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Pluto's haze as a surface material

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ABSTRACT

Pluto's atmospheric haze settles out rapidly compared with geological timescales. It needs to be accounted for as a surface material, distinct from Pluto's icy bedrock and from the volatile ices that migrate via sublimation and condensation on seasonal timescales. This paper explores how a steady supply of atmospheric haze might affect three distinct provinces on Pluto. We pose the question of why they each look so different from one another if the same haze material is settling out onto all of them. Cthulhu is a more ancient region with comparatively little present-day geological activity, where the haze appears to simply accumulate over time. Sputnik Planitia is a very active region where glacial convection, as well as sublimation and condensation rapidly refresh the surface, hiding recently deposited haze from view. Lowell Regio is a region of intermediate age featuring very distinct coloration from the rest of Pluto. Using a simple model haze particle as a colorant, we are not able to match the colors in both Lowell Regio and Cthulhu. To account for their distinct colors, we propose that after arrival at Pluto's surface, haze particles may be less inert than might be supposed from the low surface temperatures. They must either interact with local materials and environments to produce distinct products in different regions, or else the supply of haze must be non-uniform in time and/or location, such that different products are delivered to different places.

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1. Introduction

The discovery of extensive haze in Pluto's atmosphere was one of numerous striking findings from NASA's New Horizons Pluto encounter (Stern et al., 2015). The ultraviolet solar occultation data showed haze at altitudes up to at least 350 km above Pluto's surface (L.A. Young et al., 2018) and it can be seen in high phase visible wavelength images up to well over 200 km altitude (Gladstone et al., 2016; Cheng et al., 2017). The images reveal it to be divided into as many as 20 distinct layers, possibly due to the influence of orographic gravity waves. The haze is thought to have a relatively short residence time in Pluto's thin atmosphere before it settles to the surface, where it can be expected to accumulate. This paper explores the potential influence of haze particles on three very distinct terrain types on Pluto's encounter hemisphere, where the highest spatial resolution images and compositional maps were obtained (see Fig. 1). Cthulhu[1] is the largest of a group of dark, red patches that form a discontinuous belt along Pluto's equator. Portions of Cthulhu are heavily cratered and ancient, and it is mostly free of the seasonally mobile volatile ices that cover most of Pluto's surface. It thus offers a view of a thick, long-term accumulation of haze particles. In contrast, Sputnik Planitia is a smooth, bright, low-lying plain where convective overturn of volatile ice along with diurnal and seasonal cycles of sublimation and condensation refresh the surface on geologically short timescales. Lowell Regio is Pluto's northern polar region, where thick deposits rich in methane ice (Grundy et al. 2016a; Howard et al. 2017) appear to have accumulated over intermediate timescales, possibly associated with Pluto's three million year Milankovitch-like seasonal cycles (Dobrovolskis et al., 1997; Earle and Binzel, 2015; Hamilton et al., 2016; Earle et al., 2017; Stern et al., 2017).

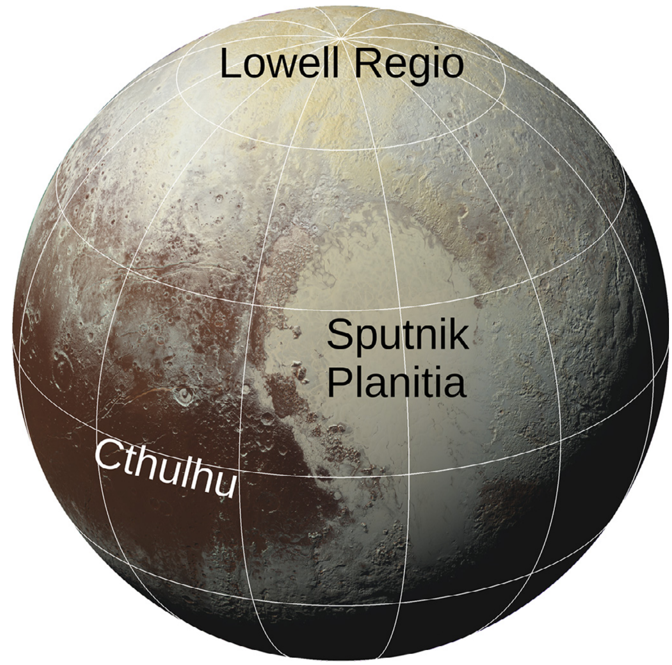

Fig. 1. The MVIC P_COLOR_2 Pluto observation with *BLUE, RED*, and *NIR* filter images displayed in blue, green, and red color channels, respectively (in color in the on-line version only). This "enhanced color" mapping of filters to display colors is used throughout the paper. The three main regions discussed in the text are indicated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Haze production and composition

Pluto's haze originates in photolysis and radiolysis of gases in the upper atmosphere: chiefly CH_4, N_2, and CO. N_2 is the dominant atmospheric species near the surface, but CH_4 becomes increasingly abundant with altitude, matching the abundance of N_2 at an altitude of ~1400 km (Gladstone et al., 2016; L.A. Young et al., 2018). Methane is the primary chemical feedstock for haze production and is also the dominant molecular species escaping to space. Various energetic radiation sources produce radicals and ions from Pluto's atmospheric molecules, leading to creation of new compounds and eventually haze particles.

Solar ultraviolet light drives photochemistry, with Ly α photons (1216 Å, 10.2 eV) being an especially important source. The solar Ly α flux at Pluto's 39.5 AU mean heliocentric distance is $\sim 3 \times 10^{12}$ photons $m^{-2}\,s^{-1}$ (Gladstone et al., 2015). Ly α photons readily break C–H bonds in methane through various pathways (to $CH_3(X) + H$, 5.7 eV; to $CH_2(a) + H_2$, 5.2 eV; and to $CH(X) + H_2 + H$, 1.14 eV) and are thus strongly absorbed by CH_4 in Pluto's upper atmosphere. In addition to direct solar illumination of Pluto's day side, Ly α photons are resonantly scattered by neutral H in the interplanetary medium, leading to diffuse irradiation of Pluto's night side by scattered Ly α comparable to the flux received on the day side (Gladstone et al., 2016; L.A. Young et al., 2018). Over Myr and longer timescales this resonantly scattered flux can be expected to vary as the Sun passes through different galactic environments. Ly α photons are not able to photodissociate the strong triple bonds N≡N in N_2 or C≡O in CO (9.8 and 11.1 eV, respectively). In the case of N_2, this is because there are no dipole-allowed transitions to repulsive states below the ionization threshold (15.6 eV). But shorter wavelength UV photons can break up N_2 through ionization and subsequent ion-molecule reactions, although their fluxes are lower. Higher energy x-ray photons (wavelengths < 1 nm) are scarcer still (Lisse et al., 2017), and highly variable with solar activity. They are more penetrating, and so contribute relatively little to atmospheric chemistry except near the surface, with the higher energy x-rays (< 0.1 nm) affecting Pluto's surface.

Another contributor to atmospheric chemistry is the plasma of protons and electrons streaming radially away from the Sun. Typical solar wind energies are in the keV range, though the distribution also includes higher energy particles (e.g., Cooper et al., 2003; Mewaldt et al., 2007). At Pluto's heliocentric distance during the 2015 New Horizons encounter, the flux of solar wind particles was highly time-variable, on the order of 10^9 to 10^{10} particles $m^{-2}\,s^{-1}$ (Bagenal et al., 2016). Details of the plasma interaction with Pluto's atmosphere are uncertain, and much of it is diverted around Pluto due to the existence of a highly-conducting day-side ionosphere (Cravens and Strobel, 2015), but it could be an important additional driver of radiolytic chemistry, with each keV particle delivering ~100 × the energy of a Ly α photon.

Cosmic rays provide yet another source of energetic particles, impinging on Pluto's atmosphere isotropically, with energies in the MeV through GeV range being especially important (e.g., Padovani et al., 2009). When one of these highly energetic particles collides with a molecule in the atmosphere (or on the surface, since the atmosphere is not thick enough to stop the more energetic particles) it triggers a cascade of lower energy secondary and tertiary particles that penetrate further, creating a substantial swath of damage: broken chemical bonds and excited radicals and ions that react to create new chemical species. At lower energies, this cascade is dominated by the component nuclei and electrons of the target atoms (elastic collisions), while at higher energies, atomic nuclei themselves can be disrupted, producing a shower of more exotic particles (inelastic collisions) (e.g., Johnson, 1990). Estimates of cosmic ray penetration into the heliosphere suggest that Pluto currently receives relatively low fluxes of 100 keV to 10 MeV protons compared with objects orbiting closer to the heliopause (Cooper et al., 2003), but above ~100 MeV, the cosmic ray

[1] Names of Pluto system regions and features mentioned in this paper include a mix of official and informal names.