Answer Key

Section A

T/F

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

Fill-in-the-blank

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

"Matching"

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

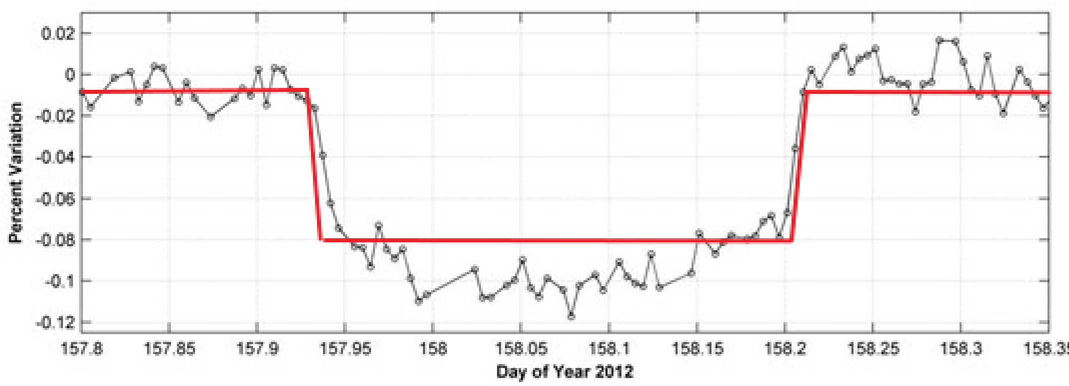
Section C

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.