**A NEW ANAYLYSIS OF THE RHEOLOGY OF CRYOLAVA FLOWS IN VULCAN PLANITIA.**
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**Introduction:** Placing firmer constraints on the emplacement timescales of cryolava flows in Vulcan Planitia is essential to obtaining a better understanding of the resurfacing history of Charon, the proximity of fluids to the surface during its evolution, and the frequency of surface-subsurface exchange in the Pluto system. Cryolava flows in Vulcan Planitia are likely water-ammonia mixtures [1-3] that were emplaced similar to the lunar maria [3]. Although the composition and emplacement style of cryolavas in Vulcan Planum have been reliably constrained, questions still remain as to their likely viscosity values. Rheologically speaking, the maintenance of extremely thick, 1-2 km flows necessitates the emplacement of high-viscosity cryolavas [3], while their ammonia-rich composition suggests that viscosities of the erupted fluids should be quite low. Further, numerous quantitative issues, such as the nature and duration of fluid supply, how long subsurface conduits remained open and capable of supplying cryolava to the surface, volumetric flow rate, and the role of the rigid insulating crust in influencing flow and final morphology all have implications for cryomagma ascent and the local surface stress conditions at the time of flow emplacement.

Assuming a constant cryolava viscosity, [3] utilized the methods of [4] to analyze the motion of lava flows in Vulcan Planitia [3]. These methods have also been used to investigate lava emplacement on Venus, Europa, Ariel, and Miranda [5-8]. However, the methods of [4], on which these models are based, contain fundamental shortcomings, and recent studies suggest that improved constraints may be placed on the motion of lava on these bodies by considering flow emplacement while a constant flux of lava is erupting at the vent, and temporal changes in lava viscosity as the flow advances [9-11]. Here, a new modeling approach that alleviates the shortcomings in the models of [4, 12] and considers temporal changes in the viscosity of the flowing lava has been applied. The application of this new approach warrants a re-assessment of the rheology of cryolava flows in Vulcan Planitia.

**New Modeling Approach:** Here, I have investigated the emplacement of cryolava flows on Charon, exploring the effect of boundary conditions on the solution of the Boussinesq equation for pressure driven fluid flow in a cartesian geometry. The continuity equation describing the horizontal expansion of a Newtonian fluid with an unbounded (free) upper surface and a time-dependent viscosity is:

$$\frac{\partial h}{\partial \theta} - \frac{g}{3\nu_o}\frac{\partial}{\partial x}\left(h^3\frac{\partial h}{\partial x}\right) = 0 \tag{1}$$

[4] found a similarity solution to the general form of (1) for a constant fluid volume with constant viscosity. This solution has been previously applied to the emplacement of lava flows on both rocky and icy bodies in our solar system [5-8]. Here we offer an alternative similarity solution to (1) that eliminates the singularity at $t = 0$ inherent to the solution in [4] and allows for the investigation of associated plausible boundary conditions. This model also addresses the issue of time dependent changes in lava viscosity due to cooling. Akin to previous investigators [4, 7-10, 12], and in keeping with the recent work of [3] it has been assumed that a constant volume of material is rapidly emplaced onto the surface, supply terminates, and the flow is shaped by subsequent relaxation of the fluid as it travels away from the vent. The similarity solution for flow thickness, $h$, is:

$$h(x,t) = \frac{9V'}{8x_o(1+\theta/t)^{1/5}}\left[1 - \frac{1}{(1+\theta/t)^{2/5}}\frac{x^2}{{x_o}^2}\right]^{1/3} \tag{2}$$

where $V'$ is the volume per unit length of the flow and $\theta$ is the time transformation constant of the form:

$$\theta(t) = \nu_o \int \frac{dt}{\nu(t)} \tag{3}$$

The time constant that eliminates the singularity at $t = 0$ is $\tau = (4/3)^4\,(5V')^3\,\nu_o x_o^5/g$. A variety of forms can be chosen for the time-dependent kinematic viscosity. However, since viscosity increases exponentially as cryolava cools [13], we assume a time dependent viscosity of the form $\nu(t) = \nu_o e^{t/\Gamma}$, as in [10]. For this expression of $\nu(t)$, $\theta(t) = \Gamma(1\text{-}e^{-t/\Gamma})$.

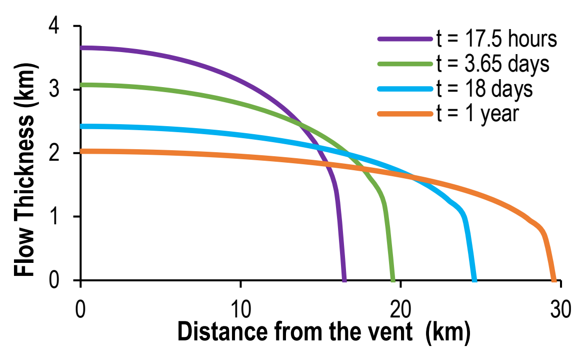


**Figure 1.** Axially symmetric Newtonian fluid flow profiles for an aqueous cryolava that contains 32 wt% $NH_3$. Profiles are obtained from (2).

Fig. 1 shows the solution of a radially spreading, Newtonian fluid with $\nu_o = 10^7$ m$^2$/s (equivalent to a dynamic visocsity ~ 9 x $10^9$ Pa-s for an $NH_3$-$H_2O$ cryolava density of 884 kg/$m^3$ at the 273 K $NH_3$-$H_2O$ liquidus temperature [14]) at four times. Here, the overall "shape" of the flow surface, as well as the aspect ratio at the final time, is very similar to the dimensions of the Vulcan Planitia flows described in [3] when $\tau = 1 \times 10^5$ sec (1.3 days), and $\Gamma = 1.2$ months. The flow's total relaxation time is ~ 1 year, which is well within the range of plausible emplacement times for lavas on icy and rocky bodies in our solar system. [7-10].

**Cryolava Crust:** The vapor pressure of an aqueous solution containing 32.1 wt% $NH_3$ is ~ 537 Pa [15]. Owing to this very low vapor pressure, cryolavas erupted onto Charon's surface will boil violently until an approximately 2 m thick coherent crust forms. As is the case for silicate lavas on Earth and Venus, and cryolavas on the icy moons in our solar system, flows can then be maintained beneath this insulating carapace [10, 16]. In the case of cryolava flows on Charon, this insulating crust will form in ~ 4 days. The entries in Table 1 illustrate the sensitivity of flow emplacement time to flow viscosity for $NH_3$-$H_2O$ flows. While it is clear that flows on Charon may have apparent bulk viscosities between $10^6$ and $10^9 m^2/s$ ($10^8$-$10^{11}$ Pa s), much runnier flows, with bulk viscosities <$10^5$ $m^2/s$ ($10^7$ Pa s) are unlikely to exist, as their emplacement times are less than the formation time of the insulating crust that would prevent flows from boiling away in Charon's low-pressure environment.

| $\nu$ ($m^2/s$) | $10^5$ | $10^6$ | $10^7$ | $10^9$ |
|---|---|---|---|---|
| $\mu$ (Pa s) | $10^7$ | $10^8$ | $10^9$ | $10^{11}$ |
| $\Gamma$ | 9 hours | 3.7 days | 1 month | 10 yr |
| $u_o$ (m/s) | 4 x $10^{-2}$ | 4 x $10^{-3}$ | 4 x $10^{-4}$ | 4 x $10^{-6}$ |
| t | 3.7 days | 1 month | 1 yr | 100 yr |

**Table 1.** Sensitivity of emplacement time to bulk viscosity for cryolava flows in Vulcan Planitia.

**Conclusions:** Previous workers have shown that the insulating crust will not inhibit lava flow [10-11, 17]. However, the crust will act to increase the apparent bulk viscosity of the cryolava by up to 4 orders of magnitude [8, 13]. Hence, the initial kinematic visocsity of the erupted lava illustrated in Fig. 1 would be $10^3$ $m^2/s$ ($10^5$ Pa), which is consistent with the viscosity of supercooled $NH_3$-$H_2O$ fluids [18] and has previously been considered as an appropriate viscosity value for flows in Vulcan Planitia [1]. Subtracting the effects of the cryolava crust suggests that according to Table 1, realistic kinematic viscosities, at the time of eruption, for cryolava flows on Charon range from $10^2$-$10^5$ m2/s (realistic dynamic viscosities range from $10^4$-$10^7$ Pa s). The results of this work suggest that flows on Charon may have had rheologies similar to terrestrial basalt or basaltic andesite. The results presented here, and those of [9-11], illustrate that improved constraints may be placed on lava viscosities when models that consider the time change in viscosity due to cooling, and lava flow in the midst of constant eruption at the vent, are applied. Determining how the rheologies of cryolavas on Charon compare to the rheologies of lavas on other planetary bodies is an important step in understanding the various ways that volcanism manifests itself throughout the solar system. The next step of this work will therefore be to apply this new modeling approach to the emplacement of cryolava flows on other small, volatile-rich bodies in the outer solar system.

**References:** [1] Borrelli, M. E. and Collins, G. C. (2018) *49th LPSC*, Abstract #2874. [2] McKinnon, W. B. et al. (2018) Cryovolcanism in the Solar System, Abstract #2030. [3] Beyer, R. et al. (2019) *Icarus* 323, 16-32. *JGR, 90,* 1151–1154. [4] Huppert, H.E., et al.(1982) *JVGR*, 14, 199-222. [5] McKenzie, D., et al.(1992) *JGR*, 97 (E10), 15,967-15,976. [6] Sakimoto, S.E.H & Zuber, M.T. (1995) *JFM*, 301, 65 - 77. [7] Fagents, S. A. (2003) JGR 108, 5139. [8] Schenk, P. M. (1991) *JGR* 96, 1887-1906. [9] Quick, L. C. et al. (2016) *JVGR* 319, 93-105. [10] Quick, L. C., et al. (2017) *Icarus* 477-488. [11] Quick, L. C. et al. (2018) *AGU*, Abstract #P41B-08. [12] Huppert, H.E., et al. (1982) *JVGR*, 14, 199-222. [13] Lorenz, R.D. (1996) *P&SS, 9*, 1021-1028. [14] Kargel, J. S. (1992) *Icarus* 100, 556-574. [15] Haynes, W. M. (2012) *CRC Handbook*. [16] Allison, M.L. & Clifford, S.M. (1987) *JGR*, *92*, 7865-7876. [17] Stofan, E. R. (2000) *JGR, 105*, 26,757-26,771. [18] Kargel, J. S. (1991)*Icarus*, *94*, 368-390.