Analysis of Convection Cells on Sputnik Planum on Pluto

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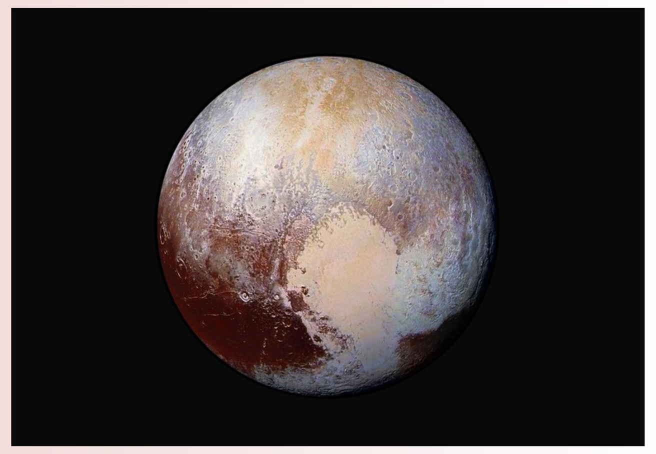
I. Problem

Pluto was first discovered in 1905, but since then not much information was known due to its inaccessibility. In order to gain access to Pluto, NASA launched the New Horizons spacecraft in 2006 to explore the geology and evolution of icy objects. New Horizons reached Pluto in 2015 and sent back new data on Pluto and its moons. Images taken revealed that the geology of Pluto is surprisingly complex. Some regions display active ice flow and cryovolcanism, while others are very old, heavily cratered surfaces. One intriguing feature is an array of polygonal shapes on the icy plain Sputnik Planum (SP), located on the western lobe of Tombaugh Regio. It raises the question of what geologic process could generate these ice polygons?



Color image of Pluto, courtesy of NASA

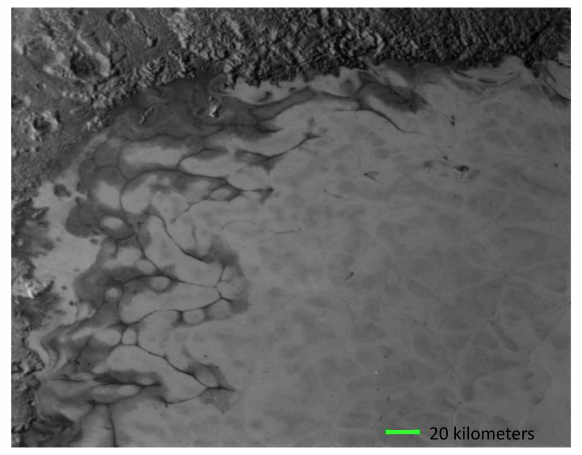


Image I: lor_0299174713_0x632_sci.fit

II. Hypotheses

I had several different hypotheses for the formation process of the features.

1. The polygonal features are formed by convection cells with a characteristic length scale
2. The required critical temperature difference calculated from the critical Rayleigh number must be small
3. The convection rate is higher than the minimum convection rate

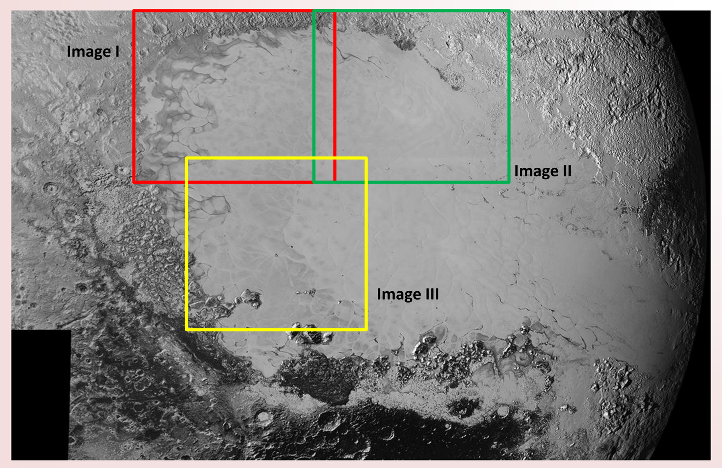
My null hypothesis is that there is no characteristic length scale, and thus no method to constrain the wavenumber k, the critical Rayleigh number, and the minimum temperature difference.

III. Methods

Part I: Selection of Study Sites

I used SAOImage ds9 software to view files downloaded from the Planetary Data Systems database. Sites were selected for the best visual resolution of the features, and were randomly distributed on SP. All images were set to squared value scaling to make features more visible.

File Name	Distance (km)	Resolution (meters/pixel)
lor_0299174713_0x632	79893.106	394.8986432
lor_0299174665_0x632	80544.651	398.1191242
lor_0299174857_0x632	77939.448	385.2420291



Location of Images I, II, III. Image of SP courtesy of NASA

Image II: lor_0299174665_0x632_sci.fit

III. Methods (continued)

Part II: Measurement of Polygons

- Assumed that each polygon was elliptical in shape and measured width and length 3 times each
- The software returned angular aperture, so I needed to convert from degrees to meters:

$$Y = \left(D * \tan\left(\frac{a}{2}\right)\right) * 2$$

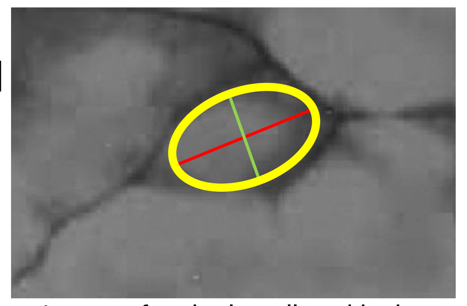


Image of a single cell; red is the length, green is the width

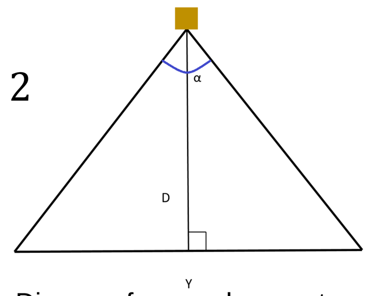


Diagram for angular aperture

- Calculated values for:
  - Area: $A = \pi a b$
  - Eccentricity: $\varepsilon = \sqrt{\frac{a^2 - b^2}{a^2}}$
  - Flattening: $f = \frac{a-b}{a}$

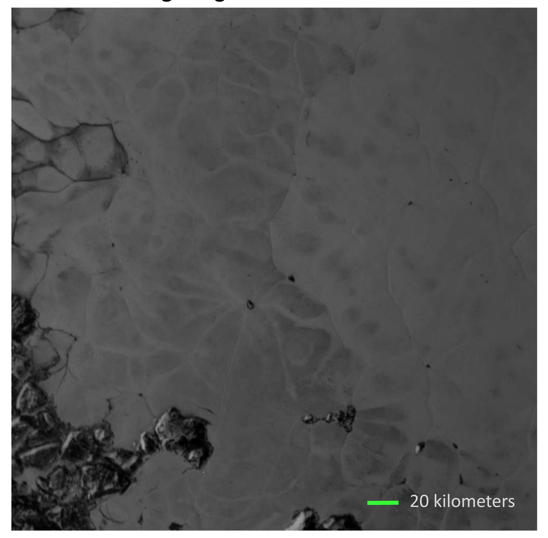
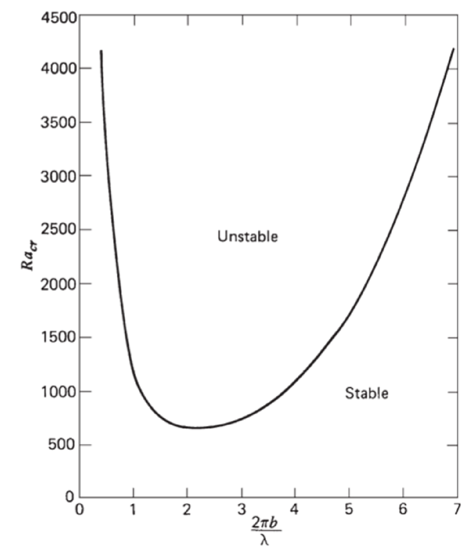


Image III: lor_00299174857_0x632_sci.fit

Part III: Critical Rayleigh Number

- Calculated the critical Rayleigh number and the wave number k to determine stability of convection cells (Turcotte 2014):
  - Critical Rayleigh number: $Ra = \frac{(\pi^2 + \frac{4\pi^2 b^2}{\lambda^2})^3}{\frac{4\pi^2 b^2}{\lambda^2}}$
  - Wavenumber k: $k = \frac{2\pi b}{\lambda}$
- Calculated critical temperature difference required for convection:
  - $Ra = \frac{\rho_0 g \alpha_v (T_1 - T_0) b^3}{\mu \kappa}$



Turcotte's stability curve for convection

Constant	Value
Density, ρ (kg/m³) (Satorre)	850
Gravitational Acceleration, g (m/s²) (McBride, et. al 2011)	0.7
Thermal Expansion Coefficient, α_v (1/K) (Heberlein, et. al 1970)	1.38
Viscosity, μ (Poise) (Forster 1963)	27800000
Thermal Diffusivity, κ (m²/s)	$6.12*10^{-7}$
Thermal Conductivity, λ (W/m*K) (Cook, et. al 1976)	0.7
Specific Heat Capacity, c_p (J/(kg*K) (Trowbridge, et. al 2016)	1344.61
Surface Temperature, T (K) (Moore, et. al 2016)	40

Thermal diffusivity: $\kappa = \frac{\lambda}{\rho c_p}$

Part IV: Calculation of Convection Velocity

- Minimum velocity: length / SP maximum age
- Peclet Number: $Pe = \frac{b v_x}{\kappa}$
- Maximum velocity: (surface area / SP maximum age) / thickness

IV. Results

Part I: Geomorphic Data

- There is a characteristic width, length, and shape to the polygons

Parameters	Image I Values	Image II Values	Image III Values	Combined Data
Mean Width (km)	19.0	21.5	18.1	19.5
Width STDEV	8.54	9.74	7.82	8.70
Mean Length (km)	33.7	36.7	35.6	35.3
Length STDEV	15.4	16.9	16.0	16.1
Mean Area (km²)	578	705	580	621
Mean Area STDEV	493	611	529	544
Mean Eccentricity	0.778	0.758	0.821	0.786
Eccentricity STDEV	0.120	0.152	0.012	0.095
Mean Flattening	0.406	0.391	0.463	0.420
Flattening STDEV	0.154	0.172	0.153	0.160

V. Results (continued)

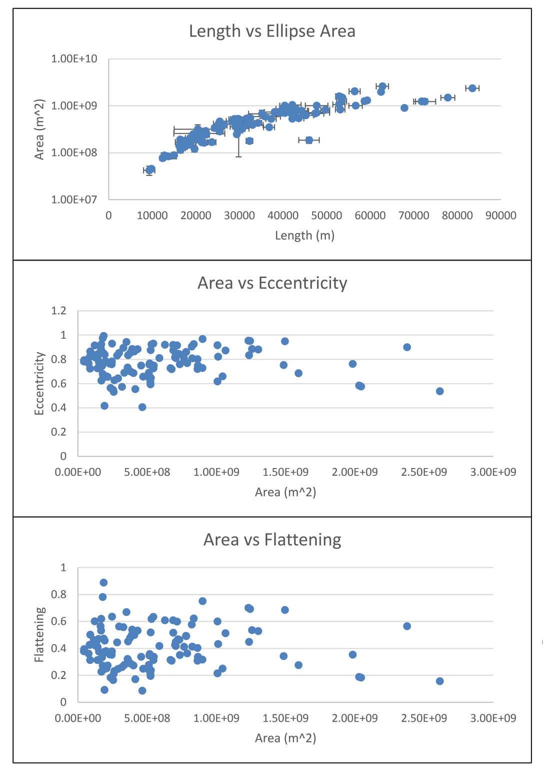


Image I results

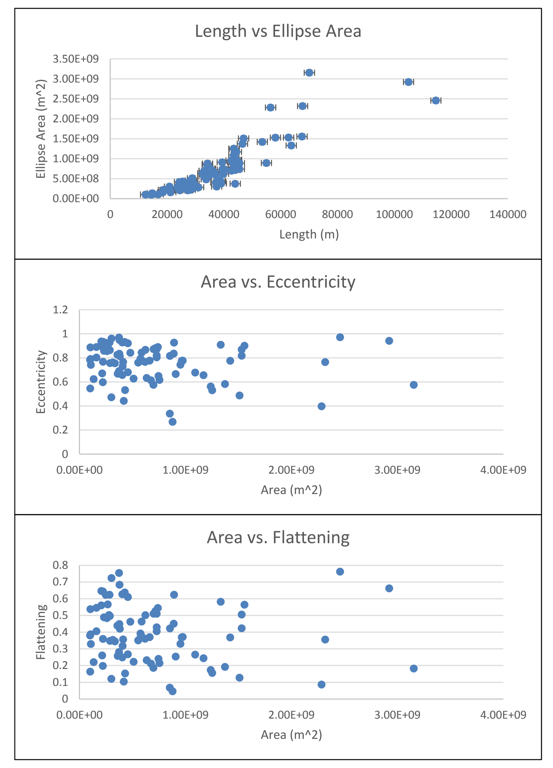


Image II results

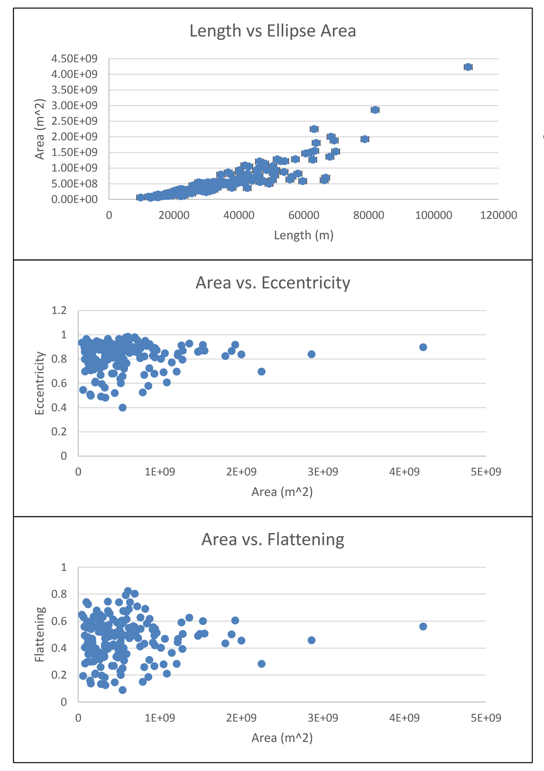


Image III results

- Results show that the polygon size and shape are generally similar for all three images
- Ellipticity of the polygonal features may indicate a preferred convection direction along the length`

Part II: Critical Rayleigh Number

- I used the average length from each image to calculate thickness from a set aspect ratio
- Aspect ratio: thickness / length

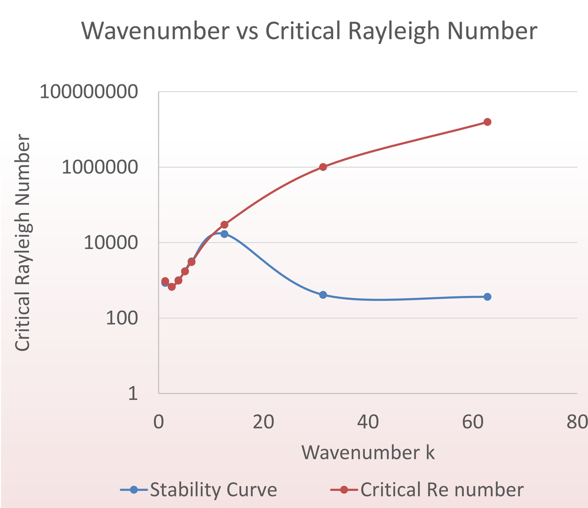
Aspect Ratio	Image I Thickness, b (km)	Image II Thickness, b (km)	Image III Thickness, b (km)	Wave number k	Critical Rayleigh number	Stability Curve
0.2	6.73	7.34	7.11	1.26	950	857
0.4	13.5	14.7	14.2	2.51	671	672
0.6	20.2	22.0	21.3	3.77	983	$1.00*10^3$
0.8	26.9	29.4	28.5	5.03	$1.72*10^3$	$1.75*10^3$
1	33.7	36.7	35.6	6.28	$3.04*10^3$	$3.16*10^3$
2	67.3	73.4	71.1	12.6	$2.99*10^4$	$1.69*10^4$
5	168	184	178	31.4	$1.00*10^6$	414
10	337	367	356	62.8	$1.57*10^7$	364

- I used the Rayleigh number to calculate the temperature difference required for the onset of convection:

$$Ra = \frac{\rho_0 g \alpha_v (T_1 - T_0) b^3}{\mu \kappa}$$

- Results in a very small temperature difference required for the onset of convection

Aspect Ratio	Image I ΔT (K)	Image II ΔT (K)	Image III ΔT (K)
0.2	$6.45*10^{-11}$	$4.98*10^{-11}$	$5.47*10^{-11}$
0.4	$5.70*10^{-12}$	$4.40*10^{-12}$	$4.83*10^{-12}$
0.6	$2.47*10^{-12}$	$1.91*10^{-12}$	$2.10*10^{-12}$
0.8	$1.82*10^{-12}$	$1.41*10^{-12}$	$1.55*10^{-12}$
1	$1.65*10^{-12}$	$1.28*10^{-12}$	$1.40*10^{-12}$
2	$2.03*10^{-12}$	$1.57*10^{-12}$	$1.72*10^{-12}$
5	$4.36*10^{-12}$	$3.37*10^{-12}$	$3.70*10^{-12}$
10	$8.53*10^{-12}$	$6.59*10^{-12}$	$7.24*10^{-12}$



Graph of critical Ra and stability curve

VI. Results (continued)

Part III: Convection Velocity

- Peclet number represents the ratio of convection to thermal diffusion
- I calculated the velocity with a Peclet number of 1; a convection rate equal to the thermal diffusivity
- Results from critical Rayleigh number showed aspect ratios of 0.2 – 1 are most plausible

Peclet Number	Aspect Ratio	Min. Velocity (mm/yr)	Velocity (mm/yr)	Max. Velocity (mm/yr)
1	0.2	3.53	2.74	12.3
-	0.4	-	1.37	6.17
-	0.6	-	0.92	4.11
-	0.8	-	0.69	3.08
-	1	-	0.55	2.47

VII. Discussion

- The calculated Rayleigh numbers fall between 0.2 – 1 aspect ratio for convection stability. Therefore, SP has an approximate thickness of 6.73-36.7 km. Previous workers speculate a thickness as small as 3-6 km (McKinnon et. al, 2016). This discrepancy leads me to recommend further study of the physical characteristics of SP
- With a very small temperature difference, convection is more than likely present across SP. Heat source could be internal, solar radiation, or tidal heating from Pluto's moons
- White et. al (2017) and McKinnon et. al (2016) state that convection is in the sluggish lid regime, rather than in the entire icy layer
- Previous papers estimate a timescale of 500,000 years (White et. al, 2017; McKinnon et. al, 2016); my calculations brackets past this estimate with renewal rates between 2.87 mm/yr to 12.9 m/yr, and a timescale between 5.1 million and 1,138 years

VIII. Conclusion

- Initial hypotheses: first, the polygonal features in SP are formed by convection cells with characteristic length scale; second, the critical temperature difference required for convection must be very small; third, the convection rate is higher than minimum convection rate
- My data and calculates support my first two hypotheses: there is a characteristic length scale, and the temperature difference is very small
- The critical Rayleigh number suggests stability for cells with an aspect ratio between 0.2 – 1
- Calculated renewal rates do not support my hypothesis; the convection rate is slightly smaller than the mean minimum convection rate
- Future work – further explore relationships among parameters and convection process

IX. References

- McKinnon, W. B., Nimmo, F., Wong, T., Schenk, P. M., & White, O. L. (2016, June 02). Convection in a volatile nitrogen-ice-rich layer drives Pluto's geological vigour. *Nature, 534*(7605), 82-85. doi:10.1038/nature18289
- Turcotte, D. L., & Schubert, G. (2014). *Geodynamics*. Cambridge, UK: Cambridge University Press.
- White, O. L., Moore, J. M., McKinnon, W. B., Spencer, J. R., Howard, A. D., Schenk, P. M., ... Schmitt, B. (2017). Geological mapping of sputnik Planitia on Pluto *Icarus, 287*, 261-286. doi:10.1016/j.icarus.2017.01.011