Show all your working for full credit.

1. Here we’ll investigate dunes on Pluto.

a) The current atmospheric pressure on Pluto is about 1 Pa. Use the ideal gas law to deduce the atmospheric density. You’ll need the temperature (40 K), molecular mass (0.028 kg mol⁻¹) and gas constant (8.3 J mol⁻¹ K⁻¹). [1]

b) The viscosity of Pluto’s N₂ atmosphere at these temperatures is about 6x10⁻⁶ Pa s. Calculate the critical diameter d, taking g=0.6 ms⁻² and assuming a particle solid density of 2 g/cc. [2]

c) Hence calculate the friction velocity v* [1]

d) Also calculate the wind speed required to initiate sediment transport at 1m above the surface (use the same roughness as in your notes). [1]

e) How does this speed compare with the speeds for Mars and Venus? Do you think dune formation on Pluto is likely under current atmospheric conditions? [2]

f) To get the required speed at 1m above the surface to be the same as for Mars, how much thicker would Pluto’s atmosphere have to be compared to the present value? [3]

g) What average global thickness of solid nitrogen would need to sublimate to give this pressure? Take the density of solid N₂ to be 1 g/cc and assume the same temperature as in part a). Hint: you will need to use the gravity of Pluto to get your answer. [2]

h) If all the solar energy was used to drive sublimation, calculate how long it would take the layer thickness in g) to sublime. The solar heat flux is 0.15 Wm⁻² and the latent heat of sublimation of N₂ is about 1.5 MJ/kg. [2] [14 total]

2. Here we’ll investigate glaciers on Pluto. We’ll assume that solid nitrogen is non-Newtonian, so that

\[ \dot{\varepsilon} = A\sigma^n \exp\left(\frac{-Q}{RT}\right) \]

a) The results of Yamashita et al. show that at 56 K, a strain rate of 10⁻³ s⁻¹ requires 0.2 MPa stress while a strain rate of 10⁻² s⁻¹ requires a stress of 0.6 MPa. Use this information to deduce n for nitrogen ice. [3]

b) We also have that at 45 K, a strain rate of 10⁻³ s⁻¹ requires 0.7 MPa stress. Use this information to deduce the activation energy Q for nitrogen ice. You can take R=8.3 J mol⁻¹ K⁻¹ and assume that n is the same as in part a). [3]
c) Also use your results to deduce the value of the quantity \( A \exp(-Q/RT) \) at 45 K. Your answer will have units of MPa\(^n\) s\(^{-1}\). [1]

d) We’ll assume that the flanks of Sputnik Planitia have slopes of 5°. If the nitrogen glaciers are 100 m thick, use the notes and your answers above to deduce the maximum speed of the glaciers. You can take \( g=0.6 \text{ ms}^{-2} \) and the density of solid nitrogen to be 1 g/cc. Hint: you will need your answer to c) and it’s easiest if you calculate \( \rho gh \) as MPa not Pa. [3]

e) If the distance from the mountains to the plains is 100 km, how many years does it take a glacier to travel that distance? [1]

f) What do you deduce about the age of the nitrogen plains? [1] [12 total]

**Question 3** (grads/bonus)

3. Here we’re going to study the development of a sublimation lag.

Assuming it’s energy-limited, we can write the rate of sublimation of a layer of thickness \( h \) as

\[
\frac{dh}{dt} = -\frac{F}{\rho L} (1 - A)
\]

Here \( F \) is the solar heat flux, \( \rho \) is the density, \( L \) is the latent heat and \( A \) is the albedo (i.e. the fraction of solar energy reflected).

a) We are further going to assume that the albedo is given by \( A = A_0 \left( \frac{h}{h_0} \right) \) where \( h_0 \) is the original layer thickness and \( A_0 \) the original albedo.

What happens to the albedo and the energy absorbed as \( h \) decreases? Explain the physical reason for using this expression. [2]

b) With this expression for albedo, we end up with a first-order linear differential equation for \( h \). Solve it, subject to the boundary conditions that at \( t=0, h=h_0 \). [6]

c) Sketch a plot of how \( h \) evolves with time. [2]

d) Write down an expression for the timescale for \( h \) to reach zero, in terms of \( h_0, \rho, L, A_0 \) and \( F \). [2]

e) What happens to this timescale if \( A_0 \) or \( F \) are larger? Does this make sense? [2] [14 total]