Answer Key

Question 1: An Assortment of Images [50 pts.]

a. Write your answers to part (a) in the following blanks, which are worth one point each:

1. Venus
2. Europa
3. Titan
4. Mars
5. Enceladus
6. Enceladus
7. Europa
8. Europa
9. Mars
10. Europa
11. Titan
12. Bennu
13. Mars
14. Europa
15. 67P/C-G
16. Enceladus
17. Europa
18. Enceladus
19. Venus
20. Mars
21. Europa
22. Enceladus
23. Titan
24. Titan
25. Mars

b. True

c. Jupiter

d. Infrared

e. Iron oxide

f. Saturn

g. Cassini

h. Visibly dark areas of chaos terrain that are sunken below adjacent terrain

i. Material that is thrown out when (in this case) an object hits the surface and forms a crater

j. MRO

k. The orange/red areas are thought to be water ice mixed with hydrated salts (possibly magnesium sulfate or sulfuric acid), while the rest is relatively pure water ice

l. That portion of the lake is drying up

m. OSIRIS-REx

n. This is Martian permafrost. The cracks and polygonal pattern are thought to form due to seasonal contraction and expansion of surface ice. The ground contracts in the winter, creating small spaces that fill with melt water in summer. When winter returns, the water freezes, which acts like wedge, enlarging cracks.

o. A boundary where two blocks (of rock, ice, etc.) move horizontally relative to each other.

p. It is thought to be a contact binary; two objects moved towards each other until they touched.

q. Large ridges on Enceladus

r. Upwelling of warmer ice while cooler ice sinks, or ice erupting onto the surface.

s. Plumes

t. Maat Mons

u. HiRISE on MRO

v. Cycloids

w. Temperature

x. The pink spot is thought to be haze illuminated from below by specular reflection off of Kivu Lacus.

y. No, it is filled with hydrocarbons like methane and ethane instead.

z. Alluvial fans form as a channel exits a steep, confined valley onto more gently sloped and unconfined terrain. The channel loses its ability to transport sediment due to the flatter ground and wider flow, depositing the sediment on the ground. The ubiquity of alluvial fans on Mars suggests that liquid water on the surface likely existed in some form in its history.

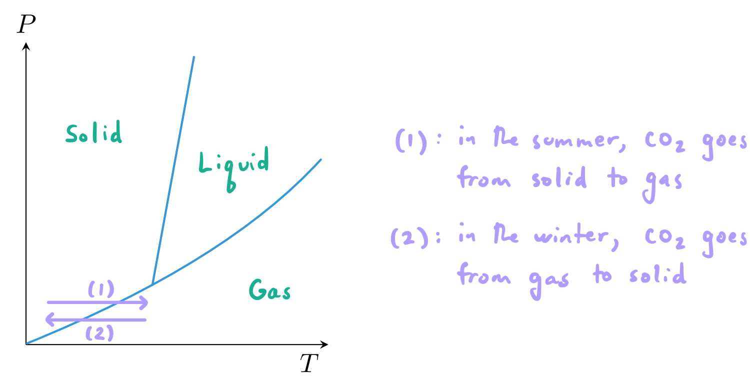
Question 2: Seasons on Mars [25 pts.]

a. When the northern hemisphere is experiencing summer, Mars is at its farthest point in its orbit from the Sun (aphelion).

b. Winter in the northern hemisphere is *shorter* than winter in the southern hemisphere. This is because winter in the northern hemisphere happens when Mars is close to the Sun. From Kepler's Laws, we know that Mars will be moving at its fastest when it is closest to the Sun, reducing the time Mars stays in that position, reducing the time the northern hemisphere experiences winter.

c. Ranking, from warmest to coolest: (2), (1), (3), (4). Generally, summer is warmer than winter. Summer in the southern hemisphere is warmer than summer in the northern hemisphere since Mars is closer to the Sun during the southern summer. Northern winter is warmer than southern winter for the same reason.

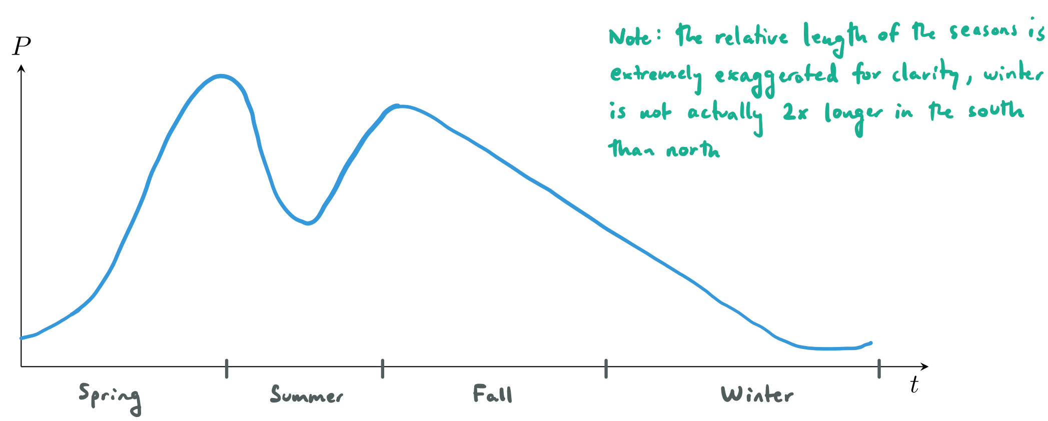
d. Draw your phase diagram on the axes below, where P represents pressure and T represents temperature.



e. Maximum: at the start of summer in the southern hemisphere. This is because spring/summer in the southern hemisphere is warmer/harsher than in the north. However, we wouldn't expect it to be in the middle of summer, since that's when it's winter in the north, where part of the atmosphere will freeze out and cause a small dip.

Minimum: winter in the south, since the south experiences longer/harsher winters than the north. As a result, more of the carbon dioxide in the atmosphere will free out, causing the biggest dip in the pressure, which will outweigh the rise in pressure due to sublimation of carbon dioxide in the northern summer.

f. Draw your plot on the axes below, where P represents the global atmospheric pressure of Mars and t represents time.



Question 3: Subsurface Oceans [25 pts.]

a. If the surface of the object is "cleaned up" regularly, the number of craters visible on the surface is kept relatively low. Otherwise, the number of visible craters on the surface would continue to grow. (Another way to think about it is that if a surface is younger, then it has had less time for something to hit it and form a crater.) This process typically occurs through internal geologic activity that modifies the surface. Having a subsurface ocean is one way this can happen. For example, water from the subsurface ocean can spill onto the surface (perhaps from cracks appearing in the surface) and "cover up" what was previously there.

b. Europa is in an eccentric orbit around Jupiter due to its gravitational interactions (Laplace resonance) with Ganymede and Io. This eccentricity leads to a difference in the forces that Europa experiences as it goes in its orbit. When Europa is close to Jupiter, tidal forces elongate Europa along the axis that goes through Jupiter and Europa, and as Europa moves away, it relaxes back into a more spherical shape in a process known as tidal flexing. (Additionally, it causes Europa's sub-Jovian point to librate.)

c. Europa doesn't have its own magnetic field, but Jupiter does. As Europa orbits around Jupiter, it experiences Jupiter's magnetic field differently. This difference leads to a current somewhere in Europa, which in turn makes its own (induced) magnetic field, which is what Galileo measured. We think that the current is from ions (dissolved salts) in Europa's subsurface ocean moving around.

d. Some of the longest linear features on the surface did not have the shapes we predicted they would if they were created by tides as Europa orbited Jupiter. However, the patterns would fit very well if Europa's surface could move independently of the rest of the planet. If Europa has a subsurface ocean, the icy surface would be floating on water, which would allow it to move independently.

e. Water vapor coming from the plumes implies that there is some (relatively large) source of liquid water nearby. The source has to be somewhat substantial, since a lot of mass is being lost by the plumes, and a lot of it isn't falling back to the surface. This could be a subsurface ocean. (Note: alone, this doesn't directly guarantee that the subsurface ocean exists or that the material for the plumes comes from the subsurface ocean; for example, it could come from pockets of water within the icy shell instead.)

f. Enceladus is not a perfect sphere; in fact, its southern half is "dented". So, scientists would expect to see a negative mass anomaly in the southern half of the moon. However, they noticed that the negative mass anomaly was not as big as they thought it would be. This implies that there has to be something denser than ice which is helping make the negative mass anomaly smaller (i.e., the anomaly is now a smaller negative number than they expected it to be), which could be liquid water in a subsurface ocean.

g. This implies that the subsurface ocean and the core of Enceladus are in contact with each other. This means that they can exchange compounds and chemical reactions can occur at their interface. Additionally, these compounds can travel through the ocean to other places, where they can react more readily. (Recall that reactions that occur in liquid form or in solution typically take place faster than those in the solid state or those only at a surface.)

Question 4: Amino Acids and Proteins in Space [25 pts.]

a. Answers will vary; proteins have many functions. For example: acting as enzymes (biological catalysts) to speed up reactions and send/receive signals.

b. Lipids (fats), carbohydrates (sugars), and nucleic acids.

c. Carbohydrates: C, H, and O
Lipids: C, H, and O
Proteins: C, H, O, and N
Nucleic acids: C, H, O, N, and P.

d. High-energy light from the Sun hits precursor molecules in the ice, creating reactive ions and radicals. If these reactive ions and radicals are close enough to each other, they can form new compounds, even at relatively low temperatures. These sort of reactions are said to occur through a free-radical mechanism.

e. Glycine. It is simpler so it is easier to make.

f. Tryptophan is more hydrophobic. This is because of the bulky side chain in the green box, which consists of many largely non-polar covalent bonds.

g. Interactions like hydrogen bonding and the hydrophobic effect depends very strongly on the solvent. For example, if the solvent is not water-based, you cannot have hydrophobic interactions in the same way. Additionally, you may not have hydrogen bonding between the solvent and protein if the intramolecular hydrogen bonding within the protein is stronger. Methane is a non-polar solvent, so essentially all of these types of interactions wouldn't work very well. The protein either wouldn't fold correctly, or wouldn't fold at all. Protein folding in a non-polar solvent would have to work very differently than it does on Earth. The main idea of asking this question is to show that protein folding follows instructions that depend on certain interactions being possible, and in certain solvents (like non-polar ones), those interactions may not exist in the same way.

h. About 30-35% ammonia by mole, -97°C

i. Since the enthalpy change is zero, heating up the reaction will not shift the position of the equilibrium significantly. In any case, the idea is that we care about the *kinetics*, not the thermodynamics of this reaction. Heating up the reaction will probably cause the reaction to occur faster, so you should follow your labmate's advice. They are correct for the wrong reason!

j. When a protein denatures, it means the amino acids stay bonded together in chains, but the connections between the chains giving the protein a specific structure start to fall apart. Essentially, the protein stays intact, but it loses its structure. This makes the protein much less effective (if it even still works).

   There are a couple of ways to think about why this happens. For one, at higher temperatures, the atoms are moving around more, making it easier to disrupt the relatively weak interactions (e.g., hydrogen bonds) that hold a lot of the protein's structure together.

Question 5: Equilibrium Temperature [25 pts.]

a. $4\pi R_*^2$

b. Here, we substitute our answer for part (a) for A in the equation provided as a hint. So, our answer to this part is $4\pi R_*^2 \sigma T_*^4$

c. The light from the star can be treated as light moving in all directions from a point source. At a given distance, the total amount passing through has to be the same, since energy is conserved. However, the area the light is passing through will scale with the square of the distance from the star. (Recall that the surface area of a sphere is $4\pi R^2$.) So, the flux will scale with $1/r^2$.

d. Using the inverse-square law, we know that the flux should fall off as D^{-2}. Putting it all together,

$$F = \frac{L}{4\pi D^2}$$
$$F = \frac{4\pi R_*^2 \sigma T_*^4}{4\pi D^2}$$
$$F = \frac{R_*^2 \sigma T_*^4}{D^2}$$

e. The cross-sectional area times the flux at D represents the total amount of energy that is blocked by the planet, which is equal to the amount of light that is incident on the planet (before thinking about absorption/albedo). It doesn't tell us anything about how that energy is distributed over the surface of the planet. If you wanted to use $2\pi R_p^2$ as your area, you certainly could. You would have to multiply it by $F/2$, which represents the *average* flux over the entire hemisphere. This average is less than F because not all parts of the hemisphere receive the light directly. For example, at the poles, the light will be at a very shallow angle (so the intensity will be lower), while at the equator, the light will be head-on, and you will essentially be experiencing the full flux. (Something interesting to think about: when you average over the entire surface of the planet, the average flux is $F/4$.)

f. The (bond) albedo of an object quantifies the fraction of light an object reflects. We would generally expect an icy object to have a higher albedo than a rocky object.

g. The power absorbed by the planet is the product of the flux at D, the cross-sectional area of the planet, and $(1 - \alpha)$:

$$\begin{aligned} P_{absorbed} &= F \times \pi R_p^2 \times (1 - \alpha) \\ &= \frac{\pi R_p^2 R_*^2 \sigma T_*^4}{D^2}(1 - \alpha) \end{aligned}$$

h. The power absorbed by the planet has to equal the power emitted by the planet.

i. Using the Stefan-Boltzmann Law, $P_{emitted}$ will be

$$P_{emitted} = 4\pi R_p T_p^4$$

Now, we set $P_{emitted}$ and $P_{absorbed}$ equal to each other, since the planet is in thermal equilibrium, and solve for T_p:

$$4\pi R_p^2 \sigma T_p^4 = \frac{\pi R_p^2 R_*^2 \sigma T_*^4}{D^2}(1 - \alpha)$$
$$T_p^4 = \frac{R_*^2 T_*^4}{4D^2}(1 - \alpha)$$
$$T_p = T_* \sqrt{\frac{R_*}{2D}}(1 - \alpha)^{1/4}$$

Question 6: More Equilibrium Temperature [20 pts.]

Situation 1: What if the planet is tidally locked?

a. Broadly speaking, an object is tidally locked when the time it takes to rotate about its axis is approximately the same as the time it takes to revolve around the object it orbits (the "parent"). As a result, (approximately) the same side of the object faces the parent object all the time.

b. Red dwarfs are cooler and smaller than the Sun, so in order for a planet around a red dwarf to have the same temperature as Earth, it'll have to be closer to its parent star than Earth is to the Sun. The force of gravity is proportional to $1/r^2$. So, the closer you get to the star, the stronger the force of gravity, and it stronger at a faster and faster rate as you get closer. As a result, when you're close to the parent star, you'll have a much bigger difference between the force the near and far sides of the planet experience, and it is this difference in gravitational force that drives tidal locking. A habitable planet around a red dwarf will be very close to its parent star (for the reasons outlined in the part earlier), so it will get tidally locked faster.

c. Answers will vary. One of the most obvious ways is through the planet having an atmosphere. Temperature differences will result in wind which (among other things) will help redistribute heat.

Situation 2: What if the planet has a substantial atmosphere?

d. The molecules in the atmosphere (especially carbon dioxide) absorb light and "trap" heat. It effectively acts as a large blanket.

e. The Earth is very far away from the Sun, so the flux of longwave radiation from the Sun is very low, even though it would be huge at the surface of the Sun. So, even though the Earth emits less longwave radiation than the Sun overall, its flux is much higher at the top of Earth's atmosphere than the flux of longwave radiation from the Sun. As a result, most of the longwave radiation we experience in this model is from the Earth. Essentially, the longwave radiation from the Sun that gets absorbed is negligible compared to the longwave radiation from Earth. Furthermore, as a blackbody, the Sun's spectrum peaks in visible light, and it emits much more shortwave radiation than longwave radiation.

f. The atmosphere absorbs longwave radiation with a flux of σT_s^4.

The atmosphere emits radiation with a flux of $2\sigma T_a^4$. Where does this value come from? From both the top (outwards towards space) and bottom (back towards the planet's surface), the atmosphere emits radiation at a flux of σT_a^4 *each*. So, we add it up for a total of $2\sigma T_a^4$.

The atmosphere has to be in thermal equilibrium, so the flux absorbed has to be equal to the flux emitted:

$$2\sigma T_a^4 = \sigma T_s^4$$

Solving for T_s, we get

$$T_s = 2^{1/4} T_a$$

Based on this expression, the surface will always be warmer than the atmosphere in our model.

Question 7: Transits and Transmission Spectroscopy [25 pts.]

a. TRAPPIST-1

b. The depth of a transit, δ, is given by ratio of the areas of the discs of the planet and the star

$$\delta = \frac{A_p}{A_*} = \left(\frac{R_p}{R_*}\right)^2$$

So, if we know the radius of the parent star, then we can get a good estimate of the radius of a planet by measuring the depth of its transit.

c. Planets that are farther away from their parent stars will take longer to complete a full orbit. On top of that, their speed during the orbit will also be slower. So, the transits will take longer (i.e., the dips will appear wider on the plot), since the planet will take a longer time to cross the disc of the star. (On top of that, the more time will pass in between each transit, but students don't need to mention this.)

d. They would be farther away. The reasoning is the same as it was for Question 6, part (a), but in reverse: red dwarfs are cooler and smaller than the Sun, so in order for a planet around a Sun-like star to have the same temperature as it would around a red dwarf, it'll have to be farther from to its parent star than it would be from a red dwarf.

e. The alien civilization is less likely to observe a transit. Transit probability is (approximately) proportional to R_*/a, where R_* is the radius of the parent star and a is the semimajor axis of the planet's orbit. Since the planets will be farther away, a will be larger, which drives the transit probability down.

f. (i) Increase
   (ii) Decrease
   (iii) Decrease

g. Molecules are flexible. The bonds between atoms can stretch and bend, almost as if the atoms were joined together by springs. The energies associated with these movements are typically around the energy of infrared light. So, when a molecule gets hit with a photon of that energy, the photon will be absorbed and excite the vibration to a higher energy state.

h. The trade-off: Planet B's transit will be deeper (making it theoretically easier to detect) and will occur more often, since the planet is closer to its parent star, since the star is smaller and less massive than the Sun. However, the signal-to-noise ratio will be worse for Planet B's transit due to the lower brightness (assuming the stars are the same distance away) and due to red dwarfs' variability.

   Overall, it's probably easier to go with Planet B. Since the transit will happen much more often, we can get many measurements, which will help us beat down the noise (recall that error goes down with $\sim 1/n^{1/2}$) rather than hoping one stronger signal will be enough to give us everything we need (because even though the signal to noise ratio will be better, it still won't be perfect data). All in all, students can make a number of arguments in favor of each. We care more about the thought process and understanding the trade-off than what planet they picked, since they have a 50% chance of picking the right planet by guessing anyways.

i. If left alone and given enough time, an atmosphere will eventually reach (or get close enough to) equilibrium (i.e., it will have a certain composition, temperature, etc.). However, an atmosphere can stay out of equilibrium if there is some process that is altering the composition, temperature, etc. continually. For example, Earth's atmosphere is not in equilibrium because of the ways life has changed it (e.g., through metabolism). If we observe an atmosphere and find that everything is out of equilibrium and that certain biology-related compounds (e.g., water, methane, N_2, O_2) are present in certain ratios, it *could* be something that supports the idea of life existing. The general idea is that eventually, our understanding of atmospheric chemistry and our observational tools/analyses could get so good that we could look at an atmosphere and think "unless there was life on this object, it's very unlikely this atmosphere could look like this".

Question 8: Mission Design [35 pts.]

This is intentionally written as an extremely open-ended question. We care primarily about students' thought process, creativity, and knowledge as opposed to getting the "right" answer.

a. Mission architecture:
Responses should include thorough descriptions/images of orbiter, lander/rover/etc. and what they will do. Possible ideas include: having a "small" orbiter used mainly for communication and a "large" lander with most of the instrumentation, doing the reverse of that, having the orbiter and lander be the same spacecraft (e.g., the Enceladus Orbilander), etc. Possible reasons why they didn't choose a design include: not choosing a rotocraft since Enceladus has an extremely thin atmosphere that would struggle to keep the vehicle in the air.

b. Power:
Responses should list some form of power source (e.g., RTG, solar panels) and ideally some form of energy storage (e.g., Li-ion battery), as well as their rationales for each. Possible response for power source: choosing using an RTG over solar panels because the flux of sunlight is so low in the outer Solar System.

c. Communication:
Responses should include sending both scientific and health/diagnostic data (e.g., data from a sensor about battery capacity), some means of communication (e.g., using deep space network), and some form of data storage and strategy for when they will transmit it (e.g., storing data on a hard drive and sending chunks of data at certain times when the orbiter is at apoapsis).

d. Instruments:
Responses should include instruments for detecting/characterizing life (e.g., mass spectrometer, microscope, etc.), remote sensing (e.g., radar sounder, thermal emission spectrometer, altimeter, narrow and wide angle cameras, etc.), understanding Enceladus' structure (e.g., radar sounder, sesiometer, etc.), and, if applicable, for sampling (e.g., funnel, scoop, etc.).

e. Other: