FIFTY YEARS OF EXPLORING PLUTO: FROM TELESCOPES TO THE NEW HORIZONS MISSION.

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Discovery and early work: Pluto was discovered in 1930 at Lowell Observatory in the belated resumption of a wide-field photographic search originally begun at Percival Lowell's direction prior to his death in 1916. Photometry in the 1950s [1] established the rotation period of 6.4 hours and a color redder than the Sun, but the mass, density, size and albedo were unknown. Near-infrared photometry in 1976 indicated the presence of CH_4 frost, suggestive of a relatively high surface albedo and a diameter comparable to the Moon [2]. The large satellite Charon was discovered in 1978 [3], followed by an epoch of mutual transits and occultations of Pluto and Charon from 1985 to 1990, as viewed from Earth. These events resulted in reliable sizes and masses of the two bodies, as well as the orbit of Charon. The mutual events also demonstrated that Pluto and Charon are in locked synchronous rotation and revolution, a configuration unique among the planets [4]. The atmosphere of Pluto was discovered in 1988 from a stellar occultation observed from the Kuiper Airborne Observatory and ground stations [5,6], with indications of a haze layer (or a temperature inversion) in the lower atmosphere. Subsequent stellar occultations showed that the extent of the atmosphere is variable on a timescale of a few years. The spectroscopic detection of N_2 and CO ice in 1993 [7] demonstrated that the atmosphere must be primarily composed of N_2, with CH_4 and CO as minor components; the spectroscopic detection of gaseous CH_4 was reported in 1994 [8].

New Horizons Mission: Discussions with NASA for a spacecraft mission to Pluto began in 1989 [9-11], and after several studies, proposals, and programmatic changes, a mission to the Kuiper Belt and Pluto was recommended by the first Planetary Decadal Survey at the highest priority for NASA's first New Frontiers mission [12]. New Horizons was selected in 2001 in competition with other mission proposals.

Scientific Results: NASA's New Horizons mission to the Kuiper Belt and Pluto was launched on January 19, 2006, and after flying by Jupiter some 13 months later, passed by Pluto at a distance of 12,500 km and Charon at a distance of 28,800 km on July 14, 2015. Four small satellites previously discovered with the Hubble Space Telescope were imaged, and their rotation periods measured. Details of the spacecraft, instruments, and the flyby are given in [9-11], with an early report on the science results in [13], while many subsequent papers, not fully referenced here, give details. The diameters of Pluto and Charon were refined to 2376 and 1210 km, respectively, and the densities were found to be 1.854 and 1.702 g/cm^3, respectively [13]. The complexity of Pluto's surface and atmosphere, as well as the near-space environment, revealed by New Horizons far exceeded predictions and expectations. The degree of current and recent geological activity was not anticipated for this relatively small, cold, and ancient planetary body [14]. In order to support the range of vertical relief of ~6 km observed across the surface, the most probable bedrock material is H_2O ice. Some exposures of H_2O ice are seen, but most of the bedrock is overlain by a veneer of much more volatile N_2, CH_4, and CO, all of which are spectroscopically detected [15-17]. The 1000-km wide nitrogen glacier (Sputnik Planitia) is being fed by ice flows from nearby highland sources, while the glacier itself is slowly convecting [18], with surface expressions of convective cells, wind-blown dunes of dark material [19], and no evidence on the surface of impact craters larger than a few hundred meters. Sputnik Planitia formed as a large impact basin, thinning the planet's crust and creating a gravity anomaly [20]. The anomaly was enhanced as solid N_2 accumulated in the basin [21]. Although there are other scenarios for the evolution of Sputnik Planitia, the net effect of the altered gravity field was to cause Pluto to reorient so as to line up exactly with Charon at the antipode of the planet's opposite hemisphere. Pluto appears to have once had a global subsurface ocean, which may persist to the present, with some regions of the surface suggesting relatively recent ($<10^9$ y) episodes of ejection of cryovolcanic fluids from subsurface reservoirs. Pluto's multiple layers of atmospheric haze and lower escape rate were unexpected [22]. The yellow and red-brown colors widely distributed on Pluto's surface are suggestive of a tholin composed of complex organic chemicals, some of which have fallen from the atmosphere as haze particles, with some created by sunlight and solar wind particles acting on the CH_4 and N_2 ices covering much of the surface. The color properties of much of Pluto's surface are closely similar to those of tholin produced in the lab by energetic processing of a Pluto-mix of ices (CH_4, N_2, CO), and consisting of a mix of many organic molecular structures [23-25].

Pluto shows evidence of major changes in atmospheric pressure on Milankovich (~million-year) timescales due to precession of the rotational pole, possibly

resulting in past episodes of running or standing liquid on the surface [26, 27]. The atmosphere is in vapor pressure equilibrium with the volatile surface ices and is well mixed horizontally above ~10 km. The tropopause is variable over location and time of day. The photochemical products C_2H_2, C_2H_4, and C_2H_6 were detected. As many as 20 haze layers were seen; the haze may contribute to cooling the atmosphere [28]. In forward scattering the atmosphere is blue as a result of Rayleigh scattering.

Before the New Horizons flyby the estimates of the atmospheric escape (presumed to be mostly N_2 molecules) ranged from as low as 1.5 x 10^{25} s^{-1} to as high as 2 x 10^{28} s^{-1}. Combining these atmospheric escape rates with Voyager and New Horizons observations of the solar wind at 33 AU produced estimates of the scale of the interaction region from 7 to 1000 Pluto radii [29]. Observations by the SWAP instrument revealed a surprisingly small interaction region, confined on its upwind side to within ~6 Pluto radii [30, 31]. The occultation measurements by New Horizons revealed Pluto's atmosphere to be colder and less extended than expected, which reduces the escape rate to only 6 x 10^{25} molecules s^{-1} and the main escaping gas is now thought to be mostly methane rather than nitrogen [32]. The surprisingly small size of the interaction region is consistent with a reduced atmospheric escape rate as well as a particularly high solar wind flux, enhanced by a factor of ~4 due to a passing compression region in the solar wind.

The cratering record on both Pluto and Charon demonstrates a paucity of small impactors in their region of the Solar System, suggesting an early depletion of small fragments of colliding Kuiper Belt bodies [33]. The generally gray-colored surface of Charon is dominated by H_2O ice, but an additional component identified as an ammonia hydrate or ammoniated salt is found in many locations. The red-brown color of the north polar region is interpreted as a tholin formed by UV processing of CH_4 ice derived from methane escaping from Pluto's atmosphere and frozen on the polar region during prolonged darkness [34]. Charon exhibits a very large equatorial extentional tectonic belt that may have formed by the freezing of a former liquid H_2O ocean [35].

Pluto's four small irregularly shaped icy satellites, Styx, Nix, Kerberos, and Hydra, range in size from16x9x8 km (Styx) to 65x45x25 km (Hydra), and all are in chaotic rotation states. Nix and Hydra have spectral bands of H_2O ice and an ammonia signature, while the other two were not measured with the imaging spectrometer [36].

Legacy: The scientific results of New Horizons at Pluto and its satellites have changed our perception of planetary bodies in their size range, demonstrating that geological activity on both large and small scales can occur long after the epoch of planet formation. A few other dwarf planets comparable in size to Pluto and Charon are known in the transneptunian population, and the extraordinary discoveries by New Horizons inform open questions of their origins and physical-chemical characteristics that will remain until they, too, can be explored.

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