THERMAL CONVECTION IN SOLID NITROGEN, AND THE DEPTH AND SURFACE AGE OF CELLULAR TERRAIN WITHIN SPUTNIK PLANUM, PLUTO. William B. McKinnon[1], F. Nimmo[2], Teresa Wong[1], J.S. Roberts[3], P.M. Schenk[4], J.M. Moore[5], J.R. Spencer[6], A.D. Howard[7], O.M. Umurhan[5], S.A. Stern[6], H.A. Weaver[3], L.A. Young[6], C.B. Olkin[6], K. Ennico[5], and the New Horizons Geology, Geophysics, and Imaging Team; [1]Dept. Earth and Planet. Sci. & McDonnell Center for the Space Sci., Washington Univ. in St. Louis, Saint Louis, MO 63130 (mckinnon@wustl.edu), [2]Dept. Earth and Planetary Sci., UC Santa Cruz, Santa Cruz CA, 95064, [3]JHUAPL, Laurel, MD 20723, [4]LPI, Houston, TX 77058, [5]NASA Ames Research Center, Moffett Field, CA 94035, [6]SwRI, Boulder, CO 80302, [7]Dept. Environmental Sci., Univ. of Virginia, Charlottesville, VA 22904.

Introduction: Understanding the vast, deep, volatile-ice-filled basin informally named Sputnik Planum (SP) is key to understanding the geology of Pluto [1,2]. Nitrogen ice is concentrated within Sputnik Planum [3], which is organized into cells or polygons between ~10-40 km diameter [1]. These cells resemble the surface manifestation of solid state convection [1,2]. Based on available rheological measurements [4], we can show that solid layers of N_2 ice $\gtrsim$1 km thick should convect for the present-day radiogenic heat flow on Pluto [2]. More importantly, convective overturn in a ~3-5-km-thick layer of solid nitrogen can explain the great lateral width of the cells: the temperature dependence of N_2-ice viscosity implies that massive layers of SP ice convect in the so-called sluggish lid regime, implying uniquely large aspect ratio (width/height) convection cells [5]. Average surface horizontal velocities of a few cm/yr imply surface transport or renewal times of ~500,000 years, well under the upper limit crater retention age for Sputnik Planum of ~10 Myr [2]. Additional work, including further laboratory experiments, should allow a more precise mapping of the depth of volatile ice layer within the planum as well as determine Pluto's heat flow. Similar convective surface renewal may also occur on other dwarf planets in Kuiper belt, which may help explain the high albedos of some of them.

Sputnik Planum: The most prominent geological feature revealed by New Horizons, SP is a ~900,000 km^2 oval-shaped unit of high-albedo plains set within a topographic basin of 3-4 km negative relief. The central and northern regions of SP display a distinct cellular or polygonal pattern. In the bright central portion, the cells are bounded by shallow troughs locally up to 100 m deep, and the centers of at least some cells are elevated by ~50 m relative to their edges [2]. The southern region and eastern margin of SP do not display cellular morphology, but instead show featureless plains and dense concentrations of km-scale pits [2].

No impact craters have been confirmed on SP in New Horizons mapping at 350 m/pixel scale. The crater retention age of SP is very young, no more than ~10 Myr based on models of the impact flux of small Kuiper belt objects onto Pluto [6]. This indicates renewal, burial, or erosion of the surface on this time scale or shorter. Evidence for all three processes are seen in the form of possible convective overturn, inflow of volatile glacial ice from higher standing terrains at the eastern margin, and likely sublimation landforms such as the pits [2]. In addition, the pronounced distortion of some fields of pits is evidence for the lateral, advective flow of SP ices [2].

From New Horizons spectroscopic mapping CO-ice is also concentrated within SP, and methane ice is also present [3]. All three ices (N_2, CO, CH_4) are weak, van der Waals bonded molecular solids; as such they are expected to flow readily on geologic time scales [4,7,8] even at the surface-ice temperature of Pluto (37 K [1]). We focus on testing the convection cell hypothesis using rheological data for N_2 ice (which demonstrate a pronounced temperature dependence), recognizing that CO and CH_4 ices are also present, likely in solid solution with N_2 ice. From buoyancy and rheologic arguments, we judge that either N_2 and CO ice (very similar materials) dominate SP volumetrically [2]. We derive quantitative constraints on the depth of the ice layer within SP, on Pluto's present-day heat flow, and the time scale of SP's surface renewal.

Convection Modeling: Given that the maximum temperature difference (ΔT) across an SP N_2 layer is 63 K (melting) – 36 K = 27 K, the maximum exponential viscosity contrast ($\Delta\eta$) should be in the range 10^2-to-10^4 (for a viscosity temperature scale between 3 and 6 K [2]). This range in $\Delta\eta$ strongly suggests that SP convects in the sluggish lid regime [9]. In sluggish lid convection the surface is in motion and transports heat, but moves at a much slower pace than the deeper, warmer subsurface. A defining characteristic of this regime — depending on Ra_b (the Rayleigh number defined with the basal viscosity) and $\Delta\eta$ — are large aspect ratio convection cells [5].

We illustrate sluggish lid convection numerically, using the finite element code CITCOM [10] (Fig. 1), varying Ra_b and $\Delta\eta$. The top example exhibits a unitary plume, which given the size of the domain implies a convective aspect ratio of 12. This calculation reached a quasi-stationary steady state. In Fig. 1b the viscosity contrast and basal Ra are reduced by a factor of e; the convective planform exhibits a slow evolution over several thermal diffusion times, and the aspect ratio varies between 6 and 12. We conclude from these and other numerical experiments that convection cells in SP may have aspect ratios as large as ~10, which for cell dimensions between 20 and 40 km imply a layer thickness between ~3 and 5 km.

Example surface horizontal velocity, dynamic topography and heat flow are shown in Fig. 1c, for a single timestep in Fig. 1b. The values shown are characteristic of the longest lived geometry seen in the otherwise periodic evolution. The values can be dimensionalized, and values for a layer depth of 3 km and ΔT = 15 K are shown at the rhs. These parameters were chosen to yield a plausible radiogenic heat flow, and the dynamic topography derived is consistent with available measurements [1,2]. Average surface velocities in this case are a few cm/yr, which for the horizontal scale of cells on SP translates into a time scale to transport surface ice from the center of a given upwelling to the downwelling perimeter of ~500,000 years. This is comfortably within the upper limit for the crater retention age for the planum.

Conclusions: Convection in a kilometers-thick N_2 layer within Pluto's Sputnik Planum basin emerges as a compelling explanation for the remarkable appearance of the planum surface. Convection is explicitly controlled by four things: the depth and temperature drop across the ice layer and the ice viscosity at the top and bottom of the layer. Our understanding of N_2 and other volatile ice rheology could be greatly improved (such as its dependence on grain size). Nevertheless, the lateral scale, three-dimensional network geometry of the cells/polygons, and surface topography offer three powerful constraints on these four unknowns through numerical modeling, if we can bound the heat flow. With improved rheological knowledge, Pluto's heat flow can in principle be independently estimated as well. Moreover, larger Kuiper belt objects (KBOs) are known to be systematically brighter (more reflective) than their smaller KBO cousins [11]. Convective renewal of volatile ice surfaces, as in SP, may be one way in which the small planets of the Kuiper belt maintain their youthful appearance.

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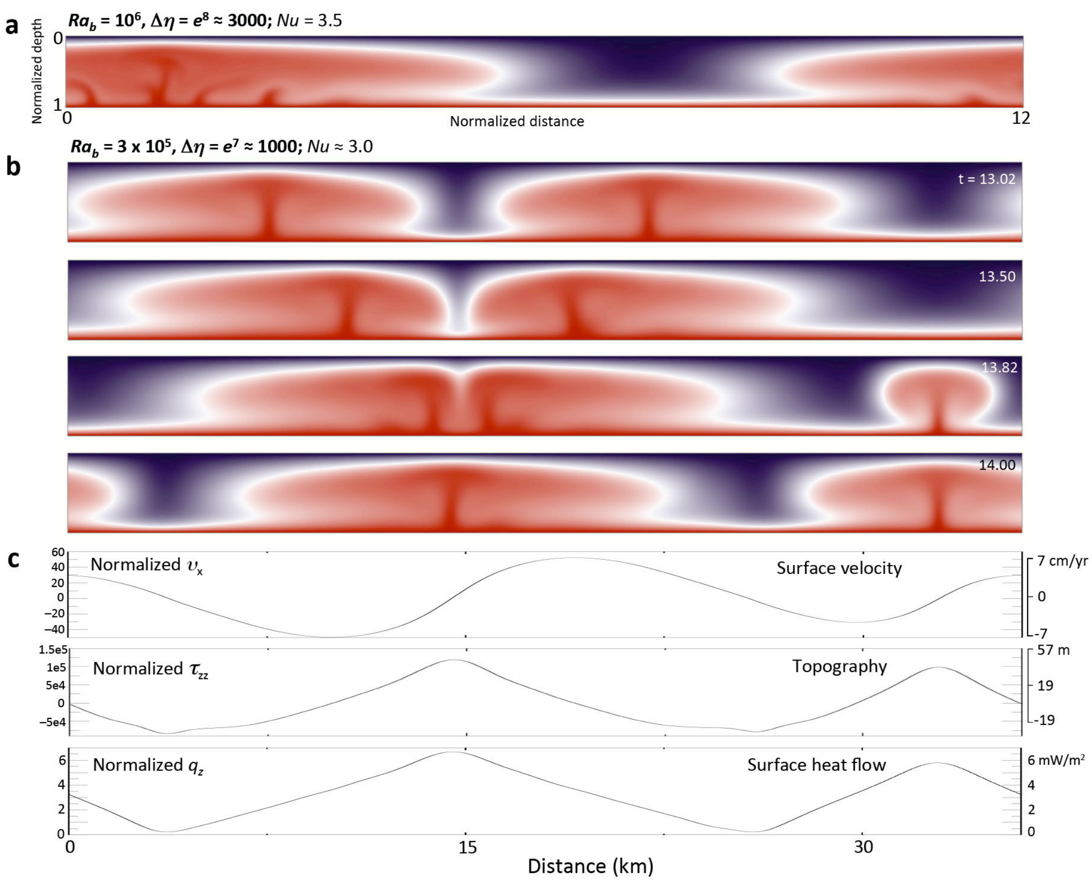

Figure 1. Two-dimensional numerical models of sluggish lid convection applicable to N_2 ice layers on Pluto. a) Temperature field for a quasi-steady solution with a large aspect ratio plume and downwelling; **b)** Time evolution of a layer with a top-to-bottom $\Delta\eta$ of 10^3 due to increasing temperature with depth. Non-dimensional time is indicated; *Nu* is Nusselt number. Behavior is cyclic, and the 2-plume geometry in the bottom panel is only temporarily stable; **c)** Surface velocity, dynamic topography and surface cheat flow for the bottom panel in **b.** Non-dimensional values are shown are show at left, dimensional values at right (see text).