Extraterrestrial Life: Problem Set #2 Solutions

1) Discuss the evidence that suggests that the water on the Earth originated from impacts with bodies originally situated in the outer asteroid belt. Why are comets not though to have dominated the delivery of the Earth's water?

   Two aspects are relevant to this question. First, we think that the planetesimals forming in the protoplanetary disk at the location of the Earth would have had rather little water content, because at the low pressure of the disk water would have been in the vapor phase rather than in the form of ice. This expectation is supported by the fact that meteorites originating from the inner asteroid belt contain very little water, whereas those from the outer belt are water rich.

   However, comets as well as the outer belt asteroids contain water. We believe that asteroids dominated the delivery of water to the Earth as a result of measuring the ratio of deuterium to hydrogen in water on Earth, and comparing that to the values found in meteorites and measured for some comets. The D / H ratio on Earth is about 150 parts per million, which is consistent with the range found for meteorites (and hence, presumably, for the asteroids) but much smaller than the 300 ppm found for comets.

2) Some stars' luminosity varies markedly due to periodic stellar pulsations. Suppose (hypothetically, since this does not happen for stars like the Sun) that the Sun's luminosity oscillated by 50% on a timescale of (a) 1 hour or (b) 1000 years. How do you think these oscillations would affect the habitability of the Earth?

   This question requires some lateral thinking, and a variety of answers are OK as long as they're carefully justified. For part (a) oscillations on a time scale of 1 hour would not, I think, impact the habitability of the Earth very much. The day / night cycle (on a time scale of 24 hours) already means that there is no Solar flux at individual points on Earth for 12 hour periods, and although it gets cold at night the ground and atmosphere remain warm enough to support life. Shorter time scale changes would presumably have even less effect. For (b) the situation is less clear. If the Sun's luminosity dropped 50% for 1000 years, that might well be long enough to allow the oceans to freeze over. How readily the earth would recover when it warmed up I don't know. The deep ocean would presumably remain liquid though, so at least pre-existing life down there would have a chance of survival.

3) Describe how feedback processes operating over long time periods maintain the stability of the Earth's climate.

   The main aspect I was hoping you would discuss is the carbonate-silicate cycle that regulates the amount of CO_2 in the Earth's atmosphere.

Volcanoes release gases, including carbon dioxide, that are locked up within rocks in the Earth. This outgassing increases the concentration of greenhouse gases in the atmosphere. Rain, however, removes CO_2 from the air and washes it (in the form of weak acids) into the oceans, where it is eventually incorporated into new sediments (today, by living organisms, but inorganic processes are also possible). If the Earth warms up there's more rain, so the rate of removal goes up, creating a negative (stabilizing) feedback loop.

4) Describe, in non-mathematical terms, how we can determine the age of rocks. Be careful to explain what is meant by `age' in this sense.

Consider a rock that, when it forms, contains some abundance of a radioactive isotope with a known half-life. As time passes, the parent isotope decays into a daughter isotope. If the rock initially contains none of the daughter isotope (as was the case with potassium / argon system we mentioned in class, though often the situation is more complex!) then measuring the ratio of the parent to the daughter isotope allows for a determination of the age – the older the rock the less of the parent is present and the more of the daughter has formed.

Age in this sense means time since the rock last solidified (or underwent other major changes that might change the abundance of isotopes within the rock).

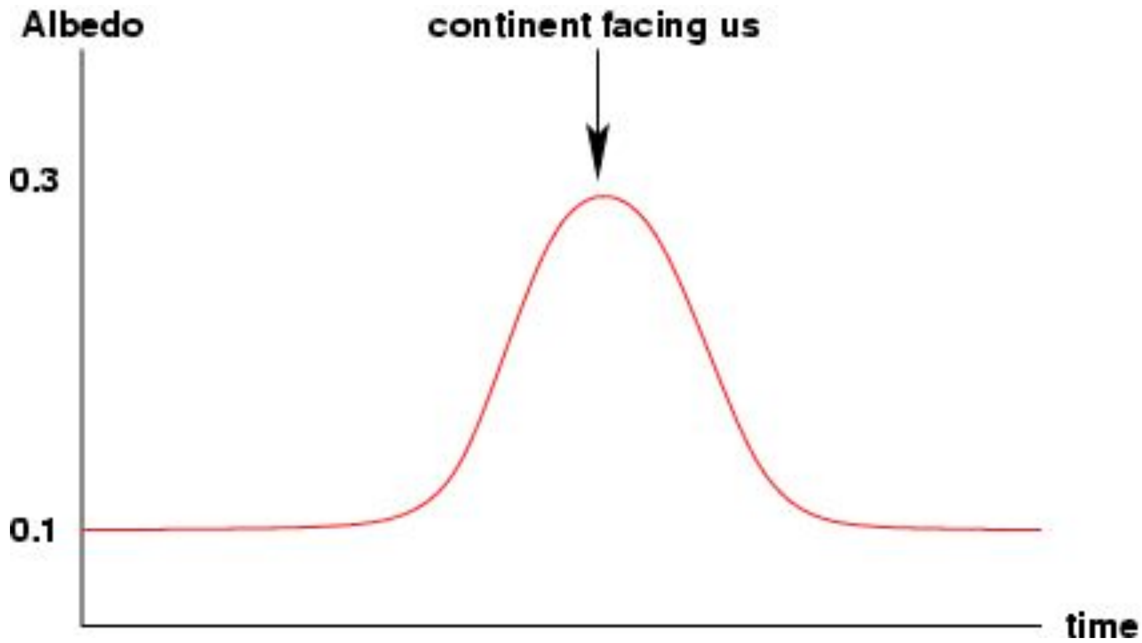
5) Imagine an extrasolar planet whose surface is 75% covered by ocean and 25% covered by land. If the ocean has an albedo of A = 0.1 and the land an albedo of A = 0.5, what is the average albedo of the planet? If all the land is in the form of a single continent close to the equator on one hemisphere of the planet, sketch how the brightness of the planet (seen by a distant observer) would vary with time as the planet rotated.

To do this, first think of a simple example in which the fraction of area covered by ocean and land is the same. In that case, one simply takes the average of the albedo. Here, we need to take an average weighted by the area fractions. So:

$$A = 0.75 \text{ x } 0.1 + 0.25 \text{ x } 0.1 = 0.2$$

(note, no need to divide by 2 at the end since the fractions – 0.75 and 0.25 – already add up to unity).

The plot of brightness vs time over one rotation period looks like:



6) In daylight, Earth's surface absorbs about 400 watts per square meter of Solar energy. The total power from radioactive decay within the Earth is 3 trillion watts (3×10^{12} watts), which leaks out through the entire surface area of the Earth. If the radius of the Earth is 6400km, calculate the internal heat flow (watts per square meter) averaged over the surface. By what factor is the Solar flux larger than the internal flux?

The surface area of the Earth, in m^2 is:

$$\text{Area} = 4\pi R^2 = 5.15 \times 10^{14}\ m^2$$

The internal heat flow, averaged over the surface, is thus:

$$\text{Heat flux} = 3 \times 10^{12}\ \text{watts} \ /\ 5.15 \times 10^{14}\ m^2 = 5.8 \times 10^{-3}\ \text{watts} \ /\ m^2$$

Compared to the Solar flux (which is given in the question, so you don't need to calculate it), the ratio is:

$$\text{Ratio} = 400\ \text{watts}\ m^{-2} \ /\ 5.8 \times 10^{-3}\ \text{watts}\ m^{-2} = 6.9 \times 10^4$$

…so the Solar flux is almost a factor of 100,000 larger.