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 CO_2 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
27. ______________ Maxwell Montes
28. ______________ Roncevaux Terra
29. ______________ Leviathan Patera
30. ______________ Oval BA
31. ______________ Chaac-Camaxtli region
32. ______________ Cthulhu Macula
33. ______________ Amirani
34. ______________ Ishtar Terra
35. ______________ Turgis Crater
36. ______________ Set Catena
37. ______________ Aphrodite Terra
38. ______________ Loki Patera
39. ______________ Cassini Regio
40. ______________ Small Dark Spot
41. ______________ Ruach Planitia
42. ______________ Engelier
43. ______________ Yasu Sulci
44. ______________ Great Cold Spot
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?*

[1]Interestingly 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.

Image Set: Section B

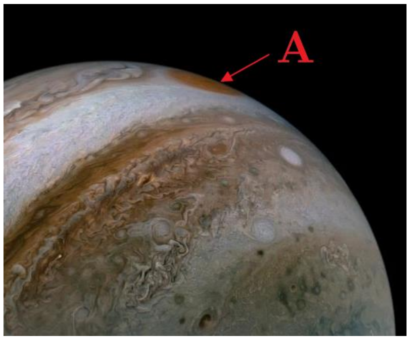


Image 1


Image 2

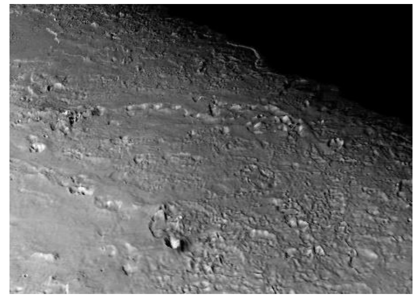
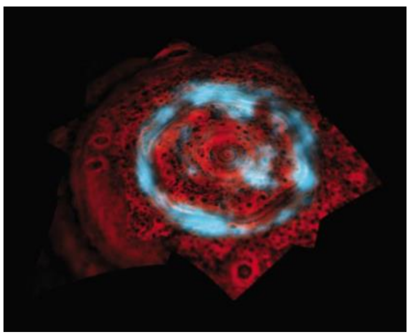


Image 3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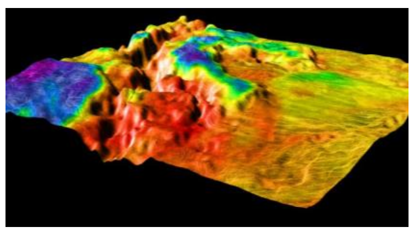
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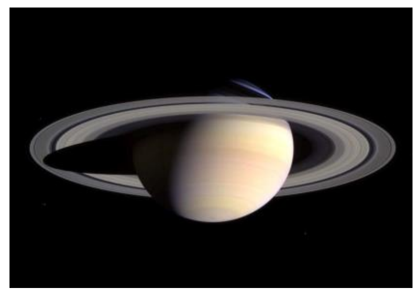


Image 6


Image 7

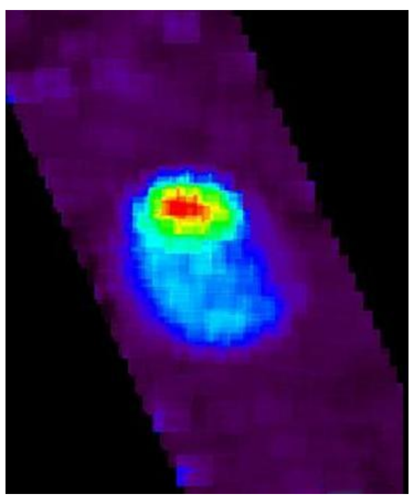


Image 8


Image 9

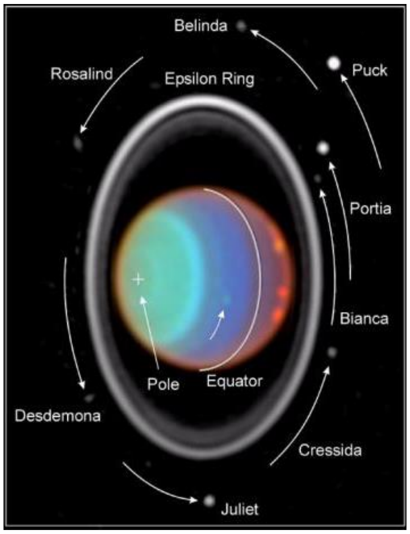


Image 10

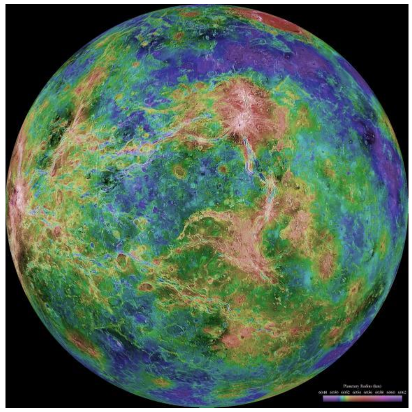


Image 11

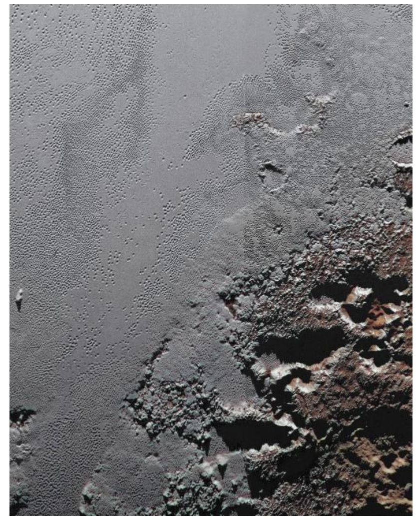


Image 12


Image 13

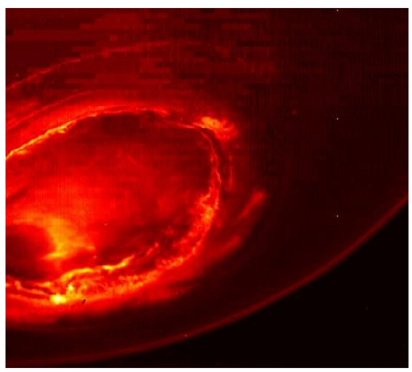
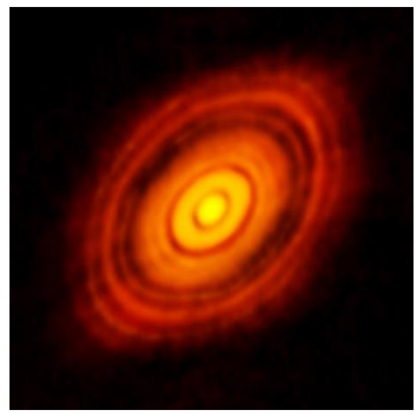


Image 14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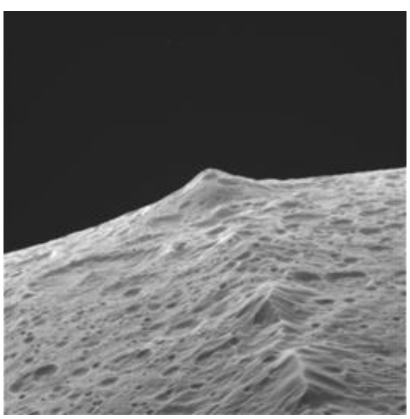
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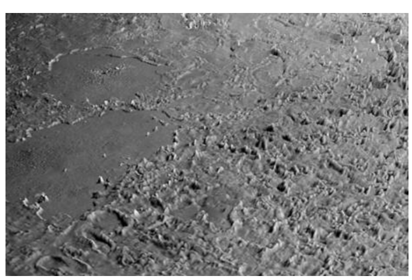


Image 17

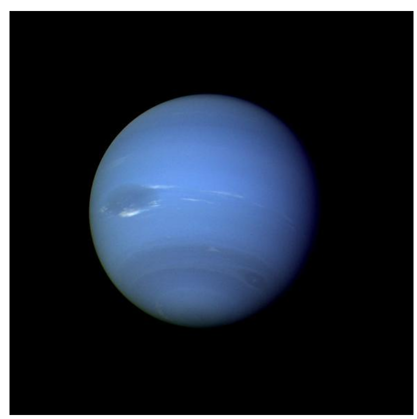


Image 18

Image Set: Section C

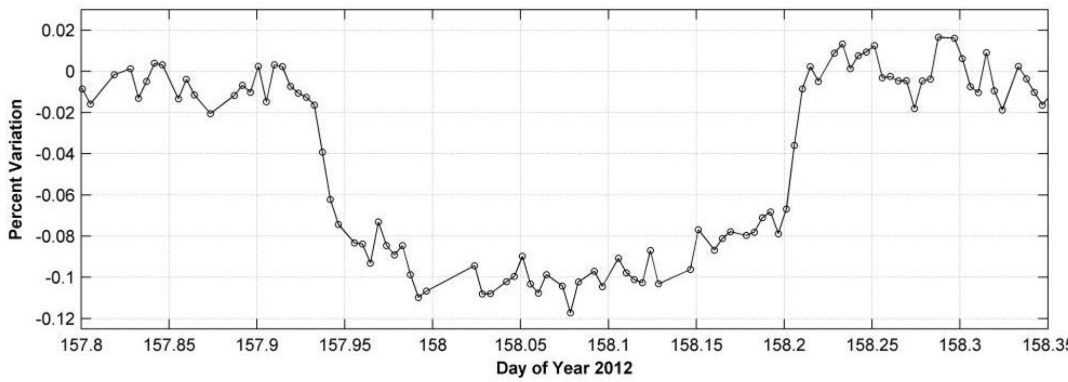


Image A

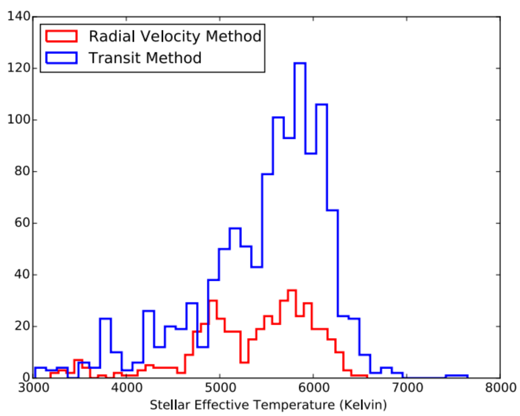


Image B

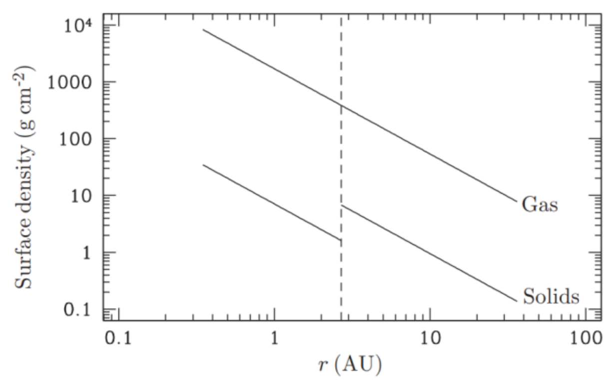


Image C

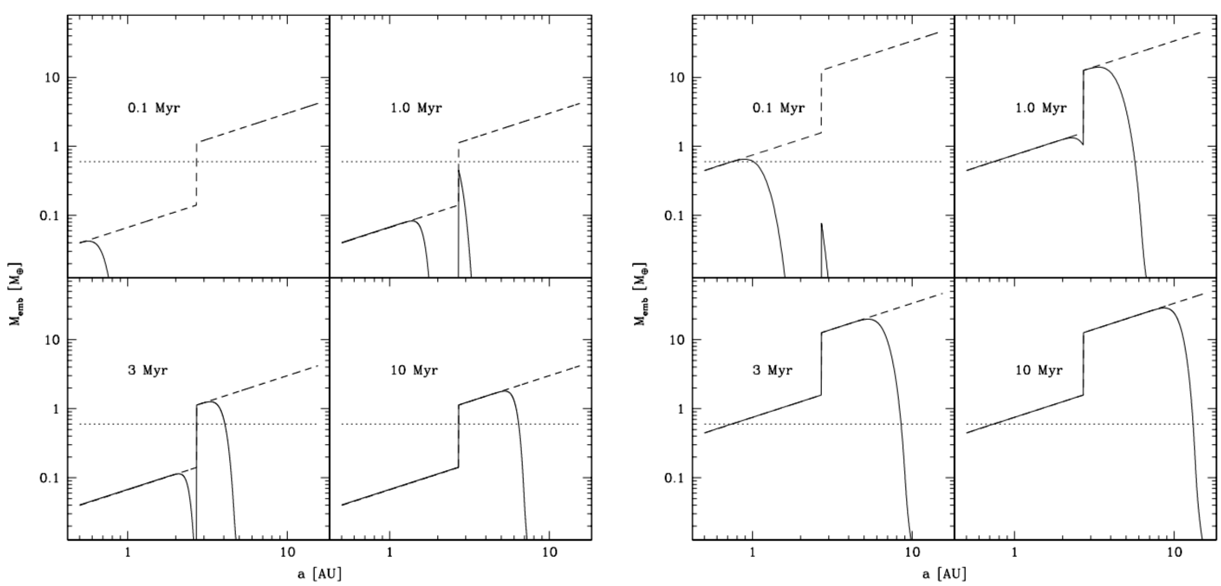


Image D

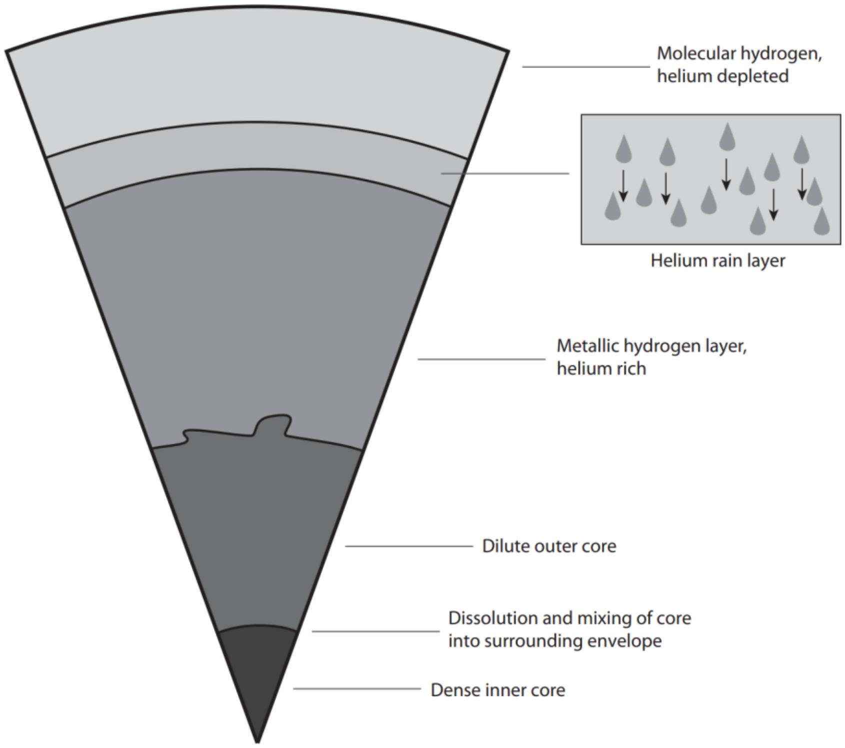


Image E

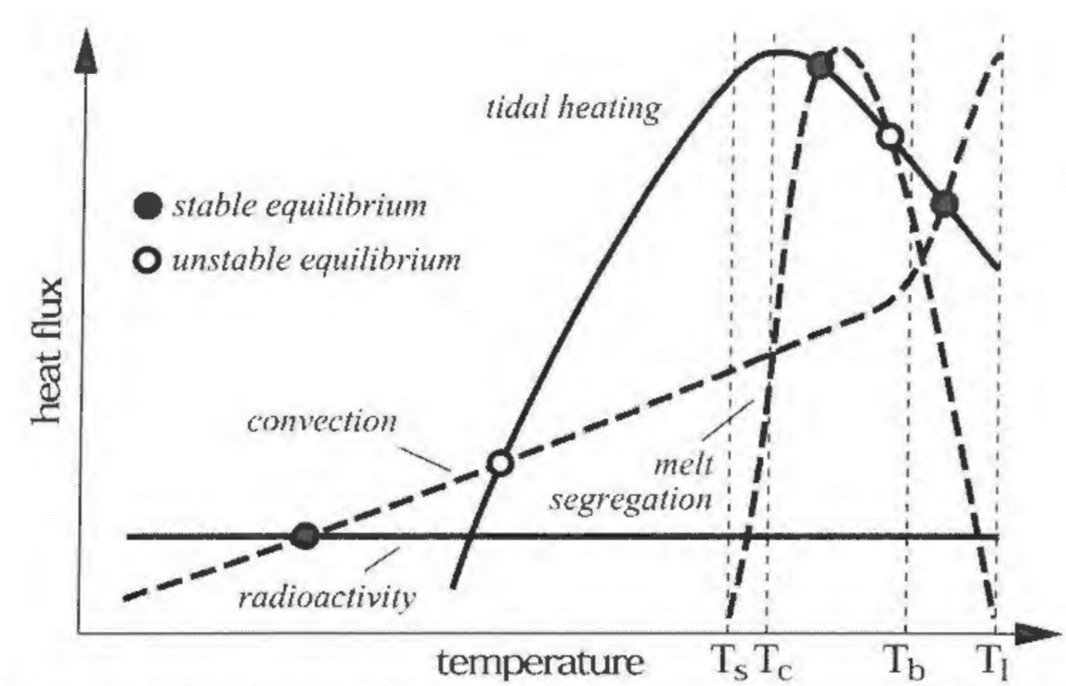


Image F

Answer Sheet

Section A

T/F

1. ____	4. ____	7. ____	10. ____	13. ____
2. ____	5. ____	8. ____	11. ____	14. ____
3. ____	6. ____	9. ____	12. ____	15. ____

Fill-in-the-blank

16. ____	19. ____	22. ____	25. ____
17. ____	20. ____	23. ____	
18. ____	21. ____	24. ____	

“Matching”

26. ____	31. ____	36. ____	41. ____
27. ____	32. ____	37. ____	42. ____
28. ____	33. ____	38. ____	43. ____
29. ____	34. ____	39. ____	44. ____
30. ____	35. ____	40. ____	45. ____

Section B

46.

47.

48. (a)
    (b)
    (c)
    (d)
    (e)

49. (a)
    (b)
    (c)
    (d)

50. (a)
    (b)
    (c)
    (d)
    (e)

51. (a)
    (b)
    (c)
    (d)

52. (a)
    (b)
    (c)

53. (a)
    (b)
    (c)

54. (a)
    (b)
    (c)

55. (a)
    (b)
    (c)
    (d)
    (e)

56. (a)
    (b)
    (c)

57. (a)
    (b)
    (c)
    (d)

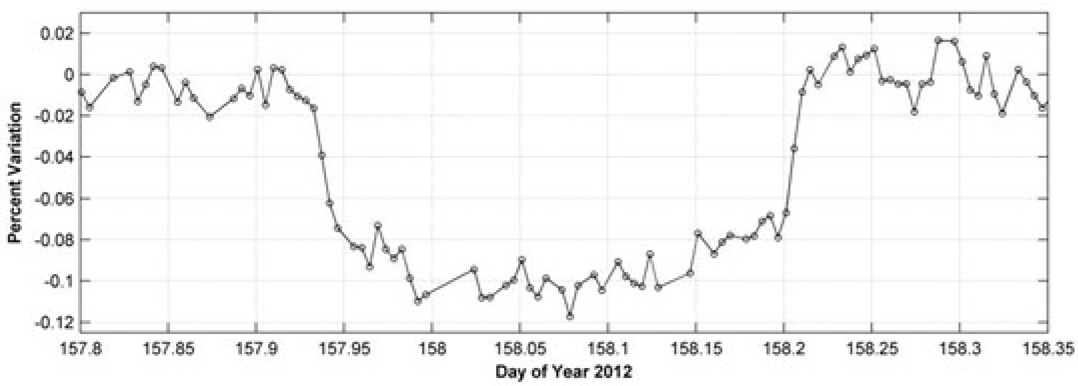
58. (a)
    (b)
    (c)
    (d)

Section C

59. (a)

(b)

(c) Sketch your theoretical light curve on top of the real light curve shown below:



(d)

(e)

(f)

60. (a)

(b)

(c)

(d)

61. (a)
(b)
(c)
(d)
(e)

62. (a)
(b)
(c)
(d)
(e)
(f)

63. (a)
(b)
(c)
(d)
(e)

Answer Key

Section A

T/F

1. T
2. F
3. F
4. F
5. T
6. F
7. T
8. T
9. F
10. T
11. F
12. T
13. F
14. T
15. F

Fill-in-the-blank

16. Uranus
17. Iapetus
18. Pluto
19. Neptune
20. K2-33b
21. Triton
22. TESS
23. Venus
24. HR 8799
25. Magellan

"Matching"

26. Pluto
27. Venus
28. Iapetus
29. Triton
30. Jupiter
31. Io
32. Pluto
33. Io
34. Venus
35. Iapetus
36. Triton
37. Venus
38. Io
39. Iapetus
40. Neptune
41. Triton
42. Iapetus
43. Triton
44. Jupiter
45. Pluto

Section B

46. 11, 9, 8, 2, 7
47. 8, 3, 10, 4, 13
48. (a) Jupiter
    (b) Juno
    (c) Great Red Spot
    (d) A giant storm on Jupiter
    (e) Image 13
49. (a) Pluto
    (b) New Horizons
    (c) LORRI
    (d) New Horizons was travelling very, very quickly (about 14 km/s) when it reached Pluto. It would take an incredible amount of energy to slow it down enough to orbit around Pluto, which requires more fuel. More fuel means that the spacecraft becomes heavier, which means it would be launched from Earth at a lower speed and take far longer to reach Pluto. It wasn't cost-effective or reasonable considering our current technology.
50. (a) Triton
    (b) Voyager 2
    (c) Image 18
    (d) Yes. Geologic activity would destroy/fill up impact craters.
    (e) Triton's surface consists of many different types of ices. These aren't very strong building materials, and if you tried to make a big structure (like a mountain), it'd probably collapse.
51. (a) Image 11
    (b) Ovda Regio
    (c) Magellan
    (d) Responses will vary. Possible answers include: (1) meteor impacts may not have the ability to generate enough magma and (2) the underlying magma is not capable of transferring enough stress
52. (a) Saturn
    (b) Image 4
    (c) Charged particles moving along the magnetic field lines of a planet into its atmosphere
53. (a) Cantaloupe Terrain
    (b) They are roughly the same size and have smooth, consistent curves
    (c) Diapirism (rising of "lumps" of less dense material through a layer of denser material)
54. (a) Image 6
    (b) Cassini
    (c) Responses will vary. Possible answers include: (1) remnant from when Iapetus was younger and rotated more quickly, (2) icy material that welled up from beneath the surface and then solidified, (3) collisional accretion of a ring system when the moon was being formed, and (4) ancient convective overturn.
55. (a) Image 10
    (b) Hubble
    (c) An image that shows an object in colors that differ from those a photograph taken using visible light. Typically, the data for false-color images is collected at wavelengths we *can't* see (e.g., UV, IR, etc.) which are assigned to colors we can see.
    (d) Infrared light
    (e) Different wavelengths of light are absorbed differently (and at different depths) by Uranus's atmosphere. In this case, the blue regions in the image show the deepest layers of the atmosphere.
56. (a) Iapetus
    (b) UV
    (c) Red
57. (a) ALMA
    (b) 10^6 years
    (c) Planets forming
    (d) Planets this large shouldn't be able to form this quickly
58. (a) Image 12
    (b) Image 2
    (c) Tholins
    (d) The Brass Knuckles

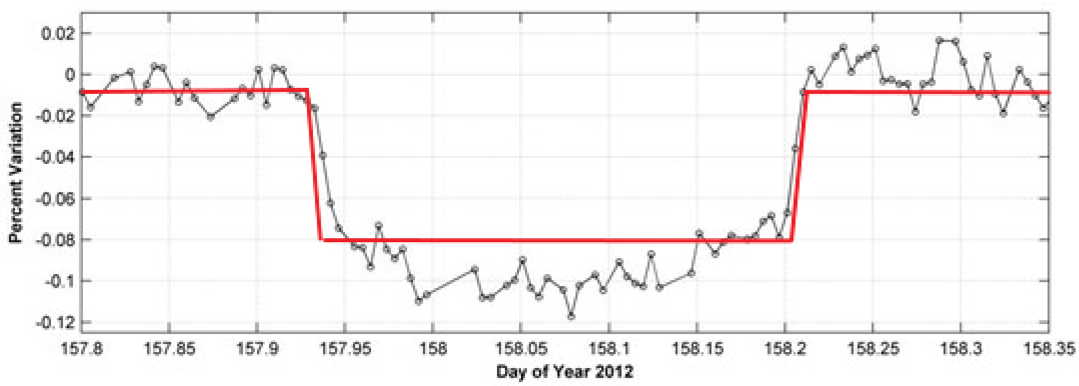
Section C

59. (a) (2 points) Accept answers between 6-8 hours (or anything else close that shows reasonable work)

(b) (3 points) Limb darkening is a phenomenon in which the center of the disk of the star appears brighter than the outer portions. This is because the temperature of the interior of the Sun increases with depth. When we look at the center of the solar disk, we see light rays which are coming radially outwards. They originate relatively deep in the photosphere, where the temperature is relatively high. When we look at the limbs, we see light rays which must skim through the photosphere at a shallow angle to reach the Earth. They originate in the upper reaches of the photosphere, where the temperature is somewhat lower.

When the disk of the planet begins to cross the disk of the star, it's covering the dimmer parts of the star's disk, so the brightness drops less quickly. As the disk of the planet moves closer and closer to the center, it blocks brighter and brighter portions of the star's disk, so the brightness continues to fall even after the entire disk of the planet is on top of the disk of the star, resulting in the upwards curved shape. Without limb darkening, the bottom of the transit curve would be flat, since the disk of the star would be uniformly bright.

(c) Correct answers should look approximately like the following:



(d) (5 points) In the equation shown in the exam, we're assuming that the planet and star are *both* so far away from us that the differences in their distances from us are negligible (which is true when we're observing planets outside of our Solar System). This means that the ratio of their actual sizes will be directly proportional to the ratio of their angular sizes. However, when Venus is transiting the Sun, it's closer to the Earth than the Sun is (and the difference is significant), so its disk (angular size) is larger.

(e) (3 points) The value of R_p would be an underestimate of the planet's true radius. This is because the brightness of the planet would make the dip in the star's brightness smaller during the transit.

(f) (3 points) When the planet crosses in front of the star, the light from the star passes through the planet's atmosphere as well. By examining which wavelengths of light get absorbed when they pass through the planet's atmosphere, astronomers can make educated guesses about which compounds must be in the atmosphere to cause that type of absorption.

60. (a) (4 points) The spectra of hot stars have fewer lines to easily measure Doppler shifts with, and hot main sequence stars are typically more massive, so their radial velocities are lower (for a given planet mass).

(b) (4 points) Cool stars are fainter and emit largely in the IR, where it is hard to have high sensitivity

(c) (4 points) Hot stars too bright and large for deep, observable, transits

(d) (4 points) Cool stars are too faint

61. (a) (2 points) They grow more quickly at small distances from the parent star
    (b) (4 points) The surface density of the disk is higher closer to the parent star. As a result, collisions between the building blocks of planets (e.g., rocks, dust, etc.) are more frequent/likely.
    (c) (2 points) They grow more quickly in the right panel.
    (d) (4 points) This discontinuity represents the Frost line, which is the (approximate) distance at which it is cold enough for volatile compounds such as water, ammonia, methane, carbon dioxide, and carbon monoxide to condense into solids. Beyond the Frost line, there are many more solid grains available for accretion into planetesimals and eventually planets, which can lead to more massive (gaseous) planets.
    (e) (4 points) They formed beyond the Frost line (i.e., not at their current locations), but then migrated inwards towards their parent stars.

62. (a) (2 points) Jupiter rotates very quickly, causing it to "flatten" a little and be wider around its equator than it is around its poles.
    (b) (4 points) Because of Jupiter isn't a perfect sphere, the gravitational field outside it depends not just on its mass and distance from its center, but also on the distribution of mass within the planet. By carefully measuring the gravitational moments of Jupiter, astronomers can constrain the distribution of mass within the planet. Then, combining the gravitational moment data with models for how different substances behave at different temperatures and pressures, scientists can make educated guesses about the interior of Jupiter.
    (c) (2 points) Higher order moments are more sensitive to the structure near the surface.
    (d) (4 points) In order for the heavy elements to diffuse into the metallic hydrogen-helium envelope, mass needs to be pulled away from the center against the force of gravity. In other words, you need to "add" energy for those substances to overcome the inwards gravitational pull. Since this is in the core (i.e., very close to the center of the planet), the gravitational force is very strong, so it requires a lot of energy.
    (e) (4 points) The extremely high pressure and temperature deep within Jupiter (and Saturn) would "break" the atoms in an H_2 molecule apart and then ionize the individual atoms. The resulting substance would be a bunch of protons (H^+) surrounded by mobile electrons in a "liquid" state.
    (f) (4 points) This would be evidence in favor of the disk instability model. If Jupiter was formed through the core accretion model, it almost certainly must have some sort of core (we just aren't 100% sure about its size/mass). However, a planet that is formed from the disk instability method does not *need* to have a core made up of heavy elements.

63. (a) (3 points) Jupiter is very massive, so it exhibits a strong tidal force on Io. Furthermore, Io is in a 1:2:4 orbital resonance with Europa and Ganymede, which keeps Io's orbit elliptical. All of these tidal forces are constantly deforming Io, resulting in friction in its interior. This so-called "tidal friction" leads to a significant amount of heat. (To summarize: the gravitational force from Jupiter and its other moons deforms Io, leading to tidal heating)
    (b) (2 points) Radioactivity
    (c) (6 points) In a more circular orbit, Io is deformed less (since the gravitational force on it from Jupiter is more constant). This reduces the amount of tidal heating that Io experiences. If it is reduced enough, the curve representing the energy from tidal heating can be shifted down enough so that it never intersects the curve representing convective heat transfer, which eliminates that equilibrium.
    (d) (6 points) If we increase the temperature by a small amount from a stable equilibrium, then both the heat removal rate and the heat generation rate will increase. However, at a stable equilibrium, the heat removal rate will increase more than the heat generation rate. This means that heat will be removed from the system, and the system will cool and return to its original stable equilibrium.
    (e) (6 points) In order for an equilibrium to be stable, the slope of heat removal rate curve must be greater than the slope of the heat generating curve at the equilibrium point.