

Science Olympiad

Solar System

UT Invitational 2021

October 30, 2021
Austin, Texas



School: _____

Team Number: _____

Name(s): _____

Directions:

- You are allowed to bring in two 8.5" × 11" sheets of paper with information on both sides.
- The question booklet and image sheet are class sets. Please write all answers on your answer sheet.
- You can take apart the test as long as you restaple the pages in the correct order at the end.
- There is no penalty for wrong answers. Answer every question, even if you aren't sure if you're correct.
- Above all else, just believe!

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Section A

Determine whether the following statements are true or false. Each question is worth 1 point for a total of 15 points.

1. ____ The Sun is at the center of the Solar System.
2. ____ Saturn is the most massive planet in the Solar System.
3. ____ Pluto was “demoted” to a dwarf planet because it was not round enough.
4. ____ Arrokoth is in the Asteroid Belt.
5. ____ Venus is the hottest planet in the Solar System.
6. ____ Io is a moon around Neptune.
7. ____ Triton is geologically active.
8. ____ Iapetus is known for its large ridge and two-tone (black and white) coloration.
9. ____ The *Galileo* spacecraft is best-known for exploring Saturn for several years.
10. ____ Venus has no moons.
11. ____ Uranus is the sixth planet from the Sun.
12. ____ HL Tauri is surrounded by a protoplanetary disk.
13. ____ The planets in the TOI-561 system were discovered through direct imaging.
14. ____ The “Great Dark Spot” is on Neptune.
15. ____ HR 8799 was discovered using the Kepler space telescope.

Complete the following statements with the name of an object or mission from the rules. No object or mission will be used more than once. Each blank is worth 2 points for a total of 20 points.

16. _____’s largest moon is named Titania.
17. _____ is the largest object in the Solar System that is *not* in hydrostatic equilibrium.
18. Alice and Ralph are instruments on the spacecraft that visited the dwarf planet _____.
19. The most massive “Ice Giant” in the Solar System is _____.
20. _____ is a “super-Neptune” that is one of the youngest planets ever discovered.
21. Although _____ is a moon, scientists believe it originally formed as a dwarf planet and was later captured.
22. TOI-561 was discovered using _____.
23. _____ has a thick atmosphere consisting mainly of CO₂ and is thought to have an internal structure similar to that of Earth’s.
24. The planets in the _____ system were discovered through direct imaging.
25. The most recent mission to Venus was _____.

Write the name of the object from the rules manual that each of the following features, regions, etc. is associated with. Each blank is worth 2 points for a total of 40 points.

- | | |
|---------------------------------|---------------------------|
| 26. _____ Tombaugh Regio | 36. _____ Set Catena |
| 27. _____ Maxwell Montes | 37. _____ Aphrodite Terra |
| 28. _____ Roncevaux Terra | 38. _____ Loki Patera |
| 29. _____ Leviathan Patera | 39. _____ Cassini Regio |
| 30. _____ Oval BA | 40. _____ Small Dark Spot |
| 31. _____ Chaac-Camaxtli region | 41. _____ Ruach Planitia |
| 32. _____ Cthulhu Macula | 42. _____ Engelier |
| 33. _____ Amirani | 43. _____ Yasu Sulci |
| 34. _____ Ishtar Terra | 44. _____ Great Cold Spot |
| 35. _____ Turgis Crater | 45. _____ Hillary Montes |

Section B

Use the attached Image Set for the questions in this section. Each question/part is worth 2 points for a total of 90 points.

46. (2 points) Order the objects shown in the following images by *their distance from the Sun*, from closest to farthest: 2, 7, 8, 9, and 11.
47. (2 points) Order the objects shown in the following images by their *mass*, from least massive to most massive: 3, 4, 8, 10, 13.
48. (a) What planet is shown in Image 1?
(b) What telescope or spacecraft took this image?
(c) What the name of the feature marked with an “A” on this image?
(d) In your own words, explain what the feature from the previous part is.
(e) Which image shows this object in UV?
49. (a) What object is shown in Image 2?
(b) What spacecraft took this image?
(c) What instrument on this spacecraft was used to make this image?
(d) This spacecraft flew by this object, but did not orbit it. Why was this the case?
50. (a) What moon is shown in Image 3?
(b) What telescope or spacecraft took this image?
(c) What image shows the planet around which this moon orbits in visible light?
(d) The foreground of this image is generally very smooth, with few (if any) notably craters. Based on this information, do you think this object is geologically active? Explain your answer.
(e) Although the surface of this object is rugged, there is a noticeable lack of any tall structures, like mountains. Why might this be the case?
51. (a) Image 5 shows a perspective view of a crustal plateau on an object in our Solar System. What image shows the object on which this surface feature exists?
(b) What is the name of the region shown in Image 5?
(c) What telescope or spacecraft collected the data used to make Image 5?
(d) Planetary scientists have developed a number of models to explain the formation of crustal plateaus on this object. One of which is the *Impact Model*, which states that crustal plateaus were formed by lava ponds from mantle melting due to meteor impacts to the planet’s thin lithosphere. What is one limitation of this model?
52. (a) Which planet is shown in Image 6?
(b) Which image shows an aurora occurring on this planet?
(c) In your own words, explain what causes this phenomenon.
53. (a) What is the name of the type of terrain shown in Image 17?
(b) This terrain contains many depressions (called *cavi*) that are approximately 30-40 kilometers in diameter. At first glance, these may seem like craters, but scientists don’t think they are. Why?
(c) What is the most likely explanation for the formation of this terrain?
54. (a) Consider the object shown in Image 16. Which image shows the planet that this object orbits around in visible light?

- (b) What telescope or spacecraft took Image 16?
 - (c) There are several theories for the formation of the large ridge shown in this image. Explain one of them.
55. (a) Which image shows Uranus in infrared light?
- (b) What telescope or spacecraft took this image?
 - (c) This is a false-color image. In your own words, explain what a false-color image is.
 - (d) In what portion of the electromagnetic spectrum was this data collected?
 - (e) By taking multiple exposures at different wavelengths, scientists can observe this planet's atmosphere at different depths. How does this work? Which color in the image corresponds to the deepest layers of the atmosphere?
56. (a) Which object is shown in Image 8?
- (b) In what portion of the electromagnetic spectrum was this data collected?
 - (c) Which of the colors in the image (red, yellow, green, blue, or purple) correspond to regions with the highest water content?
57. (a) Image 15 shows HL Tauri. What spacecraft or telescope took this image?
- (b) To the nearest power of 10 (e.g., 10^2 , 10^3 , 10^4 , etc.), how old is this object, in years?
 - (c) What do astronomers believe the dark gaps in the disk represent?
 - (d) Given your answers to the previous two parts, in what way(s) does HL Tauri challenge our existing (Solar System-based) theories of planet formation?
58. (a) Which image shows a close-up of Krun Macula?
- (b) Which image shows the object that this surface feature is on?
 - (c) This surface feature is characterized by areas that appear dark red. What class of compounds gives rise to its distinctive color?
 - (d) Krun Macula is one of four other dark spots in the region (other dark spots not pictured). Collectively, what are these dark spots known as?

Section C

Use the attached Image Set for the questions in this section. This section is worth a total of 96 points.

59. In 2012, Venus transited the Sun. **Image A** shows how the brightness of the Sun (as measured from Earth) varied with time during the transit.

- (a) (2 points) Estimate the amount of time between the start of ingress and the end of egress, in hours (i.e., the length of the entire transit). Don't worry about being too exact; as long as your work and answer are reasonable, you'll get full credit.
- (b) (3 points) The bottom of the curve shown in Image A has a slight upwards curve, which is due to a phenomenon called *limb darkening*. In your own words, explain what limb darkening is and why it would cause the curved shape we observe in Image A.
- (c) (5 points) On the graph provided on the answer sheet, sketch the shape the transit light curve would have if limb darkening did *not* exist. Don't worry about the impact parameter of the transit, b (i.e., assume $b \approx 0$).
- (d) (5 points) The depth of a transit (δ) can help us estimate the size of the planet transiting the star:

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

However, if we use the transit depth from Image A ($\delta = 0.1\% = 0.001$), we find that the “radius” of Venus is about 22,000 kilometers, which is over 3.6 times the actual value. What is the cause of this discrepancy?

- (e) (3 points) The equation mentioned in part (d) assumes that the planet transiting the star is “dark” (i.e., compared to the star that it's transiting, it doesn't produce much light). For a planet like Venus, this is a pretty accurate assumption. However, suppose that you're observing a planet outside of our Solar System that *is* “bright”. Would the value of R_p calculated using the equation from part (d) be an overestimate or underestimate (or neither) of the planet's true radius? Explain.
 - (f) (3 points) During Venus's transit, astronomers were able to closely study its atmosphere. This works for planets outside our Solar System too; in 2019, they discovered the presence of water in the atmosphere of K2-18b. In your own words, explain how scientists can use transits to discover compounds in planets' atmospheres.
60. Transits are only one of many different methods for detecting exoplanets. **Image B** shows the number of exoplanets detected using the radial velocity method (in red) and the transit method (in blue) as a function of host star effective temperature.
- (a) (4 points) What is an observational bias of the radial velocity method that explains the lack of planets for stars with temperatures greater than about 6000 K?
 - (b) (4 points) What is an observational bias of the radial velocity method that explains the lack of planets for stars with temperatures less than about 4500 K?
 - (c) (4 points) What is an observational bias of the transit method that explains the relative lack of planets for stars with temperatures greater than about 6500 K?
 - (d) (4 points) What is an observational bias of the transit method that explains the relative lack of planets for stars with temperatures less than about 4000 K?

61. Although the mass of gas and dust that formed the Solar System is unknown, it's possible to estimate the lower limit for the amount of material that must have been present in a theoretical "minimum-mass solar nebula". **Image C** shows how the surface density in this minimum mass solar nebula could vary with distance.

Now, consider **Image D**, which contains two panels of four plots each. The panel on the left shows a disk with a surface density equal to that of our Solar System's minimum mass solar nebula, while in the right panel the surface density is five times as high. Each plot in the panels shows four snapshots in time (at 0.1, 1, 3, and 10 Myr) of the masses of planetesimals at various distances away from the Sun.

- (a) (2 points) Based on the data shown in Image D, do planetesimals grow more quickly at large or small distances from the parent star?
 - (b) (4 points) Using the information in Image C, propose a physics-based explanation for your answer to the previous part.
 - (c) (2 points) In the right panel of Image D, where the overall surface density of the disk is higher, do planetesimals grow more or less quickly than in the left panel?
 - (d) (4 points) In all of the plots, there's a dashed vertical line at about 3 AU. Why does discontinuity exist, and how might it have affected planet formation in our Solar System?
 - (e) (4 points) Scientists have discovered numerous large, gaseous exoplanets that orbit very close to their parent stars, such as K2-33b. Based on your answers to the previous parts, do you think these planets could have formed in their current locations? If not, how might they have arrived there?
62. Some of our best methods of testing and constraining planet formation models come from the Solar System: by measuring the gravitational fields around giant planets, we can build models for the interiors of the gaseous planets in our Solar System. **Image E** shows an example of one model for the possible interior of Jupiter.
- (a) (2 points) Typically, an object's self-gravity will try to make it spherical. However, Jupiter isn't perfectly spherical. Why is that the case?
 - (b) (4 points) The *Juno* orbiter uses its onboard *Gravity Science* experiment to make precise measurements of Jupiter's gravitational field. How do these gravitational field measurements help scientists learn more about the internal structure of Jupiter?
 - (c) (2 points) Specifically, *Juno* measured Jupiter's "gravitational moments", which are denoted as J_n . Are higher order gravitational moments (i.e., larger n) more sensitive to the structure of the surface or center of the planet?
 - (d) (4 points) In this model shown in Image E, the "core" (which contains heavy elements) consists of two layers: a dense inner core and a dilute outer core. Consider the following quote, which is taken from the paper (Wahl *et al*, 2017) in which this model was developed:

"At the conditions at the center of Jupiter, all likely abundant dense materials will dissolve into the metallic hydrogen-helium envelope. Thus, a dense central core of Jupiter is expected to be presently eroded or eroding. However, the redistribution of heavy elements amounts to a large gravitational energy cost and the efficiency of that erosion is difficult to assess."

In your own words, explain what "large gravitational energy cost" means in this context.

- (e) (4 points) In Image E, a large portion of the interior of Jupiter consists of metallic hydrogen. What is metallic hydrogen? Why does hydrogen exist in this "metallic" form deep within Jupiter, when on Earth, we typically think of hydrogen as a gas?
- (f) (4 points) Suppose we could magically look into Jupiter and see what the core actually looked like. If Jupiter *didn't* have a core made of heavy elements, would that be evidence in favor of Jupiter forming via the core accretion model or disk instability model? Explain your answer.

63. Unlike many other objects in our Solar System, which are primarily heated through radioactive decay, the main source of Io's internal heat is tidal heating. The amount of tidal heating Io experiences depends on both its orbit (e.g., distance from other objects, eccentricity, etc.) and its interior structure.

Image F shows a plot of possible thermal equilibria (depicted using circles) for the interior of a tidally heated object like Io, with heat flux on the y -axis and temperature on the x -axis. Sources of heat (radioactivity and tidal heating) are shown with solid lines, while processes that remove heat (convection and melt segregation) are shown with dashed lines.

- (a) (3 points) In your own words, explain what tidal heating is. What causes tidal heating in Io, specifically?
- (b) (2 points) Which of the two heat sources (radioactivity and tidal heating) depends less on temperature?
- (c) (6 points) If Io's orbit is very circular (i.e., its eccentricity is very low), then the highest temperature equilibrium in Image F (the intersection of the tidal heating and the convection curves) may not exist. Why would this be the case? *Hint: how would having a more circular orbit impact tidal heating?*
- (d) (6 points) Suppose the interior of Io is at one of the stable equilibria shown in Image F. Then, the temperature is increased by a small amount (i.e., it is no longer in equilibrium). Why does the system return to equilibrium? If this was at an unstable equilibrium, how would the outcome have been different?
- (e) (6 points) Let's put everything together. In this context, what is the criterion for determining whether an equilibrium is stable or unstable?¹ Explain your answer in terms of the *slopes* of the lines in this plot at each of the equilibria. *Hint: at each stable equilibrium, is the slope of the heat generating or heat removing line greater?*

¹Interestingly enough, I got the inspiration for this question from my Reactor Design and Kinetics class in the Chemical Engineering department at UT Austin. The stability criterion in this question is the same as the one used to assess the stability of "steady states" for continuously stirred tank reactors (CSTRs) at different temperatures. I think it's pretty cool how everything in science is linked together.