2022 SCIENCE OLYMPIAD NATIONAL INVITATIONAL

JANUARY 8, 2022

Solar System B

Directions: Welcome to 2022 Science Olympiad National Invitational Tournament! This test is for Solar System in Division B. You will have 50 minutes to complete this exam.

You are allowed to use two 8.5" $\times$ 11" sheets of paper with information on both sides as notes.

You are not allowed to use any calculators on this exam. There is no penalty for wrong answers.

Above all else, just believe!

FROM THE HOSTS OF THE 2022 NATIONAL TOURNAMENT

SOUTHERN CALIFORNIA SCIENCE OLYMPIAD

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Exploring the World of Science

Section A The Sun is at the center of the Solar System.

1. (1 point) **A. True**

   B. False

2. (1 point) Pluto is a dwarf planet.

   A. True

   B. False

3. (1 point) Venus is the hottest planet in the Solar System.

   A. True

   B. False

4. (1 point) Saturn is the most massive gaseous planet in the Solar System.

   A. True

   B. False

5. (1 point) Io is in an orbital resonance with Iapetus.

   A. True

   B. False

6. (1 point) The Cassini spacecraft visited Arrokoth in 2020.

   A. True

   B. False

7. (1 point) Ralph and Alice are instruments on the Galileo spacecraft.

   A. True

   B. False

8. (1 point) Pluto's largest moon is Charon.

   A. True

   B. False

9. (1 point) The planets in the HR 8799 system were discovered using the radial velocity technique.

   A. True

   B. False

10. (1 point) The Great Red Spot is on Jupiter.

    A. True

    B. False

11. (1 point) ALMA is a ground-based telescope located in Chile.

    A. True

    B. False

12. (1 point) Iapetus is a moon around Uranus.

    A. True

B. False

13. (1 point) Uranus and Neptune are "ice giants".

    A. True

    B. False

14. (1 point) The interior of Venus is thought to contain some amount of metallic hydrogen.

    A. True

    B. False

15. (1 point) The barycenter (center of mass) of the Pluto-Charon system lies outside of either object.

    A. True

    B. False

16. (1 point) Venus's atmosphere consists primarily of sulfur dioxide.

    A. True

    B. False

17. (1 point) Io is thought to have been captured from the Asteroid Belt.

    A. True

    B. False

18. (1 point) TOI-561 is an old, metal-poor star.

    A. True

    B. False

19. (1 point) Triton has a retrograde orbit.

    A. True

    B. False

20. (1 point) Kepler-138d is a rocky super-Earth.

    A. True

    B. False

Complete the following statements with the name of an object or mission explicitly listed on the rules. No object or mission will be used more than once. Use the exact spelling shown in the word bank below.

Word Bank:

Solar System Objects: Venus, Jupiter, Saturn, Uranus, Neptune, Io, Iapetus, Triton, Pluto, Arrokoth Extrasolar Systems/Planets: HL Tauri, HR 8799, Kepler 138, K2-18b, K2-33b, TOI-561 Missions: Magellan, Galileo, Juno, Cassini, Voyager 2, New Horizons, ALMA, Kepler, TESS

21. (1 point) The innermost planet of the ______ system completes an orbit in less than one Earth day.

    TOI-561

22. (1 point) The moon ______, despite its high orbital inclination, was almost definitely not captured by the planet it orbits

    Iapetus

23. (1 point) The Galilean moons are the four largest moons of the planet ______.

Jupiter

24. (1 point) The pre-main-sequence star _______ has greatly changed our understanding of how early planets may form in a star system.

HL Tauri

25. (1 point) The Solar System mission _______ included fly-by's of Jupiter, Pluto, and 486958 Arrokoth.

New Horizons

26. (1 point) The planet _______ was the first Earth-sized exoplanet in its star's habitable zone to have its atmosphere detected.

K2-18b

27. (1 point) _______ is unique among the ice giants in our Solar System for radiating almost no excess heat relative to what it receives from the Sun.

Uranus

28. (1 point) The _______ mission succeeded Kepler in searching for exoplanets via the transit method.

TESS

29. (1 point) Though other missions have followed, _______ is the most recent American spacecraft to explore the planet Venus, not counting fly-by's.

Magellan

30. (1 point) Due to its surface activity, the moon _______ has a thin atmosphere consisting almost exclusively of sulfur and sulfur compounds.

Io

Section B

Use the attached Image Set for the questions in this section. Each part within each question is worth 1 point unless otherwise specified.

31. (2 points) Order the objects shown in the following images by their distance from the Sun, from closest to farthest: 1, 2, 5, 10, 12

Solution: 10, 2, 5, 12, 1

32. (2 points) Order the objects shown in the following images by their average density, from least dense to most dense: 2, 6, 8, 17

Solution: 17, 2, 8, 6

33. (3 points) (a) What spacecraft provided the image of Saturn shown in Image 17? [1 pt]

(b) Where is this spacecraft currently located? [1 pt]

(c) What is the number of the image that shows the message carried by this spacecraft? [1 pt]

Solution: (a) Voyager 2; (b) interstellar space; (c) Image 14

34. (2 points) (a) What is the name of the object illustrated in Image 20? [1 pt]

(b) What is notable about the composition of this object's atmosphere? [1 pt]

Solution: (a) K2-18b; (b) The atmosphere has water within the habitable zone of its parent star

35. (4 points) (a) Which image shows Venus as taken by Mariner 10 as it left the planet? [1 pt]

    (b) Which series of spacecraft was the first to land on the surface of Venus? [1 pt]

    (c) Which image shows a spacecraft on the Venusian surface? [1 pt]

    (d) Why is the photo from part (c) iconic? [1 pt]

Solution: (a) Image 4; (b) Venera; (c) Image 33; (d) It was the first color image of Venus's surface

36. (4 points) (a) What the name of the system shown in Image 7? [1 pt]

    (b) The star in this system is categorized as belonging to a rare population of stars. What is it? [1 pt]

    (c) How is the chemical composition of this group different from other groups of stars? [1 pt]

    (d) What two telescopes combined observations to study this system in detail? [1 pt]

Solution: (a) TOI-561; (b) galactic thick disk stars; (c) lower metal content; (d) Keck and TESS

37. (7 points) (a) Which object is shown in Image 12? [1 pt]

    (b) Broadly speaking, what type of object is this? (There are multiple correct answers.) [1 pt]

    (c) In what area of the Solar System is this object located? [1 pt]

    (d) What causes the blue color shown in Image 12? [2 pt]

    (e) Which object(s) in the rules is/are farther from the Sun (but still within the Solar System) than this object? Which image(s) show(s) them? [2 pt]

Solution: (a) Pluto (b) Dwarf planet (also accept Kuiper Belt Object and Trans-Neptunian Object) (c) Kuiper Belt (d) Sunlight scattering off of haze particles in Pluto's atmosphere (e) Arrokoth, Image 19

38. (4 points) (a) Which image shows Jupiter's global circulation system? [1 pt]

    (b) What mission is currently exploring this planet? [1 pt]

    (c) Which image shows the processes taking place at the south pole of Jupiter? [1 pt]

    (d) Which image shows X-ray emissions at the north pole of Jupiter? [1 pt]

Solution: (a) Image 15; (b) Juno; (c) Image 18; (d) Image 3

39. (2 points) (a) A special phenomena involving Jupiter's magnetosphere occurs at its poles. What is the name of this phenomena? [1 pt]

    (b) The Earth also displays these same phenomena. What is the major difference in these phenomena between Earth and Jupiter? [1 pt]

Solution: (a) aurora; (b) On Jupiter, they are out of sync with each other

40. (6 points) (a) What is the name of the most volcanically active object in the Solar System? [1 pt]

    (b) True or false: the volcanism on this object is icy. [1 pt]

    (c) Which image shows this object? [1 pt]

    (d) In one sentence or less, explain the root cause of this volcanism. [1 pt]

    (e) What were the first spacecraft to image a volcanic eruption on this object? [1 pt]

    (f) The image shown in part (a) above was taken by what mission? [1 pt]

    Solution: (a) Io; (b) False; (c) Image 6; (d) Tidal forces from Jupiter and other Jovian moons; (e) Voyager 1; (f) Galileo

41. (6 points) (a) One of the objects on the rules is a young T-Tauri star with a protoplanetary disk. What is its name? [1 pt]

    (b) Which image shows this object? [1 pt]

    (c) What telescope or spacecraft took this image? [1 pt]

    (d) What is the image number that shows a distance density profile for the protoplanetary disk for this object? [1 pt]

    (e) Which image shows another planetary system being discovered using direct imaging? [1 pt]

    (f) What system is shown in the image from part (e)? [1 pt]

    Solution: (a) HL Tauri; (b) Image 1; (c) ALMA; (d) Image 25; (e) Image 32; (f) HR 8799

42. (7 points) (a) One of the objects on the rules is a moon around Saturn. What is its name? [1 pt]

    (b) Which image shows this object? [1 pt]

    (c) What is notable about this object's orbit around Saturn? [1 pt]

    (d) What is the most likely cause of the extreme difference in albedo between the leading and trailing hemispheres of this object? [2 pt]

    (e) This object is also known for its distinctive equatorial ridge. There are several theories for the formation of this ridge; explain one of them. [2 pt]

    Solution: (a) Iapetus; (b) Image 2; (c) Iapetus is locked in synchronous rotation; (d) Sublimation of volatiles; (e) Answers will vary, check Wikipedia

43. (6 points) (a) Image 22 shows the surface of what object? [1 pt]

    (b) What is the name of the mission that took this image? [1 pt]

    (c) Which instrument(s) was/were used to collect the data used to create this image? [1 pt]

    (d) What is the name of the smooth area towards the right of the image? [1 pt]

    (e) What is the name of the mountains shown in the middle of the image? [1 pt]

    (f) Generally, what do scientists believe make up these mountains? [1 pt]

> **Solution:** (a) Pluto; (b) New Horizons; (c) LORRI and MVIC; (d) Sputnik Planitia; (e) al-Idrisi mountains; (f) Water ice

44. (7 points) (a) There are three methods of detecting exoplanets explicitly listed in the rules for this event. Of these, which method has detected the most exoplanets? [1 pt]

    (b) Which image depicts the exoplanet detection method from part (a)? [1 pt]

    (c) Which method has detected the second highest number of exoplanets? [1 pt]

    (d) Which image depicts the exoplanet detection method from part (c)? [1 pt]

    (e) What makes the third method so difficult for detecting exoplanets? [2 pt]

    (f) Image 30 shows a plot of planet mass vs. semi-major axis for exoplanets discovered using two methods. Which methods are represented by the colors red and blue, respectively? [1 pt]

> **Solution:** (a) Transits; (b) Image 28; (c) Radial velocity; (d) 26; (e) The star is typically very bright compared to the planet; (f) Red: radial velocity, blue: transit

45. (5 points) (a) There is one object on the rules that is a moon of Neptune. What is its name? [1 pt]

    (b) Which image shows this object? [1 pt]

    (c) What is unique about the orbital motions of this moon? [1 pt]

    (d) Which image shows a colored global map of this moon's surface? [1 pt]

    (e) Image 31 shows white domes on Earth similar to those seen on the Neptunian moon, suggesting that this moon may be a watery world. What type of feature is shown? [1 pt]

> **Solution:** (a) Triton; (b) Image 8; (c) retrograde and/or poles face Sun; (d) Image 27; (e) salt domes

46. (2 points) (a) From where is the moon from the previous question thought to have originated? [1 pt]

    (b) The moon from the previous question is most similar in formation, structure, and origin to which of the other objects listed in the rules? [1 pt]

> **Solution:** (a) Kuiper Belt; (b) Pluto

47. (2 points) (a) Which image shows Neptune? [1 pt]

    (b) Which spacecraft visited Neptune and its moons? [1 pt]

> **Solution:** (a) Image 5; (b) Voyager 2

48. (4 points) (a) Which image shows Kepler-138? [1 pt]

    (b) Broadly speaking, what type of exoplanet is the "b" component in this system? [1 pt]

    (c) What exoplanet detection method was used to discover the planets in this system? [1 pt]

    (d) Which image shows the radial velocity of the parent star in the system? [1 pt]

Solution: (a) Image 13; (b) Super Earth; (c) Transit; (d) Image 24

49. (2 points) (a) Image 29 shows the spectra of some planet and exoplanet atmospheres, with Earth's atmosphere represented by the green line. Which line represents the Kepler-138b? [1 pt]

    (b) One of the spectra in Image 29 represents a planet in our Solar System. Which line is it, and which planet does it represent? [1 pt]

Solution: (a) Blue; (b) Orange, Venus;

50. (3 points) (a) Which object is shown in Image 11? [1 pt]

    (b) Which spacecraft or telescope took this image? [1 pt]

    (c) In which portion of the electromagnetic spectrum was this image taken? [1 pt]

Solution: (a) Uranus; (b) Hubble Space Telescope; (c) Near infrared

51. (7 points) (a) Which image shows a map of the surface of Venus? [1 pt]

    (b) Which spacecraft or telescope took the image from part (a)? [1 pt]

    (c) Which image shows a complex impact on the surface of Venus taken by the mission from part (b)? [1 pt]

    (d) Which image shows the southern polar region of Venus and was taken by the Venus Express spacecraft? [1 pt]

    (e) Saturn has a similar feature near its poles. Which image shows this feature? [1 pt]

    (f) Which spacecraft or telescope took the image from part (e)? [1 pt]

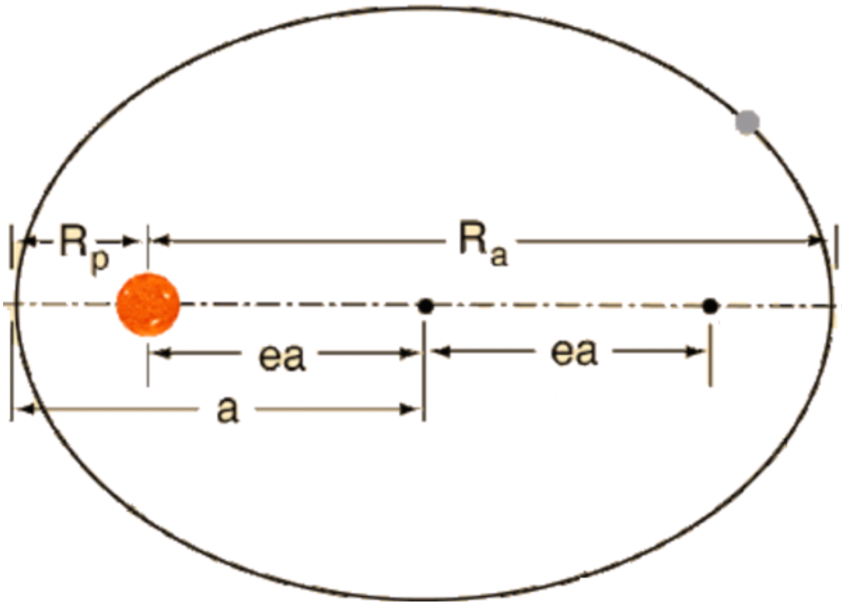
    (g) In no more than a couple of words, what are these features? [1 pt]

Solution: (a) Image 10; (b) Magellan; (c) Image 16; (d) Image 23; (e) Image 21; (f) Cassini; (g) Hurricanes or storms

Section C

Kepler's Laws

The figure below depicts a geometrically-exaggerated diagram of a planet (grey) in orbit around a star (orange). Let the planet, which orbits with period P, have a mass m, and the star have a mass M.



In your answers to the following four questions, you may indicate subscripts using the "_" character (e.g., A_B would be A_B) and superscripts using the $^{\text{“”}character(e.g.,X^2}$ would be X^2).

52. (6 points) In your own words, give a brief explanation of what a, R_a, and R_p represent in this diagram. Then, write a formula for for a in terms of R_a, R_p, and any other necessary constants.

> **Solution:** "a" indicates the semimajor axis of the system (1pt), Ra indicates the radius of apoapsis (or just apoapsis) (1pt), and Rp indicates the radius of periapsis (or just periapsis) (1pt) and can be determined by: a = $(\frac{1}{2})$ * (R_a + R_p) (3pts)

53. (4 points) Write a formula that would allow you to determine a if you knew the values of P, m, and M without knowing R_a or R_p. Assume that each value is given in base SI units, not AU, years, or solar masses.(i.e., be sure to include all necessary constants, like π).

> **Solution:** a = [(G*(M+m)*P^2)$/(4*pi^2)]^()(oralgebraicequivalent)(4pts)$

54. (3 points) By what factor would the value of a change if the period of the planet's orbit, P, was doubled, with all other values held constant?

> **Solution:** "a" would increase (1pt) by a factor of 2^$(2/3)(2pts)$

55. (7 points) By what factor would the value of P change if the mass of the planet were doubled with all else constant? What if the mass of the star were doubled with all else constant? Explain why these two values either differ or are the same, based on your answer.

> **Solution:** If the planet's mass is doubled then the change to P is by a factor of essentially zero (2pts).If the mass of the star is doubled then P will decrease (1pt) by a factor of 2^$(1/2)(2pts)$. This difference is due to the fact that the mass of the planet is ultimately negligible within the equation, since it is taken in sum with the mass of the star, which is likely several orders of magnitude greater. (2pts)

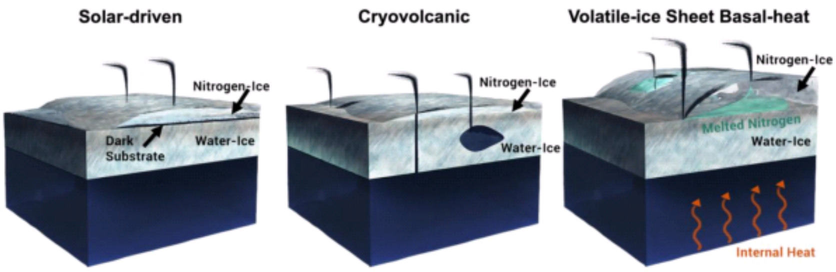
Triton's Plumes

Currently, Io, Titan, Europa, Enceladus, and Triton are the only moons thought to be currently geologically active. Triton's plumes were discovered in 1989 when the Voyager 2 spacecraft visited it, but their origin is still an open question in the field. Currently, there are five theories for the source of these plumes, some with more plausibility than others:

Solar-driven Cryovolcanism Volatile-ice Sheet Basal-heat Buoyant Methane Dust Devils

56. (2 points) The "Buoyant Methane" and "Dust Devil" hypotheses for Triton's plumes are no longer considered likely candidates. Why is this the case?

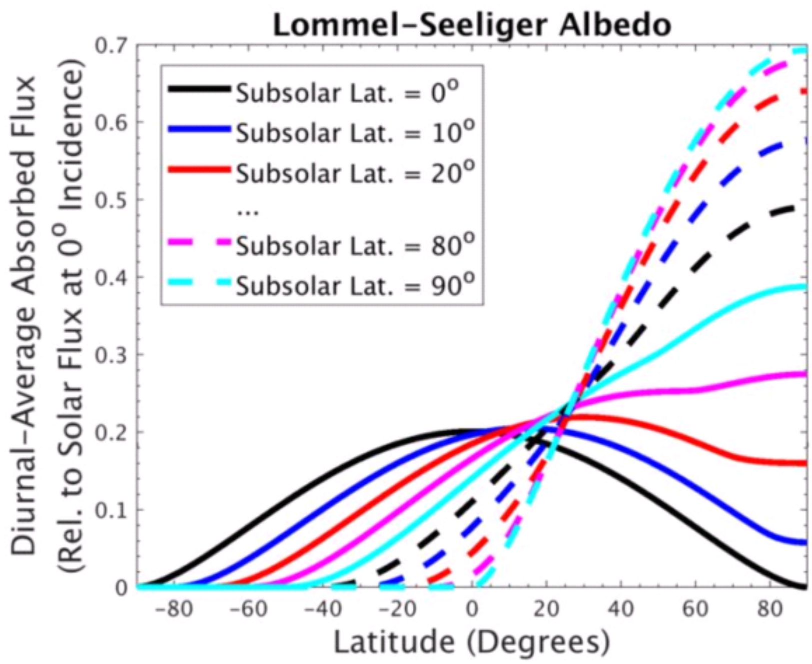
Solution: The winds in the atmospheric vortices are not strong enough to pick up dust (i.e., the dark material in plumes and fans) and to prevent shear of the vertical column, which was not observed.



Artistic depiction of three remaining, eruption-based hypotheses for Triton's plumes, taken from Hofgartner et al. (2019). Features are not shown to scale. The dark blue portion towards the bottom of the figure represents a subsurface water ocean (which Triton may have), but this isn't necessary in any of the three hypotheses.

57. (6 points) Hansen et al. (1990) and Kirk et al. (1990) argued that the geographic distributions of plumes and fans on Triton was strong evidence of the plumes being solar-driven. For three decades, this was the leading hypothesis for the origin of Triton's plumes, as when Voyager 2 had observed Triton, the plumes were close to the subsolar latitude (i.e., the latitude where the sun appears directly overhead at that moment). Recently, however, Hofgartner et al. (2019) argue that this isn't necessarily the case.

The plot below shows how the daily-averaged solar flux varies with latitude for different subsolar latitudes. Using this plot and knowing that the two confirmed, active plumes on Triton were located at 49° S and 57° S, briefly explain why the plumes' locations aren't necessarily as supportive of the solar-driven hypothesis as previously thought.



Solution: The maximum average daily solar insolation can actually be a significant distance from the subsolar latitude. The two plumes were located near the subsolar latitude when Voyager 2 observed them, but given their location, the maximum average daily solar insolation would actually take place close to the South Pole, and we didn't see plumes there.

58. (4 points) Hofgartner et al. suggest that it is possible to determine which of the three remaining theories is the origin of Triton's plumes through remote sensing.

Suppose that in the future, a spacecraft visits Triton. It finds the following:

The distribution of active plumes is independent of seasons and the distribution of nitrogen ice The fans and plumes are water-rich The temperatures associated with plumes are above the boiling point of nitrogen on Triton

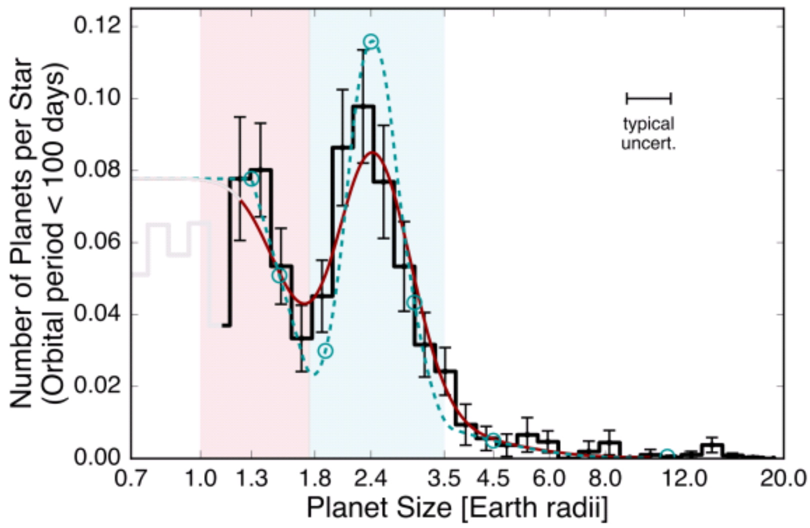
Based on this information, which of the three theories would you think is the origin of Triton's plumes?

Solution: Cryovolcanism

The Radius Gap

Our Solar System has small, rocky planets (e.g., Earth and Mercury) and large planets with thick, gaseous envelopes (e.g., Jupiter and Neptune), but nothing in between. Outside of our Solar System, however, we know that planets between the size of Earth and Neptune exist. What are these planets like, and how common are they?

Using the California-Kepler survey, Fulton et al. (2017) find that the radii of these types of planets has a bimodal distribution, leading to a "radius gap" (sometimes called a "radius valley"). In other words, although it's very common to see planets with a radius of 1.2 or 2.4 Earth radii, a planet with a radius of 1.8 Earth radii is relatively uncommon, resulting in a distribution with two peaks as shown below:



59. (4 points) What is the difference between the atmospheres of the planets that comprise each of the peaks in the distribution?

In your answer, refer to the peaks as the "lower peak" (which has a red background) and "higher peak" (which has a light blue background) to prevent any misunderstandings while grading.

Solution: Lower peak: rocky cores without significant gaseous atmosphere. Higher peak: rocky planets with some gaseous envelope, which significantly inflates the radius of the planet.

60. (4 points) One possible cause of this bimodal distribution is photoevaporation. Briefly explain what photoevaporation is and how it could result in the planet characteristics you mentioned in the previous question.

> **Solution:** Light from the parent star (e.g., UV, x-ray) hits the atmosphere of a planet, heating up the molecules in it and causing some of them to "escape", slowly stripping the planet of its atmosphere. For some planets, it will strip away essentially all of the atmosphere, leaving behind a rocky core. For other planets, which have slightly stronger gravities, it won't, and the extra gaseous layer (which is not very dense) will lead to a significant increase in the radius of the planet.

61. (6 points) Ginzburg et al. (2017) proposes an alternate mechanism for the radius gap based on the residual heat of the core of the young planet leading to atmospheric erosion (also known as "core-powered mass loss"). In order to determine which mechanism (photoevaporation or core-powered mass loss) contributes more, they suggested seeing how the radius gap varies with stellar type (i.e., seeing if having a hotter or cooler parent stars effects the radius gap). Theoretically, how would this help astronomers distinguish between the two?

> **Solution:** Photoevaporation, which is powered by the high-energy radiation, should see a strong dependence on stellar types, given that different types of stars give off different proportions of their energy in high-energy radiation. On the other hand, core-powered atmospheric erosion should be the same as long as the bolometric insolation (i.e. planets' equilibrium temperature) is held constant.

Planetary Migration

Our Solar System's structure is also unique. All eight planets lie in roughly the same plane and move in the same direction as the spin of our Sun. Furthermore, the four rocky planets are close to the Sun, while the large, gaseous planets are all farther away. This "tidiness" led astronomers centuries ago to think that planets (and planetary systems) stayed roughly the same after the planets first formed.

Over the past few decades, astronomers have discovered systems that shatter these antiquated theories. Among these are systems that include large planets that orbit very, very close to their parent stars. K2-33b is such a planet.

62. (2 points) The radial velocity and transit detection methods are very effective for finding large planets that orbit close to their parent stars. Why is this the case?

> **Solution:** RV: larger radial velocities; Transit: higher transit probability and greater transit depth

63. (4 points) Observationally, there are many spectroscopic indicators that K2-33 is a very young system, such as the infrared excess in K2-33's spectral energy distribution (SED). What causes this "infrared excess", and how would it be an indicator that the system is young?

> **Solution:** Light from the young protostar is absorbed by gas and dust in the envelope and disk around it. The light is then reemitted in the IR. The disk persists longer than the envelope. A system that is older would not have the envelope or disk and would not have the "bump" in the IR in the SED. Protostars with both an envelope and a disk will have larger "bumps" than those with only a disk.

64. (6 points) Determining whether planets like K2-33b formed near their present position (in situ) or formed elsewhere and migrated to their present position is an open question. Conceptually speaking, planet migration mechanisms can be loosely classified into three categories:

interactions with the protoplanetary disk
interactions with a stellar companion and the planet
interactions between multiple planets in the system

Due to its size, location, and age, what can K2-33b tell us about what is possible in terms of planetary migration? Between forming in-situ and the three migration mechanisms outlined earlier, which one(s) seem(s) plausible for K2-33b?

Solution: K2-33b shows that it is *possible* for a large planet to be very close to its star at a very young age. Migration involving the protoplanetary disk occurs earlier/faster than migration involving a stellar companion or multiple planets. Based on this information, it probably formed in-situ or migrated inwards using a mechanism involving the protoplanetary disk. This does not mean that *all* planets like K2-33b went through this sort of formation.

65. (4 points) Studying exoplanets has yielded new insight into the formation and early evolution of our Solar System. The earliest investigators focused primarily on whether gravitational interactions within the Solar System could scatter or even eject objects, which would populate the Oort Cloud.

A planet ejecting an object results in the planet's orbit moving inwards slightly. From an energy conservation perspective, why is this the case? Of the eight planets in the Solar System, which would scatter or eject objects the most efficiently?

Solution: The planet gives kinetic energy (which is positive) to the object getting ejected. The total energy in the system has to stay constant, so the planet's gravitational potential energy becomes more negative, corresponding with an orbit that is closer to the Sun. More massive planets will not have to move as far inwards when the scatter objects (for a given mass of the object being scattered), so Jupiter would be the planet most efficient for this process.

66. (4 points) Planetary scientists have had difficulty explaining the formation of Neptune via the core accretion process at its current location. In 2005, a series of papers by Rodney Gomes, Hal Levison, Alessandro Morbidelli, and Kleomenis Tsiganis established the first version of the Nice model (named after the French city, where some of the original work was done). In what way(s) does the Nice model potentially address this issue?

Solution: In the Nice model, Neptune formed much closer to the Sun, where the surface density of the disk was higher. This means that Neptune would have had enough time to form. Then, it migrated outwards to its present location. In some versions, Neptune and Uranus even switch places after forming (i.e., Neptune formed closer to the Sun than Uranus, but due to planetary migration, they switched places).

Conclusion: We hope you had a wonderful time taking this exam! Please consider filling out the official feedback form for the National Invitational and/or posting on the Scioly.org forums to help us make this event the best it can be.