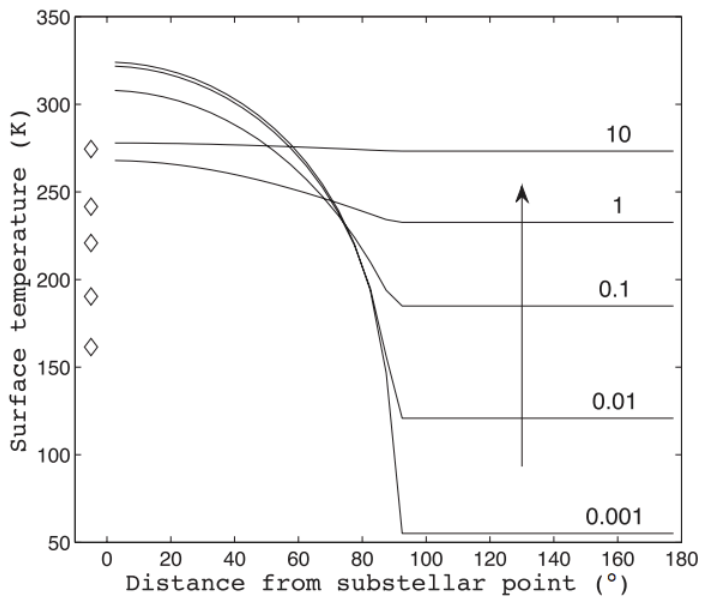
GEOS 22060/32060 – Winter 2020 – Homework 4

Due Thursday 20 February.

Q1. Tidally Locked Exoplanet. Many, perhaps most, of the rocky habitable-zone planets in the Universe orbit M-dwarf stars; these are also the easiest habitable-zone rocky planets to detect and characterize. However, because M-dwarfs are faint, the habitable zone is located close to the star (i.e. the ratio of planet radius r to orbital radius a is much smaller than on Earth). Because tidal locking timescales scale as a^{-5} for constant r, such planets are very vulnerable to tidal locking.



Surface temperature on a tidally locked planet, calculated using an idealized 1D climate model. The numbers 0.001→10 correspond to atmospheric pressure in bars. Local temperature is controlled by the greenhouse effect, but also by the tendency of thicker atmospheres to redistribute energy from the lightside to the darkside. (From Kite et al. ApJ 2011)

Consider the tidally locked planet from the figure.

(a) As in previous question, assume weathering rate scales as

$$\varpi \propto e^{-E/RT}$$

where E is activation energy and R is the gas constant. Assume an effective activation energy for weathering ("effective" including the effect of temperature on rainfall) of 74 kJ/mol, as for the previous homework. For the 0.01 bar tidally locked planet case, what is the ratio of weathering rate at the substellar point to weathering rate at 60° from the substellar point?

(b) Assuming mountain belts / tectonic uplift zones are randomly distributed with distance from the substellar point, comment on where on the planet most weathering occurs. Consider the likely effect of ice cover.

(c) Now assume that the gas that is the principal constituent of the atmosphere is also the principal greenhouse gas. (This assumption was used to calculate the temperatures shown in the plot. This assumption is not true for the Earth, but is true for Mars, Venus, Triton, and arguably also Titan). Explain how the planet-integrated weathering rate changes as we increase pressure from 0.001 → 10 bars.

(d) Is this hypothetical planet stable to a sudden two-fold step increase in the volcanic outgassing rate? Why?

(e) Now assume that everything is the same as in (e), but the effective activation energy is now 1000 kJ/mol. Is this hypothetical planet stable to a sudden two-fold step increase in the volcanic outgassing rate? Why? ***Hint:*** Recall that the threshold surface temperature for runaway greenhouse on a planet with water oceans is ~330K.

Q2. Ejecta weathering. In addition to tectonic uplift, impacts can eject fresh-mineral surface area for weathering. Assume the mass distribution of impactors contains no impactors smaller than a pebble or larger than Ceres, and within that range follows the power law $N(>m) = (m/m_{max})^{-b}$, where m_{max} is the mass of the largest impactor, $N(>m)$ is the cumulative number of impactors greater than mass m, and $b = 3/4$.

a) Is impacting mass concentrated in the largest impactors or the smallest impactors? Show why.

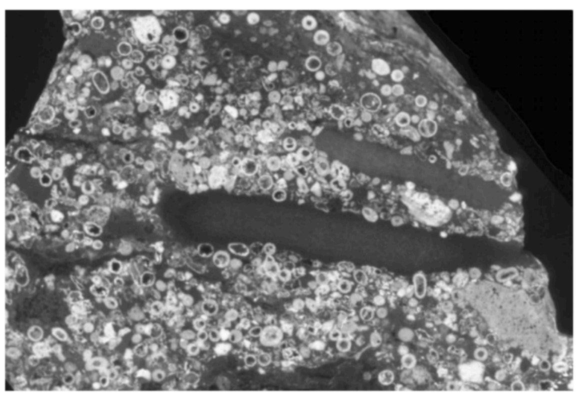


Figure 2 Polished surface of hand sample from lower, spherule-rich part of late Archean Jeerinah layer. Spherules range in shape from spheres to ovoids and typically have an outer rim of fibrous K-feldspar (*light gray*) plus a core of sparry quartz and/or K-feldspar crystals (*dark gray to black*). Long dark slabs are shale intraclasts. Medium gray particle in lower right corner is an irregular, finely vesicular impact melt clast. Long axis of field of view is 33 mm.

Simonson & Glass, Annual Reviews of Earth and Planetary Science, 2004. The scale given in this image will be helpful in answering the question.

b) Ancient impactors on Earth are recorded by spherule beds (the craters have subducted). Spherules condense from rock vapor in impact plumes during the minutes after impact, then fall to Earth as fresh, initially unweathered material. Assume a weathering (dissolution) rate for spherules of 3 mm/(10^6 yr), what is the duration of the weathering pulse associated with the above layer?

c) Assuming a (Ca+Mg) content of 10 wt %, a (spherule layer):impactor mass ratio of 10^2, and an Archean atmosphere+ocean C inventory and recycling time equal to that of the modern Earth (300 Kyr), what is the impactor radius needed in order for the Jeerinah layer to have transiently doubled Earth's weathering rate?

d) Suppose that a planet has ongoing volcanism but no plate tectonics and no mountain uplift (modern Mars is an example). Suppose that the rate of volcanism is sufficient to increase CO_2 pressure by 100 mbar every 10 Myr. Assume the gravity and surface area of Mars. Determine the flux of 10 km-diameter (dinosaur-killing) impactors needed to generate enough weathering to consume as much CO_2 as is released and thus prevent runaway warming.

e) Comment, given your answer to (a), on whether this set-up can lead to a stable climate in practice. For what value of *b* might your answer change?

f) Now consider a Super-Earth (r = 2x Earth, g = 25 m/s^2). How does your answer to part (d) change? Why?