ASTR/GEOL-2040-001: Final exam <u>model solutions</u>

Search for Life in the Universe (May 11, 2017)

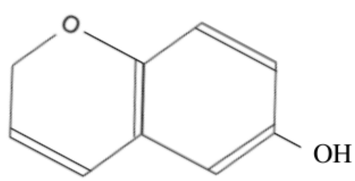
Work carefully, you'll have enough time. Give enough details, not just the numbers. Don't expect full credits if you forget to draw a sketch. For the multiple choice questions, there is only one correct/best answer! Mark it with a circle.

1. Life produces
   (a) more order inside the cell
   (b) more disorder outside the cell
   (c) more disorder over all of the Universe
   (d) all of the above

2. H_2O is a
   (a) polar molecule
   (b) nonpolar (or apolar) molecule

3. Which of the following macromolecules can act as an enzyme?
   (a) polysaccharides
   (b) proteins
   (c) lipids
   (d) DNA

4. What kind of macromolecule is



(a) lipid (b) carbohydrate (c) protein (d) nucleic acid

5. What kind of macromolecule is

(a) lipid (b) carbohydrate (c) protein (d) nucleic acid

6. Granite belongs to which of the following three basic rock types:

(a) igneous rock (b) metamorphic rock (c) sedimentary rock

7. The discovery of 4.4 Gyr old zircons has been regarded as evidence for

(a) sterilizing impact (b) stable continents (c) early water oceans (d) photosynthesis

This was not discussed in class this time and will not be tested in the final exam, but you can read about it in Longstaff, Sect. 5.6.2.1.

8. In the icy bodies of the solar system, the mantle consists mostly of

(a) water ice (b) liquid water (c) water vapor (d) ammonia

9. Finding exoplanets with the radial velocity (or Doppler) method allows one to obtain
   (a) the radius of the planet
   (b) the mass of the planet
   (c) a lower limit on the mass of the planet

10. Finding exoplanets with the transit method allows one to obtain
    (a) the radius of the planet
    (b) the mass of the planet
    (c) a lower limit on the mass of the star system
    (d) the mass of the star

11. Which of these chemical reactions occurs in alkaline vents to produce the energy for autotrophs?
    (a) $3Fe_2SiO_4 + 2H_2O \rightarrow 2Fe_3O_4 + 3SiO_2 + 2H_2$
    (b) $3Fe_2O_3 + H_2 \rightarrow 2Fe_3O_4 + H_2O$
    (c) $CO_2 + H_2S \rightarrow CH_2O + 2S$
    (d) $CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2$

    As a simplified version of the production of hydrogen from reduced iron (FeO or ferrous iron), you may think of the reaction $2FeO + H_2O \rightarrow Fe_2O_3 + H_2$. Here, Fe_2O_3 is called ferric iron.

12. Earth's first atmosphere was chemically similar to those of Mars and Venus. How did our current atmosphere become so drastically different from our nearest neighbors'?
    (a) Life – early photosynthetic organisms converted CO_2 to O_2.
    (b) Volcanism & Tectonics – Earth's numerous volcanoes expel O_2 gas while plate tectonics undertakes carbonate rocks.
    (c) Asteroids – Impacts from space debris converted CO_2 into O_2 by impact ablation and high energy explosions.
    (d) Water – Earth's liquid oceans provide a natural filter that strips the carbon from CO_2, leaving the O_2.

13. Measuring the mass of the satellites of Jupiter and Saturn during fly-bys has been important for the realization that the satellites
    (a) are tidally locked
    (b) have significant geological activity
    (c) have significant amounts of water in frozen or liquid form

14. "RNA world" refers to
    (a) the possibility that life migrated from Mars,
    (b) the idea that RNA was life's genetic material before DNA,
    (c) the idea that early life was made exclusively from RNA, needing no other organic chemicals

15. Why does Venus have so much CO_2 in its atmosphere?

    (a) Venus has extreme volcanic activity leading to significant outgassing,
    (b) Venus has no rain water allowing CO_2 to be returned to the mantle,
    (c) Venus is no magnetic field allowing the CO_2 to be removed by the solar wind.
    (d) Venus has a strong greenhouse effect owing to its proximity to the Sun.

16. Stromatolites are

    (a) iron-reducing lithotrophs extracting energy from the rocks they are living on,
    (b) photosynthesizing cyanobacteria growing on top of each other,
    (c) hydrothermal alkaline vents harboring methanogens that life of hydrogen and CO_2,
    (d) sedimentary rocks in Western Australia where the oldest microfossils have been found.

17. In their original experiment, Miller/Urey used the gases H_2, NH_3, and CH_4. They were chosen because they are all

    (a) reducing gases
    (b) oxidizing gases
    (c) polar molecules
    (d) apolar molecules

18. In later experiments of Miller/Urey type, sulfur and carbon dioxide were also added, because on the early Earth they would be produced by

    (a) photosynthesis
    (b) volcanoes
    (c) lightning
    (d) photolysis

19. A planetary system with a big Jupiter-sized planet could increase the possibility of finding life on an inner terrestrial planet, because it

    (a) prevents synchronous rotation on the inner planets
    (b) helps reducing the rate of bombardment on the inner planets
    (c) protects the inner planets from electrically charged particles
    (d) facilitates panspermia on the inner planets

20. The Search for Extraterrestrial Intelligence has traditionally been conducted at or around the 21 cm radio wavelength, because

    (a) those waves penetrate dust and planetary atmospheres
    (b) it is the wavelength used by any civilization to observe hydrogen in the galaxy
    (c) any technically developed civilization would have sensitive receivers
    (d) all of the above

21. Which of these nucleobases is a component in DNA but not in RNA?

    (a) Uracil [U] (b) Cytosine [C] (c) Adenine [A] (d) Thymine [T]

22. The dense core of an Earth-like planet is found to occupy 8/27 the volume of the planet – what fraction of the planet's radius does the core occupy?

(a) 2/27 (b) 4/9 (c) 2/3 (d) 1/9

23. Two powders, one yellow and one purple, are stirred into a beaker of liquid *methane*. The purple powder dissolves completely, but the yellow powder collects on the bottom. What can you reasonably state about the chemical nature of these powders?

(a) Purple is polar; yellow is apolar
(b) Neither powder is polar
(c) Yellow is polar; purple is apolar
(d) Both powders are apolar

24. ^{40}K decays into two daughter products: ^{40}Ca and ^{40}Ar. Why are we only concerned with the measurement of the second of these, ^{40}Ar?

(a) ^{40}K decays principally into ^{40}Ar
(b) ^{40}Ca from radioactive decay is indistinguishable from most other calcium
(c) ^{40}Ca is solid and can't be measured in a laboratory
(d) ^{40}Ar is twice as massive as ^{40}Ca and is easier to detect

25. In which of these environments would you likely find a xerophile?

(a) A high-altitude desert
(b) An Amazon rain forest log
(c) A deep-sea vent
(d) A wall in the Chernobyl reactor

26. Which of these is not necessarily needed for terrestrial life to function?

(a) Free O_2 gas (b) Liquid water (c) A carbon source (d) Nitrogenous bases

27. Where do we think the Moon came from?

(a) Earth captured the Moon after a close encounter between the two.
(b) The Moon formed at the same time as the Earth, already in orbit.
(c) A giant impact launched material into orbit around Earth which coalesced into the Moon.
(d) The Moon was "spat out" by a rapidly rotating liquid Earth.

28. Marble is created when limestone is subducted beneath the surface and repeatedly folded over itself in the hot mantle (without melting). Knowing this, what kind of rock is marble?

(a) Sedimentary. (b) Metamorphic. (c) Igneous. (d) Marble is none of these types.

29. Why do we think life didn't begin in Earths early oceans?

    (a) Earth's early oceans were too hot for life to form.
    (b) Nutrients in the ocean were too dispersed to be useful.
    (c) Earth's early oceans were actually liquid ammonia, not liquid water.
    (d) Early ocean water didnt contain dissolved carbon.

30. In the reaction $CO_2 + H_2O + \text{energy} \rightarrow CH_2O + O_2$,

    the energy comes from: sunlight, so the relevant prefix is "photo",

    the electron donor is: the electron donor is: H_2O, which is inorganic, so "litho",

    and the carbon source is: CO_2, which is inorganic, so "auto",

    and so it is a: photolithoautotroph.

31. In the reaction $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$,

    the energy comes from: molecules (reduction of carbon), so the relevant prefix is "chemo",

    the electron donor is: H_2, which is inorganic, so "litho",

    and the carbon source is: CO_2, which is inorganic, so "auto",

    and so it is a: chemolithoautotroph.

32. Explain why the simultaneous detection of oxygen (or ozone) together with methane in the infrared spectrum of an exoplanet's atmosphere constitutes strong evidence for life on that planet? *(Hint: can oxygen and methane coexist under equilibrium conditions?)*
    Ozone is highly oxidizing and rapidly destroys methane. The simultaneous occurrence of both ozone and methane means that they are continuously being reproduced, and faster than being destroyed. This can only be done by life, which produces both methane and oxygen, which in turn leads to easily detectable ozone in the upper atmosphere.

33. We know that diseases evolve in response to the medicines designed to combat them. Explain briefly why this constitutes evidence supporting the theory of Darwinian evolution. Mention clearly the assumptions in Darwin's theory that you need for your argument.
    Darwinian evolution assumes that during replication, life forms can undergo *small variations*. It also assumes that these life forms have to *struggle for survival*, so not all of them will survive. Introducing new medicines reduces the survival of the bacteria and thus increases their struggle for survival. However, the occurrence of small variations during replication continues, which means that those variations that tend to be immune to the new medicine continue to survive and replicate. Thus, these bacteria *have evolved*, just as predicted by Darwin.

34. List some of the arguments suggesting that carbon might be a central element also in extraterrestrial biochemistry.

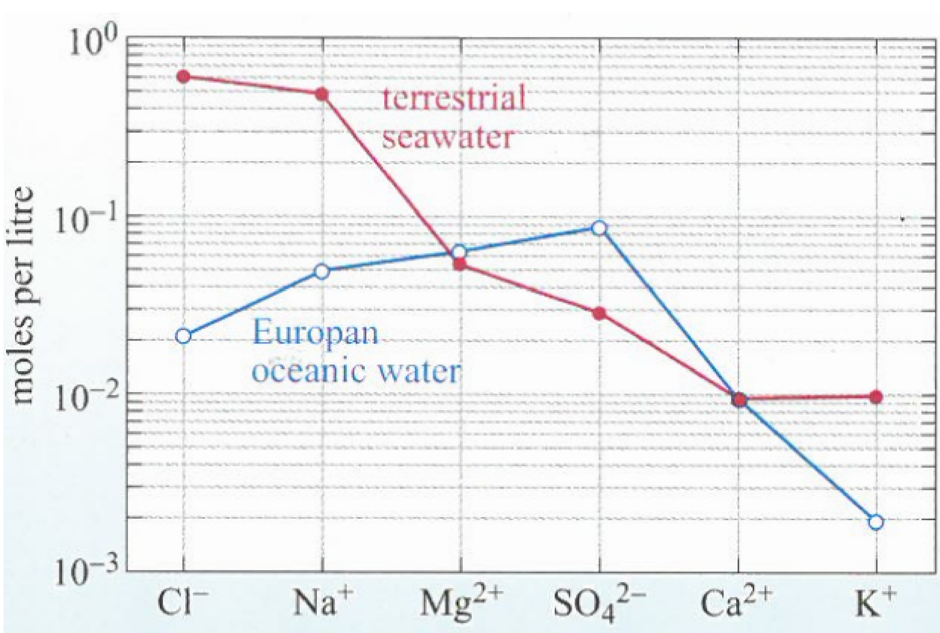
- carbon is one of the most abundant elements in the Universe
- it is tetravalent and therefore versatile in that it can bond with a large variety of other chemical groups
- the bonds are relatively stable, unlike silicon, which is also tetravalent.
- it can occur is the gas phase as CO_2 and is therefore mobile

35. What are the cell walls of life on Earth made of? Sketch them and list their important properties.

- Cells are made of (bilayers of) lipids [fatty acids].
- They are insoluble in water.
- They act as an energy substrate.
- They are semipermeable, allowing nutrients to enter.

36. According to the figure below, how many more times greater is the concentration of chloride (Cl^-) in terrestrial seawater than in Europa's ocean? *(Check carefully the numbers on the vertical axis, write down the two concentrations, and then divide.)*

Cl^- is shown on the left; the concentrations for terrestrial seawater (upper line) is 6×10^{-1} moles per liter and that of Europa's ocean is 2×10^{-2} moles per liter. The ratio is $3 \times 10 = 30$, so the concentration of chloride in terrestrial seawater is 30 times greater than in Europa's ocean.



37. A strain of gray slime producing bacteria is recovered from a deep gold mine in South Africa. This strain was found within a rock crevasse next to an active lava tube where pressures and temperatures routinely reach 10 atm and 190°F; moreover, this gold mine has an unusual concentration of other heavy metals like Zn, Cu, and Pt.

(i) What kind of extreme environments does this gold mine possess?

It has high pressures and high temperatures. It is also rich in heavy metals.

(ii) What kind of extremophile is this gray slime?

It has to be piezothermophile (or even a piezothermolithophile). Its metabolism is that of an chemolithoautotroph.

38. An alien genome is found to encode information using DNA very much like ours – however, this genome uses six bases (A,T,C,G,M,S) rather than the usual four (A,T,C,G).

(i) How many possible amino acids could this alien genome uniquely encode for? *(Explain how you calculate this; don't write just numbers!)*

If each amino acids corresponds to a codon of 3 letters, and there are 6 different letters, then we can have $6 \times 6 \times 6 = 6^3 = 36 \times 6 = 216$ different words and this 216 different amino acids.

(ii) How many possible amino acids could this genome encode for if each amino acid had three possible corresponding codons? *(Again, explain what you are doing!)*

If each amino acid corresponds to 3 different words, the number of different amino acids can only be 1/3 of the number of words, so $216/3 = 36 \times 2 = 72$ different amino acids.

39. What are three of Darwin's primary tenets for evolution by natural selection?

- struggle for survival due to limited resources
- more individuals are produced that can survive
- offspring can show small variations
- (individuals produce similar offspring)

40. List some key properties of life as we know it.

- Order
- Reproduction
- Growth & development
- Energy utilization
- Response to environment
- Evolutionary adaptation

41. Using your answer to the problem #40, answer the following, making special note of how *each of these* succeeds or fails:

(i) Is a star alive?

- Order? *Yes* stars do have low entropy owing to cooling.
- Reproduction? *Yes*, one gets offspring from stardust.
- Growth & development? Growth *yes*, & development in the sense of stellar evolution.
- Energy utilization? *Yes*, the do use nuclear energy.
- Response to environment? *Yes*, the mass of a star depends on the initial conditions
- Evolutionary adaptation? *No*, stars do not have a genetic code.

So, the analogy fails because of evolutionary adaptation!

(ii) Is a virus alive?

- Order? *Yes,* viruses have an orderly structure.
- Reproduction? *Yes, but* only in the presence of a host cell.
- Growth & development? Growth *yes, but* only in the presence of a host cell.
- Energy utilization? *Yes, but* only in the presence of a host cell.
- Response to environment? *Yes*, viruses only thrive in a suitable environment.
- Evolutionary adaptation? *Yes*, viruses have a genetic code that can be modified.

So, viruses are *almost* alive, but they do require a host cell.

42. The temperature T on a planet at a distance d from the Sun with radius R_S and surface temperature T_S is given by

$$T(d) = \sqrt{\frac{R_S}{2d}}\, T_S. \tag{1}$$

(i) Show that

$$\frac{d(T)}{d(273\,\mathrm{K})} = \left(\frac{273\,\mathrm{K}}{T}\right)^2. \tag{2}$$

where $d(273\,\mathrm{K})$ is the distance where water freeze at $273\,\mathrm{K}$ temperature.

This is a rather complex exercise. Don't worry: the final exam will not contain anything related to thus subject!

Square Equation (1), so we get rid of the square root.

$$T(d)^2 = \frac{R_S}{2d}\, T_S^2. \tag{3}$$

Multiply by d (i.e., move it to the left), and divide by $T(d)^2$, i.e., move it to the right, so we have

$$d(T) = \frac{R_S}{2}\frac{T_S^2}{T^2}. \tag{4}$$

where we have written $d(T)$ instead of just d to emphasize that d will be different for different values of T. Next, write down the same equation, but replace T by $273\,\mathrm{K}$, so

$$d(273\,\mathrm{K}) = \frac{R_S}{2}\frac{T_S^2}{(273\,\mathrm{K})^2}. \tag{5}$$

Now, divide the last 2 equations by each other and not the factors R_S, T_S, and 2 all cancel, so we arrive at

$$\frac{d(T)}{d(273\,\mathrm{K})} = \left(\frac{273\,\mathrm{K}}{T}\right)^2. \tag{6}$$

(ii) Compute $d(190\,\mathrm{K})/d(273\,\mathrm{K})$, where $d(190\,\mathrm{K})$ is the distance from the Sun where ammonia freezes, which is at $190\,\mathrm{K}$ temperature. *You may use Equation (2) even if you weren't able to derive it.*

Replace T by $190\,\mathrm{K}$, so we have

$$\frac{d(190\,\mathrm{K})}{d(273\,\mathrm{K})} = \left(\frac{273\,\mathrm{K}}{190\,\mathrm{K}}\right)^2 = 1.437^2 = 2.06. \tag{7}$$

(iii) Compute $d(190\,\mathrm{K})$, assuming that $d(273\,\mathrm{K}) = 1.05\,\mathrm{AU}$.

We have $d(190\,\mathrm{K}) = 2.06 \times d(273\,\mathrm{K}) = 2.06 \times 1.05\,\mathrm{AU} = 2.17\,\mathrm{AU}$.

(iv) As (iii), but now locate the boiling distance of ammonia, which occurs at 240 K temperature.

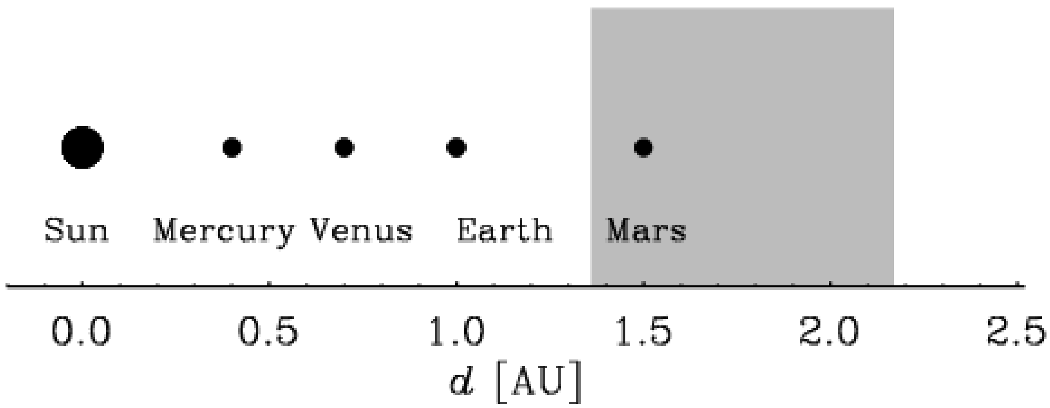
First, we find

$$\frac{d(240\,\mathrm{K})}{d(273\,\mathrm{K})} = \left(\frac{273\,\mathrm{K}}{240\,\mathrm{K}}\right)^2 = 1.138^2 = 1.29. \quad (8)$$

Thus, we have $d(240\,\mathrm{K}) = 1.29 \times d(273\,\mathrm{K}) = 1.29 \times 1.05\,\mathrm{AU} = 1.36\,\mathrm{AU}$.

(v) Shade the habitable zone of ammonia on the plot below.

Shaded betwee $1.36\,\mathrm{AU} < d < 2.17\,\mathrm{AU}$; see modified figure.



(vi) Do any of the Sun's planets fall within this ammonia habitable zone?

Yes, Mars falls within the habitable zone of ammonia.

43. As Cassini flew over the "tiger stripes" on the surface of Enceladus, it recorded enhanced levels of periodic variations of hydrogen. Why is this thought to be evidence for hydrothermal vents at the subsurface ocean floor of Enceladus? *(Hint: inspect the reactions in question 11 above!)*

One of the key properties of hydrothermal vents is that they produce hydrogen (see the reaction $3Fe_2SiO_4 + 2H_2O \rightarrow 2Fe_3O_4 + 3SiO_2 + 2H_2$ in question 11. Since hydrogen is highly volatile, it must come directly from the vents somewhere in the ocean beneath the ice.)

As noted above, as a simplified version of the production of hydrogen from reduced iron (FeO or ferrous iron), you may think of the reaction $2FeO + H_2O \rightarrow Fe_2O_3 + H_2$, where Fe_2O_3 is ferric iron.

44. The second law of thermodynamics states that the degree of disorder of all of the Universe can only increase. Explain what life does to the degree of disorder and why this is not in conflict with the second law of thermodynamics.

- Life produces order locally (e.g., in the cell), but disorder in the surroundings such that the total degree of disorder is still increasing. This is not in conflict with the second law of thermodynamics.

45. Name the three basic rock types and explain them in a few words.

- Igneous rock: forms from molten rock, which then cools and solidifies
- Metamorphic rock: chemically/structurally altered by pressure/temperature, not molten
- sedimentary rock: formed from compression of sediments

46. Iron-reducing bacteria make their biological living by performing the following reaction

$$2H_2O + Fe_2O_3 \rightarrow 2Fe(OH)_2 + \tfrac{1}{2}O_2.$$

In this reaction, iron (Fe) plays the same role that inorganic carbon (C) would play in "regular" biological reactions like photosynthesis. (Thus, instead of a carbon source, look for an iron source instead when making your choice.)

With this in mind, determine what kind of -troph this iron-reducing bacteria would be. Justify each of the prefixes used in your answer.

- The energy comes from molecules (reducing iron), so *chemo*.
- Fe gets reduced (from oxidation state III to II) and oxygen gets oxidized (oxidation state increases both for water and for ferric iron). The electron donor is therefore oxygen, which is inorganic, so *litho*.
- There is no carbon, but the source of metabolism is iron, which is inorganic, so *auto*.
- Thus, we have a chemolithoautotroph.

47. A sample of lunar rock had 80 mg of ^{40}K at its formation. Assume for its half-life 1.25 Gyr and that 90% decays into ^{40}Ca and 10% into ^{40}Ar.

- How much ^{40}K will be left after 2.5 Gyr?

  2.5 Gyr is exactly 2 half-lives. Thus, the ^{40}K will have dropped to 1/4 (two times 1/2), i.e., to 20 mg.

- How much ^{40}Ca will be produced after 2.5 Gyr?

  The difference between the amounts of ^{40}K initially (80 mg) and after 2 half-lives (20 mg) is 60 mg. 90% of it, which is 54 mg, will have decayed to ^{40}Ca.

- How much ^{40}Ar will be produced after 2.5 Gyr?

  The remaining 10%, which is 6 mg, will have decayed to ^{40}Ar.

- After 2.5 Gyr, what is the total mass of ^{40}K, ^{40}Ca, and ^{40}Ar?

  The total mass is thus 20 mg potassium + 54 mg calcium + 6 mg argon, so altogether 80 mg. Mass is therefore conserved.

48. On the Earth, the carbon dioxide cycle between atmosphere and mantle operates in such a way that it regulates its temperature. Explain how this works with words *and a diagram* and why rain water and carbonate minerals are important for the CO_2 cycle.

- When there is a lot of CO_2 in the atmosphere, it gets hotter.
- When it gets hotter, there is more rain, which dissolves the CO_2 to form carbonic acid.
- Carbonic acid turns calcium silicate to calcium carbonate via the reaction above.
- This lowers the CO_2 in the atmosphere, so it gets cooler.
- When it is cooler, there is less evaporation and less rain, so CO_2 builds up again.
- It gets hotter again, constituting therefore a negative (stable) feedback cycle.