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Modeling glacial flow on and onto Pluto's Sputnik Planitia☆

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ABSTRACT

Observations of Pluto's surface made by the New Horizons spacecraft indicate present-day N_2 ice glaciation in and around the basin informally known as Sputnik Planitia. Motivated by these observations, we have developed an evolutionary glacial flow model of solid N_2 ice that takes into account its published thermophysical and rheological properties. This model assumes that glacial ice flows laminarly and has a low aspect ratio which permits a vertically integrated mathematical formulation. We assess the conditions for the validity of laminar N_2 ice motion by revisiting the problem of the onset of solid-state buoyant convection of N_2 ice for a variety of bottom thermal boundary conditions. Subject to uncertainties in N_2 ice rheology, N_2 ice layers are estimated to flow laminarly for thicknesses less than 400–1000 m. The resulting mass-flux formulation for when the N_2 ice flows as a laminar dry glacier is characterized by an Arrhenius–Glen functional form. The flow model developed is used here to qualitatively answer some questions motivated by features we interpret to be a result of glacial flow found on Sputnik Planitia. We find that the wavy transverse dark features found along the northern shoreline of Sputnik Planitia may be a transitory imprint of shallow topography just beneath the ice surface suggesting the possibility that a major shoreward flow event happened relatively recently, within the last few hundred years. Model results also support the interpretation that the prominent darkened features resembling flow lobes observed along the eastern shoreline of the Sputnik Planitia basin may be the result of a basally wet N_2 glacier flowing into the basin from the pitted highlands of eastern Tombaugh Regio.

1. Introduction

The New Horizons flyby of Pluto has revealed a planetary surface exhibiting evidence of recent geological activity (Stern et al., 2015; Moore et al., 2016). In a compendium study found in this volume (Howard et al., 2017, this volume) we have examined the evidence for both ancient and recent glacial flow on Pluto based on imaging data taken by the MVIC and LORRI cameras as well as spectroscopic data obtained by the LEISA instrument.[1] The aim of this work is to develop a physical model framework to use with investigating various scenarios pertaining to N_2 ice glacial flow into and within Sputnik Planitia (SP, hereafter and note that all place names on Pluto are informal).[2] N_2, CH_4 and CO are observed to be

☆ All place names of the Pluto system are informal.

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[1] These are cameras and instruments onboard New Horizons: MVIC (Multispectral Visible Imaging Camera) is the medium-resolution color wide-angle "push-broom" camera while LORRI (LOng Range Reconnaissance Imager) is the high resolution framing panchromatic camera. LEISA (Linear Etalon Imaging Spectral Array) is the 256 channel imaging spectrometer (Stern et al., 2015; Reuter et al., 2008).

[2] An earlier version of this manuscript referred to this region as "Sputnik Planum". The designation of this feature from *planum* to *planitia* is a result of recent

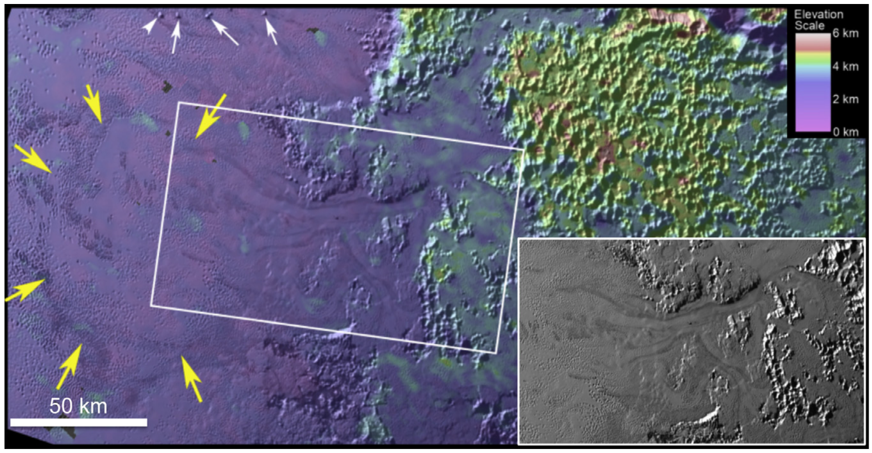

Fig. 1. A LORRI image section of eastern Sputnik Planitia abutting the pitted highlands of ETR color-coded for elevation. Streak patterns emanating from the higher elevations are seen to follow an apparent flow path to the lower reaches of Sputnik Planitia. Yellow arrows indicate the extent of flow lobes. Examples indicating englaciated debris shown with white arrows. In this image, north is up. Location of this section is found in Fig. 3.

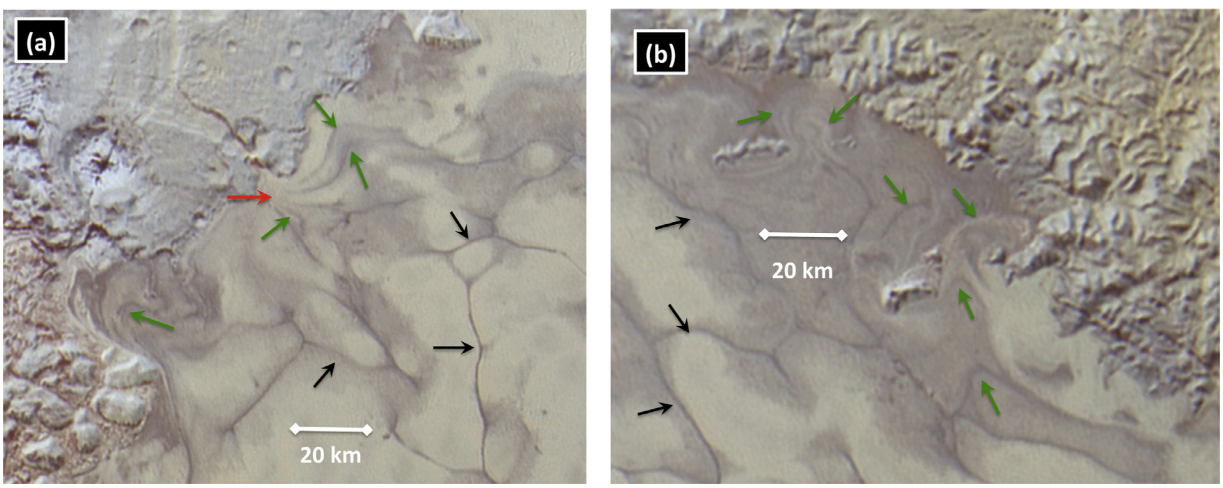

Fig. 2. MVIC sections of the northwestern (left panel) and northeastern (right panel) shorelines of Sputnik Planitia. The dark ovoid patterning found on the lower portion of both images (black arrows) have been interpreted as downwellings involving solid-state convection of N_2 ice (McKinnon et al., 2016). The near shoreline dark patterning (green arrows) may be indicative of either flow advection of recently inactivated convective downwellings or an imprint of surface topography beneath the observable surface. The red arrow indicates a possible undersurface drainage point (Howard et al. 2017, this volume). In both images, north is up. Location of this section is found in Fig. 3. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

present within and around SP (Grundy et al., 2016) as well as in Pluto's atmosphere (Gladstone et al., 2016). Based on the relative overabundance of N_2 compared to CO on SP, we shall assume that it is the primary material undergoing glacial flow – however, this should be subject to further scrutiny.

Fig. 1 depicts a prominent example of features suggesting recent N_2 glacial flow from the pitted uplands of eastern Tombaugh Regio (ETR, hereafter) and down onto the plains of SP. Dark streaks reminiscent of medial moraines, emanating from the highlands, connect to the floor of SP by commonly passing through narrow throats 2–5 km wide. The dark streaks terminate on SP with a pattern resembling flow lobes. There are also lone protruding H_2O ice blocks with trailing dark streaks leading towards the higher elevation N_2 icy flats, highly suggestive that these structures may be englaciated debris (Howard et al., 2017, this volume).

Interestingly, flow also appears to be moving from the interior of SP out toward both its northern and southern shores (Howard et al. 2017, this volume). Fig. 2(a-b) depicts examples of indicators of flow toward Sputnik Planitia's northern shoreline. The lower portion of Fig. 2(a) depicts ovoid patterning interpreted to be downwellings associated with solid-state convection of N_2 ice (Stern et al., 2015; Moore et al., 2016; McKinnon et al., 2016). However the near shoreline manifestation of the dark patterns takes on a markedly different quality, becoming increasingly wavy closer to shore. Fig. 2(b) depicts similar features with the additional appearance of transverse surface patterning suggestive of viscous flow around an obstacle. Two ways in which these observations may be interpreted are: (i) the northward moving N_2 ice flow advects darkened, possibly inactive, convective downwelling zones giving rise to the observed near shoreline gentle undulations or (ii) the wavy patterns are an imprint of topography beneath SP's surface.

In order to test the viability of scenarios pertinent to Pluto's apparent present-day glacial flow, a physical model needs to be constructed that takes into account, among other things, the known thermophysical and rheological properties of solid N_2 and CO under the very cold physical conditions of Pluto's surface. Of the latter molecule, very little laboratory data is available under Plutonian surface conditions, but given CO's similar molecular bonding structure to N_2, we assume that its behavior resembles that of

topographic refinements indicating that this planar region has an elevation below the mean radius of Pluto.