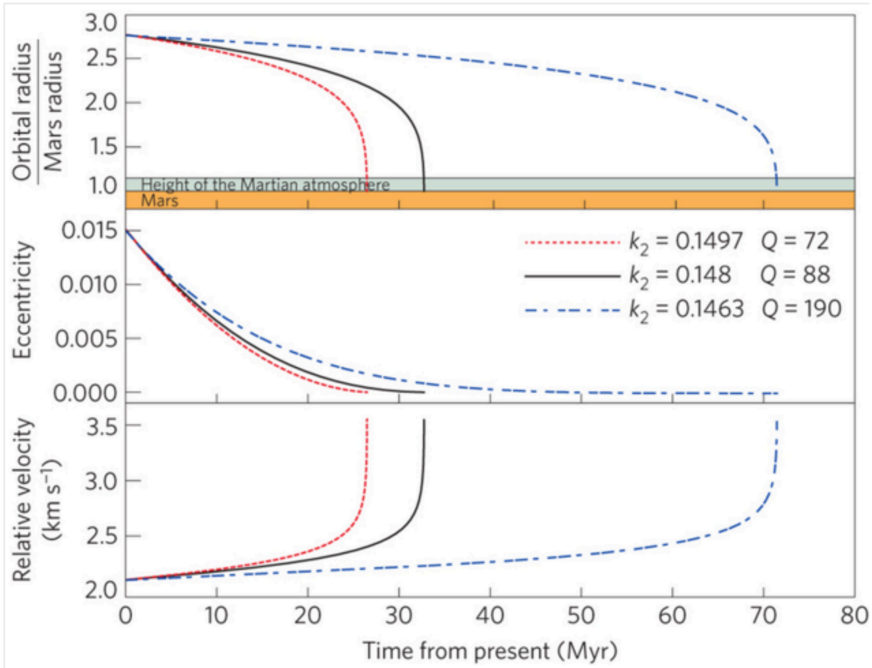
GEOS 32060 / GEOS 22060 / ASTR 45900
Homework 7

Due at the time of the final, Wednesday 16 March.
No credit will be given for answers without working. It is OK to use e.g. Mathematica, but if you do, please print out the work.

Q1. Dusting by Phobos.
Phobos, a dark moon, is accelerating towards Mars and will disintegrate in 20-70 Myr due to tidal forces[1].



Black & Mittal, Nature Geoscience 2015 (k2 and Q refer to tidal dissipation parameters for Mars).

This question is about the climatic consequences.

(a) Calculate the global-equivalent depth of Phobos dust (Phobos diameter ~10 km) following disintegration of Phobos and reentry of the fragments. Assume all material arrives as dust. (The duration over which fragments reenter could be Myr, or even longer).

(b) Assume Phobos dust (albedo = 0.1) falls on the north polar water ice cap and Mars obliquity = 60 degrees, Mars semimajor axis a is unchanged (1.52 AU)[2] and Mars eccentricity e is slightly higher than today (0.15)[3]. Noting that perihelion distance $q = a(1 - e)$, what is the theoretical maximum polar melt

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[1] The details, which are not necessary for this homework, are in Black & Mittal, Nature Geoscience, 2015. The acceleration has been confirmed by (among other methods) Phobos-eclipse timing using the Mars rovers.
[2] Semimajor axis change is negligible since >3 Gya.
[3] Mars eccentricity goes through 10^5-10^7 yr cycles and ranges from 0-0.15.

rate (kg/m²/hr) when perihelion is aligned with northern summer solstice? (Assume all absorbed sunlight goes into melting water ice).

(c) Correct your answer for upwelling longwave radiation at the melting point – what is the corrected melt rate? Assume dusty ice radiates in the thermal infrared as a blackbody.

(d) Correct your answer to (c) for evaporitic cooling using the following table (from Ingersoll, Science, 1970), assuming an atmospheric pressure of 25 mb[4] – what is the melt rate including this second correction?

Table 1. Heat fluxes (in calories per square centimeter per minute) necessary to maintain an evaporating frost deposit at constant temperature, for various temperatures and pressures.

T_0 (°C)	Heat flux at various pressures P_0 (mb)			
	6	10	15	25
0	1.25	0.76	0.55	0.38

(e) As the meltwater reacts with atmospheric CO2 and with the Phobos dust, carbonates will form, reducing CO2 pressure. Assuming Henry's law solubility of CO2 in the meltwater - 3.4×10^{-2} mol/(liter x bar) – and that the polar cap covers 10% of the planet, what is the maximum (dissolution-limited) rate of CO2 consumption? How long would it take for the atmosphere to disappear at this rate?

(f) In reality, CO2 consumption will stop when either when the carbonate-forming potential of Phobos dust is used up or when increased evaporitic cooling (due to the lower total atmospheric pressure) prevents further meltwater production – whichever comes first. Show, by quantitative use of Table 1, whether reactant-mass or water availability will limit the CO2 consumption. Assume Phobos dust has density 2 g/cc and is 10 wt% Mg (no Ca). Approximate interpolations are OK.

The one-sided negative feedback you have just worked through (minus the disintegrating moons, although it is quite possible that Phobos is merely the latest in a chain of inspiralling moons) is one hypothesis for what regulates atmospheric pressure on the real Mars. Optional reading: Kahn (Icarus, 1985) is credited with suggesting this one-sided negative feedback.

Q2. Resurfacing mechanisms on Europa (how to get the oxygen to the ocean)

In class, we discussed the geological evidence that Europa has been resurfaced by liquid water, but did not discuss driving forces for this resurfacing. In this question,

[4] This assumes that buried CO2 ice and adsorbed CO2 is released at high obliquity: probable but unproven.

you will investigate one hypothesis for resurfacing (optional reading: Manga & Wang, GRL 2007).

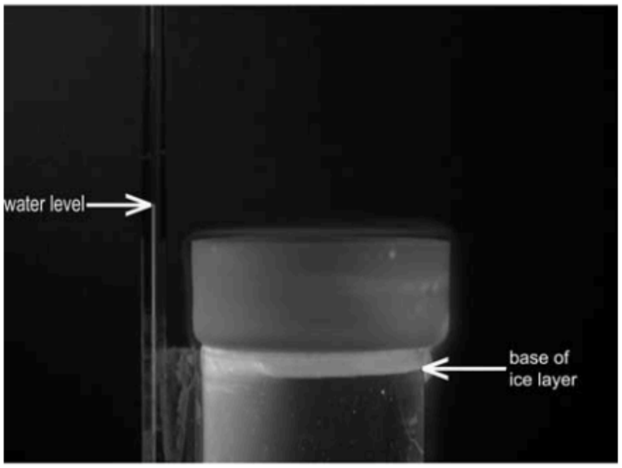

Figure 1. Experiment showing the evolution of pressure in water trapped below a freezing front; water is contained in a cylinder (7.5 cm diameter), open at the top and sealed at the bottom. The small capillary is connected to the cylinder and monitors its pressure. (top) Initial condition before freezing. (middle) Water level in the capillary rises 45 cm (well above the image) after a few mm of ice forms. (bottom) After a crack forms, inferred from acoustic emissions, water pressure returns to close to its original value. Horizontal white line indicate elevation of the water level in the capillary tube.

Manga & Wang, GRL 2007

(a) Assume that Enceladus undergoes heating-cooling cycles every 100 Myr due to the orbital-thermal feedbacks – let's exaggerate and assume that the ice shell goes from almost completely frozen to almost completely unfrozen each cycle. Consider freezing of an initially very thin ice shell. Ocean pressure builds up according to

$$\frac{\partial P_{\text{ex}}}{\partial z} = \frac{3(\rho_w - \rho_i)r_i^2}{\beta \rho_w \left(r_i^3 - r_c^3\right)}$$

(neglecting ice-shell expansion), where z is the ice shell thickness, water density is 1000 kg/m^3, ice density is 910 kg/m^3, and water compressibility (beta) 4 x 10^{-10} Pa^{-1}. r_c is rocky-core radius (the rock is assumed incompressible), and r_i is the radius at the top of the liquid-water ocean (i.e. r_i = R – z, where R is moon radius). Let r_c = R – 200 km and let R = 1600 km. How thick is the ice when the shell cracks?

(b) Assume that once the shell cracks the overpressured water can erupt onto the surface.[5] Taking into account the length of the heating-cooling cycle, for a typical water molecule, what is the typical wait time after being erupted before being erupted again?

[5] This is controversial; there is suggestive geologic evidence in favor, but theoretical arguments against.