

SOLUTIONS

Instructions: You may put your answers right on the quiz sheets. If you need extra space feel free to attach additional pages, but indicate by the question that you've gone to extra pages. There is a stapler at the front of the room. The last page of the quiz lists equations, constants, and conversions that you may need.

Remember: READ EACH QUESTION COMPLETELY!!!! SHOW YOUR WORK!!!! BE CAREFUL OF UNITS!!!!

True or False (circle T or F to indicate True or False, each is worth 3 points):

1. **T** or **F** The cloud layer on Venus is primarily composed of H₂SO₄ (sulfuric acid) droplets.
2. **T** or **F** The most significant source of gases for the atmosphere of Venus is sputtering from the surface by micrometeorite impacts.
3. **T** or **F** The eccentricity of the orbit of Mars is what causes the southern summers to be short but hot and the southern winters to be long and cold.
4. **T** or **F** When a cloud forms by condensation of water from the air, the air gets colder.
5. **T** or **F** The outflow channels and valley networks on Mars are evidence of very recent water flow on the surface.
6. **T** or **F** The superrotation of the upper atmosphere of Venus is caused by the planet's large coriolis force.
7. **T** or **F** When processes occur in series (meaning process A has to occur before process B can occur and process B has to occur before process C can occur and so on) it is the slowest process which determines the overall rate of the system.
8. **T** or **F** Earth and Venus are the only terrestrial planets to show evidence of volcanism.
9. **T** or **F** Solar Wind Pickup is a negligible loss process for the atmosphere of Mars because Mars has a strong magnetic field which protects the upper atmosphere from the solar wind.
10. **T** or **F** The seasonal polar caps on Mars are primarily made of frozen CO₂ (dry ice).

Short Answers (Write a few sentences to answer each question):

11. In springtime in Colorado meteorologists use the equation "upslope = snow". Explain what conditions were necessary for the big spring snowstorm of March 17-19, 2003 and how those conditions lead to Dr. Eparvier's house in Nederland (west of Boulder) being buried by five feet of snow but a friend's house in Limon (east of Denver) only getting a few inches of snow. (10 pts)

The necessary conditions are winds coming from the east (an upslope) and lots of moisture in the air. (These conditions are met by having a Low pressure system to the south, picking up moisture from the Gulf of Mexico and being positioned just right so that its counterclockwise rotation carries the moisture from the Gulf and slams it into the mountains from the east.) The wet air is near saturation; as it rises to go over the mountains it cools and becomes completely saturated (colder air can hold less water) and the extra moisture condenses out as snow. Dr. Eparvier's house is at a higher altitude in Nederland than his friend's in Limon, so more moisture condenses out and he gets more snow!

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12. Assume that Venus and Earth both started with similar amounts of CO₂ and H₂O being outgassed into their early atmospheres in the era just after the planets formed. Describe how Venus ended up with a thick CO₂ atmosphere with very little water anywhere, whereas Earth ended up with hardly any CO₂ in the atmosphere and lots of water everywhere. (10 pts)

On Earth temperatures were cool enough for lots of liquid water to form. The CO₂ released into the atmosphere was dissolved into the water and subsequently put into carbonate rocks. On Venus it was warm enough that not much (if any) liquid water could form, so all the CO₂ and H₂O stayed in the atmosphere. The greenhouse effect from all that CO₂ and H₂O kept Venus' atmosphere hot enough to guarantee that no liquid water could form and that any liquid water that was there would be evaporated. This is called the runaway greenhouse effect. The H₂O in the atmosphere of Venus was then gradually lost as UV light from the Sun broke it apart and the hydrogen escaped to space.

13. Explain why the temperature at the surface of the south polar cap of Mars is always around 150 K regardless of season (in the current epoch). Also explain what it would take to get the temperature there to go above 150 K and what it would take for the temperature to go below 150 K. (10 pts)

*150 K is the freezing point of CO₂ on Mars and the southern polar cap is covered (mostly) with frozen CO₂ year round. The temperature cannot change from the phase-change temperature until all of the substance has undergone the phase change. For the temperature at the south polar cap to get above 150 K then **all** of the frozen CO₂ at the cap would have to sublime to become a gas. For the temperature at the south polar cap to get below 150 K, then all of the CO₂ gas above it would have to freeze out (then entire atmosphere!).*

14. Pretty much all theories about stellar evolution agree that our Sun was only 70% as bright right after the planets formed as it is now. Yet most people who study the past climate of Earth (paleoclimatologists) agree that four billion years ago the Earth was the same temperature as it is now (or even warmer). This is called the “Faint Early Sun Paradox”. Give an explanation for why this isn’t really a paradox; in other words present a reasonable theory about what was different about the Earth back then that made the planet as warm as now even with a dimmer Sun. (10 pts)

The most reasonable explanation is that the early Earth had a larger greenhouse effect than it does now, keeping it warmer despite the dimmer Sun. This was probably due there being more CO₂ in the atmosphere, because it hadn't all been dissolved into the oceans and put into the rocks yet.

Calculations (Perform the necessary calculations showing your all your work):

15. Some scientists believe that Mars had oceans of water billions of years ago. For this to be true, it had to be much warmer than it is now.

- a. Assuming that the current effective temperature on Mars is 216 K, that the early Sun was 70% as bright as it is now, and that the albedo and orbit of Mars were the same as they are now, calculate what the effective temperature of Mars in the ancient past. (5 pts)

$$T_{eff,past} = \left[\frac{0.7 \cdot S_0 \cdot (1 - \alpha)}{D^2 \cdot 4 \cdot \sigma} \right]^{1/4} = [0.7]^{1/4} \cdot T_{eff,now} = 0.915 \cdot 216K = 198K$$

so $T_{eff,past} = 198 K$.

- b. Given the effective temperature you calculated in part (a), determine what the optical depth of the early Martian atmosphere would have had to be to make the mean surface temperature 288 K (the mean temperature of Earth today). If you were unable to get an answer for part (a) then just show how you would do the calculation using variables. (5 pts)

Use: $T_g^4 = (1 + \tau) \cdot T_e^4$

Rewriting as: $\tau = \frac{T_g^4}{T_e^4} - 1 = \frac{288K^4}{198K^4} - 1 = 4.5 - 1 = 3.5$

So $\tau_{past} = 3.5$

- c. The current optical depth on Mars is 0.14. How much more of a CO₂ atmosphere is needed to give the optical depth in part (b)? Again, if you don't have a numerical answer for part (b) do it all with variables. (5 pts)

Since optical depths scale like vertical column densities, all we have to do is divide the optical depth from the past by the optical depth from the present:

$$\frac{\tau_{past}}{\tau_{now}} = \frac{3.5}{0.14} = 25$$

So the atmosphere had to have at least 25 times as much CO₂ as it does now. (Note: 25 times 6.4 millibars is 160 millibars, while most modellers say much more was needed. We neglected in (a) to account for a higher albedo if there are oceans and clouds around in the past, which means a lower effective temperature to overcome with the greenhouse effect.)

16. Surface temperatures at the equator of the planet Mercury can reach temperatures of 740 K during the daytime. The mass of the planet is 3.3×10^{23} kg. Mercury's radius is 2440 km.

- a. Calculate the minimum speed necessary for a hydrogen atom (mass of H = 1.67×10^{-27} kg) at the surface of Mercury to escape the pull of gravity. (5 pts)

$$v_{esc} = \sqrt{\frac{2 \cdot G \cdot M}{r}} = \sqrt{\frac{2 \cdot 6.67 \times 10^{-11} \frac{\text{Newtons} \cdot \text{m}^2}{\text{kg}^2} \cdot 3.3 \times 10^{23} \text{ kg}}{2440 \text{ km} \cdot 1000 \frac{\text{m}}{\text{km}}}} = 4250 \text{ m/s} = 4.25 \text{ km/s}$$

so the escape velocity is 4.25 km/sec. (Note: escape velocity is independent of the mass of the atom escaping.)

- b. Calculate the most probable speed for a hydrogen atom at the equator of the surface of Mercury when the temperatures are hottest, assuming that the speeds are in a Maxwellian distribution. (5 pts)

$$v_m = \sqrt{\frac{2 \cdot k \cdot T}{m}} = \sqrt{\frac{2 \cdot 1.38 \times 10^{-23} \frac{\text{Joules}}{\text{K}} \cdot 740 \text{ K}}{1.67 \times 10^{-27} \text{ kg}}} = 3500 \text{ m/s} = 3.5 \text{ km/s}$$

so the most probable speed for a hydrogen atom is 3.5 km/sec. (Note: Rather than the escape speed being way out on the tail of the Maxwellian, it is close to the peak, so we'd expect rapid escape of H from Mercury.)

- c. What temperature would the surface of Mercury have to be for the escape speed of a hydrogen atom to equal the most probable speed? (5 pts)

Set the escape speed equal to the most probable speed and solve for temperature:

$$\sqrt{\frac{2 \cdot G \cdot M}{r}} = \sqrt{\frac{2 \cdot k \cdot T}{m}}$$

$$T = \frac{G \cdot M \cdot m}{r \cdot k} = \frac{6.67 \times 10^{-11} \frac{\text{Newtons} \cdot \text{m}^2}{\text{kg}^2} \cdot 3.3 \times 10^{23} \text{ kg} \cdot 1.67 \times 10^{-27} \text{ kg}}{(2440 \text{ km} \cdot 1000 \frac{\text{m}}{\text{km}}) \cdot 1.38 \times 10^{-23} \frac{\text{Joules}}{\text{K}}} = 1092 \text{ K}$$

So the temperature would have to reach about 1100K for the peak of the Maxwellian to be the same as the escape speed (Note: under this condition we would expect really, really fast loss of H).

Some potentially useful equations:

$$Power = Area \cdot \square \cdot T^4$$

$$T_e = \left[\frac{S_0 \cdot (1 - \square)}{D^2 \cdot 4 \cdot \square} \right]^{1/4}$$

$$p = n \cdot k \cdot T$$

$$dp = \square g \cdot n \cdot \bar{m} \cdot dz$$

$$\square = n \cdot \bar{m}$$

$$\bar{m} = \frac{\sum_i f_i \cdot m_i}{\sum_i f_i}$$

$$f_i = \frac{n_i}{n_{total}}$$

$$p \square p_{ref} \cdot e^{\frac{\square(z - z_{ref})}{H}}$$

$$n \square n_{ref} \cdot e^{\frac{\square(z - z_{ref})}{H}}$$

$$H = \frac{k \cdot T}{m \cdot g}$$

$$\frac{dT}{dz} = \square \frac{g}{c_p}$$

$$I = I_0 \cdot e^{-\square z}$$

$$\square_i = \sum_s \square_i \cdot n_i \cdot ds$$

$$N = \sum_s n \cdot ds$$

$$\square_{total} = \sum_i \square_i$$

$$\square_{max} = \frac{2.9 \square 10^6 \text{ nm} \cdot K}{T}$$

$$T_g^4 = (1 + \square) \cdot T_e^4$$

$$F = m \cdot a$$

$$F_g = \frac{G \cdot m_1 \cdot m_2}{R^2}$$

$$E = \frac{1}{2} \cdot m \cdot v^2$$

$$E = k \cdot T$$

$$E = h\nu$$

$$\nu = \frac{c}{\square}$$

$$v_{esc} = \sqrt{\frac{2 \cdot G \cdot M}{r}}$$

$$v_m = \sqrt{\frac{2 \cdot k \cdot T}{m}}$$

Some potentially useful constants and conversions:

$$\square = 5.67 \square 10^{08} \frac{Watts}{m^2 \cdot K^4}$$

$$1 \text{ Watt} = 1 \frac{Joule}{sec}$$

$$k = 1.38 \square 10^{23} \frac{Joules}{K}$$

$$1 \text{ Pascal} = 1 \frac{Newton}{m^2} = 10^{02} \text{ millibar}$$

$$G = 6.67 \square 10^{11} \frac{Newtons \cdot m^2}{kg^2}$$

$$1 \text{ atm} = 1013 \text{ millibar} = 1.013 \square 10^5 \text{ Pascal}$$

$$1 \text{ AU} = 1.5 \square 10^8 \text{ km}$$

$$N_A = 6.022 \square 10^{23} \frac{particles}{mole}$$

$$c = 3 \square 10^8 \frac{m}{sec}$$

$$h = 6.626 \square 10^{34} \text{ Joules} \cdot \text{sec}$$

$$S_o = 1368 \frac{Watts}{m^2} \text{ at } 1 \text{ AU}$$

$$c_p = \frac{5}{2} \cdot \frac{k}{m}, \text{ or } \frac{7}{2} \cdot \frac{k}{m}, \text{ or } \frac{9}{2} \cdot \frac{k}{m}$$

$$1 \text{ m} = 100 \text{ cm} = 10^9 \text{ nm} = 10^{03} \text{ km}$$

$$1 \text{ Newton} = 1 \frac{kg \cdot m}{sec^2}$$

$$1 \text{ Joule} = 1 \text{ Newton} \cdot \text{m}$$