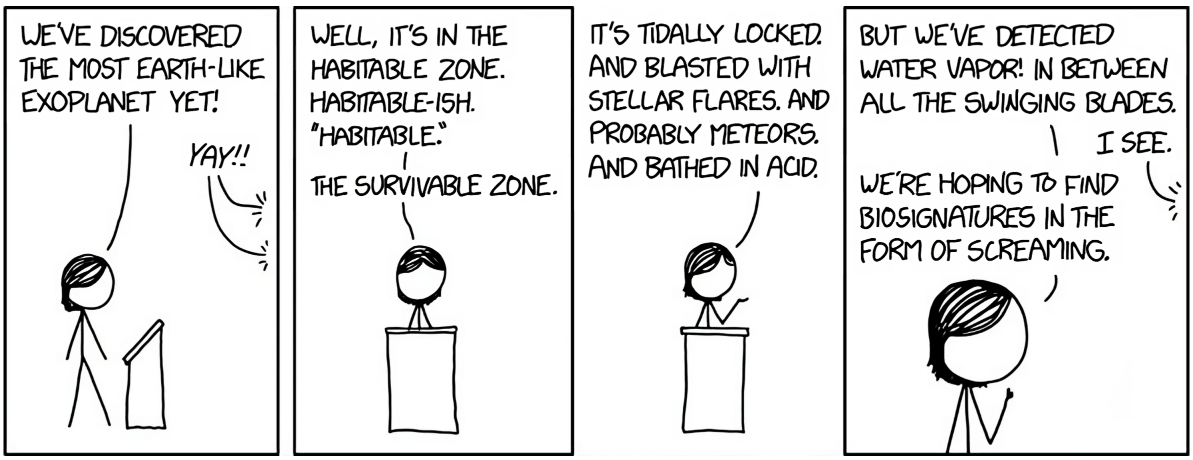
Science Olympiad
MIT Invitational
January 25, 2025

Astronomy C



Directions:

- Each team will be given **50 minutes** to complete the exam.
- There are **80 questions** split into two sections: **§A** (Multiple Choice) and **§B** (Free Response).
- **Do not write on the exam or image sheet**. Only write on your answer sheet.
- For calculation questions, **work will be graded**. Please show all your work.
- The use of AI tools (e.g. ChatGPT) are expressly forbidden.
- Tiebreakers, in order: Q1–6, §B-I, §B-II, §B-IV, §A.
- Good luck! And may the stars align for you.

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Section A: Multiple Choice

This section consists of 20 multiple choice(-ish) questions about general astronomy concepts. Each question is worth 2 points, for a total of 40 points.

Stars begin their lives as collapsing dust and gas from ____1____ . This material, more often than not, is rotating and leads to the formation of ____2____ which produce ____3____ . ____4____ this excess angular momentum, crash into the surrounding medium, and form luminous bulbs known as ____5____ . Eventually, these stars begin to fuse ____6____ , reaching the main sequence.

1. A. filaments C. spiral nebulae
   B. starfields D. molecular clouds
2. A. bow shocks C. dusty envelope
   B. stellar winds D. accretion disks
3. A. HII regions C. absorption lines
   B. planetesimals D. emission lines
4. A. Viscous boundaries consolidate
   B. Bipolar jets draw out
   C. Proplyds attenuate
   D. Density waves dissipate
5. A. HH objects C. T Tauri nebulae
   B. Bok globules D. shock clouds
6. A. hydrogen C. lithium
   B. helium D. iron

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7. Four brown dwarfs are found with different masses. Which mass is most likely to correspond to a brown dwarf that fuses lithium? Here, M_J denotes the mass of Jupiter.
   A. $10\,M_J$
   B. $20\,M_J$
   C. $40\,M_J$
   D. $80\,M_J$

8. Estimate to order of magnitude the pressure at the center of a brown dwarf with mass $10\,M_J$ and density 10 times that of water.
   A. 10^{10} Pa
   B. 10^{13} Pa
   C. 10^{16} Pa
   D. 10^{19} Pa

9. According to observations thus far, which of the following radii is least likely to be observed for a sub-Neptune planet? Here, $R_\oplus$ is the radius of the Earth.
   A. $1\,R_\oplus$
   B. $1.75\,R_\oplus$
   C. $2.5\,R_\oplus$
   D. $3.5\,R_\oplus$

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10. On a log-log plot, a power law (i.e. $y \propto x^\alpha$) forms a ________.
    A. straight line
    B. convex curve
    C. concave curve
    D. Depends on α

11. Which of the following orbits of a comet around a star has positive total energy? (Only considering the energy of the comet)
    A. Elliptical
    B. Circular
    C. Parabolic
    D. Hyperbolic

12. A common assumption in calculating the surface temperature of a planet is that the absorption and emission surface area of the planet are equal, $A_{\text{abs}} = A_{\text{em}}$. What if instead the planet is tidally locked to its host star, with the same side of the planet always facing the star? Calculate the ratio of the planet's surface temperature in this case to the temperature in which $A_{\text{abs}} = A_{\text{em}}$.
    - A. $2^{-1/4}$
    - B. $2^{-1/2}$
    - C. $2^{1/2}$
    - D. $2^{1/4}$

13. Where would the Balmer spectral lines be most likely to be found?
    - A. HI regions only
    - B. HII regions only
    - C. Neither HI nor HII regions
    - D. Both HI and HII regions

For the next 3 questions, match a key feature (A–D) to the model.

14. Gravitational instability model of giant planet formation.

15. Core accretion model of giant planet formation.

16. Widely accepted model for terrestrial planet formation.

    - A. The formation of a solid core through the accumulation of dust and gas
    - B. The direct collapse of a giant molecular cloud into a gas giant
    - C. "Pebble accretion" of colliding planetesimals, leading to a phase of oligarchic growth
    - D. The fragmentation of the disk into a planetary ring system, leading to the formation of planets

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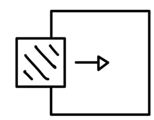
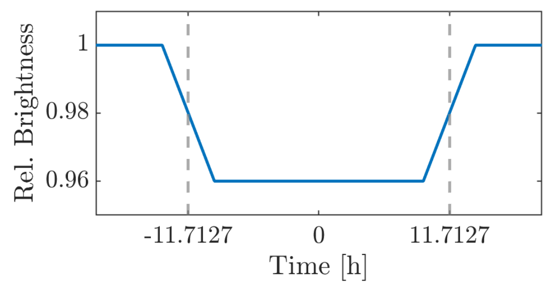
17. The transit method is more sensitive to which types of planets?
    - A. Large planets with large orbits
    - B. Large planets with small orbits
    - C. Small planets with large orbits
    - D. Small planets with small orbits

For the next 3 questions, you find yourself in an alternate reality where stars and planets are cubes. You observe a planet transiting a star and generate the light curve below. (For simplicity, we assume the star is much brighter than the planet and there is no limb darkening.) <u>Do not show work.</u>

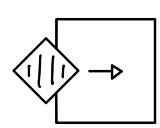


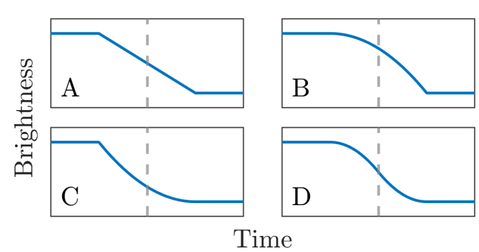


18. What is the ratio between the side length of the star and the planet? (Whole number)

19. From Doppler measurements, you determine the planet's velocity is $1\,\text{au}\,\text{yr}^{-1}$. What is the side length of the planet in km? (1 sig. fig.)

20. Suppose the planet is rotated 45° when it transits the star. Which of the following light curves would you expect to see during ingress? (A–D)





Section B: Free Response

This section consists of 7 subsections of free response questions, each investigating one of this year's deep-sky objects. Points are shown for each question, for a total of 120 points.

Numerical answers must be provided to 3 significant figures. Please show your work: no work, no points. Partial credit may be awarded for correct work.

Subsection B-I: The Tarantula Nebula

21. [1 pt] Image 1 shows the Tarantula Nebula in which wavelength regime?
22. [3 pts] Most of the illumination in this image comes from extremely hot gas. Why is this wavelength regime a good tracer of hot gas? Explain with the radiation laws.
23. [2 pts] What is primarily responsible for the heating of this gas?

Near the center of the image, there are four bright stars in a cavity. The remaining questions will focus on this part of the Tarantula Nebula.

24. [1 pt] What is the name of this stellar association?
25. [2 pts] What are two phenomena that are primarily responsible for the cavity?
26. [1 pt] What types of stars are these?

Image 2 shows an H-R diagram of this stellar association. The probability density distribution of the stars are shown by the colored contours on the right panel; the gray contours on the left panel show the probability density distribution of Milky Way stars. Evolutionary tracks are also shown for different zero-age main sequence masses.

27. [1 pt] What evolutionary stage are the stars marked by blue circles?
28. [3 pts] ~~The stars marked by red circles are thought to be background contaminants and not a part of the star cluster. Explain how this can be interpreted from this H-R diagram.~~
    This question was thrown out.
29. [1 pt] On each panel, there are two vertical curves marked in black. What does the left vertical curve represent?
30. [2 pts] What does the right vertical curve represent?
31. [3 pts] From both Images 1 and 2, is the star formation rate of the Tarantula Nebula significantly above, about the same, or significantly below the average star formation rate of the local group? Justify your answer with both images.

Subsection B-II: The Orion Nebula

32. [2 pts] Identify which image(s) depict the Orion Nebula. For each image, which telescope(s) took them?
33. [2 pts] Calculate the distance to this object in light years if its absolute magnitude is −4.1 and its apparent magnitude is 4.0.
34. [1 pt] Revise your estimate of the distance if 0.05 mag of extinction was unaccounted for in the previous calculation.

The Orion Nebula has apparent dimensions of 65 $\times$ 60 arcmin. Assume that the nebula is disk-shaped and appears as an ellipse in the night sky, with the semiminor axis independent of inclination.

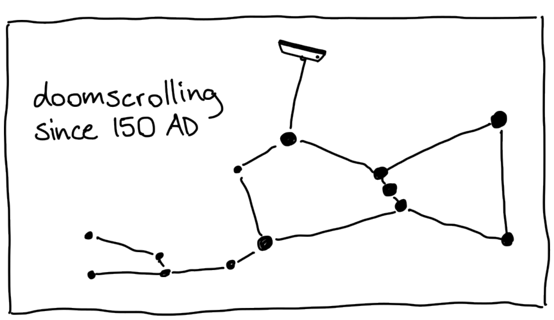
35. [3 pts] For what inclination angle(s) i would its cross-section actually trace out a circle? Assume $i = 0$ corresponds to the situation where the cross-section is perpendicular to the line of sight.
36. [3 pts] Assuming the inclination angle calculated above and that stars at the outer edge of the nebula have an orbital velocity of 2 $\mathrm{km\,s^{-1}}$, calculate the mass of the Orion Nebula in solar masses. Could this velocity measurement have been easily ascertained from a radial velocity measurement?
37. [2 pts] Use your answers to the previous questions to calculate the orbital period of stars at the outer edge of the nebula in years.
38. [3 pts] Does it make sense to characterize the dynamics of stars in this nebula with Keplerian orbits around the center of the nebula? Why or why not? In what regions of this nebula might such an approximated description be valid?

Researchers discovered a eclipsing binary of brown dwarfs named 2MASS J05352184-0546085 in the Orion Nebula and found that the less massive component was actually more luminous!

39. [3 pts] Propose a possible explanation for this observation and a follow-up measurement that could be conducted to confirm this hypothesis.

Image 3 shows supersonic "bullets" that were discovered in this nebula.

40. [1 pt] What is the name of the electromagnetic spectrum in which this image taken? Be as specific as possible.
41. [1 pt] What is the composition of the blue-glowing tips of the bullets?
42. [1 pt] What is the composition of the orange trailing edges of the bullets?



Subsection B-III: WASP-17b

WASP-17b is a famous exoplanet that was discovered in 2009.

43. [1 pt] Identify the detection method used in its discovery.

44. [1 pt] What is significant about the orbital motion of this exoplanet?

45. [2 pts] What is the ratio of the density of this exoplanet to that of Jupiter if it has a radius twice that of Jupiter and mass half that of Jupiter?

The phenomenon in the previous part was probed using the Rossiter-McLaughlin effect.

46. [2 pts] If a star is rotating, one part of its photosphere will be moving towards the observer. What will happen to a spectral line measured from this part of the star?

47. [3 pts] As WASP-17b transits across its host star, what happens to a spectral line measured from the star? Explain what is happening physically.

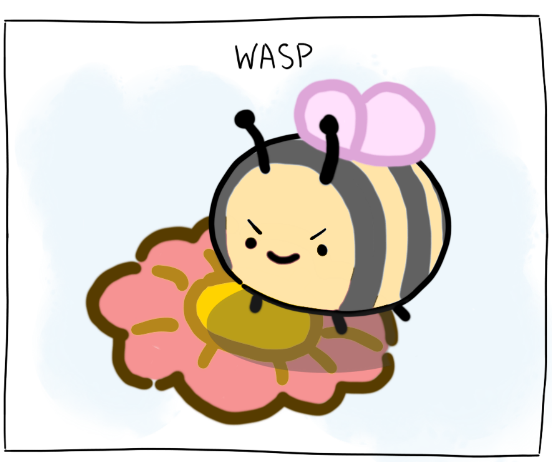
Quartz clouds were detected in the atmosphere of WASP-17b in 2023 through transmission/absorption spectroscopy, as shown in Image 7.

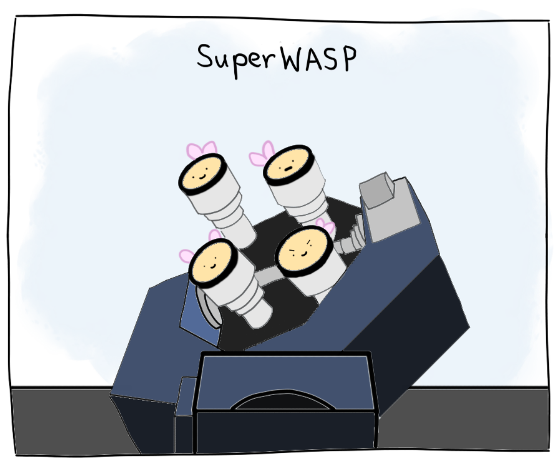
48. [1 pt] Name the range of the electromagnetic spectrum in which this detection was performed. Be as specific as possible.

49. [3 pts] Why was the finding of pure quartz significant? How could quartz be distinguished from the more common alternative in exoplanet atmospheres in a measurement of the planet's spectrum?

50. [2 pts] Physically, what causes the resonance from quartz in the absorption spectrum at around 8.5 μm?

51. [4 pts] In addition to the quartz feature, there is a sharp resonance around 4–5 μm and a broader resonance around 7 μm. What causes each of these resonances? Propose one reason why the latter resonance is much broader than the former.

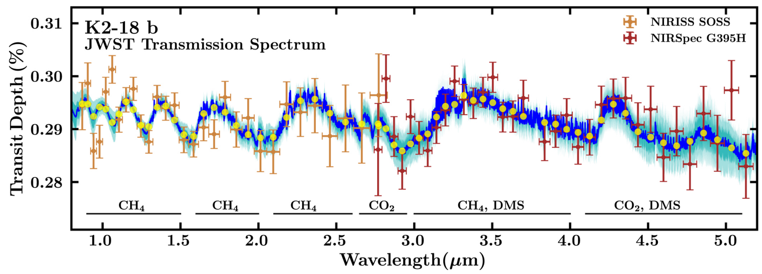




Subsection B-IV: K2-18b

This subsection is the JS9 lab! Access chandra.si.edu/js9/. Here, we will use observations made by Spitzer between 3170 nm and 3950 nm to look at a transit of K2-18b.

52. [2 pts] The transmission spectrum of K2-18b is given below. Spitzer Channel 1 takes images in the 3170 nm to 3950 nm band. Do any spectral lines in the transmission spectrum of K2-18b occur in this range of wavelengths? If so, for what compound(s)?



Now, on the JS9 window, select [File > Open remote] and enter bit.ly/mit25-js9-star. Select [Open], and wait for the file to load in.

This image is an image of the star K2-18 shortly before K2-18b transits in front.

53. [1 pt] On what date were these pre-transit observations taken?

54. [1 pt] If we wanted to make a second follow-up observation of a K2-18b transit as soon as possible after this one, how many days would we have to wait?

55. [2 pts] What is the observed counts of the star, in mJy? (This is the default unit of the net_counts column in the [Counts in Regions] analysis.)

56. [2 pts] There appears to be a bright spot in the bottom left corner of this image. If you can't see it, make sure [Scale > log] is selected. What is the angular distance (in arcseconds) to this spot?

57. [2 pts] We can say with high certainty that this spot is NOT K2-18b. What is one feature of this spot that clues us into this?

Now, on the JS9 window, select [File > Open remote] and enter bit.ly/mit25-js9-transit. Select [Open], and wait for the file to load in.

This file is a subtraction of two images. We took the original image of K2-18 (star) that you just observed, and subtracted the image with K2-18b transiting in front. Thus, this file gives the brightness difference between the star, and the star with the planet transiting.

58. [3 pts] What is the value measured in the lowest-value pixel in this image (in counts)? Why might a value like this occur if the subtracted images are not perfectly aligned?

59. [2 pts] What is the counts difference between the star, and the star with K2-18b transiting in front, in mJy? *(Hint: Image subtraction does not change how* [Counts in Regions] *works.)*

60. [2 pts] Using these measurements, estimate the ratio of the cross-sectional area of K2-18b to the star, K2-18 (assuming that the star radiates uniformly over a perfect circle, and the planet blocks 100 % of emission over a perfect circle).

61. [4 pts] Given that the radius of K2-18 is 3.26×10^5 km, estimate the radius of K2-18b. Report:
    (a) Your radius estimate of K2-18b, in km.
    (b) The accepted value of the radius of K2-18b, in km.
    (c) The percent error of your measurement.

Subsection B-V: LTT 9779b

LTT 9779b is a hot Neptune discovered using TESS. It has a high albedo of 0.8.

62. [1 pt] What atmospheric phenomenon on Earth (a part of the water cycle!) increases its albedo?
63. [2 pts] The dayside of LTT 9779b has a peak wavelength of 1.16 μm. What is its temperature?
64. [2 pts] Based on your answer in question 63, does the phenomenon in question 62 occur on the dayside of LTT 9779b? Why or why not?
65. [2 pts] What is the current explanation for the exoplanet's high albedo?

Traditional theories about hot Neptunes predict that their close proximity to their host star results in rapid atmospheric stripping, which is why they are so scarce.

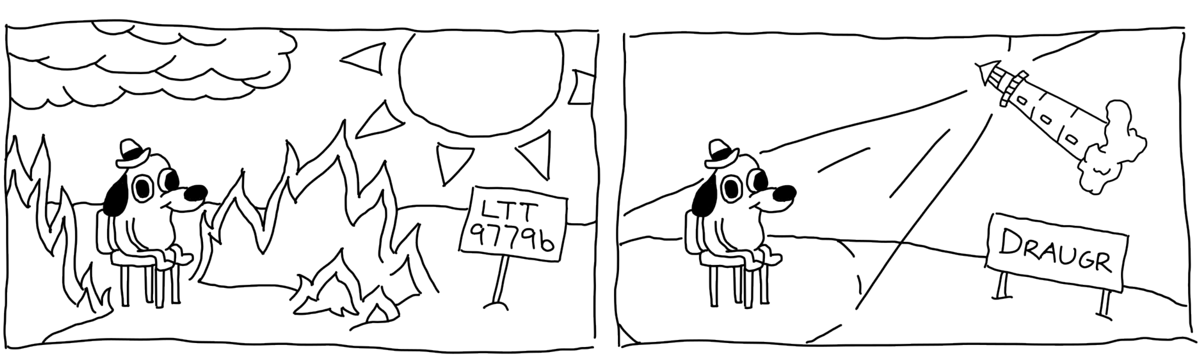
66. [2 pts] Discuss one current theory for how the atmosphere of LTT 9779b has been able to survive.

Subsection B-VI: PSR B1257+12

A pulsar—a rapidly spinning "corpse" of a massive star—is one of the last places you'd expect to see a planet. PSR B1257+12 is the host of not one, but three of these extreme planets. The time of arrival (TOA) of its pulses are compared to three different models to produce the TOA residuals in Image 8.

67. [2 pts] Compute the wavelength of the pulses in meters.
68. [2 pts] The top panel shows the residuals of fit to a "standard timing model without planets". How does this model model the TOAs?
69. [2 pts] The large residuals in the top panel lead astronomers to incorporate the effect of planets on the pulse TOAs. In this second model, astronomers assume the influence of each planet on the pulsar acts independently. Explain why this is a reasonable initial assumption.
70. [2 pts] The second model folds in the effect of each planet independently and its residuals are shown in the middle panel. Why are there still significant TOA residuals?

Taking the effect from the last question into account, astronomers found good agreement with the measurements as seen by the small residuals in the bottom panel.



Subsection B-VII: WD 1856+534

WD 1856+534 is a white dwarf in a triple star system. It hosts a single giant planet, WD 1856+534b.

71. [2 pts] Sketch the orbital configuration of the system. (For illustration purposes, you may assume the triple star system, as well as the exoplanet, lie in a single orbital plane.) Label each star as well as the center of mass, and show the orbit of WD 1856+534b. The diagram should be (very) roughly to scale.
72. [1 pt] The most common spectral classification for white dwarfs is DA. What do the "D" and "A" indicate, respectively?
73. [2 pts] Hydrogen lines for WD 1856+534 are very weak and were initially undetected. What implications does this have for measuring the mass of the planet?

For questions 74–75, refer to Image 9, which shows the infrared (Spitzer 4.5 μm) flux of WD 1856b in μJy as a function of its age and mass, computed from models of brown dwarfs and giant planets.

74. [2 pts] Suppose we have a planet with mass 15 M_J and age 7 Gyr, and that its distance to Earth is twice that of WD 1856b. What is its infrared flux in μJy?
75. [3 pts] Image 10 shows the visible (Gran Telescope Canarias) and infrared (Spitzer) transit light curves of WD1856+534b. Combined with the model presented in Image 9, explain how astronomers were able to infer that WD 1856+534b is a planet (rather than e.g. a brown dwarf).

WD 1856+534b is unusual because of its tight orbit, with a semi-major axis of (0.0204 ± 0.0012) au. Recall that, for example, that the sun is expected to engulf Earth's orbit when it becomes a red giant. The question is then how WD 1856+534b either survived the engulfment of the envelope or migrated inward from a much wider orbit.

76. [2 pts] One hypothesis for explaining WD 1856+534b's orbit is called *common envelope evolution*. Describe what a common envelope is in binary evolution, and how it can tighten the orbit of the exoplanet.
77. [2 pts] Name another astrophysical system whose formation may involve common envelope evolution.
78. [2 pts] What is the energy source for the ejection of the envelope?
79. [3 pts] Several brown dwarf–white dwarf binaries with short periods are thought to have formed via common envelope evolution. Explain why this hypothesis may be less suitable for WD 1856+534b, which has a much longer period and smaller mass, with the common envelope hypothesis.
80. [2 pts] An alternative explanation involves the gravitational influence of the other stars in the triple star system. Give the name of this mechanism and briefly explain it.