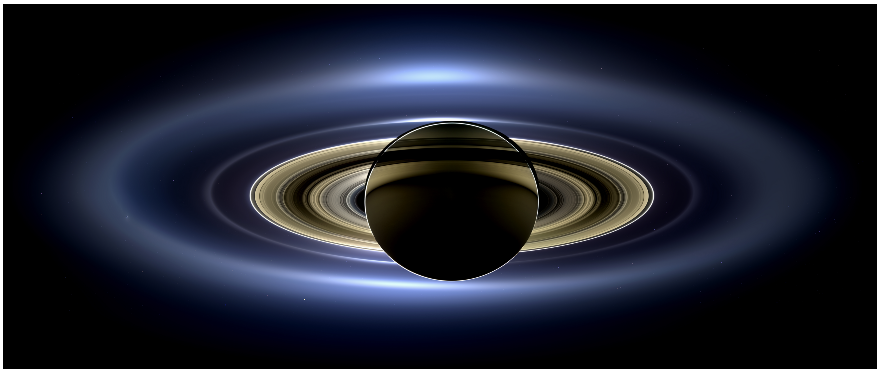
Science Olympiad
Solar System
Sample Annotated Test and Event Guide

2025-2026 Season



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Note: if you are a student taking this exam for practice, then use the blank exam. This document is more of an annotated test and event guide that is useful to look at *after* taking the test.

About this document

This document consists of three sections: general advice, specific resources, and a sample test.

There is advice for both competitors and event supervisors alike. Since there are usually far fewer resources for event supervisors than for students, I have aimed most of the advice towards event supervisors, with the advice for competitors condensed into a few bullet points. However, I think competitors will still gain something from reading through the notes to event supervisors. The resources that follow are meant to be useful for both competitors and event supervisors.

The sample test is intended to be written at the level of a competitive, national-level invitational (e.g., UT Austin Invitational). I think it will probably be longer and more difficult than the average students take throughout the year, but I hope that allows it to show the *range* of questions that may appear in this event.

The sample test is filled with blue and green annotations that explain some of the choices I made for this test and the event as a whole. Blue annotations are typically more general, while green annotations typically give insight for a specific question.

I want to stress that this is a *sample* test, not a perfect or ideal test. I am certain that other, more knowledgeable event supervisors will write better questions and tests than what I have here. However, I hope it shows one example of what a test for this event could look like so that competitors and less-experienced event supervisors have something to refer to.

General advice

Solar System has been part of the Science Olympiad Division B astronomy rotation since the 2005–2006 season. It alternates every two years with **Reach for the Stars**. Initially, Solar System focused on general knowledge of our own Solar System. However, starting in the 2013–2014 season, the event began incorporating rotating topical focuses (e.g., terrestrial planets, icy bodies). Since the 2021–2022 season, the topics for the two-year cycle are **planet formation and structure** in year 1 and **habitability** in year 2.

For competitors

Solar System was my favorite event when I was a Science Olympiad competitor. I think it is a beautiful mix of so many subjects and helps us answer some of the deepest questions humanity has thought about. I hope you have a wonderful time doing this event!

Preparation

- Planetary science can seem very daunting, especially due to all the abbreviations and unusual units (parsecs, AU, arcseconds, magnitudes, etc.). Personally, I found resources like COSMOS (Swinburne Astronomy Online's encyclopedia) very helpful for learning these building blocks.
- Prioritize image analysis, identifying and interpreting features on objects, explaining trends and concepts in your own words. One great way to find high-quality images is to look at image galleries for relevant missions (e.g., CICLOPS for *Cassini* or this for the LRO).
- Do not worry about trivia (e.g., names of random scientists, locations, dates, etc.). Although I cannot control what other event supervisors put on their exams, I do not intend for trivia (or at least, what I consider trivia) to be a substantial portion of the event.
- Reading through A Student's Guide to the Mathematics of Astronomy by Daniel Fleisch and Julia Kregenow is, in my opinion, the best starting point to prepare for the math problems in this event.

- Although you should not worry too much about numerical values of different properties, constants, etc., I think you should include some of them (e.g., mass of the Sun, Earth, and Jupiter). It is helpful for building intuition as well as preparing you for order of magnitude estimation questions.
- Put as many images, with explanations for them, onto your notes as possible. Include what portion of the electromagnetic spectrum the data was collected in, what spacecraft took it, what the colors mean, etc. If you are using Microsoft Word for your notes (which is what I did when I was a competitor), then turn of image compression so that your images do not become blurry.
- Take as many practice tests as you possibly can. If you are preparing for a specific tournament, prioritize taking tests from that tournament in previous years and tests written by that event supervisor at different tournaments so you can pick up on any patterns or tendencies.

Test-taking

- If it is allowed, it is usually beneficial to split the test apart when you and your partner are taking it.
- Avoid spending too much time on one problem, unless you have already finished everything else. If you don't know how to do a certain problem, skip it and work on a different problem that you have a better chance of getting correct.
- Points are not always allocated "fairly" in an exam. Two problems may be worth the same amount of points, but one of them may take much longer to complete than the other. When possible, work on the problems/sections with the best ratio of points/effort.
- Writing more does not mean your answer is better. Being concise can save you time, which can be very useful for long tests.

For event supervisors

Thank you for being an event supervisor! Your hard work and generosity go a long way towards inspiring the next generation of students. I have been an event supervisor for ∼40 tournaments over the past ∼decade, and it has been an immensely fun and fulfilling experience. What follows are some tips that may aid you in running this event.

Planning your test

Division B students have a wide range of knowledge and abilities. Furthermore, tournaments will have varying levels of competitiveness depending on the attending teams and point in the season. As a result, you should think about how difficult your test should be. A test for a small regional tournament with many new teams should be much shorter and easier than a test for a competitive, national-level invitational (e.g., UT Austin Invitational), for example. If possible, I recommend reviewing previous years' tests at your tournament for ideas about question formats, length, and difficulty.

Your exam should also reflect the size of the tournament and how many resources they are able to give to support you. Consider whether testing occurs all at once or in blocks and how much time you will have between the end of testing and the time when scores are due. Some tournaments are able to give you a team volunteers that will help you grade exams.

Writing questions

Questions on the exam should generally pertain to the major themes listed in the rules. These rules are available on the official Science Olympiad website, or you may request them from your tournament director.

The universe is not divided neatly into distinct categories; planetary science is a beautiful mix of physics, astronomy, chemistry, geology, biology, and more. I have tried to write the rules in such a way that they reflect and allow this diversity. I encourage you to create unique, interdisciplinary questions to your heart's desire, as long as those topics are still relevant to the topic of planet formation and structure. Because this is a rapidly evolving field, it is perfectly reasonable to write questions that draw upon recent discoveries, provided they are relevant to the year's topic and students could reasonably encounter them in their studies.

Tests should assess both factual knowledge and analytical thinking. Avoid having too many questions about trivia or obscure details that are unlikely to be relevant to planetary science. Instead, focus on questions that require students to interpret scientific data, compare planetary processes, derive equations, etc. This can come in many forms; for example, I personally like having questions that "build up" to an idea or walk the student through the type of analysis/thinking a "real scientist" would do.

It is important to have a questions that cover a broad spectrum of difficulties. In my opinion, every test should include many questions that every team should be able to answer even after only cursory review of the rules, some very difficult questions that most teams will not be able to answer correctly, and everything in between. The difficult questions should not be difficult due to obscurity or randomness (e.g., asking "who published astronomical tables of the orbit of Uranus in 1821?" would not be a good question). Instead, they should be difficult due to complex concepts in planetary science, physics, chemistry, math, etc. By having a wide spread of difficulties, we (1) make the test more interesting and accessible to teams of all experience levels and (2) allow for better separation in the teams' scores, allowing us to rank them more easily.

This event deliberately does not allow calculators. However, mathematical reasoning is absolutely meant to be part of the event. If you want to incorporate math into your exam, please consider doing so through problems with simple math (e.g., clean numbers, proportions, etc.) that can easily be done by hand (e.g., #10, #38, and #39), order-of-magnitude estimation (e.g., #40), or derivations (e.g., #41). If you use order-of-magnitude estimation, I think it is good to provide at least a few relevant, simple numbers (e.g., mass of the Sun) to the students as starting points, since they are only allowed to bring two sheets of notes in. There are a couple of reasons why I do not want to have calculators in the event:

- I think they would incentivize "plug-and-chug" questions where success comes from memorizing formulas and using a calculator as quickly as possible
- Many students (including myself) have hidden a lack of conceptual understanding behind the ability to crunch lots of numbers. If we minimize the number crunching, then it is easier to test the heart of the concept itself, especially though conceptual questions, proportions, etc.
- There are times when having actual numbers is useful. It gives a sense of scale, and allows us to make comparisons. In these cases, calculations with simple numbers and order-of-magnitude estimation are often useful. In particular, the latter forces students to make simplifying assumptions that emphasize the underlying science (e.g., physical laws, scaling relations, etc.) as opposed to worrying about largely unimportant factors like $1/2$ or π.

I am young and still developing my philosophy on teaching. If you disagree, please do not hesitate to reach out to me. I would never pretend I know everything and am certainly open to changing my mind.

Images

Images are a major component of Solar System tests. You should absolutely include them if at all possible. I recommend having most, if not all, of the images for your test on an "Image Sheet" that is separate from the rest of the (black and white) exam. This significantly reduces printing costs and makes it easier for students to look at multiple images at once (useful for questions like #21, #24(a), #30(d), and #37(a), for example).

When including images, be sure to label them clearly (most people I know use numbers or letters) and reference them explicitly in the questions. Although some image-based questions can be simple identification, many of them should assess a student's ability to interpret or compare visual data related to geological or atmospheric features, orbital diagrams, etc.

Grading

It is typically a good idea to include space for team number and name on all answer sheets, in case tests become disorganized, and in case there is some confusion with team numbers. A key should usually be printed and recorded in the same format as the test answer sheets to speed the grading process and assist any volunteer graders who may be working with you grading tests. Efficiency is especially important when a large number of tests must be graded and ranked in time for the awards ceremony. If you have time, I highly recommended that taking your own test to check for inconsistencies in numbering, oddly phrased questions, and inconveniences like answer spaces that are not large enough for adequate answers to be comfortably provided.

Resources

Practice tests

Looking at other exams for this event is extremely helpful. Many tests are available on SciOly.org. Furthermore, some tournaments, such at the UT Austin Invitational and Regional, release their exams online. Exams that I have written (or helped write) can be found on my website. This year's topic is the same as that of the 2021-2022 competition season, so tests from that year are especially useful.

Websites

Websites serve as a great resource, whether you are a beginner or looking to deepen your understanding of a particular topic. The following are a good place to start.

- Science Olympiad Inc. website
- NASA Solar System Exploration
- Wikipedia
- JPL Photojournal

Planet formation and structure is often taught in classes at universities, and many of them post notes, homework assignments, and exams (with keys!) online. As a starting point, you can easily find some great resources by searching something like `planet formation lecture notes site:edu file:pdf` on Google. Similarly, there are many online resources for order-of-magnitude estimation. I am especially fond of Sanjoy Mahajan's textbook and Eugene Chiang's course at UC Berkeley.

Textbooks

Textbooks can be useful in the right circumstances. The one textbook that I always recommend for this event is A Student's Guide to the Mathematics of Astronomy by Daniel Fleisch and Julia Kregenow. This introductory book walks students through unit conversions, proportions, and more. I recommend reading it cover to cover (even the sections that don't *seem* relevant) simply it builds such strong physical intuition.

However, I recommend not relying on most other textbooks too much, because: (1) they do not have as many images, so they are not as useful for identification, (2) planetary science is so fast-moving that they can easily become outdated, and (3) most textbooks on planet formation and structure are too difficult for the average middle school student to understand. If you *do* want to use textbooks, here are some other ones that may be useful:

- Astrophysics of Planet Formation by Philip J. Armitage (freely available)
- Fundamental Planetary Science by Jack J. Lissauer and Imke de Pater

Some tips for using textbooks:

- If you see anything with complicated math (e.g., calculus), skip it. However, if you see short, simple derivations that rely on basic algebra or scaling arguments, I think those are great to work through.
- Actively seek out diagrams, plots, and pictures. Focus on being able to explain things in words.
- Only attempt to read the sections of the textbooks that are relevant to the event (i.e., in most cases, do not try to read it cover to cover)

Section A [20 points]

Each multiple choice question has only one answer and is worth 1 point for a total of 20 points.

> I believe it is important that an exam has questions that even beginners can answer with confidence. As a result, I often start my invitational/regional exams with a short section of straightforward multiple choice questions. These are simple questions with unambiguous answers that test basic knowledge, vocabulary, etc. In general, this section is meant to (1) build students' confidence, (2) improve the scores/test-taking experience for beginners, and (3) reward teams for knowing the basics.
>
> MCQs are a good fit for this purpose as they are quick to grade and only require recognition of the right answer rather than recalling and reproducing it independently, making them slightly easier. However, other question types can fill the same role, and you have complete freedom to use them instead. I have used MCQs in invitational and regional exams, but do not use them for the national exam.

1. Which of the following terms best describes the Sun?
   - A. A moon
   - B. A planet
   - C. A star
   - D. A galaxy
   - E. A constellation

2. How many planets are in the Solar System? *Note: this does not include dwarf planets.*
   - A. 4
   - B. 7
   - C. 8
   - D. 9
   - E. None of the above

3. In what portion of the Solar System is Ceres located?
   - A. Between Mercury and the Sun
   - B. In the Asteroid Belt
   - C. In the Kuiper Belt
   - D. In the Oort Cloud
   - E. Trick question; Ceres is not located in the Solar System

4. What force keeps planets in orbit around the Sun?
   - A. Gravitational force
   - B. Electromagnetic force
   - C. Weak nuclear force
   - D. Strong nuclear force

5. Which of the following planets is the largest, by volume?
   - A. Mercury
   - B. Jupiter
   - C. Saturn
   - D. Uranus
   - E. Neptune

6. Which of the following planets has the highest average density?
   - A. Mercury
   - B. Jupiter
   - C. Saturn
   - D. Uranus
   - E. Neptune

7. Which of the following planets is the closest, on average, to the Sun?
   - A. Mercury
   - B. Jupiter
   - C. Saturn
   - D. Uranus
   - E. Neptune

8. The most prevalent element in Jupiter's atmosphere is ____________.
   - A. Iron
   - B. Oxygen
   - C. Hydrogen
   - D. Carbon
   - E. Silicon
   - F. None of the above

9. Triton is a moon of ___________.
   A. Mercury
   B. Jupiter
   C. Saturn
   D. Uranus
   E. Neptune

10. If you double the distance between two objects, the gravitational force between those objects will:
    A. Become 1/4 of what it used to be
    B. Become 1/2 of what it used to be
    C. Stay the same
    D. Increase by a factor of 2
    E. Increase by a factor of 4

11. True or false: a cool planet's blackbody spectrum will peak at a longer wavelength than that of a hot planet.
    A. True
    B. False

12. Which of the following is inside the Solar System?
    A. 51 Pegasi
    B. 486958 Arrokoth
    C. HD 209458
    D. HL Tauri

13. Which of the following is a comet?
    A. HD 209458
    B. HL Tauri
    C. 25143 Itokawa
    D. Tempel 1

14. The Great Dark Spot is an atmospheric feature on ___________.
    A. Mercury
    B. Jupiter
    C. Saturn
    D. Uranus
    E. Neptune

15. True or false: Earth's Moon is thought to have formed before Earth itself. Later, it was gravitationally captured by Earth.
    A. True
    B. False

16. True or false: When an object is moving towards us, we say light from that object is blueshifted.
    A. True
    B. False

17. True or false: 51 Pegasi b is considered a "hot Jupiter".
    A. True
    B. False

18. Most long-period comets are thought to originate in the ___________.
    A. Asteroid Belt
    B. Kuiper Belt
    C. Oort Cloud
    D. None of the above

19. *Cassini* is a mission that primarily studied ___________ and its system.
    A. Mercury
    B. Jupiter
    C. Saturn
    D. Uranus
    E. 486958 Arrokoth
    F. 25143 Itokawa

20. Which of the following portions of the electromagnetic spectrum has the highest frequency?
    A. Infrared
    B. Visible
    C. Microwave
    D. X-rays
    E. Radio

Section B [125 points]

When applicable, use the Image Set to answer the following questions. Unless otherwise specified, each part of each question is worth 2 points.

> Image identification and interpretation are the foundation of this event. As a result, they should be integrated into a large part of the test. In their most minimal form, questions should ask students to identify the objects (and features of all kinds on these objects) listed in 3.a.i and 3.a.ii on the rules. Unless you have good reason to, please do not ask students to identify objects that are not on this list. The initial identification serves as a gateway to testing other concepts. Within reason, I encourage you to incorporate a very wide range of topics and generally be as creative as you want.

21. (3 points) Order the following images by how far the objects they depict are from the Sun, from closest to farthest: 1, 2, 3, 4, 5

    > I sometimes include questions like these because they require students to chain together multiple things, which requires a lot of thinking. In this case, students have to (1) successfully identify the objects in the images, (2) think about how far those objects are from the Sun, and then (3) order the image numbers (not the objects) from closest to farthest.

22. (a) Which object is shown in Image 1?
    (b) What spacecraft collected the data to create this image?
    (c) This spacecraft flew by the object instead of orbiting it to observe it for more time. Why?

    > 22(c) is an example of the type of "engineering principles" I think students should know regarding missions. I do not care much about specific numbers or specifications, but the ideas underlying the decision highlight the type of conceptual understanding I want students to have.

    (d) In the image, we see a large heart-shaped feature. What is its name?
23. (a) Which object is shown in Image 2?
    (b) This object is well-known for its beautiful ring system. What are the rings made of?
    (c) What causes the pale yellow color of this object's atmosphere?
24. (a) One of the images on the Image Sheet shows a comet. Which one?
    (b) What is the name of this comet?
    (c) What mission(s) collected the data to create this image?
25. (a) What planet is the Great Red Spot on?
    (b) Briefly describe what the Great Red Spot is.
    (c) What image shows the Great Red Spot?
    (d) What mission(s) collected the data to create this image?
    (e) In what portion(s) of the electromagnetic spectrum (e.g., visible, infrared, etc.) was/were the data in this image collected?
26. (a) Which object is shown in Image 4?
    (b) What mission(s) collected the data to create this image?
    (c) How do scientists believe this object formed?

27. (a) One of the objects on the rules was visited by a spacecraft called *Hayabusa*. What is the name of that object?
    (b) What space agency/country led the development of *Hayabusa*?

> This is “trivia” in some sense since it is not entirely about science. I personally think it is fruitful and fun to highlight the worldwide nature of science a little bit, so I am okay with a small amount of questions like this.

    (c) What image shows this object?

28. (a) There are two images that show Mercury on the Image Sheet. Which ones are they?
    (b) What mission(s) collected the data to create these images?
    (c) Which of the following best describes Mercury: (1) rocky/metallic or (2) gaseous?

29. (a) Images 7 and 8 show different surface features on the same object. Which object?
    (b) The surface feature in the red dashed circle in Image 7 is a mountain. What is its name?
    (c) In Image 7, the mountain itself has very few craters, but the area surrounding it has many small craters. What does this imply about the age of the mountain compared to the age of the surrounding terrain?
    (d) Image 8 shows a surface feature called Kwanzaa Tholus. Briefly explain what a tholus is.
    (e) Using the color bar in Image 8, estimate the height, in kilometers, of Kwanzaa Tholus.

> I enjoy including questions that involve images that students can interact with to measure, calculate, or explain something, since I feel that they usually encourage deeper thinking. It can be difficult to find images that are good fits for these types of questions, but if you can, I encourage you to include them on tests.

    (f) Scientists believe that Kwanzaa Tholus was the same height as the mountain in Image 7 when they first formed. Based on this information, which do you think is older: (1) Kwanzaa Tholus or (2) the mountain in Image 7? Explain your reasoning.

> 29(c) and (f) are meant to highlight the type of thinking/understanding I want to prioritize in this event. In principle, a student could “brute force” this question by having all of the numbers on their notes. However, by knowing the basics, one can “think through” some of these questions and arrive at the right answer: (1) young surfaces have fewer visible craters since they were created more recently, (2) surface features on Ceres often consist of lots of ice, which is structurally weak, (3) since a tholus is a small hill, it may be an older version of a mountain that has degraded over time.

30. (a) Image 9 shows a portion of the surface of Triton. What image shows the planet that this object is a moon of?
    (b) The type of terrain shown in Image 9 has a specific name. What is it?
    (c) What mission(s) collected the data to create Image 9?
    (d) There is one other image of Triton on the Image Sheet. Which one is it?
    (e) Scientists believe Triton was gravitationally captured by its planet after forming. Name two pieces of evidence that support this theory.

31. (a) What image shows HL Tauri?
    (b) What mission(s) collected the data to create this image?
    (c) In what portion(s) of the electromagnetic spectrum (e.g., visible, infrared, etc.) was/were the data in this image collected?

(d) If we observed HL Tauri in visible light, we would not be able to clearly make out the central star and protoplanetary disk. Why is that the case?

> Another example of the emphasis I put on multi-wavelength astronomy. I want students to understand that different portions of the electromagnetic spectrum are good for different things. On a more difficult test, I think it is reasonable to ask students about the underlying physics of light absorption/scattering/etc., but since this is meant to be a medium-difficulty exam, I leave it out.

(e) Scientists believe that the gaps visible in the disk may be due to planets forming. Why would the formation of planets in the disk cause gaps?

32. (a) Which object is shown in Image 10?
    (b) What mission(s) collected the data to create this image?
    (c) Image 10 happens to be a false-color image. In your own words, please explain what that means.
    (d) There are a few circular splotches on this object, particularly towards the right side. Three of them have been indicated by red arrows. What are these circular splotches?
    (e) There are also several labeled objects (e.g., Rosalind, Belinda, Puck, etc.) whose motion is shown with curved white arrows. What type of object (e.g., asteroid, planet, moon, etc.) are these?

33. (a) Image 12 shows a plot associated with the discovery an object. Which one?

> The images on the exam do not have to be photographs (or data overlaid on photographs). I strongly encourage you to incorporate plots (like Image 12), maps, diagrams, etc. as you see fit. They are especially useful for questions on the extrasolar systems, which we do not have many (if any) direct photographs of.

(b) Briefly explain what values are plotted on the x and y axes.

34. (a) Image 14 shows storms near Jupiter's north pole in visible light, microwave, and infrared. Which panels (left, center, and right) correspond to which portions of the electromagnetic spectrum?
    (b) What mission(s) collected the data to create this image?
    (c) What *instruments* on these mission(s) were used to collect the data?

> Throughout my exams, I frequently ask students about the spacecraft/telescopes/instruments used to collect data for an image. I do so for three reasons: (1) it rewards students who prepared meticulously, (2) it highlights the breadth of technologies we have developed to study the universe, and (3) I want students to understand how different wavelengths/technologies have different strengths/weaknesses and give us different types of information about an object, which is very important conceptually.

(d) Of these three wavelengths (visible light, microwave, and infrared), order them by the depth into Jupiter's atmosphere that they see, from shallowest to deepest.

(e) The central storm is visible in the middle and right panels, but not as much in the left panel. What does this imply about the structure/depth of that storm?

35. (a) Images 18 and 19 show different surface features on the same object. Which object?
    (b) What mission(s) collected the data to create this image?
    (c) Is the surface feature in Image 18 a crater or mountain? How can you tell?

> This is a question that involves interacting with the image by using the colorbar. It can be difficult to visually distinguish craters from mountains (see the crater illusion), but by looking at the elevation we see that the rim of the feature is elevated and then gets progressively lower in elevation, so it must be a crater.

(d) The surface feature in Image 19 is a crater. What is its name?

(e) Which surface feature has the larger diameter: the one in Image 18 or 19? Explain your reasoning.

> This is another question that could be "brute-forced" if the students have these craters and their diameters on their notes. However, if the students understand the concepts underlying crater morphology, then they know that small craters are typically small and bowl-shaped with smooth walls, while large craters feature more complexity and intricate structures like central peaks.

36. (a) Image 20 shows an exoplanet discovered by through the *transit* method. What is its name?

    (b) Is Image 20 a photograph or an artist illustration? How do you know?

> Artist illustrations of objects like Image 20 are, in my opinion, also fair game for identification. For some things, like exoplanets or the Oort cloud, the only illustration you can get of them is through an artist. However, I try not to use generic illustrations of objects for identification questions too often. And when I do, I sometimes pair them with information independent of the illustration that helps students determine the object/system (like "shows an exoplanet discovered by through the transit method").

37. (a) Every object/system on the rules is represented on the Image Sheet except for one. Which one?

    (b) Give a brief, one-sentence description of what this object/system is.

Section C [70 points]

For the following questions, please explain your answers (i.e., do not just write "yes" or "no").

> I usually put the most difficult, time consuming questions (on average) towards the end of the exam. These questions are usually a mix of math and more difficult conceptual questions. In this exam, this section is a little heavy on the math (mainly because I wanted to show many examples of how math can be incorporated into the event, since there aren't as many examples out there). Although it isn't present in this section, simply because this test was already a little too long, these sorts of questions can (and are encouraged to) involve image interpretation, analyzing plots, etc.

38. (16 points) Imagine that you are part of a team studying small, icy objects in the Solar System. Preliminary measurements of a new object indicate that it is made up of some combination of ice ($\rho = 0.9$ g/cm^3) and rock ($\rho = 3.6$ g/cm^3) and has an overall density of 1.8 g/cm^3.

    > To make the math in this question easier, I intentionally made the numbers multiples of 0.9.

    (a) (3 points) What fraction of the object's *volume* is ice?

    (b) (3 points) What fraction of this object's *mass* is ice?

    > The concepts in parts (a) and (b) are easily confused; therefore I try to test students on it.

    (c) (3 points) Suppose that the object is completely differentiated with a rocky core surrounded by ice. What is the ratio of the radius of the core to the radius of the object?

    > This question reduces down to a simple geometry problem that can easily be solved using proportions *if* the students understand the difference between parts (a) and (b).

    (d) (2 points) If the ice and rock were distributed uniformly throughout the object (i.e., there was no differentiation), would the moment of inertia of the object be higher, lower, or the same compared to the case in part (c)? Explain.

    > Moment of inertia is a concept that can get complicated quickly, especially if we allowed calculators in this event. However, through a question like this, we can quickly assess a student's understanding of the concept without them ever having to calculate a number.

    (e) (3 points) After more analysis, your team realizes that the mass of the object was underestimated by 10%, but the original radius was correct. Would your answers to parts (a), (b), and (c) of this question increase, decrease, or stay the same?

    > I also try to write questions that show how changing one value can affect the value of other derived values. This forces the students to "follow" the path of the calculation to determine the overall effect. These questions can be used to test students on observational biases, error propagation, and more.

    (f) (2 points) In part (c), we assumed that the object was completely differentiated. Does this assumption become better or worse as the size of the object increases?

39. (12 points) Your friend at NASA is planning a mission to study Neptune, but they are not sure whether to power it using RTGs or solar panels. They've asked you for some advice.

(a) (3 points) In your own words, explain what an RTG is. What are some of the advantages and disadvantages of using an RTG over solar panels?

(b) (3 points) The amount of available sunlight is critical to evaluating the effectiveness of solar panels. If the intensity of sunlight at Earth is $\sim$1350 W/m^2 and Neptune is 30 AU from the Sun, what is the intensity of sunlight at Neptune, in W/m^2?

(c) (4 points) Your friend tells you that their spacecraft will require $\sim$150 W to operate safely. Modern solar panels in space operate at about 20% efficiency and have a mass of $\sim$1 kg/m^2. Estimate the surface area and mass of the solar panels that would be required to power your friend's spacecraft.

(d) (2 points) Let's put it all together. In your opinion, would you recommend that your friend uses solar panels or an RTG? Explain your choice.

> This question tests students' understanding of the tradeoffs that go into mission design. It very easily could have been an order-of-magnitude estimation question, but I intentionally chose Neptune (30 AU from the Sun) and rounded the intensity of sunlight at Earth to 1350 W/m^2 to make the math easy to do by hand. Mission-related questions do not have to cover power sources; they can be about mission architecture, propulsion, instrumentation, or anything in between.

40. (22 points) When a planet is in thermal equilibrium, the power it absorbs is equal to the power it emits. However, Saturn's total luminosity is $\sim$2 times greater than the power that it absorbs from the Sun. One theory is that the excess energy comes from liquid hydrogen and helium inside Saturn demix (i.e., separate) and the helium droplets fall down as "rain", converting their gravitational potential energy to heat.

(a) (2 points) Scientists do not think Jupiter will exhibit H/He demixing as much as Saturn. Part of the reason is that Jupiter's interior is much hotter than Saturn's. Explain.

(b) (2 points) Why do the helium droplets sink towards the center of Saturn instead of staying where they are?

(c) (10 points) Estimate, to the nearest few orders of magnitude, the energy, in Joules, that would be released if *all* of the helium from Saturn's envelope rained onto the surface of the rocky core of Saturn. This is intentionally written as an open-ended problem with incomplete information; use your knowledge of planetary science to make reasonable assumptions and guesses. Since this is just an order-of-magnitude estimate, the exact values don't matter as much. Some helpful information:

- Saturn's total mass is $\sim 100 M_{\oplus}$ and its radius is $\sim 6 \times 10^7$ meters
- $G = 7 \times 10^{-11}$ N m^2 kg^{-2} and $1\ M_{\oplus} = 6 \times 10^{24}$ kg

(d) (6 points) Estimate, to the nearest order of magnitude, the *excess* energy Saturn has emitted over its lifetime, in Joules. Some helpful information:

- The intensity of sunlight at Earth is $\sim$1350 W/m^2
- Saturn is about 9.5 AU from the Sun and absorbs 60% of the light that hits it
- 1 year = 3×10^7 seconds

> Parts (c) and (d) of this question are examples of order-of-magnitude estimation questions. Since students are only allowed two pages of notes, I give them some values that could be helpful. Part (c) is much more of a rough estimate than part (d).

(e) (2 points) Compare your answers to the previous two parts and comment on whether you think helium rain is a possible candidate for Saturn's excess luminosity.

Note: this question was adapted (essentially copied) from Question 4 on Problem Set 2 of Eugene Chiang's Planetary Astrophysics class at UC Berkeley.

41. (20 points) As a star forms, the material around it forms a rotating disk of gas and dust.

(a) (2 points) Many objects in the universe are spinning disks. In your own words, explain why.

(b) (2 points) Planets form inside this disk. The two leading theories of planet formation are the core accretion and disk instability models. Briefly describe what the core accretion model is.

Now, we'll take a closer look at the disk instability model, in which a local overdensity in the disk collapses in on itself to form a planet. Within the disk, multiple forces are at play, such as self-gravity, shear, and pressure. Consider a small chunk of the disk that has radius Δr, centered at a distance R from the star. Ignoring dimensionless factors of order unity, the three timescales in the disk at R are

$$t_{\text{grav}} \sim \sqrt{\frac{\Delta r}{G\Sigma}} \qquad t_{\text{shear}} \sim \frac{1}{\Omega} \qquad t_{\text{pr}} \sim \frac{\Delta r}{c_{\text{s}}}$$

where G is the gravitational constant, Σ is the surface mass density of the disk, c_{s} is the speed of sound in the disk, and Ω is the angular velocity of the disk at R.

(c) (3 points) What causes shear forces in a protoplanetary disk? *Hint: think about Kepler's third law*

> I often try to ask "why?" questions. Instead of just telling you that shear forces exist (something many students will know), I also want to ask *why* shear forces would exist to begin with.

(d) (1 point) Within the disk, which will dominate: the force with the shortest or longest timescale?

(e) (3 points) Physically, what is happening when t_{shear} and t_{pr} are both much less than t_{grav}? Do these conditions make it easier or harder for a chunk of the disk to collapse?

(f) (7 points) One model for planet formation involves a local overdensity in this disk collapsing to form the planet. Using the timescales above, derive Toomre's instability criterion: $Q \sim \frac{c_{\text{s}}\Omega}{G\Sigma} < 1$.

(g) (2 points) Having $Q < 1$ at the start of the collapse is a necessary, but not sufficient condition for disk fragmentation. What else do we need, and why?

42. *Tiebreaker #1:* When preparing for this event, you probably studied some concepts that weren't covered explicitly on this exam, simply because this exam can't be infinitely long. Choose one of them and write about it in as much detail as you can.

> I often include this question at the end of my invitational and regional exams. Students may have studied a specific concept/object in depth that did not explicitly appearas much on the exam; for example, in this exam, exoplanets were not emphasized as much. I want to give them an opportunity to show it off so that they do not feel that it is "wasted". It is also fun for me as an event supervisor to read students' responses about topics they are passionate about.