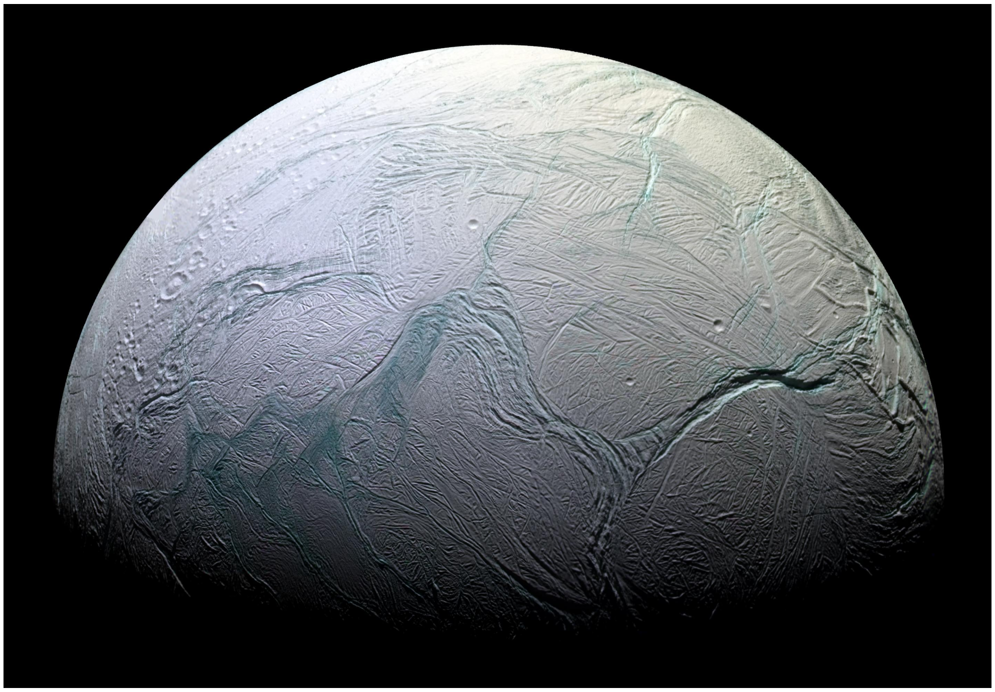
Science Olympiad
Solar System
National Exam

Wichita State University
May 20, 2023



Directions:

- This exam consists of **8 questions** worth **230 points**. There is no penalty for wrong answers.
- The top five tiebreakers, in order, are: Q1, Q2, Q3, Q8, and Q5.
- You are allowed to bring in one 8.5" × 11" sheet of paper with information on both sides.
- This exam will be posted online after the competition at `https://chandra.si.edu/edu/` and `https://www.universeunplugged.org/series/nso-webinars`.
- Above all else, just believe!

Written by:
The Solar System A-Team
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Question 1: An Assortment of Images [50 pts.]

For each part of this question, please refer to the attached image set. Part (a) is worth 25 points, while parts (b) through (z) are worth 1 point each.

a. For each of the 25 images, list the object from the rules it is associated with. Every photo is of an object in the Solar System. *Hint: the following parts may give valuable information about each image, which could help you in determining which object it is.*

b. True or false: the object shown in Image 1 is closer to the Sun than Earth.

c. What planet does the moon shown in Image 2 orbit?

d. In what portion of the electromagnetic spectrum (e.g., ultraviolet, visible, infrared, etc.) was Image 3 taken?

e. The object shown in Image 4 is often called the "Red Planet". What causes the red color?

f. What planet does the moon shown in Image 5 orbit?

g. What spacecraft collected the data used to create Image 6?

h. Image 7 shows two dark spots named Thera Macula and Thrace Macula. In your own words, explain what they are.

i. The white material in Image 8 is ejecta around a crater. In your own words, what is ejecta?

j. What spacecraft collected the data used to create Image 9?

k. Image 10 shows a color-coded area of an icy moon. How is the composition of the ice represented with orange/red different from the rest of the ice in the image?

l. The lake on the right of Image 11 has slightly lighter patches. What does this indicate?

m. What spacecraft collected the data used to create Image 12?

n. Image 13 shows cracks creating a polygonal pattern in the ground. Briefly describe the process that created these cracks/shapes.

o. Image 14 shows a series of cracks in the surface which were distorted by a strike-slip fault. In your own words, explain (or draw) what a strike-slip fault is.

p. How is the object shown in Image 15 thought to have formed?

q. Image 16 shows a surface feature called Cufa Dorsa. Briefly explain what a "dorsa" is.

r. The surface features shown in Image 17 are sometimes nicknamed "freckles". How are they formed?

s. What type of geological feature is being shown by the data in Image 18?

t. What is the name of the mountain shown in Image 19?

u. What instrument on what spacecraft collected the data used to make Image 20?

v. What is the name of the type of surface feature shown in Image 21?

w. What variable (e.g., temperature, pressure, composition, etc.) are the colors (purple, red, orange, and yellow) in Image 22 representing?

x. What is causing the pink dot shown in Image 23?

y. Image 24 shows a stable body of liquid on an object in the Solar System. Is it filled with water? If not, what is in it?

z. Image 25 shows an alluvial fan. In your own words, explain how alluvial fans are formed and what their existence on this object implies about the object's geologic history.

Question 2: Seasons on Mars [25 pts.]

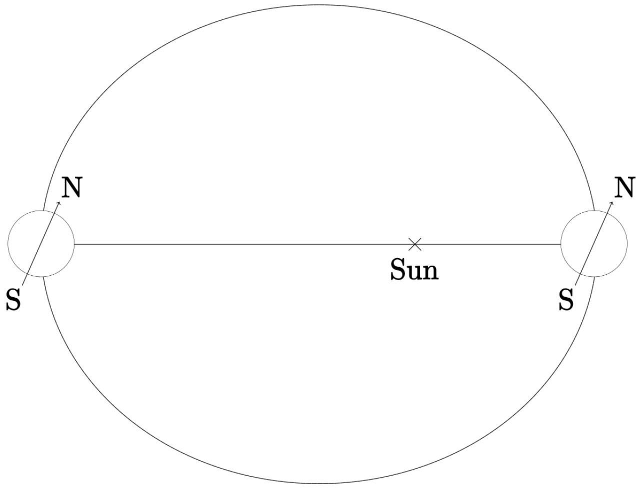

Figure 1: Mars's orbit, which is in the plane of the page, with its eccentricity significantly exaggerated for clarity. The slanted line going through Mars represents its axis of rotation, which goes through the plane of the page. The "N" and "S" stand for "north" and "south".

Like Earth, seasons on Mars are caused by the tilt of its axis. However, Mars's orbit has a significantly higher eccentricity (i.e., it is more oval-shaped) than Earth's orbit, so the variation in distance from the Sun also contributes to how intense the seasons are, as seen in Figure 1.

a. (2 points) When it is summer in the northern hemisphere of Mars, is Mars at its closest point in its orbit to the Sun, or at its farthest? *Hint: when a hemisphere is experiencing summer, it is pointing towards the Sun.*

b. (3 points) Is winter in the northern hemisphere of Mars longer or shorter than that in the southern hemisphere? Explain your answer. *Hint: think about Kepler's Laws and how the speed of a planet changes depending on its distance from the Sun.*

c. (5 points) Rank the following situations by average temperature, from warmest to coolest: (1) summer in the northern hemisphere, (2) summer in the southern hemisphere, (3) winter in the northern hemisphere, and (4) winter in the southern hemisphere. How did you determine your ordering? *Hint: think about how the intensity of light Mars receives from the Sun changes with distance.*

Seasonal temperature differences on Mars cause its global atmospheric pressure to change as well. For example, when the northern hemisphere is experiencing winter, carbon dioxide in the atmosphere near the north pole "freezes out" and is deposited onto the north polar ice cap. In the summer, when it is much warmer, the carbon dioxide from that pole returns to the atmosphere.

d. (4 points) On your answer sheet, sketch a temperature-pressure phase diagram of carbon dioxide and label the solid, liquid, and gas phases. Draw two arrows on the phase diagram representing the phase transition the carbon dioxide undergoes during the summer and winter at a given pole.

e. (4 points) When one pole is experiencing winter, the other is experiencing summer, so we might expect the amount of carbon dioxide removed from one pole to be deposited on the other, keeping the atmospheric pressure relatively constant. However, the rates of addition and removal of carbon dioxide from each pole are different due to the eccentricity of Mars's orbit.

   Based on the above information and your answers to parts (a) through (c), during (approximately) what part of the Martian year will the global atmospheric pressure of Mars be the highest? When will it be the lowest? Explain your answers, and be sure to specify both the season *and* the hemisphere.

f. (7 points) Let's put all of this together. On your answer sheet, sketch a plot of global atmospheric pressure vs. time for one Martian year, starting at the beginning of spring in the southern hemisphere. Your sketch will have two peaks and two dips, each of different sizes, since the contribution of each hemisphere is different. In your sketch, please:

   (i) mark the start and end of each season on the x-axis in a way that shows the seasons are different lengths

   (ii) be clear about which peaks and dips are higher/lower than the others

Question 3: Subsurface Oceans [25 pts.]

Europa and Enceladus (among potentially many other objects) are thought to have subsurface oceans containing liquid water. In this question, we'll examine some of the evidence for these subsurface oceans and explore what they mean for the geology and potential habitability of these objects.

a. (4 points) Both Europa and Enceladus are known to have young (on a geologic timescale) surfaces with relatively few craters. Why would a low amount of craters imply a young surface? How can the young surface be interpreted as supporting the idea of a subsurface ocean existing?

b. (3 points) Let's take a closer look at Europa. If Europa has a subsurface ocean, almost all of of the heat energy used to keep the ocean liquid probably comes from tidal heating. In your own words, briefly describe the process through which Europa experiences tidal heating.

c. (4 points) One strong piece of evidence supporting the idea of a salty subsurface ocean on Europa (whether it is liquid water or a slush of ice and liquid) is the measurement of an induced magnetic field by *Galileo*. In a few sentences, describe how this induced magnetic field arises on Europa.

d. (3 points) Europa's surface is covered in long, linear fractures, which are often cited as evidence supporting the existence of some form of subsurface ocean on Europa. Why?

e. (3 points) In 2005, *Cassini* photographed plumes (consisting of over 90% water vapor) coming from "tiger stripes" around the south pole of Enceladus. Why did the existence of these plumes lead scientists to speculate about the existence about a subsurface ocean near the south pole of Enceladus?

f. (5 points) The existence of a subsurface ocean on Enceladus was inferred taking careful measurements of the gravity around Enceladus's south pole using *Cassini*. Scientists found a negative mass anomaly, meaning that they measured less mass in that location than would be expected in the case of a uniform spherical body.

   However, liquid water is denser than ice, implying that if we were to replace ice with liquid water, the mass would *increase*, not decrease. Why did scientists expect to see a negative mass anomaly near Enceladus's south pole? How did their measurements lead them to conclude that a subsurface ocean likely exists? *Hint: consider the shape of Enceladus near the south pole.*

g. (3 points) Going back to the plumes: in addition to the water, scientists also found inorganic salts. What does this imply about the possibility of physical contact between the subsurface ocean and Enceladus's core? Why is this exciting from an astrobiology perspective?

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

Amino acids are the building blocks of proteins. There are (about) 20 different amino acids used in nature, each with their own structure and properties. Two amino acids, glycine and tryptophan, are shown below:

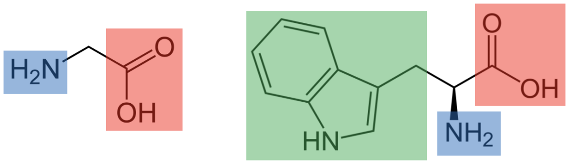

Figure 2: Examples of two amino acids used in nature. Glycine (left) is one of the simplest amino acids, while tryptophan (right) is one of the most complicated. The red and blue boxes are used to highlight common functional groups between the two. The green box highlights a side chain on tryptophan that glycine doesn't have.

a. (2 points) Proteins are some of the most versatile biological macromolecules. List two of the functions they have in life as we know it.

b. (3 points) Proteins are one of four key biological macromolecules. What are the other three?

c. (2 points) Which elements primarily make up each of the four biological macromolecules? For each, choose some subset of C, H, O, N, and P.

d. (3 points) During its mission, Rosetta detected glycine on 67P/Churyumov-Gerasimenko. In a chemistry lab on Earth, we often synthesize small organic molecules in a liquid solution, but this isn't possible on a comet. Broadly speaking, through what type of mechanism do scientists think small organic compounds like glycine form in space? *Note: this question is not looking for a specific mechanism, which is beyond the scope of this event – instead it is just looking for a general description of what type of reaction occurs and how it happens.*

e. (2 points) Scientists generally believe that early lifeforms used basic proteins made from a small set of amino acids, which grew over time. Based on your knowledge of biological evolution and chemistry, which of amino acids mentioned in this problem (glycine or tryptophan) do you think first appeared in life as we know it in the Solar System? Why do you think so?

f. (2 points) Proteins are formed by long chains of amino acids that "fold" together in a very specific way. One of the driving forces behind this process is the *hydrophobic effect*, in which hydrophobic (i.e., water "fearing") portions of the chains move to the core of the protein, where they are shielded from water molecules in the solvent. Between glycine and tryptophan, which amino acid do you think would play a larger role in these hydrophobic interactions? In other words, which one is more hydrophobic? Why do you think so?

g. (2 points) On Earth, life uses water (which is polar) as its solvent to carry out biological reactions. Imagine a lifeform on Titan that has evolved to use methane (which is non-polar) as its solvent for biological reactions. If this lifeform tried to fold proteins in the same way that organisms do on Earth (using hydrophobic interactions, hydrogen bonding, etc. with the same $\sim$20 amino acids), do you think it'd work? Why or why not?

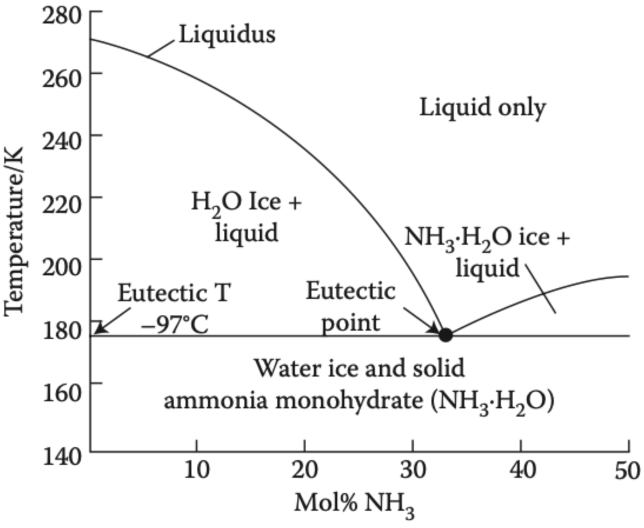

Figure 3: Binary phase diagram for a water-ammonia system.

h. (2 points) Titan is thought to have a subsurface ocean containing a mixture of liquid water and ammonia, allowing it to stay liquid even even though Titan is so cold. What composition (in mol% NH_3) would allow the ocean to stay liquid at the coldest temperature? What is that temperature?

Simulations suggest that Earth-based proteins in Titan's subsurface ocean would have different shapes than they do on Earth, which could significantly change their functions. One way to estimate the shape of a protein is to put it in a bath of heavy water (D_2O, where "D" refers to deuterium, an isotope of hydrogen). Some of the hydrogen atoms on the surface of the protein will be replaced with deuterium, which we can measure. This process can be represented by the "reaction" below:

$$\tfrac{x}{2}\,\mathrm{D_2O} + \mathrm{H}_x\!\cdot\mathrm{P} \longrightarrow \tfrac{x}{2}\,\mathrm{H_2O} + \mathrm{D}_x\!\cdot\mathrm{P}$$

where x is the number of hydrogen atoms on the surface of the protein that get exchanged and "·P" represents being attached to the protein.

i. (4 points) Imagine you are an astrobiologist working at NASA running this experiment. However, it's taking longer than you expected for the hydrogen and deuterium to exchange. Your labmate recommends that you heat up the sample a small amount, which should shift the equilibrium of the reaction towards the products. Is your labmate correct? Should you take their advice? Why or why not? *Hint: the enthalpy change, ΔH_{rxn}, is essentially zero.*

j. (3 points) If you heat up the solution too much, the protein may denature. What does it mean for a protein to denature? Why would increasing the temperature cause that to happen?

Question 5: Equilibrium Temperature [25 pts.]

Imagine you're part of a team of scientists looking for Earth-like planets outside the Solar System. Recently, your team found a planet orbiting a star at a distance D, but you aren't sure if it's in the star's habitable zone. The star has a radius R_* and temperature T_*, and the planet has a radius R_p and albedo α. Your team wants to estimate the equilibrium temperature of the planet, T_p.

a. (2 points) What is the surface area of the star? Assume the star is perfectly spherical, and express your answer in terms of R_* and constants.

b. (2 points) What is the luminosity, L, of the star? Express your answer in terms of R_*, T_*, and constants. *Hint: use the Stefan-Boltzmann Law:* $L = A\sigma T^4$.

c. (2 points) The inverse-square law describes how the flux of the star changes as we move further away from it. From a geometry perspective, why does the flux change as $1/r^2$, as opposed to $1/r$ or $1/r^3$?

d. (2 points) What is the flux, F, from the star at a distance D? Express your answer in terms of R_*, T_*, D, and constants. *Hint: use the inverse-square law.*

e. (4 points) Derivations of equilibrium temperature typically multiply F and the cross-sectional area of the planet, πR_p^2, to find the power absorbed by the planet (before accounting for albedo). However, the light from the star falls on a hemisphere of the planet, which has an area of $2\pi R_p^2$. Why does multiplying F and πR_p^2 give the right answer? If you wanted to use $2\pi R_p^2$ as your area, what quantity would you have to multiply it by, and what would that quantity physically represent? *Hint: is the intensity of light falling on the planet equal everywhere?*

f. (3 points) In this question, we have mentioned the word "albedo" several times. Briefly explain what albedo is. Would you expect an icy object or a rocky object to have a higher albedo?

g. (2 points) Taking the albedo, α, into account, what is the power absorbed by the planet? Express your answer in terms of R_*, T_*, D, R_p, α, and constants.

h. (2 points) In order to find the equilibrium temperature of a planet, the planet has to be in thermal equilibrium. In this context, what does that mean?

i. (6 points) Let's put it all together. What is the equilibrium temperature, T_p, of the planet? Express your answer in terms of R_*, T_*, D, R_p, α, and constants.
   (i) *Hint #1: find the luminosity of the planet when it is at* T_p *using the Stefan-Boltzmann Law, just as you did in (b). Assume the planet radiates away the energy over its entire surface area and that the internal luminosity of the planet is negligible.*
   (ii) *Hint #2: relate the planet's luminosity to the power absorbed by the planet using your answer to (g) and solve for* T_p.

Question 6: More Equilibrium Temperature [20 pts.]

In the previous question's derivation, we made a number of assumptions. However, reality is not quite so simple. Here, we'll take a quick look at some of the factors that can complicate things.

Situation 1: What if the planet is tidally locked?

a. (3 points) Many of the objects in this year's rules are tidally locked to the objects they orbit. In your own words, briefly explain what it means for an object to be tidally locked.

b. (3 points) Planets in the habitable zones of red dwarfs are often tidally locked. Generally, why do these planets tend to have a higher probability of being tidally locked than planets in the habitable zone around larger, hotter stars?

c. (2 points) Generally, being tidally locked to a star makes one side of the planet significantly hotter than the other. Can you think of any ways the planet could redistribute the heat?

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

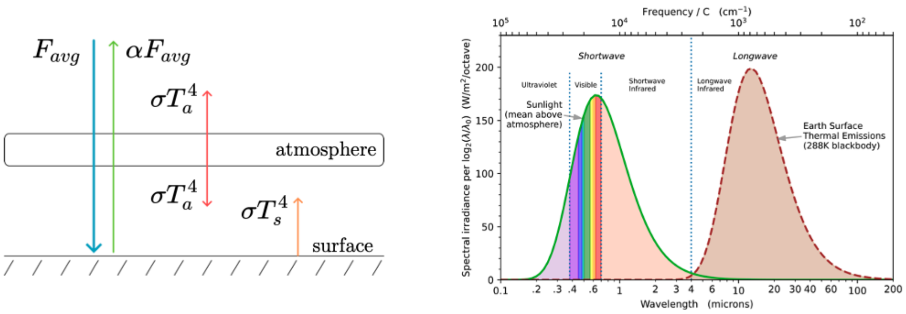

Figure 4: Structure of a single layer atmosphere (left) and spectral intensity of sunlight at the top of Earth's atmosphere compared to thermal radiation emitted by Earth's surface (right).

d. (2 points) The equilibrium temperature of Venus is about 230 K, but its actual surface temperature is about 730 K. How does Venus's atmosphere make it warmer?

e. (4 points) Consider a case where our planet is orbiting around a Sun-like star. On the left side of Figure 4, we imply that the planet's atmosphere is completely transparent to light from the star (blue and green arrows), but absorbs all light from planet's surface (orange arrow). This is not really true: the atmosphere will essentially absorb all "longwave" light that hits it, regardless of where it's from. Why is our approximation that all of the star's light will make it through the atmosphere still reasonably valid, even when the star is much more luminous than the planet? *Hint: look at the plot on the right side of Figure 4, which is for the Sun and Earth.*

f. (6 points) Write an energy balance for the atmosphere and find the ratio of T_s to T_a in the left side of Figure 4. In this (highly simplified) model, will the atmosphere or surface always be warmer? Assume that the atmosphere radiates equally up and down and everything can be treated as a perfect blackbody.

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

One method used to detect exoplanets is looking for a planetary transit. Here, the exoplanet in question passes in front of its parent star, causing the star's apparent brightness to dim when we observe it on Earth. Below, we show the light curves for seven exoplanets from the same system.

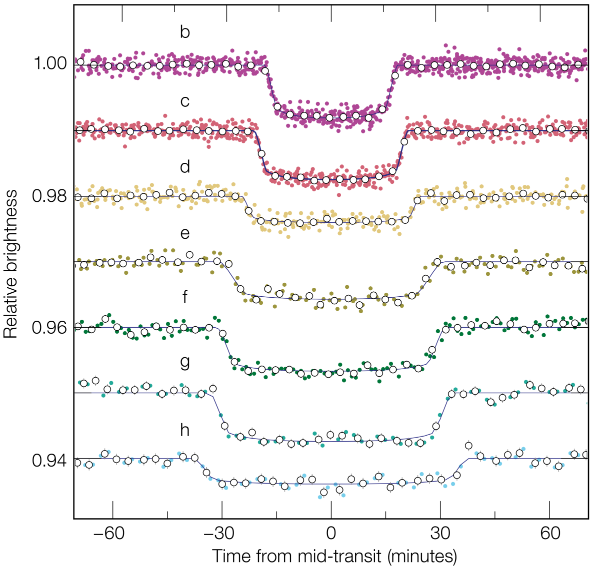

Figure 5: Light curves for seven exoplanets from the same system. The curves are vertically shifted so that they are all not on top of each other. The light curves are ordered such that the one from the closest planet to the parent star is on top, while the one furthest is on the bottom.

a. (1 point) The planets whose transits are depicted in this light curve are from one of the extra-solar systems on this year's rules. Which one?

b. (2 points) What determines the depth of each transit? In other words, what information about the planets does the depth of the transit give?

c. (3 points) Visually, how does the distance a planet is from the parent star affect the shape of its transit in the light curve? From a physics perspective, what causes this change in the planet's motion that results in the new shape? *Hint: think about Kepler's Laws.*

The exoplanets in this system orbit a red dwarf, which is smaller, cooler, and less massive than a Sun-like star. Imagine a "copy" of this system where all of the planets have the same equilibrium temperature as before, but they orbit a Sun-like star, not a red dwarf.

d. (3 points) Would the planets orbiting the Sun-like star be orbiting their parent star closer or farther away than the planets orbiting the red dwarf? Explain.

e. (2 points) Suppose an alien civilization is trying to observe both of these systems. Would they have a higher probability of observing a transit of the red dwarf or the Sun-like star? Explain.

When light passes through a planet's atmosphere, some of it will be absorbed by compounds in the planet's atmosphere, which we can detect during transits. This gives us valuable information about the composition of the planet's atmosphere and whether those chemicals are in equilibrium with each other, which has profound implications for our search for extraterrestrial life.

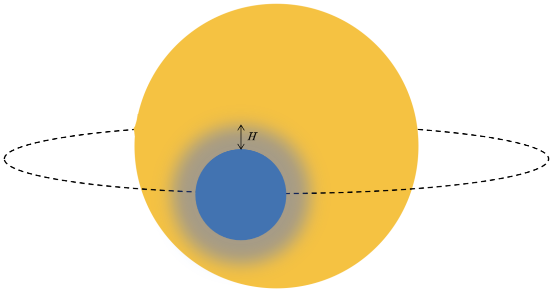

Figure 6: Planet with an atmosphere of thickness H transiting a star.

f. (3 points) One of the reasons transmission spectroscopy is very difficult for rocky planets is because the thickness/height of the atmosphere (shown as H in Figure 6) is typically small compared to the radius of the planet. For each of the following cases, determine whether H will increase or decrease, assuming all other variables are held constant:

  (i) increasing the temperature of the atmosphere
  (ii) increasing the average molecular weight of the compounds in the atmosphere
  (iii) increasing the surface gravity of the planet

g. (3 points) Scientists often look for spectroscopic evidence of compounds like water, ozone, and methanol at infrared wavelengths within the transit data, since that's where molecules have distinctive absorption patterns. What causes these molecules to absorb infrared radiation?

h. (4 points) Consider two identical planets, which we'll call Planet A and Planet B. Both are the same size and have the same equilibrium temperature, but Planet A is around a Sun-like star, while Planet B is around a red dwarf. Realistically, would it be easier to detect the presence of biologically-significant compounds in the atmosphere of Planet A or B through transmission spectroscopy?

i. (4 points) Some scientists believe that once our telescopes and atmospheric modeling techniques improve enough, data about an exoplanet's atmosphere could potentially be used to make educated guesses about whether life exists on it. Imagine that several decades from now, we observe an exoplanet in the habitable zone of its parent star and find that its atmosphere has a composition that is very different than what we would have expected from chemical equilibrium. Could this data be used to support (**not** prove) the idea that the exoplanet may harbor life as we know it? Explain.

Question 8: Mission Design [35 pts.]

You are the leader of a research team that has just been awarded a large grant to develop a mission to explore Enceladus. Your mission must include some form of an orbital element and landing element, but their roles (and whether they are even different spacecraft) are completely up to you. NASA Science Mission Directorate has provided you with the following requirements:

1. Mission goal: Assess the extent to which Enceladus' ocean, crust, and surface are habitable by studying the moon's structure, physical and chemical environment, and plumes.
2. The orbiter shall be capable of:
    (a) Maintaining (and adjusting when necessary) its orbit around Enceladus.
    (b) Reliably communicating with Earth.
3. The science payload shall enable:
    (a) Physical, chemical, and biological measurements of Enceladus's plume materials, surface, and subsurface ocean.
    (b) Visual observations of Enceladus's surface for safe landing and sampling.
    (c) Characterization of the structure and dynamics of Enceladus's interior (including crust).

Using your knowledge of other missions, as well as the science of habitability, design your own mission capable of meeting all three requirements above. In your design, mention the following:

a. **<u>Mission architecture:</u>** Is there a separate lander, rover, or rotocraft? Or, does the same spacecraft do everything? What will the spacecraft(s) do when they reach Enceladus?

b. **Power:** What power source will you use, and why? What will you use to store energy?

c. **Communication:** What hardware, software, and network will your spacecraft use to communicate with Earth, and when will it do so? What data will your spacecraft send?

d. **<u>Instruments:</u>** What types of instruments will your spacecraft(s) have? What data will they collect, and how will it help you achieve the mission goal? If applicable, mention which instruments will be on which spacecraft. Don't worry about specific names; just list general classes of instruments (e.g., mass spectrometer).

e. Plus ***anything*** else you think is relevant, cool, fun, etc., whether it's a sketch, mission patch, or whatever your heart desires.

The two underlined sections (mission architecture and instruments) are especially important – please dedicate the bulk of your mission proposal to these.

Your design will generally be graded on its feasibility (10 points), whether it satisfies the requirements listed above (20 points), and its creativity (5 points). Keep in mind that there is no "right" answer for many of these decisions – we care mainly about you explaining your line of reasoning and thinking deeply about what goes into a mission. Have fun!

Image Set for Question 1


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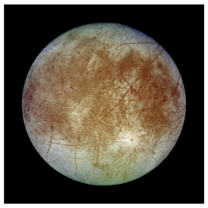
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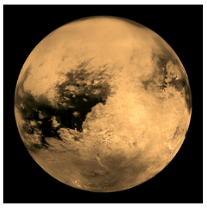
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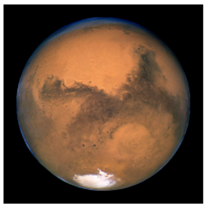
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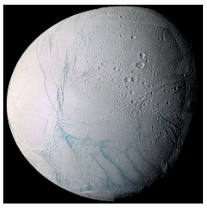
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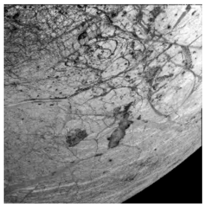
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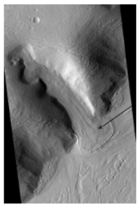
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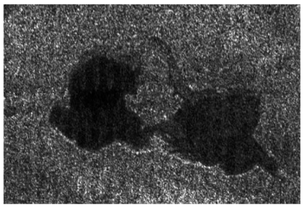
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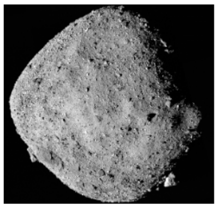
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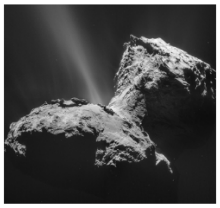
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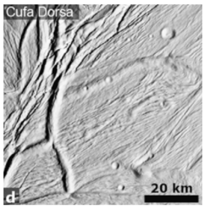

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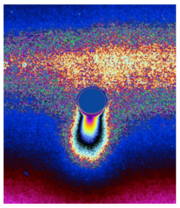
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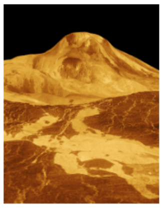
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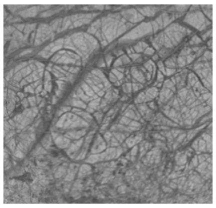
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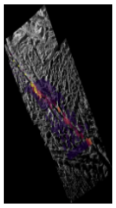
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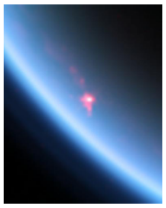
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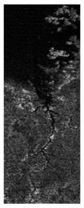
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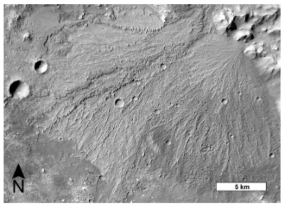


25

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.

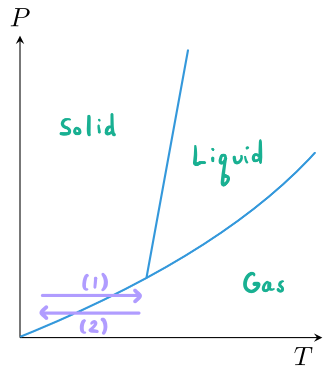
Question 2: Seasons on Mars [25 pts.]

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.



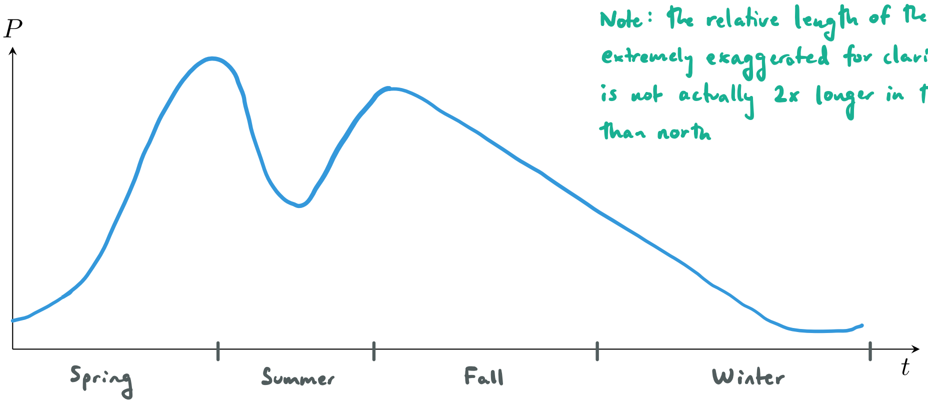
(1): in the summer, CO_2 goes from solid to gas

(2): in the winter, CO_2 goes from gas to solid

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.



Note: the relative length of the seasons is extremely exaggerated for clarity, winter is not actually 2x longer in the south than north

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: