Answer Key

Section A [40 points]

1. (a) Enceladus
   (b) Saturn
   (c) Image 12
   (d) Younger on the left, since it has fewer craters.
2. (a) Venus
   (b) DAVINCI and VERITAS
   (c) DAVINCI will orbit Venus to learn more about its atmosphere (and also send a probe through Venus' atmosphere). VERITAS will also orbit Venus, but it will focus on understanding Venus' surface and interior.
3. (a) 101955 Bennu
   (b) OSIRIS-REx
   (c) Asteroid
4. (a) North Pole
   (b) Dry ice (carbon dioxide ice)
   (c) They are explosive marks left behind from carbon dioxide sublimation/avalanches
5. (a) Europa
   (b) Galileo
   (c) It is (or recently was) geologically active
6. (a) Europa
   (b) Hubble Space Telescope
   (c) It is not a photograph. Instead, HST "spectroscopically detected auroral emissions from oxygen and hydrogen", which is thought to be a proxy for the plumes themselves.
7. (a) Titan
   (b) Infrared
   (c) Shangri-La
   (d) Broadly speaking, scientists think it is an immense sand sea of dark, organic material of unclear origin/composition.
   (e) *Dragonfly* is a rotocraft lander (answers like "helicopter" will also be accepted).
8. (a) Image 7
   (b) Cassini
   (c) Enceladus
   (d) It's a ridge, not unlike the ones found on Europa
9. (a) Ultraviolet
   (b) MAVEN
   (c) Hydrogen is much lighter than carbon or oxygen
10. (a) Image 2
    (b) Rosetta
    (c) Two objects slowly came into contact due to their mutual gravitational attraction - this is called a "contact binary".
11. (a) Mars
    (b) Perseverance
    (c) Igneous rocks are rocks that are formed due to lava or magma cooling and solidifying
    (d) Contact with liquid water rich in carbon dioxide
12. (a) Proxima Centauri
    (b) Radial velocity

Section B [45 points]

13. (a) (3 points) TOI-700 d is the other planet in the habitable zone (+1). TOI-700 d is slightly larger (+1) and receives less light from TOI-700 (+1) than TOI-700 e.

    (b) (2 points) Generally speaking, "habitable zones" refer to a range of distances where scientists think the temperature of a planet would be able to support liquid water (assuming a suitable pressure). They usually include a bit a variation due to assumptions about atmospheres, heat distribution, albedo, etc. (+1). Being in a habitable zone does *not* mean that a planet has life on it (+1).

    (c) (2 points) Tidally locked planets always have the same side facing the parent star. As a result, one side of the planet is always experiencing daytime, while the other is experiencing nighttime (+1). It is more common for planets in the habitable zone of their parent stars to be tidally locked around red dwarfs than the Sun, since red dwarfs are much dimmer, forcing the planets to be closer, where tidal forces are stronger (+1).

    (d) (2 points) Planets cross in front of their parent star as viewed by us. This causes the star to appear slightly less bright, since the planet is blocking some of its light. We measure the dip in the star's brightness to estimate how large the planet is (+2).

    (e) (2 points) Based on our current understanding of planet formation and structure, we know that certain types of planets tend to be a certain mass or radius, and different things (e.g., solid accretion, gas accretion, self-compression, etc.) affect their size. In other words, mass and radius are closely related to each other (planets don't exist with random combinations of them). As a result, we can use mass-radius relationships for planets of different classes (e.g., rocky planets, Neptune-like planets, etc.) to empirically correlate a radius to a mass. See Chen and Kipping (2017) for more details if you're interested.

14. (a) (3 points) The equilibrium constant will be higher (+1). There are a couple of ways to rationalize this; let's examine it from the perspective of Le Chatelier's Principle. Catabolic reactions release energy in the form of heat, so we can think of heat as a "product" of the reaction. Decreasing the temperature removes heat, so the equilibrium will shift to produce more heat. This corresponds with an increase in the equilibrium constant (+2).

    (b) (2 points) This part can be understood using collision theory. At higher temperatures, molecules will be moving around more (and faster), leading to more collisions. Molecules need to collide to react with each other, so more collisions give them more chances to react (+1). Additionally, the molecules need to have a certain amount of energy (called an *activation energy*) in order to actually react. So, when the temperature is increased, the molecules collide with more energy, and a larger proportion of them have enough energy to get over the activation energy barrier (+1).

    (c) (2 points) Atoms or molecules in a solid are typically "locked" into position and cannot move around very easily (+1). As a result, it makes it very difficult for them to react with each other, since collisions between molecules are rarer than they are in gases or liquids (or solutions). Furthermore, in a reaction between two solids, the reaction can usually only take place at the interface between the two solids (and a little more, depending on the solubilities of the solids in each other). However, in a liquid or gas, the molecules can easily mix (+1).

(d) (4 points) This is a nice idea if the properties of the compounds and reaction stay (relatively) constant throughout the entire reaction. Scientists use relations like the van 't Hoff equation and the Arrhenius relation to do this stuff. However, on the surface of Titan, the temperatures are low enough such that some of these hydrocarbons may condense or even freeze. These phase changes completely change what the reaction would be like, so the data you collect from the reaction where everything is a gas would not be very useful. (+4).

15. (a) (4 points) The equation for equilibrium temperature is:

$$T = T_{star}\sqrt{\frac{R_{star}}{2a}}(1-\alpha)^{1/4} \tag{1}$$

We assume that T_{star} and R_{star} are the only variables that are changing. So,

$$\frac{T_{new}}{T_{old}} = \frac{0.5 \times T_{star}}{T_{star}}\sqrt{\frac{100 \times R_{star}}{R_{star}}} = 0.5 \times 10 = \boxed{5} \tag{2}$$

(b) (3 points) The greenhouse effect is caused by methane (+1), while the anti-greenhouse effect is caused by haze in the atmosphere reflecting incident light back (+1). Overall, the greenhouse effect is stronger (+1). Specifically, it increases Titan's temperature by about 21 Kelvin, while the anti-greenhouse effect decreases Titan's temperature by only 9 Kelvin.

(c) (2 points) The atmosphere becomes much thicker (+1) due to the mechanics of haze production on Titan. This makes it harder to light to get through to the surface of Titan (+1).

(d) (3 points) Haze is produced by UV radiation (and other highly energetic particles) hitting molecules in Titan's atmosphere (+1), leading to complicated chemical reactions. If the UV radiation goes away, then the haze production will drop significantly (+1). Since haze contributes to the anti-greenhouse effect, less haze will help warm up the moon, and it will make the haze layer less optically thick (+1).

(e) (3 points) You could add another substance (e.g., ammonia) to the water (+1), which would decrease the freezing point. The addition of a solute to the water will make the act of freezing less favorable from an entropy-perspective, which will drive the freezing point down (+2).

(f) (3 points) Answers will vary. Graded entirely based on effort, level of detail, and accuracy.

16. (5 points) Answers will vary. Graded entirely based on effort, level of detail, and accuracy.