (~36 km long) Cold Classical KBO designated 2014 MU_{69} Arrokoth (formerly Ultima Thule). That flyby culminated in a closest approach on 1 January 2019; data from that flyby are still being transmitted to Earth as of this writing and are expected only to be complete in 2021.

The New Horizons spacecraft carries a payload that significantly broadened the minimum mission scientific objectives over those specified by the Pluto Kuiper Express Science Definition Team (SDT: Lunine et al. 1995). This, along with spacecraft pointing and other capabilities that well matched the payload's highest resolution sensors, and the inclusion of two 64 Gb solid state flight recorders, allowed the mission to far exceed the baseline scientific objectives of both the SDT and the NASA Announcement of Opportunity (01-OSS-01) that called for flyby mission proposals to Pluto and the Kuiper Belt.

The enhanced payload and spacecraft capabilities of New Horizons, combined with a very highly optimized flyby observing plan at the Pluto system, allowed New Horizons to make numerous groundbreaking discoveries about Pluto and its satellites, as this Space Science Series volume details at length. Among the most significant findings from this exploration are the following: Pluto is far more complex than like-sized icy satellites explored by other missions and it remains intensely geologically active 4.5 billion years after its formation. The planet displays evidence for all of the following: geologic activity even to the recent past or today; extensive tectonics and true polar wander, and strong evidence for cryovolcanism; a global internal liquid water ocean; a water ice crust; several styles of putative volcanism; ancient terrains that date back close to the planet's formation epoch; a haze-filled atmosphere with a rich hydrocarbon and nitrile minor species composition accompanying the major gas, molecular nitrogen; strong mega-seasonal cycles and epochs of much higher atmospheric pressure than the current epoch, owing to obliquity cycles; and a lack of newly detected satellites or rings.

Pluto's giant satellite Charon, the other object in the binary planet pair, displays evidence for: a former liquid water ocean in its interior; early epoch tectonics; an age as great as Pluto's; a lower bulk density than Pluto; several kinds of unique geological expressions not yet seen elsewhere; and a lack of detectable atmosphere at a level orders of magnitude below Earth-based limits. Pluto's four small satellites, which orbit the binary pair, were found to each be irregular in shape, complex in their rotational dynamics, and to have surface ages (where observed) as old as Pluto and Charon's oldest terrains, and surface compositions that include both water ice and ammonia or ammoniated species. Additionally, a major advance in understanding of the small-diameter size-frequency distribution of KBOs was made using crater statistics on both Pluto and Charon.

The flyby exploration of Arrokoth also yielded numerous discoveries (see the chapter in this volume on MU69 Arrokoth by Stern et al.). In brief, these include discovering that the object is a contact binary with unexpectedly flattened lobes that formed near one another, very likely in a local pebble collapse cloud, then became an orbiting pair, and then gently merged into the contact binary configuration; it also displays discrete geological units and significant albedo heterogeneity, but only small color variegation and spectroscopic evidence for methanol on its surface. The paucity of detected craters on Arrokoth implies a relative dearth of KBOs <1 km in diameter and collisionally benign ancient and present-day KB environments. No satellites, orbiting rings/dust structures, or evidence of atmosphere were found to accompany this fascinating object.

4.2 The contextual successes of New Horizons

Results from the New Horizons mission are detailed in the chapters on the geology (White et al. "Geology of Pluto", Spencer et al. "Geology of Charon"), color (Olkin et al. "Colors and Photometric Properties (surface properties etc.)"; Howett et al. "Charon: Colors and Photometric Properties", surface composition (Cruikshank et al. "Surface Composition", Protopapa et al. “Charon Surface Composition”), atmospheric structure (Summers et al. “Atmospheric Structure and Composition”), plasma environment (Bagenal et al., “Solar Wind Interaction with the Pluto System"), and in the small satellites chapter (Porter et al., **“**Small Satellites and Their Dynamics”)

As a first mission to both a previously unexplored planet and two new types of body (the ice dwarf planets and KBOs of the outer solar system), New Horizons very much falls in context with the earliest Mariners, Pioneers, and the Voyagers, which each undertook similarly groundbreaking first reconnaissance of closer planets. However, in large measure because that spacecraft and its instrument payload were based on advanced technologies not available to those much earlier missions, the scientific return from the first flybys New Horizons conducted of the Pluto system and Arrokoth generated much larger datasets and accomplished the collection of dataset resolutions and types (e.g., surface composition mapping) that predecessor first flyby missions could not. For example, if one compares the New Horizons Pluto flyby datasets to the exploration of Mars, it can fairly be said that New Horizons took the Pluto system to a state of knowledge crudely equivalent to Mars after about a generation of spacecraft exploration from the 1960s to the 1990s.

New Horizons demonstrated that the reconnaissance exploration of planets and smaller bodies in the Kuiper Belt need not incur the multi-billion-dollar cost (adjusted to today’s dollars) of Voyagers 1 & 2 despite yielding similarly spectacular results. New Horizons also demonstrated the viability of the New Frontiers class of PI-led missions, roughly twice the cost of the Discovery missions with a commensurately higher science return. This in turn not only opened the door to further exploration of the Kuiper Belt and its planets with such missions, but also a variety of other targets throughout the solar system.

The long battle for a Pluto mission revealed a change around the year 2000 in how planetary missions were advocated and selected (Neufeld, 2014a). Previously, NASA Headquarters, usually the Associate Administrator for Space Science in cooperation with the Director of Solar System Exploration (the division’s name at the time), routinely assigned missions to JPL. But Goldin's "faster, better, cheaper" approach and the rise of competed missions in the Discovery Program opened up the planetary mission selection process to a larger number of actors. Notably, it made APL and later Goddard Spaceflight Center into viable competitors with JPL for planetary missions, which in turn encouraged political intervention by the Maryland congressional delegation, especially Mikulski. Around the same time, the planetary science community made its advocacy voice much more effective through the AAS-DPS and the NAS Decadal Survey process. The fight over New Horizons sped the 2002 to 2003 decadal process toward prioritizing Pluto and hence the resurrection of the mission. it also impelled the creation of the New Frontiers line, expanding competitive missions. The decadal process now reigns more-or-less supreme in prioritization, and competition remains central outside of Flagship missions. The fight over a mission to Pluto may therefore have been one of the most consequential episodes in the history of planetary science policy in the last 30 years.

4.3 Where do we go from here in the post-NH era?

In a broad sense, the era of the initial reconnaissance of all the planets and the major types of solar system objects known at the dawn of the Space Age, came to a close with New Horizons. That said, the exploration of the solar system in general and Pluto and the Kuiper Belt, all remain very far from complete.

Going forward, much more the detailed exploration of the bodies of our solar system lies ahead. Such exploration is already yielding a wide variety of orbital, surface, and even subsurface robotic exploration of increasing diversity and capability. Similarly, we are now also seeing the beginnings of sample return from many more bodies than simply Earth's Moon, and plans for new human exploration of the Moon and the first human explorations of Mars are now under way.

As to Pluto and the Kuiper Belt, there is little debate that further exploration is necessary (see the chapter by Buie, "Future Pluto Observations of and Missions to the Pluto System"). This is likely to come in at least two forms in the next few decades, including the flyby reconnaissance of more (current and former if one includes Centaur missions) KBOs and a wider variety of dwarf planets, and to more in depth studies of the Pluto system with an orbiter bringing time domain, complete mapping, and new kinds of investigations New Horizons could not (or did not know to) bring.

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TABLE 1. Partial list of Pluto/Charon discoveries through 1992 (from Lunine et al, 1995; Stern and Mitton, 1998).

Year	Discovery	Reference
1930	Pluto discovered; orbit determined	Bower and Whipple (1930)
1955	Rotation period of 6.4 days determined	Walker and Hardie (1955)
1965	Neptune-Pluto 2:3 orbit resonance found	Cohen and Hubbard (1965)
1973	Extreme obliquity of Pluto discovered	Andersson and Fix (1973)
1976	Discovery of methane ice on Pluto	Cruikshank et al (1976)
1978	Charon discovered; system mass measured	Christy and Harrington(1978)
1985-90	First maps of Pluto	Buie and Tholen, (1989)
1986	First reliable radii of Pluto and Charon	Dunbar and Tedesco (1986)
1987	Discovery of water ice on Charon	Marcialis et al. (1987)
1988	Stellar occultation sees Pluto's atmosphere	Elliot et al. (1989)
1991-3	Pluto-Charon mass ratio	Young et al. (1994)
1992	Atmospheric methane	Young et al. (1997)
1992	Discovery of N_2 and CO ice on Pluto	Owen et al. (1993)

Not all references to a given discovery listed.