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ATMOSPHERE/SURFACE/SUBSURFACE INTERACTION AT PLUTO

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Abstract

We need to account for the structure of the subsurface when modeling volatile transport. Our aim is to model the over-abundance of CH_4 in Pluto's atmosphere, and also its under-abundance in the N_2-rich ice. When we quantify different models of atmosphere/surface/subsurface interaction, we can make testable hypotheses, and extend models into other epochs.

1. N_2, CO, CH4 in Disequilibrium at Pluto

Gaseous N_2, CO, and CH_4 are key to many aspects of Pluto's evolution, and, possibly, the evolution of other CH_4-rich Kuiper Belt Objects (KBOs). In Pluto's current atmosphere, CH_4 is the primary escaping volatile [1]; CH_4 and N_2 are critical to Titan-like photochemistry and haze production; N_2 and CH_4 shield the surface from most UV radiation [1]; deposition of gaseous N_2 and CH_4 helps form and sculpt massive land forms such as the bladed terrain [2] and the original infilling of Sputnik Planitia; and N_2 and CH_4 sublimation may affect the porosity and thermal properties of the subsurface [3]. The challenge is to use models, laboratory data, and current observations to extrapolate to other epochs.

This work is aided by (i) recent theoretical work on the state of N_2, CO, and CH_4 in thermodynamic equilibrium [4, 5]; (ii) observations from New Horizons of the N_2 surface pressure and gaseous CH_4 mixing ratio [6, 1], the spatial distribution of CH_4-rich and N_2-rich ices, and their grain sizes and dilution states (e.g., fraction of CH_4 in N_2-rich ice) [7, 8], and (iii) recent modeling of the sublimation and condensation cycles of Pluto's multi-component volatiles 9]. Although N_2 is consistent with vapour-pressure equilibrium over Sputnik Planitia [6], the gaseous CH_4 mixing ratio (~0.3%) is 10-100x *higher* than predicted for vapour-pressure equilibrium at Sputnik Planitia's temperature [4]. The mole fraction of CH_4 in N_2-rich terrains within Sputnik Planitia is also ~0.3%, which is 10x *lower* than expected for thermodynamic equilibrium.

2. Atmosphere-Surface-Subsurface Interaction

The problem of the over-abundance of gaseous CH_4 had been known pre-encounter [7, 11, 12, 3]. The under-abundance of CH_4 in N_2-rich ice was also known pre-encounter [13, 14], but not appreciated as a problem until the recent thermodynamical work [4, 5].

In the most general terms, there is a mismatch between the drivers of sublimation and condensation (Pluto's day, year, and 3-million-year obliquity cycle) and the timescales for relaxation toward equilibrium (a few minutes for N_2 vapour-pressure equilibrium [10], a few Earth-months for horizontal mixing of CH_4 [15] and longer, but hard-to-model, for diffusion within the ice).

Disequilibrium is likely to lead to vertical structure or layering, which in turn affects rates of sublimation and condensation. Examples of subsurface structure include: (i) a ***homogenous slab*** [11, 4]; (ii) a very thin molecular layer of CH_4-rich ice in balance with the atmosphere (***Detailed Balance*** model [10]), which resets the relative equilibrium vapour pressures of CH_4 and N_2 in the solid solution according to their surface mole fractions; (iii) thick ***CH_4 patches*** that build up on top of N_2 by sublimation, which can be warm, and supply CH_4 into the atmosphere through turbulent diffusion [12]; (iv) ***solar gardening*** [3]), wherein sunlight is absorbed many cm within the surface, and thermal photons are emitted from much closer to the surface, leading to CH_4-rich ice below the surface; (v) ***equilibrium altitude segregation*** [4], wherein low-altitude, N_2-rich ice and high-altitude, CH_4-rich ice are in equilibrium with the N_2 and CH_4 partial pressures; (vi) and ***CH_4-triggered coldtrap*** [9], wherein bright CH_4 condenses first, raising local albedo and allowing subsequent N_2 condensation. The implied structure varies from CH_4-rich above N_2-rich (detailed balance, CH_4 patch), N_2-rich above CH_4-rich (solar gardening, CH_4-triggered coldtrap), neither (homogenous slab), or multi-layer, depending on the time-varying atmospheric structure (equilibrium altitude segregation).

The evolution of the atmosphere with time will depend on the volatile ice composition vs. depth, and on how deeply the atmosphere can communicate with the subsurface ices.

3. Conclusions:

New theoretical predictions on the equilibrium state of volatile ices on Pluto, and new observations of the disequilibrium can be used with volatile transport models to test implications of different subsurface structures on the evolution of the atmosphere and surface/subsurface. These can be tested against observations such as the state of Pluto's atmosphere and ices during the 2015 flyby, or the evolution of the CH_4 abundance in Pluto's atmosphere.

Acknowledgements

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