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Structure and composition of Pluto's atmosphere from the New Horizons solar ultraviolet occultation

Leslie A. Young[a,*], Joshua A. Kammer[b], Andrew J. Steffl[a], G. Randall Gladstone[b], Michael E. Summers[c], Darrell F. Strobel[d], David P. Hinson[e], S. Alan Stern[a], Harold A. Weaver[f], Catherine B. Olkin[a], Kimberly Ennico[g], David J. McComas[b,h], Andrew F. Cheng[f], Peter Gao[i], Panayotis Lavvas[j], Ivan R. Linscott[k], Michael L. Wong[i], Yuk L. Yung[i], Nathanial Cunningham[a], Michael Davis[b], Joel Wm. Parker[a], Eric Schindhelm[a,l], Oswald H.W. Siegmund[m], John Stone[b], Kurt Retherford[b], Maarten Versteeg[b]

[a] Southwest Research Institute, Boulder, CO, United States
[b] Southwest Research Institute, San Antonio, TX, United States
[c] George Mason University, Fairfax, VA, United States
[d] The Johns Hopkins University, Baltimore, MD, United States
[e] SETI Institute, Mountain View, CA, United States
[f] Johns Hopkins University Applied Physics Laboratory, Columbia, MD, United States
[g] NASA Ames Research Center, Moffett Field, CA, United States
[h] Princeton University, Princeton, NJ, United States
[i] California Institute of Technology, Pasadena, CA, United States
[j] Universite´de Reims Champagne-Ardenne, 51687 Reims, France
[k] Stanford University, Stanford CA, United States
[l] Ball Aerospace, Boulder CO, United States
[m] Sensor Sciences, Pleasant Hill, CA 94523, United States

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ABSTRACT

The Alice instrument on NASA's New Horizons spacecraft observed an ultraviolet solar occultation by Pluto's atmosphere on 2015 July 14. The transmission vs. altitude was sensitive to the presence of N_2, CH_4, C_2H_2, C_2H_4, C_2H_6, and haze. We derived line-of-sight abundances and local number densities for the 5 molecular species, and line-of-sight optical depth and extinction coefficients for the haze. We found the following major conclusions: (1) We confirmed temperatures in Pluto's upper atmosphere that were colder than expected before the New Horizons flyby, with upper atmospheric temperatures near 65–68 K. The inferred enhanced Jeans escape rates were (3–7) × 10^{22} N_2 s^{-1} and (4–8) × 10^{25} CH_4 s^{-1} at the exobase (at a radius of ∼ 2900 km, or an altitude of ∼1710 km). (2) We measured CH_4 abundances from 80 to 1200 km above the surface. A joint analysis of the Alice CH_4 and Alice and REX N_2 measurements implied a very stable lower atmosphere with a small eddy diffusion coefficient, most likely between 550 and 4000 cm^2 s^{-1}. Such a small eddy diffusion coefficient placed the homopause within 12 km of the surface, giving Pluto a small planetary boundary layer. The inferred CH_4 surface mixing ratio was ∼ 0.28–0.35%. (3) The abundance profiles of the "C_2H_x hydrocarbons" (C_2H_2, C_2H_4, C_2H_6) were not simply exponential with altitude. We detected local maxima in line-of-sight abundance near 410 km altitude for C_2H_4, near 320 km for C_2H_2, and an inflection point or the suggestion of a local maximum at 260 km for C_2H_6. We also detected local minima near 200 km altitude for C_2H_4, near 170 km for C_2H_2, and an inflection point or minimum near 170–200 km for C_2H_6. These compared favorably with models for hydrocarbon production near 300–400 km and haze condensation near 200 km, especially for C_2H_2 and C_2H_4 (Wong et al., 2017). (4) We found haze that had an extinction coefficient approximately proportional to N_2 density.

* Corresponding author.
E-mail address: layoung@boulder.swri.edu (L.A. Young).

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1. Introduction

We report here on the ultraviolet solar occultation by Pluto's atmosphere observed with the Alice spectrograph on NASA's New Horizons spacecraft. Ultraviolet occultations have proven invaluable for measuring the structure and composition of the other two N_2-rich atmospheres in the outer solar system, Titan (Smith et al., 1982; Herbert et al., 1987; Koskinen et al., 2011; Kammer et al., 2013; Capalbo et al., 2015) and Triton (Broadfoot et al., 1989; Herbert and Sandel, 1991; Stevens et al., 1992; Krasnopolsky et al., 1992). By observing how the absorption by molecular species and extinction by haze particles vary with altitude as the Sun passes behind an atmosphere, it is possible to measure their vertical density profiles, and infer the pressure and temperature from the density of the majority species. Because pressure, temperature and composition are central to nearly every aspect of atmospheric science, the Pluto ultraviolet (UV) solar occultation was ranked as a Group 1 (required) observation for the New Horizons mission (Young et al., 2008). The UV solar occultation drove aspects of both the design of the Alice Ultraviolet Imaging Spectrograph (Stern et al., 2008) and the mission design of the New Horizons flyby past Pluto (Guo and Farquhar, 2008). We built the Alice instrument to observe the occulted solar flux from 52 to 187 nm, covering absorption by the N_2 continuum on the short end and extinction by haze on the long end. We designed the spacecraft trajectory to pass through the Sun and Earth shadows of both Pluto and Charon, nearly diametrically for Pluto.

The UV solar occultation occurred from approximately 2015 July 14 12:15 to 13:32 UTC (spacecraft time). Roughly one terrestrial day later, at approximately 2015 July 15 12:38 UTC (ground receipt time), we received confirmation that the observations were successful and that the spacecraft successfully flew through Pluto's solar shadow. Downlink data volume constraints meant that this first "contingency download" of the UV solar occultation contained only the Alice housekeeping data, which included the total number of photons detected across all wavelengths each second; these data were discussed by Stern et al. (2015). The full downlink of the Pluto solar occultation (0.67 Gigabits) was completed on 2015 Oct 2. Initial analysis of Pluto's ultraviolet solar occultation (Gladstone et al., 2016) presented line-of-sight column abundances (aka light-of-sight column densities) of N_2, CH_4, C_2H_2, C_2H_4, and C_2H_6, and the local densities of N_2, CH_4, C_2H_2, and C_2H_4.

This paper extends the analysis of Gladstone et al. (2016) in the following ways: (i) it uses an improved reduction of the raw observations, and includes more details about the observation and reduction process, (ii) it presents error analysis, including correlations between the measurements of various species, (iii) it includes analysis of extinction by haze at the long-wavelength end of the Alice range, (iv) it improves or extends the density retrievals of N_2, CH_4, C_2H_2, C_2H_4, C_2H_6 and haze, and (v) it includes a joint analysis with new results from the New Horizons radio occultation (Hinson et al., 2017).

2. Observations and reduction

We recap here the salient features of the Alice ultraviolet spectrograph on the New Horizons spacecraft and its observation of Pluto's atmosphere during the solar occultation. Alice (which is a name, not an acronym) is described in more detail in Stern et al. (2008), and a previous Alice stellar occultation by Jupiter is described in Greathouse et al. (2010). Alice is an imaging spectrograph that has a bandpass from 52 to 187 nm, with a photocathode gap from 118 to 125 nm designed to decrease the count rate near Ly-α. Alice has two data collection modes (pixel list and histogram), two adjoined slit elements (a wider $2° \times 2°$ "box" and a narrower $4° \times 0.1°$ "slot"), and two apertures (the lower-throughput "solar occultation channel" or SOCC and the higher-throughput "airglow aperture"). For the Pluto solar occultation, we used the pixel list data collection mode for higher time cadence. We also placed the Sun in the "box" to avoid slit losses, and used the SOCC to avoid oversaturation and to observe the UV solar occultation simultaneously with the radio earth occultation (Fig. 1).

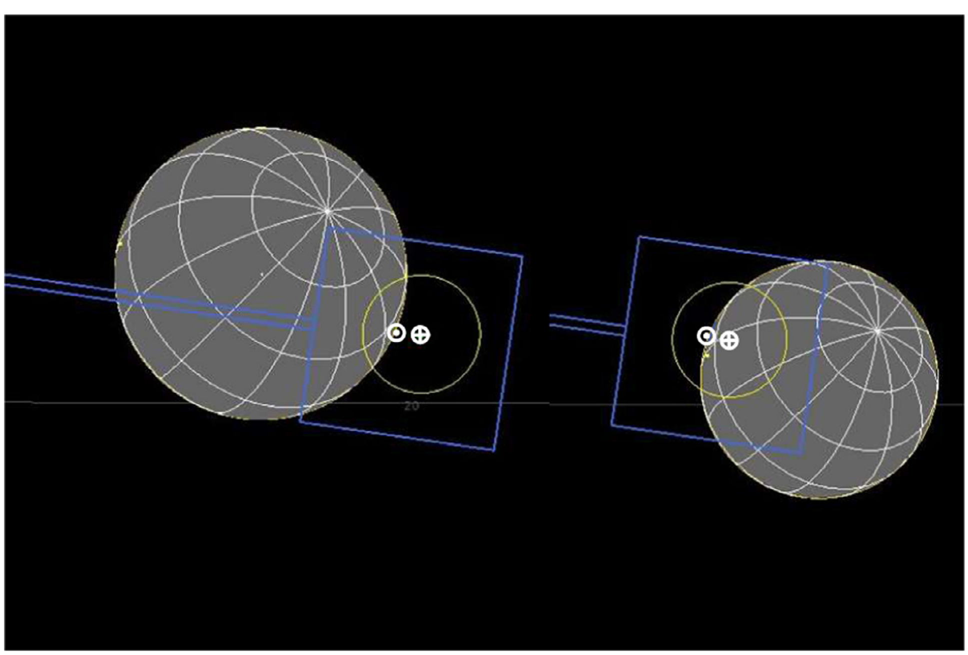

Fig. 1. The Alice Solar Occultation Channel (SOCC), Pluto, and the Sun at the time of solar ingress at 2015 Jul 14 12:44 UT (left) and egress at 12:55 UT (right) as seen from New Horizons. The REX field of view (yellow circle, indicating the 1.2° diameter of the REX 3 dB beamwidth) was centered on the Earth (white Earth symbol). The Alice slit (the blue "box" and "slot") had the box portion centered on the Sun (white Sun symbol). The figure is oriented with celestial North up and East to the left. This figure also shows the scale of Pluto at ingress and egress, and a latitude-longitude grid (at 30° intervals) on Pluto. The southern (winter) pole was in view. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).