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Primordial N_2 provides a cosmochemical explanation for the existence of Sputnik Planitia, Pluto

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ABSTRACT

The presence of N_2 in the surface environment of Pluto is critical in creating Pluto's richness of features and processes. Here, we propose that the nitrogen atoms in the N_2 observed on Pluto were accreted in that chemical form during the formation of Pluto. We use *New Horizons* data and models to estimate the amounts of N_2 in the following exterior reservoirs: atmosphere, escape, photochemistry, and surface. The total exterior inventory is deduced to be dominated by a glacial sheet of N_2-rich ices at Sputnik Planitia, or by atmospheric escape if past rates of escape were much faster than at present. Pluto's atmosphere is a negligible reservoir of N_2, and photochemical destruction of N_2 may also be of little consequence. Estimates are made of the amount of N_2 accreted by Pluto based on cometary and solar compositions. It is found that the cometary model can account for the amount of N_2 in Sputnik Planitia, while the solar model can provide a large initial inventory of N_2 that would make prodigious atmospheric escape possible. These consistencies can be considered preliminary evidence in support of a primordial origin of Pluto's N_2. However, both models predict accreted ratios of CO/N_2 that are much higher than that in Pluto's atmosphere. Possible processes to explain "missing CO" that are given quantitative support here are fractional crystallization from the atmosphere resulting in CO burial at the surface, and aqueous destruction reactions of CO subject to metastable thermodynamic equilibrium in the subsurface. The plausibility of primordial N_2 as the primary source of Pluto's nitrogen (vs. NH_3 or organic N) can be tested more rigorously using future constraints on the $^{14}N/^{15}N$ ratio in N_2 and the $^{36}Ar/N_2$ ratio.

1. Introduction

With a similar general role as water on Earth, methane on Titan, and especially CO_2 on Mars, molecular nitrogen (N_2) is the key volatile on Pluto that brings activity to the frigid surface environment of this remote world (see Olkin et al., 2017 and Stern et al., 2018 for recent reviews on the Pluto system). A volatile is defined here as a chemical species that can readily transition in a macroscopic sense between gaseous and condensed forms at the temperature of a planetary body. Solid N_2 appears to be the most abundant ice on the surface of Pluto accessible to spectroscopy (Owen et al., 1993; Cruikshank et al., 2015; Grundy et al., 2016a; Protopapa et al., 2017). The *New Horizons* mission discovered what is inferred to be an N_2-rich ice sheet in a near-equatorial region called Sputnik Planitia (formerly referred to as Sputnik Planum; Stern et al., 2015), which constitutes the western lobe of Pluto's "heart" (Tombaugh Regio). Because of its relatively low viscosity at Pluto surface temperatures (~40 K), solid N_2 is able to deform and flow, which maintains the youthful appearance of Sputnik Planitia (McKinnon et al., 2016; Trowbridge et al., 2016), and leads to the erosion of bedrock and the formation of glacial landforms (Moore et al., 2016; Howard et al., 2017). The relatively low triple point temperature of N_2 (63 K) facilitates melting, which could occur at the base of glaciers (Howard et al., 2017), or in the ambient surface environment if there has been modest warming (a few tens of kelvins) via large impacts locally or global climate change (Stern et al., 2017). Because N_2 ice has a relatively high vapor pressure, it can readily sublimate at Pluto's surface, which initiates a volatile cycle that results in pitting of such deposits (Moore et al., 2017), seasonally dependent mass and heat transport (Earle et al., 2017), and the deposition of bright frosts (Buratti et al., 2017). This cycle is also largely responsible for the existence of an atmosphere on Pluto (Hubbard et al., 1988; Elliot et al., 1989; Yelle and Lunine, 1989; Gladstone et al., 2016; Young et al., 2018).

What was the original molecular carrier of the nitrogen atoms that are now contained in N_2 on Pluto? Mandt et al. (2016) studied the isotopic evolution of Pluto's nitrogen for primordial N_2 and NH_3 sources of nitrogen. It has been suggested that organic N (i.e., organic molecules containing nitrogen atoms in their chemical structures) could also be a significant carrier of N to Pluto and

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other Kuiper belt objects (McKinnon et al., 1997; 2008). A primordial (accretional) origin of Pluto's N_2 would be simple in the sense that only outgassing is required to explain the observations of N_2 (e.g., Owen, 1982). In contrast, an NH_3 source of N_2 requires both chemistry and outgassing, in either order depending on whether the generation of N_2 takes place in the interior (e.g., Glein et al., 2009), or near the surface (e.g., Atreya et al., 1978; McKay et al., 1988; Sekine et al., 2011). An organic source requires a more specific process of thermally driving the formation of N_2 in a putative rocky core, followed by outgassing (e.g., Miller et al., 2017). Of course, a mixed source of N_2 is not to be excluded. These hypotheses, borrowed from the Titan literature, view the N_2 as being derived from the bulk planetary inventory. A different approach is to consider exogenous mechanisms of bringing N_2 to the surface of Pluto (e.g., cometary impacts; Singer and Stern, 2015). Beyond an intrinsic interest in the source of N_2, insights into the origin and evolution of Pluto and the solar system as a whole can be elucidated by addressing the issue of the origin of N_2 on Pluto (Lunine, 1993a). These pertain to the composition of the building blocks of Pluto and the conditions of their formation (e.g., temperature-pressure); the thermal history of the interior, surface, and atmosphere of Pluto; and the processes responsible for similarities and differences between Pluto and other N_2-bearing bodies such as Titan, Triton, and Eris (e.g., Broadfoot et al., 1989; Niemann et al., 2010; Tegler et al., 2012).

The purpose of this paper is to examine the hypothesis of a primordial origin of N_2, which represents an effort to take a step forward in determining the origin of Pluto's N_2. How consistent with the available data is the notion that N_2 was obtained from the formation environment of Pluto in that chemical form? Owen et al. (1993) discussed their discovery of N_2 on Pluto's surface in the context of a primordial origin, because Pluto seems to have formed far from the Sun where temperatures are presumed to have been low enough to accrete N_2 (e.g., < 30 K). However, such a low-temperature origin cannot be guaranteed, as Pluto could have formed inside its present orbit and been scattered outward during a period of giant planet migration (e.g., Levison et al., 2008). The relatively high bulk density of Pluto (1854 kg/m^3; Nimmo et al., 2017) suggests that Pluto formed beyond the giant planets (McKinnon and Mueller, 1988), but this does not necessarily mean that temperatures in its formation environment were sufficiently cold to accrete N_2. Stern et al. (1997) attempted to use the N_2/CO ratio of Pluto's surface as a cosmochemical constraint, but the high value seemed to be most indicative of volatile removal processes (e.g., atmospheric escape or hydrothermal geochemistry), which led to ambiguity between potential N_2 and NH_3 sources of the observed nitrogen.

Our understanding of the origin of Pluto's N_2 progressed little over the last twenty some years. However, the success of the *New Horizons* mission has changed the situation, and detailed observational data (e.g., Stern et al., 2015; Gladstone et al., 2016; Grundy et al., 2016a; Moore et al., 2016) can now be brought to bear on this problem (Section 2). It is timely to examine the primordial N_2 hypothesis in particular, given the recent first detection of N_2 from a comet by the *Rosetta* spacecraft (Rubin et al., 2015). These two datasets allow a mass balance test of this hypothesis to be performed (Section 3), based on a cosmochemical model of Pluto as a "giant comet" (for a pioneering application of this type of comparative approach to Triton, see Lunine, 1993b; Lunine et al., 1995; and McKinnon et al., 1995). We also consider the possibility that the building blocks of Pluto could have been as rich as the solar composition in terms of the abundance of N_2. We discuss in Section 4 physical and chemical mechanisms that might reconcile possible primordial values of the CO/N_2 ratio with observations of this ratio on Pluto. Lastly, we conclude this paper with a summary of our findings, and some open questions and suggestions for future observations (Section 5).

Table 1
Simple estimates for the exterior inventories of N_2 on Pluto from *New Horizons* observations and models.

Model	Past Like Present (PLP)	Large Loss (LL)
Reservoir	Moles of N_2	Moles of N_2
Atmosphere	1×10^{15}	1×10^{15}
Escape	5×10^{16}	$(0.1–1) \times 10^{22}$
Photochemistry	2×10^{18}	5×10^{18}
Surface[a]	$(0.4–3) \times 10^{20}$	$(0.4–3) \times 10^{20}$
Sum ≈ Outgassed amount	$(0.4–3) \times 10^{20}$	$(0.1–1) \times 10^{22}$

[a] The surface inventory is assumed to be dominated by volatile ices in Sputnik Planitia (see Section 2.3).

2. The apparent inventory of N_2 on Pluto

The goal of this section is to estimate the amount of N_2 that may have been outgassed from Pluto's interior, which can be regarded as an apparent inventory (we call it "apparent" because it is an inventory that can be quantified on the basis of our current understanding of Pluto, which is undoubtedly incomplete). Broadly, we can define two reservoirs of volatiles on Pluto: exterior and interior. We focus on Pluto's exterior because there is a lack of data that can be used to probe the N_2 content of its interior (e.g., Glein, 2015), where N_2 could be stored in clathrate hydrates, dissolved in a liquid water ocean (Hammond et al., 2016; Johnson et al., 2016; Keane et al., 2016; Nimmo et al., 2016), or trapped in a rocky core. The possibility of a global, kilometer-scale crustal layer of N_2 ice residing above a water ice mantle is implausible, as its existence may prevent the detection of widespread water ice on Pluto's surface (Grundy et al., 2016a), and an N_2 crust would be too weak to support the mountainous terrains observed by *New Horizons* (Stern et al., 2015). The exterior can be divided into sub-reservoirs that presently contain volatiles or are irreversible sinks of volatiles. We term these sub-reservoirs: atmosphere, escape, photochemistry, and surface.

2.1. Atmosphere

The mass of Pluto's atmosphere (m_{atm}) can be estimated from the atmospheric pressure at the surface (P_{atm}) using the following equation

$$P_{\mathrm{atm}} \approx \frac{m_{\mathrm{atm}} g}{4\pi R_{\mathrm{avg}}^2}, \quad (1)$$

where $g = 0.616$ m/s^2 designates the gravitational acceleration at the surface (Stern et al., 2015), and $R_{avg} = 1188$ km the average radius of Pluto (Nimmo et al., 2017). For $P_{\mathrm{atm}} \approx 12$ μbar (~1.2 Pa; Hinson et al., 2017), the mass of the atmosphere is $\sim 3.5 \times 10^{13}$ kg. This is consistent with earlier estimates that were made using Earth-based observations (e.g., $\sim 3 \times 10^{13}$ kg; Singer and Stern, 2015). The calculated mass can be assumed to be essentially identical to the mass of N_2 in Pluto's atmosphere as the near-surface atmosphere is $> 99\%$ N_2 by volume (Young et al., 2018). Hence, there are $\sim 1 \times 10^{15}$ moles of atmospheric N_2 (Table 1).

2.2. Escape and photochemistry

It has been inferred that Pluto's atmosphere is escaping by the Jeans mechanism, with an escape rate for N_2 of $\sim 5 \times 10^{22}$ molecules/s ($\sim 3 \times 10^6$ mol/yr; Young et al., 2018). This is several orders of magnitude slower than pre-*New Horizons* predictions (Tian and Toon, 2005; Tucker et al., 2012; Zhu et al., 2014), but