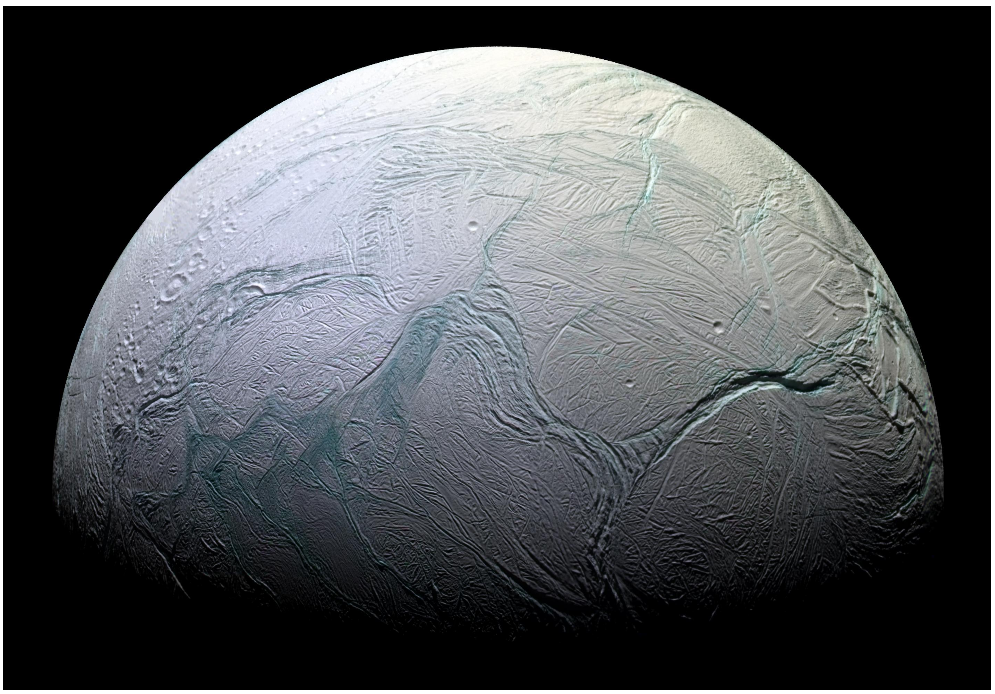
Science Olympiad
Solar System
National Exam

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.]

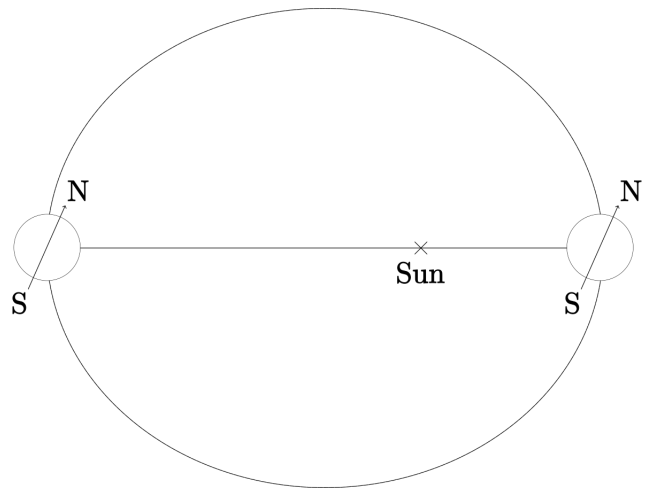

Figure 1: Mars's orbit, which is in the plane of the page, with its eccentricity significantly exaggerated for clarity. The slanted line going through Mars represents its axis of rotation, which goes through the plane of the page. The "N" and "S" stand for "north" and "south".

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:

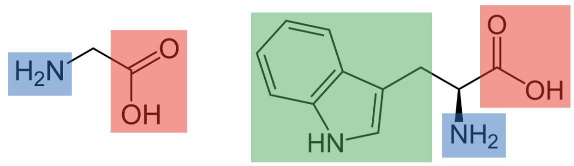

Figure 2: Examples of two amino acids used in nature. Glycine (left) is one of the simplest amino acids, while tryptophan (right) is one of the most complicated. The red and blue boxes are used to highlight common functional groups between the two. The green box highlights a side chain on tryptophan 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 ∼20 amino acids), do you think it'd work? Why or why not?

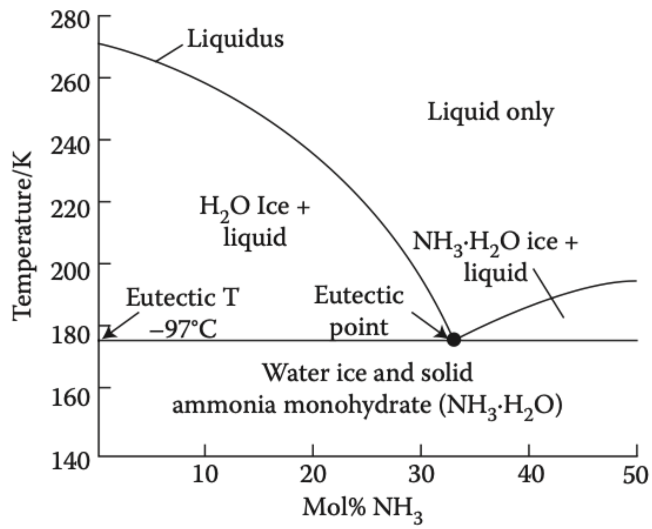

Figure 3: Binary phase diagram for a water-ammonia system.

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:

$$\tfrac{x}{2}\, D_2O + H_x\cdot P \longrightarrow \tfrac{x}{2}\, H_2O + D_x\cdot P$$

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?

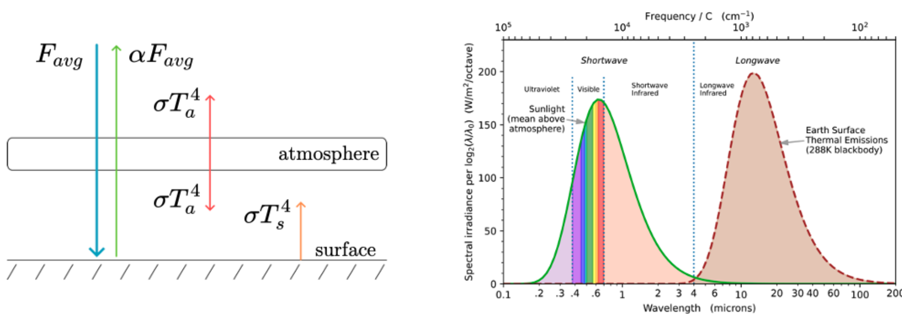

Figure 4: Structure of a single layer atmosphere (left) and spectral intensity of sunlight at the top of Earth's atmosphere compared to thermal radiation emitted by Earth's surface (right).

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.

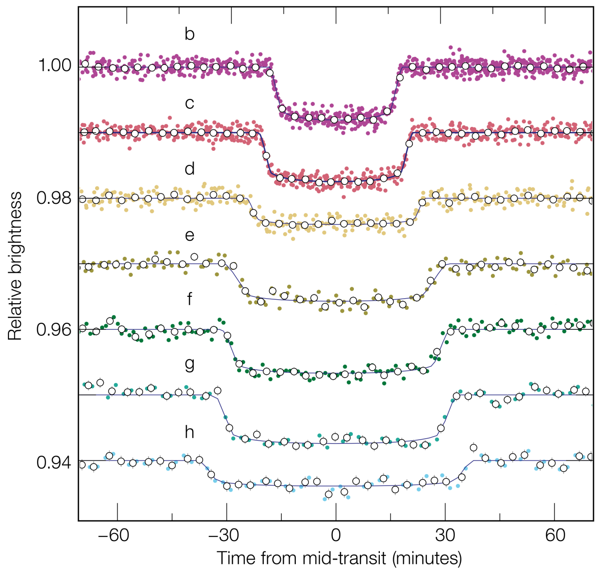

Figure 5: Light curves for seven exoplanets from the same system. The curves are vertically shifted so that they are all not on top of each other. The light curves are ordered such that the one from the closest planet to the parent star is on top, while the one furthest is on the bottom.

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.

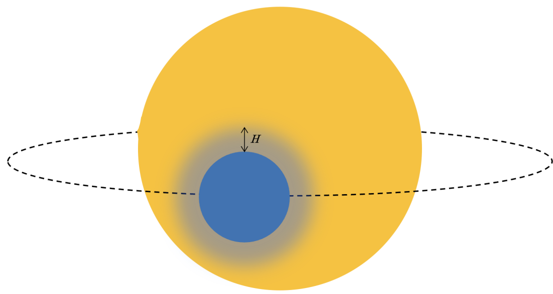

Figure 6: Planet with an atmosphere of thickness H transiting a star.

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!