Solar System B - Solar System - National Tournament 2022 - 05-14-2022

Welcome to the Science Olympiad National Tournament 2022! This test is for **Solar System** in **Division B**.

Directions:

- You will have 50 minutes to complete this exam.
- You are permitted to have two 8.5" × 11" sheets of paper with information on both sides.
- There is no penalty for wrong answers.
- Good luck! Above all else, just believe.

Section A [60 points]

For each image given below, the questions which follow refer to that image alone.

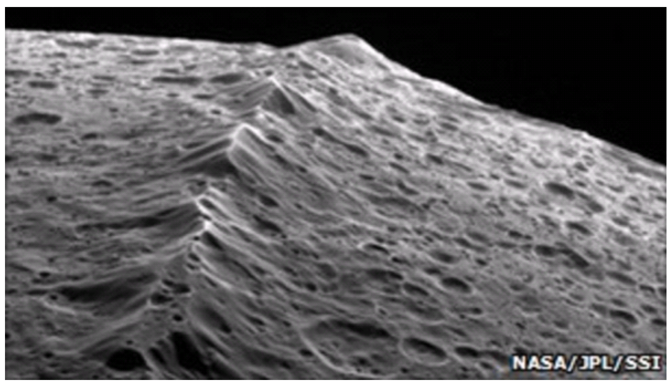


Image Credit: NASA/JPL/SSI

The image above depicts a surface feature of unknown origin on a rocky Solar System object.

1. (1.00 pts) What is the name of this object?

Iapetus

2. (1.00 pts) What spacecraft or telescope took this image?

Cassini

3. (1.00 pts) What is the primary compositional material of the ridge feature seen in this image?

Ice

4. (1.00 pts)
This feature is thought to be very old, perhaps even as old as the object itself. Just by looking at this image, why might planetary scientists think that this feature is very old?

Expected Answer: The presence of numerous craters on the feature

5. (2.00 pts)
There are multiple prominent theories regarding the formation of this feature, with some external to the object and others internal to it. Briefly describe one external theory and one internal theory for the formation of this surface feature.

Expected Answer: Answers will vary. Possible answer: External: early formation created a sub-moon which was destroyed by tidal forces and had its material distributed equatorially Internal: de-spinning stresses post-formation drove buoyant ice in its interior to the surface, pushing up against the crust

Image Credit: NASA/JPL-Caltech

The image above depicts a close-up of the atmosphere of one of the outer planets of our Solar System.

6. (1.00 pts) Which spacecraft was responsible for capturing this image?

Juno

7. (1.00 pts) What instrument on this spacecraft collected the data used to create this image?

JunoCam

8. (2.00 pts) What type of fluid instability are the shapes in this atmosphere consistent with? What causes this instability in the atmosphere?

Expected Answer: Kelvin-Helmholtz instability, caused by cloud decks of different densities interacting with each other

9. (3.00 pts) Theoretically, could this same phenomenon be seen on other planets in the outer Solar System? Could it be seen on Earth? Explain.

Expected Answer: Yes to both, since they all have the same variable-density atmospheric interactions

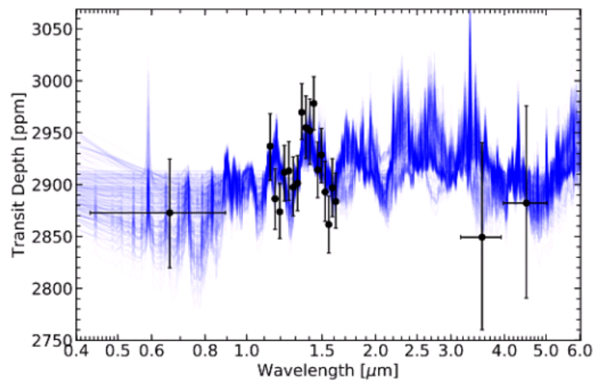


Image Credit: B. Benneke et al. (2019)

The image above depicts data captured of the exoplanet K2-18b.

10. (1.00 pts) What process/technique was used to generate the data in this plot?

Expected Answer: Transit spectroscopy OR transmission spectroscopy

11. (2.00 pts) Briefly describe the process/technique from the previous question.

Expected Answer: As K2-18b passes in from of its host star, light from the star passes through its atmosphere and is partially blocked at certain wavelengths by various molecules

12. (1.00 pts) What significant feature of K2-18b does this plot depict?

Expected Answer: Water vapor in its atmosphere

13. (1.00 pts) How would you expect this plot to change if this feature were not present?

Expected Answer: The large peak at ~1.5 um would not be present

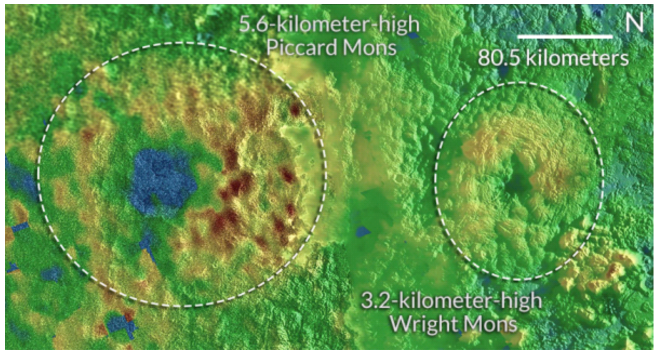


Image Credit: NASA/SwRI/JHUAPL

The image above depicts two prominent surface features on a rocky Solar System object.

14. (1.00 pts) What is the name of this object?

Pluto

15. (1.00 pts) What spacecraft or telescope took this image?

New Horizons

16. (1.00 pts) What do the various colors in this image represent?

Expected Answer: Topographic profile (height above surface)

17. (1.00 pts) These features appear to be analogous to what geologic feature of the Earth's surface?

Expected Answer: Shield volcanoes

18. (2.00 pts) If these features were in fact the same as those on the Earth they are similar to, what would that imply about the history and structure of this object?

Expected Answer: Pluto would have to have been geologically active now or in the past, with an internal structure at least resembling Earth's mantle and crust

19. (1.00 pts) In the case of the above scenario, how would these features necessarily differ from analogous ones on Earth?

Expected Answer: They would erupt with compounds of ice, nitrogen, ammonia, etc instead of molten rock

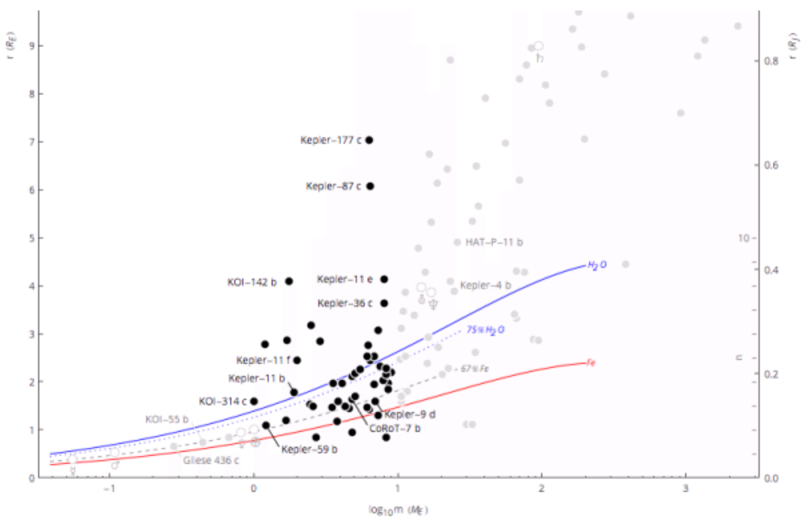


Image Credit: Aldaron, a.k.a. Aldaron - Own work, Public Domain, Wikimedia Commons

The image above plots detected radius against mass to characterize exoplanet type.

20. (1.00 pts) Based on the masses and radii shown in the plot, what general type of exoplanet do the black dots represent?

Super-Earths

21. (2.00 pts) What do the lines labeled 'H_2O' and 'Fe' represent?

Expected Answer: These lines represent boundaries of radius/mass ratio in planets whose composition is entirely water or iron respectively

22. (1.00 pts) Where on this plot (including proximity to H_2O/Fe lines) would you expect to find the exoplanet Kepler-138b?

Expected Answer: Bottom-left, closer to the Fe line than the H2O line

23. (1.00 pts) Where on this plot (including proximity to H_2O/Fe lines) would you expect to find the exoplanet TOI-561b?

Expected Answer: ‘Halfway’ between 0 and 1 on x-axis, close to the H2O line

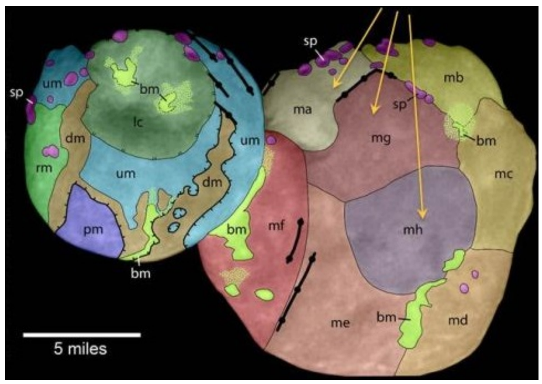


Image Credit: NASA/JHUAPL/SwRI/ESA

The image above depicts the geologic composition of a Solar System object.

24. (1.00 pts) What is the name of this object?

Expected Answer: Arrokoth, or Ultima Thule, or 2014 MU69

25. (1.00 pts) What is unique about the geologic composition of this object relative to others of its type?

Expected Answer: It has many variable rock beds which are entirely dissimilar across its two lobes

26. (2.00 pts) What does this composition imply about the formation of this object?

Expected Answer: The two lobes most likely formed separately, hence their differences in composition and lack of shared rocky material, and coalesced into a single object

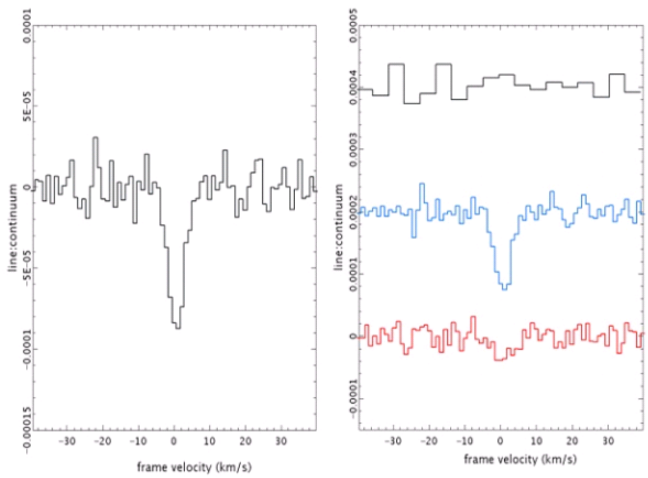


Image Credit: arXiv:2009.06593v1 [astro-ph.EP]

The image above plots the combined (left) and altitude-separated (right) spectra of the atmosphere of Venus.

27. (2.00 pts) What is indicated by the prominent dip seen as ~0 km/s frame velocity in both plots?

Expected Answer: The strong presence of a molecule or compound in the atmosphere that blocks light at that frequency in unexpectedly high concentration

28. (1.00 pts) This dip was interpreted at first as a potential biosignature in the planet's atmosphere; why might this have been assumed?

Expected Answer: If the dip corresponded to a molecule only produced through biological processes, it could indicate life

29. (2.00 pts)
The theory above has since been disproven, with the assumption of a biosignature in the spectra disregarded. Name two possible sources for this incorrectly-attributed spectral feature.

Expected Answer: Another molecule occupying a similar spectral location; errors in the data analysis; telescope malfunction (other possibilities accepted within reason)

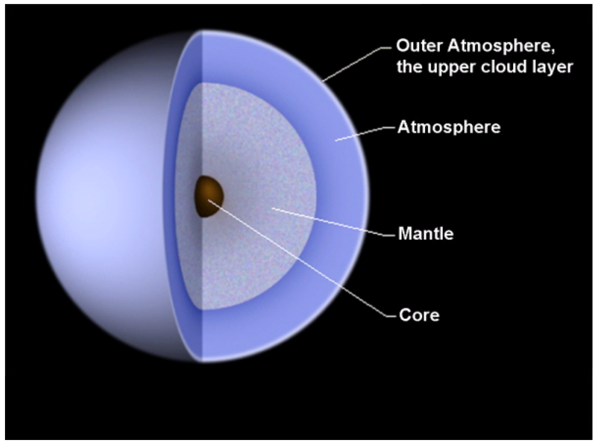


Image Credit: NASA

The image above depicts the generic interior structure of a type of planet seen in our Solar System.

30. (1.00 pts) Which planet(s) in our Solar System could this diagram represent?

Expected Answer: Uranus, Neptune

31. (2.00 pts) What is the primary component of the layer labeled ‘Atmosphere’? What about the layer labeled ‘Core’?

Expected Answer: Hydrogen, silicate/iron-nickel rock

32. (2.00 pts) What general type of planet does this diagram represent, and how does it differ from planets of a different type but similar size/density?

Expected Answer: Ice giant planet, atmosphere containing water ice particles and elements heavier than hydrogen/helium like gas giants

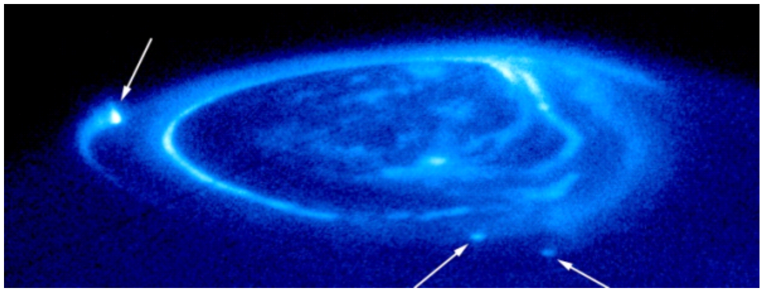


Image Credit: NASA/STScI/AURA

The image above depicts the polar region of a Solar System object.

33. (1.00 pts) What is the name of this object?

Jupiter

34. (1.00 pts) Which spacecraft or telescope was responsible for capturing this image?

Hubble

35. (1.00 pts) What instrument on this spacecraft or telescope collected the data used to create this image?

WFPC2

36. (1.00 pts) What atmospheric feature is prominently displayed in this image?

Expected Answer: Aurora

37. (1.00 pts) In this image, there are three arrows that point to small white dots. What do these dots represent?

Expected Answer: Locations of increased magnetized particle density

38. (2.00 pts) Within this system, what (types of) objects are the source of these dots? How do these objects create the white dots shown in the image?

Expected Answer: The source is particles released from the exospheres of Jupiter's moons which follow along Jupiter's strong magnetic field lines and impact the surface, creatin increased electron density in the areas they impact

39. (2.00 pts)
Suppose you're part of a NASA/JPL team designing a spacecraft to visit the object pictured in this image. How might the process observed in this image (and the planetary/atmospheric structures that help enable it) influence the design of your mission's orbit around this object?

Expected Answer: Because Jupiter's magnetic field creates such regions as this of increased electron density, the mission's orbit will have to to avoid these regions and image Jupiter from afar to avoid damaging its on-board instruments

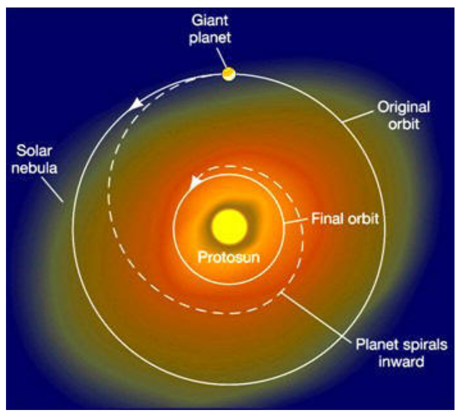


Image Credit: D. N. C. Lin et al. (1996), F. A. Rasio et al. (1996)

The image above depicts a process thought to occur early in the life of some planetary systems.

40. (1.00 pts) What is the name of the process being depicted here?

Expected Answer: Inward orbital migration

41. (1.00 pts) Which exoplanet from this year's rules is most likely to have undergone this process in the last 10 million years?

K2-33b

42. (1.00 pts) What is the most notable characteristic about this exoplanet?

Expected Answer: It is extremely young, only ~9.3 million years old, despite orbiting extremely close to its parent star

43. (1.00 pts) How would this characteristic be explained by the process depicted above?

Expected Answer: Orbital migration could imply it formed further out and transitioned to its current orbit

44. (2.00 pts) Why is it unlikely that this planet came to be the way it is without some exterior process occuring?

Expected Answer: Since its orbit is so close to its parent star, it is extremely hot, which means it is much harder for the materials necessary to form a planet to condense out and accumulate

Section B [72 points]

HR 8799 Exomoon Limits

Just like how exoplanets are planets outside of the Solar System, exomoons are moons outside of the Solar System. Exomoons are difficult to detect, and the objects that would b the easiest to detect (large exomoons and binary planets) are exceedingly rare. As a result, searching for exomoons and understanding how they affect the formation and evolution of their planets has been an area of active research. In a paper published last fall, Andrew Vanderburg (MIT) and Joey Rodriguez (Michigan State University) have found a way to place limits on the presence of exomoons (or even binary planets) around HR 8799 b, c, and d through the radial velocity technique and some clever data analysis.

45. (3.00 pts)
One of the ways a planet can gain a moon (or binary planet) is through the gravitational capture of an object that was formed somewhere else. One of the moons on the rules for thi event is thought to have been gravitationally captured just like this. What is the name of this moon? What planet does it orbit around? Why do we think it was gravitationally captured as opposed to being formed around the planet itself?

Expected Answer: Triton, Neptune, composition, retrograde orbit, lack of other satellites around Neptune (and the ones that are there have eccentric orbits)

46. (3.00 pts)
Alternatively, moons can form "in place" around the planet they orbit. Previous work shows that it's pretty easy for less massive moons to form like this, but more massive companions (which are the easiest to detect) are very rare. Why might it be difficult to form more massive companions directly from circumplanetary disks around planets?

Expected Answer: M_moon/M_p is higher for smaller, rocky planets, but the planet mass is small, so the moons can't end up being super big anyways. Having larger planet masses doesn't help that much. That ratio is on the order of 10^{-4} for gas planets, so the largest moons they can USUALLY form are about the size of Earth's moon or Mars. The gas loss rate from the circumplanetary disk for gas planets is much higher. So, forming a super big moon (or a binary planet) in situ would be pretty hard.

47. (2.00 pts)
Vanderburg and Rodriguez used the radial velocity measurements of the **planets** (not the parent star) to search for any signs of moons orbiting around HR 8799 b, c, and d*. Based on your knowledge of HR 8799 (and its orientation to us), would you expect the planets in the system to have a large radial velocity even if they had very large moons orbiting around them? Why or why not?

Hint: Moons typically orbit in the same plane as their planets, and HR 8799 is a directly imaged system.

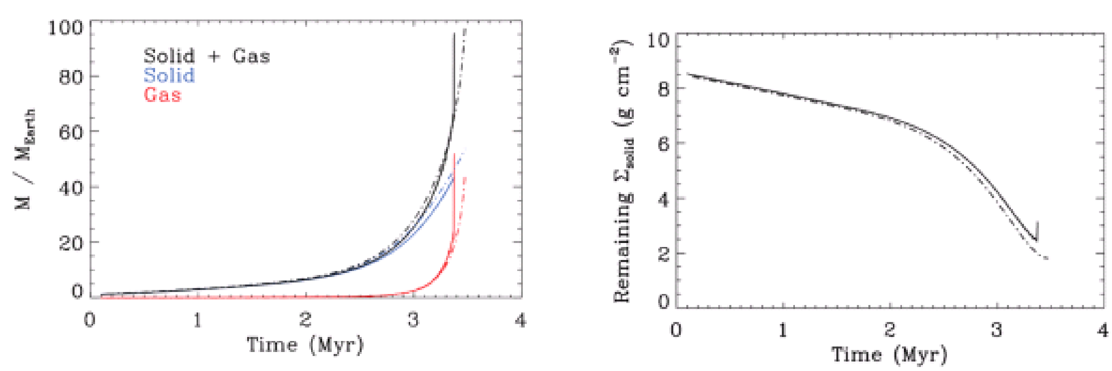
Expected Answer: We would not expect the RV signal to be very strong since we are viewing the HR 8799 system almost perfectly face-on

48. (4.00 pts)
Vanderburg and Rodriguez didn't find any obvious moons or binary planets from the radial velocity signals, but their work was groundbreaking in that they were able to search for exomoons with short periods around planets that orbit far from their parent stars, which had never been done before.

Other researchers have looked for exomoons using both the transit method and direct imaging. Compared to the radial velocity technique, which types of moons do you think transits and direct imaging would be best suited to find? Frame your answer in terms of two variables: how close the moon is to the planet, and how close the planet is to the parer star.

Expected Answer: Transit: planets close to the parent star; direct imaging: moons far away from planets, which in turn are far away from the parent star

The Formation of Saturn



The image above shows two plots from Dodson-Robertson *et. al.* (2008) in which researchers simulated the formation of Saturn. On the left, we see the mass of Saturn as it formed as a function of time. The black curves show the total planet mass, which is the sum of the blue and red curves, which show the only the solid mass and gas mass, respectively. Or the right, we see the remaining solid surface density, not yet accreted by Saturn, as a function of time. The researchers stop their simulation at 3.4 Myr, when the total mass of their planet reaches the present-day mass of Saturn.

49. (3.00 pts)
Based on the plots above, which theory of planet formation (core accretion or disk instability) do you think the authors of this study used to simulate the formation of Saturn? How do you know?

Expected Answer: Core accretion model (1), correct explanation (2)

50. (3.00 pts)
Based on their data, Dodson-Robertson and colleagues do not think Saturn reached its isolation mass during its formation. How does the data in the rightmost plot support this conclusion?

Expected Answer: When the simulation ended, the surface density of solids is greater than 0

51. (4.00 pts)
There are several reasons why Saturn may not have reached its isolation mass during its formation. One of them is that Saturn is too far away from the Sun. Why would this prevent it from reaching its isolation mass?

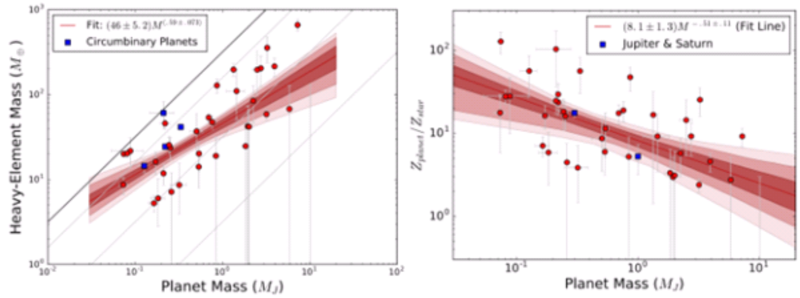
Hint: Based on your knowledge of Kepler's Laws, do objects further from the Sun move in their orbits at higher or lower speeds? How might the speed at which an object moves affect its ability to form a planet through this planet formation method?

Expected Answer: The low orbital speeds far from the Sun prevented Saturn from accreting solids efficiently enough to reach isolation mass

52. (5.00 pts)
Consider an alternate universe in which Saturn *did* reach its isolation mass during the formation process. Would the ratio of solid mass to gaseous mass in the alternate universe's Saturn be higher, lower, or the same as that of in our universe's Saturn?

Expected Answer: Lower

Mass-Metallicity Relation for Gaseous Planets



The image above shows two plots taken from Thorngren *et al.* (2015). On the left, we see the trend between heavy-element and planet masses for modeled gas giant planets, while on the right, we see the fraction of the planet-to-star metallicity as a function of planet mass.

53. (3.00 pts)
Thorngren and colleagues made the conscious decision to exclude Hot Jupiters from their set of planets, as the relationship between their mass and radii are not as well-defined. Why would the mass-radius relationship for Hot Jupiters be more difficult to quantify accurately than for more "generic" planets?

Expected Answer: Being so close to their parent stars causes Hot Jupiters to become very hot, giving them "puffy" atmospheres that inflate their radii compared to their mass. Determining the amount the radii are inflated depends on many different factors and is non-trivial.

54. (6.00 pts)
There is a known correlation (not shown in either of the two plots above) between giant planet mass and the metallicity of the host star. Do you expect these two variables to be correlated positively or negatively? How can this observation be described using planet formation theory?

Expected Answer: Positive correlation. More metal-rich disks can more easily create the cores of giant planets which then accrete gaseous envelopes.

55. (6.00 pts)
Looking at the two plots, we see a negative correlation between the planet mass and planet metallicity but a positive correlation between planet mass and heavy element mass, which may seem a little counterintuitive at first glance. Explain why we see these two trends.

Hint: Looking at the leftmost plot in the "Formation of Saturn" series of problems may help with this question.

Expected Answer: larger cores -> larger planet masses, but they attract gas faster than solids, so the extra mass comes from gases more than solids (metals)

Transiting Multi-Planet Systems

In addition to understanding the structure and formation of individual planets in a system, astronomers are also very interested in the structure and formation of planetary systems, many of which contain multiple planets, like TOI-561. In this series of questions, we'll explore how one of the most widely-used exoplanet detection technique fares in finding these types of systems by first taking a closer look at our own Solar System.

56. (2.00 pts) Of the planets in our Solar System, which one has the highest probability of transiting the Sun when viewed by an external observer? Explain why.

Expected Answer: Mercury, it is the closest to the Sun

57. (4.00 pts)
Suppose an alien civilization discovers our Solar System using the radial velocity method. As a result, they know the periods and semimajor axes of the planets, but they don't knov anything about their relative orbital inclinations. Would they have a higher chance of seeing at least one transiting planet if (a) all the planets in our Solar System were perfectly coplanar (aligned), or (b) all the planets had very different inclinations relative to each other? Explain your answer.

Expected Answer: Very different inclinations

58. (6.00 pts)
Although the planets in our Solar System are mostly coplanar, their relative inclinations are still on the order of a couple of degrees (0.05 to 0.1 radians). If an alien civilization were t observe our Solar System, is it more likely that they (a) see most, if not all our eight planets if they see any at all, or (b) even if they see any transits, they only see one or two planets?

Hint: This question doesn't require any rigorous calculations, but it may need a bit of geometry and some order-of-magnitude estimation that can be done using a pencil and paper. I may be helpful to know that for small angles, $\tan^{-1}(x) = \arctan(x) \approx x \text{ radians}$

Expected Answer: one or two planets

59. (3.00 pts)
Based on your answer to the previous few questions, do you think that the true proportion of multi-planet systems in the universe is higher, lower, or the same as the proportion of multi-planet systems we've discovered? Why do you think so?

Expected Answer: higher than what we've discovered so far

The Gravitational (Disk) Instability Model

In a protoplanetary disk, there are multiple forces at play: self-gravity within the disk (causing the disk to clump up), shear (causing the disk to smear), and the pressure of the hot gas in the disk (which generally opposes self-gravity). Each of these forces have an accompanying timescale, which is a measure of the amount of time necessary for the force to "act". In this model for planet formation, a local overdensity in the protoplanetary disk collapses in on itself to form the planet.

60. (2.00 pts) Which will dominate: the force with the shortest timescale, or the force with longest timescale?

Expected Answer: shortest

61. (4.00 pts) Why would shear forces exist in a protoplanetary disk? In your answer, be sure to mention Kepler's Laws explicitly.

Expected Answer: Keplerian disks rotate differentially meaning that angular velocity decreases with increasing radius. This results in the shear force.

62. (9.00 pts)
Challenge: The three timescales in the disk, at radius R, are roughly approximated using the following relations:

$t_{grav} \sim \sqrt{\frac{R}{G\Sigma}}$

$t_{shear} \sim \frac{1}{\Omega}$

$t_{pressure} \sim \frac{R}{c_s}$

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. Furthermore, we know that $t_{grav} \ll t_{shear}$ and $t_{grav} \ll t_{pressure}$.

Using these inital constraints, derive the Toomre instability criterion:

$\frac{c_s\Omega}{G\Sigma} \ll 1$

Expected Answer: based on effort

We hope you enjoyed this exam! Planetary science is a beautiful mix of subjects, from chemistry and physics to astronomy and geology, and we hope this event does it justice. If you have any feedback about the exam or the event as a whole, please let us know through this form: tinyurl.com/sont22ss