Science Olympiad
UT Invitational
December 2, 2023

Astronomy C

Directions:

- Each team will be given **50 minutes** to complete the test.
- There are three sections: **§A** (Qualitative), **§B** (Deep-Sky Objects), and **§C** (Quantitative).
- For significant figures, **use 3 or more in your answers** unless otherwise specified.
- Tiebreakers, in order: §C, §C2, §C4, §A-I, §B.
- Best of luck! And may the odds be ever in your favor.

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Feedback? **Test Code**: *2024UT-AstronomyC-Exoplanet*

Section A: Qualitative

Use the image in Image Set A to answer the following questions. This section contains a total of 60 points.

A-I: General Knowledge

There are 15 questions in this subsection. Unless otherwise specified, each question is worth two points, for a total of 32 points.

1. Which of the following processes is a Sun-like star undergoing in its core?
   - A. Hydrogen fusion
   - B. Carbon fusion
   - C. The CNO cycle
   - D. Technetium fusion

2. For a star in hydrostatic equilibrium, which of the following counteracts the inward force of gravity?
   - A. The strong force
   - B. Energy generated through chemical reactions in the star's core
   - C. The weak force
   - D. Radiation pressure

3. [3 pts] How would the spectrum of an O-type and A-type star compare? (Select all that apply)
   - A. The O-type star would have more ionized spectral lines.
   - B. The A-type star would have more ionized spectral lines.
   - C. The O-type star would have a higher peak wavelength in its continuous emission.
   - D. The A-type star would have a higher peak wavelength in its continuous emission.
   - E. The O-type star would show more neutral hydrogen lines.
   - F. The A-type star would show more neutral hydrogen lines.

4. Which of the following B-V color indices would correspond to the coolest star?
   - A. -1.5
   - B. 0
   - C. 0.5
   - D. 2

5. A protostar is beginning to contract. How will its temperature and luminosity change during this process?
   - A. Temperature decreases, luminosity decreases
   - B. Temperature increases, luminosity decreases
   - C. Temperature increases, luminosity increases
   - D. Temperature decreases, luminosity increases

6. The protostar in the previous question is shown at point A in image A1. Toward which of the following points will it evolve?
   - A. I
   - B. II
   - C. III
   - D. IV

7. Suppose there are four stars in hydrostatic equilibrium each located at points I, II, III, and IV in image A1. Using what you know about blackbody radiation, which star has the greatest radius?
   - A. I
   - B. II
   - C. III
   - D. IV

8. What is the heaviest element fused by nuclear fusion in the cores of stars?
   A. Helium
   B. Carbon
   C. Iron
   D. Lead
9. Due to their size, brown dwarfs cannot sustain fusion processes.
   A. True
   B. False
10. Which fundamental mode of heat transfer is most significant when determining the equilibrium temperature of a planet?
    A. Advection
    B. Conduction
    C. Convection
    D. Radiation
11. Which of the following exoplanets would most likely be discovered with direct imaging?
    A. A young, self-luminous planet
    B. A recently formed super-Earth
    C. A mature gas giant
    D. A high rotation hot Jupiter
12. Which of the following could possibly be classified as a Herbig Ae/Be star?
    A. A fully convective star with infrared excess and illuminating a bright nebulosity
    B. A recently formed protostar that will evolve into a Sun-like star
    C. An A-type star with a helium core and strong emission lines
    D. A B-type star in luminosity class V surrounded by circumstellar dust

The following three (3) questions investigate T Tauri stars (TTS).

13. TTS were initially characterized by their "(1) irregular light variations of about 3 mag., (2) spectral type F5-G5 with emission lines resembling the solar chromosphere, (3) low luminosity, and (4) association with dark or bright nebulosity" (Joy 1945). They are now characterized based on their strength of what emission line?
    A. 21-cm line
    B. H-alpha line
    C. [O III] line
    D. Lyman-beta line
14. What property of this emission line is used to divide TTS into their subtypes: classical TTS and weak-line TTS?
    A. Line width
    B. Relative intensity
    C. Doublet ratio
    D. Redshift
15. [3 pts] Compared to a normal photosphere, classical TTS have excess infrared emission and ultraviolet radiation. What two physical phenomena/processes does this indicate? (Select two)
    A. Ionized gas
    B. Protoplanetary disk
    C. Polarized emissions
    D. Forward and reverse shock
    E. Accretion
    F. Planetesimal formation

A-II: JS9 Investigation

There are 10 questions in this subsection. Points are shown for each question, for a total of 28 points. Please read the questions carefully.

Setup Instructions

- Navigate to competition-js9.onrender.com/ut-24-js9
- In the window, open the Chandra X-ray file using the instructions on the page.
- Select `[Analysis > upload FITS to make tasks available]` and wait for the progress bar.
- In the text box under `[Analysis > Blur, set equivalent sigma]`, type 3, and hit enter.
- Zoom out twice using the magnifying glass with a minus sign in it.
- Select `[File > window > light window]`.
- In the new window, open the Spitzer infrared file.
- In the original window (with the Chandra X-ray image), select `[View > Sync Images]`.
- From the checkboxes, select the top checkbox with the name of the other image (probably will start with a 4). Then select `alignment`, `pan`, and `zoom`. Click `[Sync Repeatedly]`. You should see the two images sync up. You can close this window.
- Finally, select `[View > show > crosshair for this image]` in both images. Then (in either image), select `[View > show > match wcs crosshairs]`. *(Note: In order for the crosshairs to appear, you will need to hold shift.)*

Go ahead and adjust both images (click and drag around) so that you can see their features clearly.

16. [2 pts] This object is either an HI or HII region. Which is it, and how do you know?

17. [2 pts] Where does diffuse hot gas in an HII region come from?

    A. Active supermassive black holes

    B. Type Ia supernova explosions

    C. Hydrostatic equilibrium of the gas

    D. Stellar winds of massive stars

18. [2 pts] What are we seeing in the filaments and diffuse emission in the infrared image?

    A. 'Currents' of gas

    B. Interstellar dust

    C. Large clusters of stars

    D. Radiation from the hydrostatic pressure in the object

19. [4 pts] In the Chandra X-ray image, click on the circle icon in the upper bar to get a circular region. Move this circle down to the bright source in the lower right corner of the image, and make it larger. Use `[Analysis > Energy Spectrum]` to generate an X-ray spectrum of this object. Now, move your circle to the cloudy region below the center of this image. Generate an X-ray spectrum here as well. How do these spectra compare? Does the emission in two regions appear to come from the same source/process?

Holding shift while mousing over either image will cause the crosshairs to appear. Use these to compare the locations in the features of both images.

20. [3 pts] First, mouse over the bright emission in the center of the Chandra X-ray image. What features does this appear to correspond to in the Spitzer infrared image? You may have to zoom in a bit.

21. [2 pts] What objects might these be? (That is, the objects at the location in the previous question.)

    A. Pulsars

    B. Supernova remnants

    C. Young hot stars

    D. Warm gas clumps

22. [4 pts] Next to the center, in the Spitzer infrared image, there is a huge dark spot. What is this dark spot, and how might the above objects form it?

23. [3 pts] Now, look at the other areas of diffuse, bright X-ray emission. How do these compare to what you see in the Spitzer infrared image?

24. [3 pts] Why do we observe the phenomenon in the previous question?

25. [3 pts] Based on all of your above observations, which of the following sets of coordinates would be good candidates for places where there is high potential for star formation? (Select all that apply)

    A. 05:38:42 -69:06:10

    B. 05:38:31 -69:02:15

    C. 05:38:46 -69:02:39

    D. 05:38:32 -69:06:23

Section B: Deep-Sky Objects

Use the images in Image Set B to answer the following questions. Points are shown for each sub-question, for a total of 65 points.

1. (a) [2 pts] Luhman 16 is shown in which image?
   (b) [2 pts] How far is Luhman 16 located, in pc? Give your answer to one significant figure.
   (c) [3 pts] Image B1 traces the light curve of Luhman 16. Which component is the source of the light variability and what feature causes it?
2. (a) [2 pts] Name the object shown in image B2 and determine the wavelength it is depicted in.
   (b) [2 pts] What type of cluster is it?
   (c) [3 pts] A bit less than half of the cluster members that show up in image B2 were not detected by *Spitzer* observations. What type of object are these cluster members? Specify their class.
3. (a) [3 pts] V830 Tauri is a young, M-type star. Donati et. al. (2016) reported the discovery of what type of exoplanet? In a few words, describe the key qualitative properties of this type of exoplanet.
   (b) [2 pts] What detection method was used in its discovery?
   (c) [3 pts] Identify the type of activity that is prevalent in stars like V830 Tauri. Assess how this would affect the validity of and/or confidence in the exoplanet discovery.
4. (a) [2 pts] Image B3 shows what object in what wavelength?
   (b) [3 pts] The dark concentric rings suggest what process is occurring? Why aren't these dark outlines different shapes (e.g. triangles or squares)?
5. (a) [2 pts] Which planet in the Solar System has a mass most similar to WASP-39b?
   (b) [3 pts] List three compounds found in the atmosphere of WASP-39b.
   (c) [5 pts] Suppose you were an astronomer lucky enough to get observation time with JWST. You wanted to confirm the detection of the compounds in part (b). Describe the data you would want to get from JWST and how the data would confirm the atmosphere of WASP-39b contains the compounds. *(Hint: WASP-39b was discovered using the transit method. What can we compare between transits and occultations?)*
6. (a) [1 pt] Which Herbig-Haro object is shown in image B4?
   (b) [2 pts] Describe how HH objects are formed.

   The red contours in image B4 correspond to the [S II] forbidden line. More precisely, it corresponds to the intensity ratio between the $\lambda 6716$ and $\lambda 6731$ de-excitation. Astronomers are interested in these forbidden lines as they can reveal information about gas density.

   (c) [4 pts] Using the spectrum in image B5, determine the electron density of the object in cm^{-3}. It may be useful to use image B6.
   (d) [4 pts] Which transition ($\lambda 6716$ or $\lambda 6731$) has a longer lifetime? Assume the statistical weights of the energy levels involved with the transitions are all the same. Justify your conclusion using image B6.

7. (a) [2 pts] Which image depicts 2M 1207? It also depicts 2M 1207b, first exoplanet imaged directly.

   (b) [3 pts] A strong, broad Hα emission line was discovered. The existence of what physical structure can be inferred? Explain how they are related.

   (c) [2 pts] What does the existence of the physical structure mentioned in part (b) imply about the age of 2M 1207?

Consider the abstract below from Mamajek (2005) to answer the following sub-questions.

> A candidate extrasolar planet companion to the young brown dwarf 2MASSW J1207334-393254 (2M1207) was recently discovered by Chauvin et al. They find that 2M1207 B's temperature and luminosity are consistent with being a young, $\sim$5 M_{Jup} planet. The 2M1207 system is purported to be a member of the TW Hya association (TWA), and situated $\sim$70 pc away. Using a revised space motion vector for TWA, and improved proper motion for 2M1207, I use the moving cluster method to estimate the distance to the 2M1207 system and other TWA members. The derived distance for 2M1207 (53 ± 6 pc) forces the brown dwarf and planet to be half as luminous as previously thought. The inferred masses for 2M 1207 A and B decrease to $\sim$21 M_{Jup} and $\sim$3-4 M_{Jup}, respectively, with the mass of B being well below the observed tip of the planetary mass function and the theoretical deuterium-burning limit. After removing probable Lower Centaurus-Crux (LCC) members from the TWA sample, as well as the probable non-member TWA 22, the remaining TWA members are found to have distances of 49 ± 3 (s.e.m.) ± 12 (1σ) pc, and an internal 1D velocity dispersion of $0.8^{+0.3}_{-0.2}$ km s^{-1}. There is weak evidence that the TWA is expanding, and the data are consistent with a lower limit on the expansion age of 10 Myr (95% confidence).

   (d) [3 pts] What is the main astrometric result of this paper? How does it compare to the accepted value before the publication of this paper?

   (e) [3 pts] How does this result affect the derived parameters of 2M 1207?

   (f) [4 pts] Identify the method used to determine the result in part (d) and describe the key assumption(s) for its application.

Section C: Quantitative

Points are shown for each question or sub-question, for a total of 75 points.

1. [4 pts] A star has a temperature of 6500 K, and a radius of 7.0×10^8 m. How far away does the habitability zone of this star begin and end, in meters?

2. A main-sequence star has an apparent magnitude of 15.73 and the spectrum in image C1.
   (a) [4 pts] Calculate the temperature of this object, in kelvin.
   (b) [4 pts] Estimate the distance to this star, in parsecs. Image C2 may be useful.

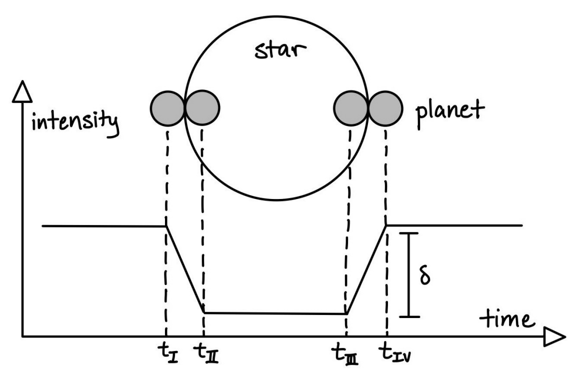
3. [4 pts] It took on the order of 700 million years of evolution while the Sun was in the main-sequence phase for the first traces of life to appear on Earth. What is the main-sequence lifetime of a $10.5\,M_\odot$ star, in years, and would life (in theory) have enough time to form around this star if this timeline holds true?

4. Data collected from an observation in January and one in July is analyzed and a star is found to have a parallax of 1.25 mas.
   (a) [3 pts] What is the distance to this star, in parsecs?
   (b) [3 pts] You discover observations were also taken in April and October. Analyzing this data, you find that the same star barely moves at all; it has a parallax very close to 0 mas. What went wrong?

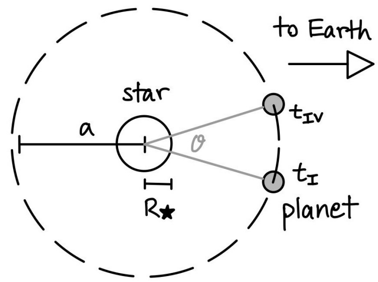
5. **Photobombing**

Transits are a powerful method for exoplanet discovery, accounting for the majority of all discoveries. With thousands of telescopes scanning wide swaths of the sky over the course of many years, many stars can be surveyed. With good luck, some stars are found exhibiting regular dips in brightness on the order of 1% or less. These dips are formed by planets in an edge-on orbit passing in front of the star. In this question, we'll derive some basic relationships at the core of this detection method and investigate an exoplanet found in 2007.

(a) The basic model of a transit is shown below. For simplicity, we will assume the system is viewed from directly edge-on and all orbits are circular. The planet travels from left to right, beginning to cover the star at t_{I}, completely enter the star at t_{II}, begin exiting at t_{III}, and fully exit at t_{IV}. The brightness of the system can be seen to change with time.



Viewing this system from above, we find that the star subtends an angle θ through the duration of the transit. The diagram below depicts this geometry. $R_\star$ is the radius of the star, R_{p} is the radius of the planet, and a is the separation distance between the two. Assume $a \gg R_\star \gg R_{\mathrm{p}}$ and that we are observing this system from a distance $d \gg a$.



One key relationship is between the total duration $T_{\rm tot} = t_{\rm IV} - t_{\rm I}$ and the system parameters. In part (a), we will derive the relationship

$$T_{\rm tot} = \frac{P}{\pi} \sin^{-1}\left(\frac{R_\star}{a}(1+k)\right), \tag{1}$$

where P is the orbit period, and $k = R_{\rm p}/R_\star$.

i. [3 pts] First, derive the distance the planet must travel from $t_{\rm I}$ to $t_{\rm IV}$. Express your answer in terms of $R_\star$ and k.

ii. [3 pts] Next, approximate the angle θ that is swept from $t_{\rm I}$ to $t_{\rm IV}$. Express your answer in terms of $R_\star$, k, and a.

iii. [3 pts] Finally, find $t_{\rm IV} - t_{\rm I}$ in terms of θ, P, and other fundamental constants, as appropriate. By doing so, you have successfully derived equation (1).

iv. [4 pts] Repeat these steps to find the full equation for $t_{\rm III} - t_{\rm II}$. Your answer should be expressed with the parameters in equation (1).

(b) A light curve of a transit readily gives the necessary temporal information; however, some more work still needs to be done to determine, or at least estimate k.

i. [3 pts] Given the disk-average intensities $I_\star$ and $I_{\rm p}$ of the star and planet, respectively, determine an equation for the transit depth δ, which is the relative dip in brightness of the system during transit. Use k, defined above as $k = R_{\rm p}/R_\star$, wherever possible.

ii. [2 pts] Now, assume $I_{\rm p} \ll I_\star$. How does that change your equation in the previous question?

(c) Image C3 depicts a normalized and phase folded light curve.

i. [3 pts] Explain why the light curve does not exhibit the same shape as the diagram in part (a). What effect causes this?

ii. [5 pts] With the light curve and the results from part (a) and (b), compute $R_\star/a$.

(d) From Kepler's 3rd law, we can derive

$$\frac{M_{\rm p}}{(M_{\rm p} + M_\star)^{2/3}} = \frac{K_\star\sqrt{1-e^2}}{\sin i}\left(\frac{P}{2\pi G}\right)^{1/3}, \tag{2}$$

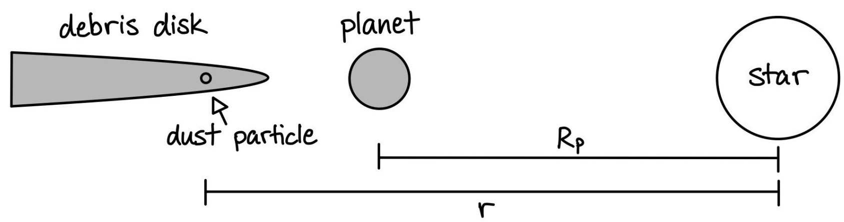
where $K_\star$ is the velocity semiamplitude of the star, e is the orbit eccentricity, and i is the inclination of the orbit normal with respect to the sky plane. All variables are in standard SI units.

i. [4 pts] Using image C4 of the radial velocity variations of the star and the fact that $P = 1.5\,\rm d$, calculate $M_{\rm p}/M_\star^{2/3}$, in $\rm M_\odot^{1/3}$. Assume $M_{\rm p} \ll M_\star$.

ii. [4 pts] With the information provided, we can only determine $M_{\rm p}/M_\star^{2/3}$, a relative value, and not $M_{\rm p}$ itself, an absolute value. Thus, we need some external information about the star. Describe one possible method of determining the mass of the star.

6. **A Dusty Adolescence**

Consider a very simplified model of a forming stellar system below.



Assume that the debris is composed of spherical particles of mass 5×10^{-6} kg, and is all moving at velocities between $1.3 \times 10^{4}\,\mathrm{m\,s^{-1}}$ and $2.3 \times 10^{4}\,\mathrm{m\,s^{-1}}$. The protoplanet is 2.25×10^{11} m from the star, and has a mass of 2×10^{25} kg. The star has a mass of 2×10^{30} kg. All orbits are circular.

(a) [3 pts] Will the lower- or higher-velocity particles in this debris disk be closer to the star? Why?

(b) [3 pts] Assuming the dust particle, planet, and star are collinear, as in the diagram above, set up an equation for the difference between the net force on a dust grain (F_{net}), and the centripetal force required to hold an object traveling at a given velocity in uniform circular motion (F_c) in terms of:

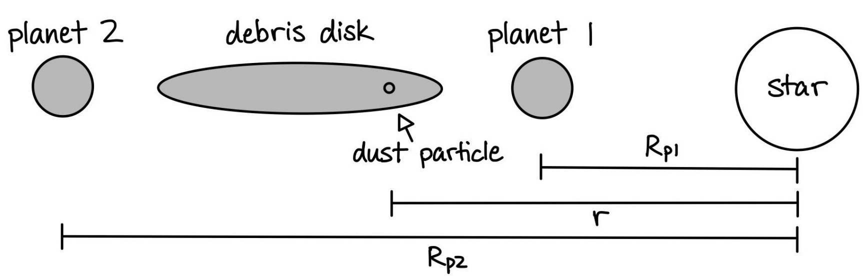
- G (universal gravitational constant),
- $M_\star$ (mass of the star),
- M_{p} (mass of the protoplanet),
- R_{p} (distance from the planet to the star),
- r (distance from the star to the particle),
- m (mass of the particle),
- v (the velocity of the dust particle).

That is, set up an equation for the net gravitational force (F_{net}). Set up an equation for the required centripetal force (F_c) in terms of velocity. Then subtract the two. Do not simplify.

(c) [4 pts] Now, graph of the equation you derived for $F_{\text{net}} - F_c$ as a function of r. *(Note: You do not need to draw out the graph on the answer sheet. Use the graph to answer the following prompt.)* Estimate the radius that the debris disk begins, in meters. *(Hint: Start looking for a minimum distance at orbital distances just past that of the planet.)*

(d) [4 pts] If the particle's mass is increased by a factor of N, how does the answer to part (c) change?

(e) [5 pts] Now, we add another planet on the other side of the debris disk (shown below), with a mass of 5×10^{27} kg and a distance of 8×10^{11} m away from the star.



First, modify your equation in part (b) to account for this scenario. Then, graph this equation to determine the width of the debris disk, in meters. *(Hint: Objects traveling with different velocities will have different equilibrium radii.)*

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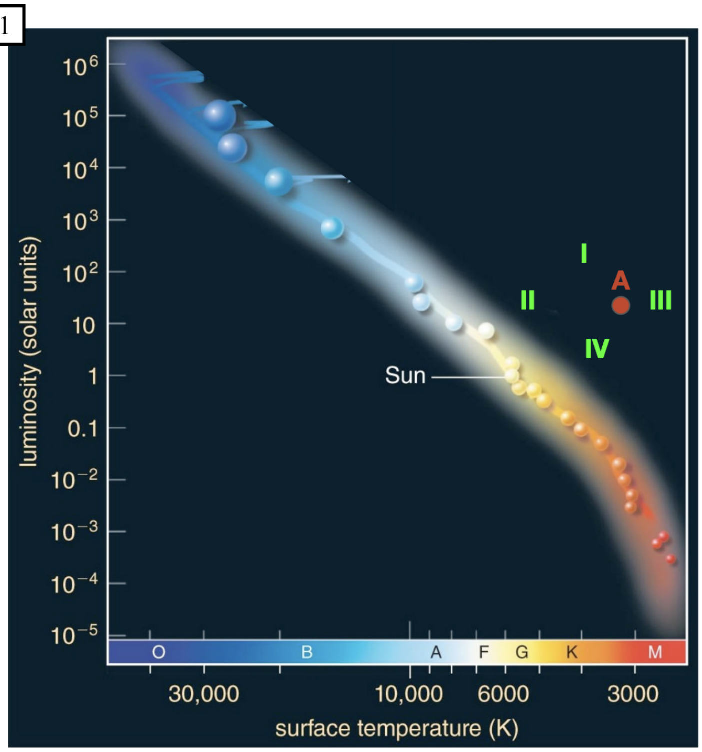
Astronomy C Image Sheet

Directions:

- Do not open until the test begins.

Image Set A

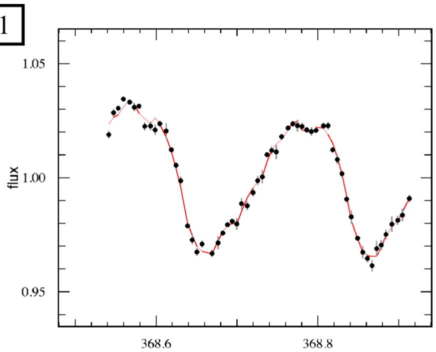
1



10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
luminosity (solar units)
I
A
II
III
IV
Sun
O
B
A
F
G
K
M
30,000
10,000
6000
3000
surface temperature (K)

Image Set B

1



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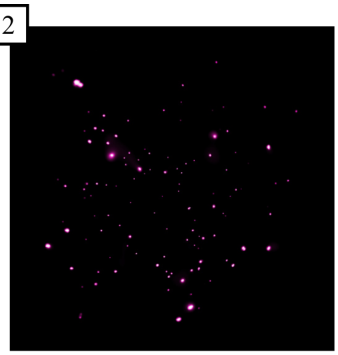

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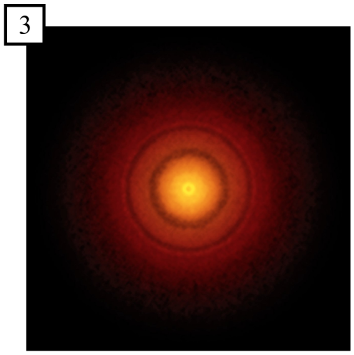

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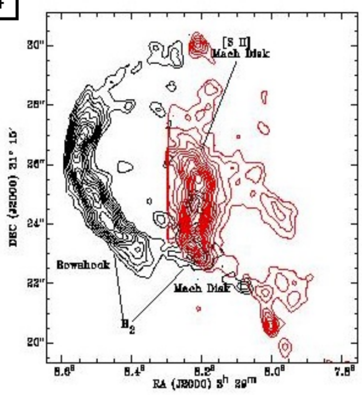

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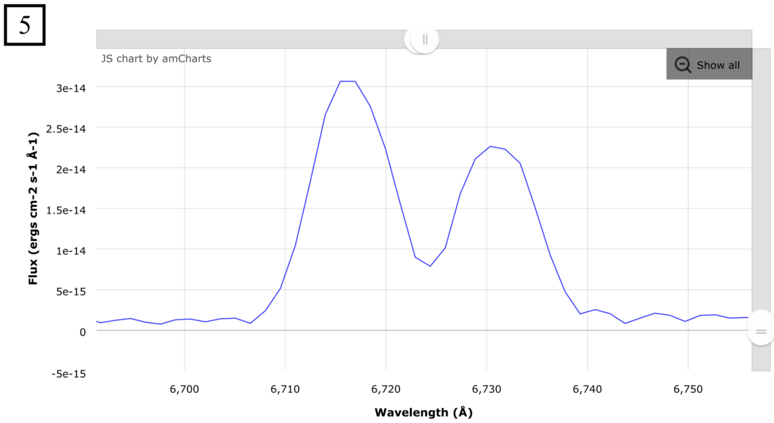

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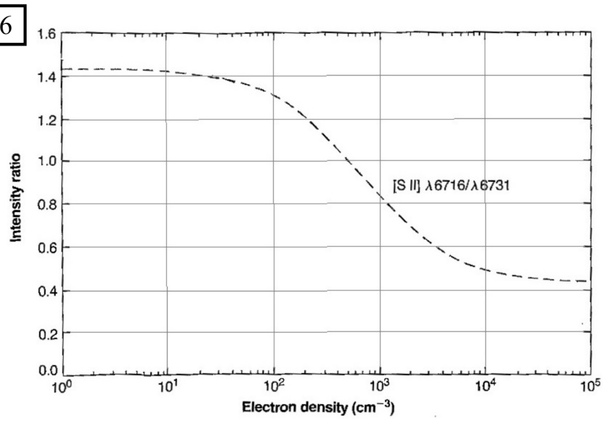

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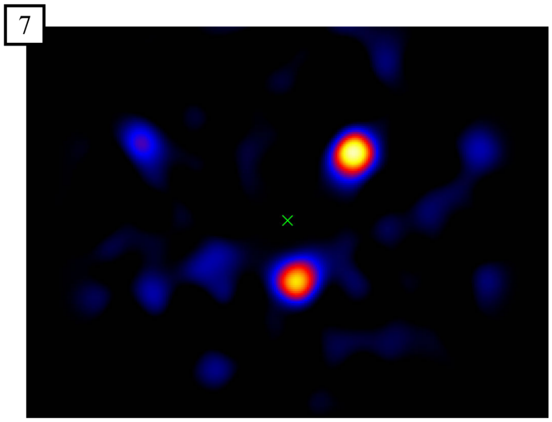

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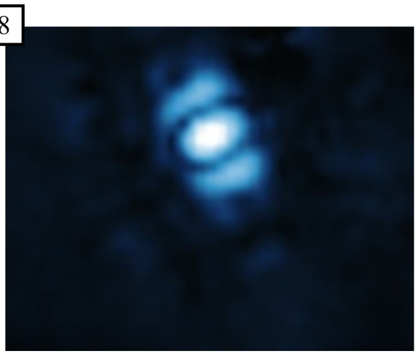

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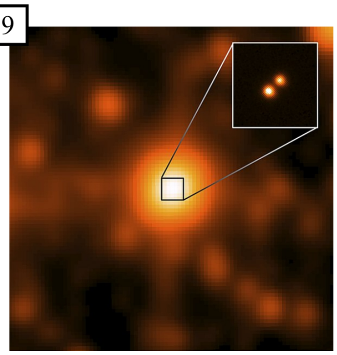

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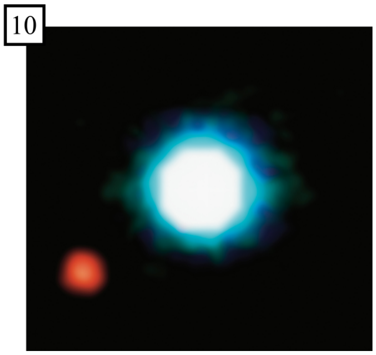
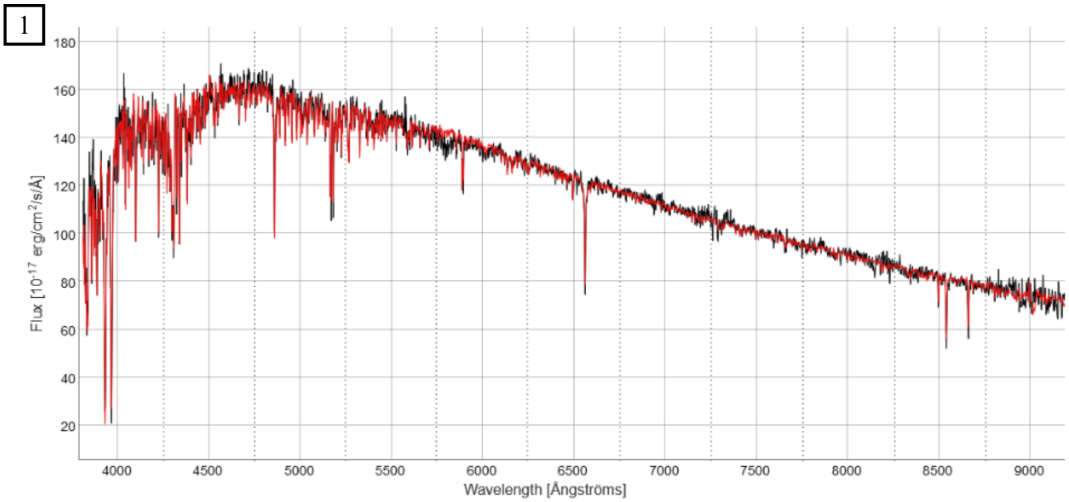


Image Set C

1



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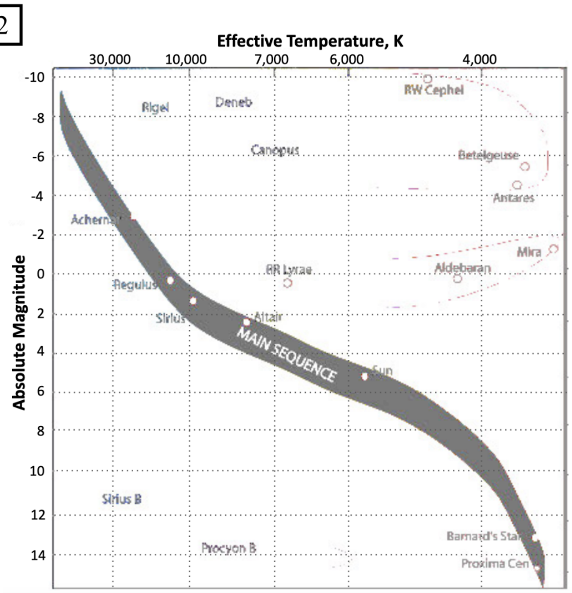

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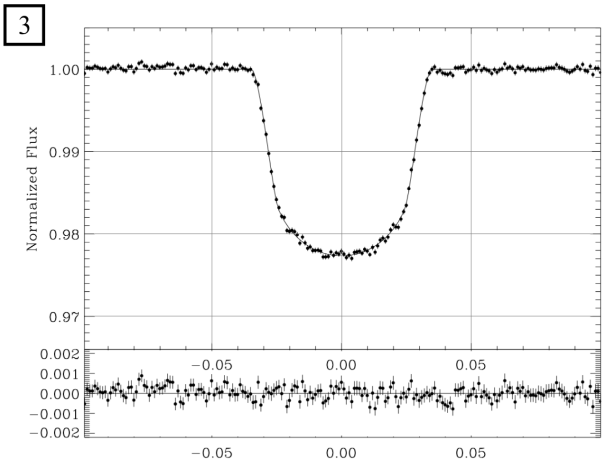

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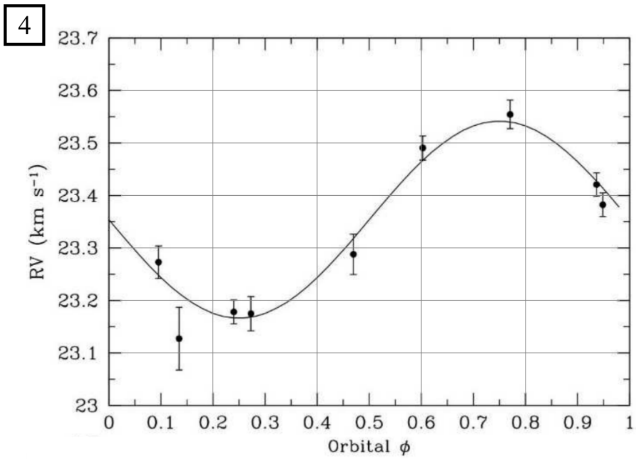

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Astronomy C Answer Sheet

Team Name and Number: ______________________________

Participant Name(s): ______________________________

Total Score: ____ / 200 **Rank:** ____

Directions:

- Read the directions on the test cover.

Section A (60 points)

1. ____ 2. ____ 3. ____ 4. ____ 5. ____

6. ____ 7. ____ 8. ____ 9. ____ 10. ____

11. ____ 12. ____ 13. ____ 14. ____ 15. ____

16. ____

17. ____

18. ____

19. ____

20. ____

21. ____

22. ____

23. ____

24. ____

25. ____

Section B (65 points)

1. (a)
   (b)
   (c)
2. (a)
   (b)
   (c)
3. (a)
   (b)
   (c)
4. (a)
   (b)

5. (a) ____________________

   (b) ____________________

   (c) ____________________

6. (a) ____________________

   (b) ____________________

   (c) ____________________

   (d) ____________________

7. (a) ____________________

   (b) ____________________

   (c) ____________________

   (d) ____________________

   (e) ____________________

   (f) ____________________

Section C (75 points)

1.

2. (a)

(b)

3.

4. (a)

(b)

5. (a) i.

ii.

iii.

iv.

(b) i.

ii.

(c) i.

ii.

(d) i.

ii.

6. (a)

(b)

(c)

(d)

(e)

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Anything written here will not be graded.

Science Olympiad
UT Invitational
December 2, 2023

Astronomy C Answer Key

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Section A (60 points)

1. A	2. D	3. ACF	4. D	5. B
6. D	7. A	8. C	9. B	10. D
11. A	12. D	13. B	14. A	15. BE

16. [2 pts] HII **[0.5 pts]**; the presence of hot enough gas to produce X-Rays **[1.5 pts]**
17. [2 pts] D
18. [2 pts] B
19. [4 pts] One of these spectra is much sharper, and is shifted over a bit **[2 pts]**. They do not appear to come from the same source **[2 pts]**.
20. [3 pts] This X-ray emission appears to correspond to some point sources in the infrared image.
21. [2 pts] C
22. [4 pts] This is a cavity in the nebula **[2 pts]**, and outflows from stars can shove the dust around, carving out cavities **[2 pts]**.
23. [3 pts] The bright X-Ray areas only appear to be in areas where the infrared image is dim.
24. [3 pts] Hot gas from young, massive stars rapidly expands to fill cavities in HII regions.
25. [3 pts] BD

Section B (65 points)

1. (a) [2 pts] Image B9
   (b) [2 pts] 2
   (c) [3 pts] 16B **[1 pt]**. Irregular, patchy clouds **[2 pts]**.

2. (a) [2 pts] NGC 1333 **[1 pt]**, X-ray **[1 pt]**
   (b) [2 pts] Open
   (c) [3 pts] Class III **[1 pt]** YSO **[2 pts]**

3. (a) [3 pts] Hot Jupiter **[1 pt]** (Half credit for Jupiter only). Gas giant and short orbital period/close proximity to host star **[2 pts]**.
   (b) [2 pts] Radial velocity
   (c) [3 pts] Magnetic **[1 pt]**. This activity generates a jitter in the RV data more than a magnitude greater (∼20x) than the RV planet signal, thereby requiring a significant amount of filtering/processing of the data to draw out exoplanet evidence. This decreases the validity of and confidence in the discovery **[2 pts]**.

4. (a) [2 pts] TW Hya **[1 pt]**, radio (millimeter/submillimeter) **[1 pt]**
   (b) [3 pts] Planet or planetesimal formation **[1 pt]**. Material orbits semi-stably in a circle around the central star, so the merging of particles only sweeps up other particles in the same orbit **[2 pts]**.

5. (a) [2 pts] Saturn
   (b) [3 pts] Water, carbon dioxide, sulfur dioxide, carbon monoxide **[1 pt each, up to 3]**. No credit given for elements (e.g. hydrogen)
   (c) [5 pts] The detection of compounds in exoplanet atmospheres relies on spectroscopy and the detection of absorption or emission lines as light from the host star passes through **[2 pts]**. Since WASP-39b was discovered using the transit method, we can collect spectra with JWST during the primary and the secondary transits and use their difference to bring out the spectral features of the exoplanet itself **[3 pts]** (**[2 pts]** given for mentioning transits).
6. (a) [1 pt] HH 7
   (b) [2 pts] Small patches of nebulosity are formed when gas from a young stellar object (YSO) hits the interstellar medium (ISM) at a high speed **[1 pt]**. This material is a by-product of stellar formation as a jet shoots out a small portion of the material accreting onto the YSO **[1 pt]**.
   (c) [4 pts] The ratio of the peaks is 1.35. Using image B6, we find $60\,\mathrm{cm}^{-3}$ [50, 70].
   (d) [4 pts] $\lambda 6716$ **[1 pt]**. Since the $\lambda 6716$ line is stronger at lower electron density (Image B6) **[2 pt]**, we infer the transition takes longer as a lower density decreases the frequency of collisions **[1 pt]**.
7. (a) [2 pts] Image B10
   (b) [3 pts] Circumstellar disc **[1 pt]**. A strong line indicates an abundance of (heated) dust **[1 pt]**. A broad line indicates high velocity material **[1 pt]**.
   (c) [2 pts] It is relatively young
   (d) [3 pts] Distance to 2M 1207 **[2 pts]**. Lower value **[1 pt]**.
   (e) [3 pts] Decreases luminosity **[1.5 pts]** and thereby its inferred mass **[1.5 pts]**
   (f) [4 pts] Moving cluster method **[2 pts]**. Stars are in a cluster moving with the same velocity vector **[2 pts]**.

Section C (75 points)

1. [4 pts] $R_{\text{high}} = 2.1 \times 10^{11}$ m, $R_{\text{low}} = 4.0 \times 10^{11}$ m (**[1 pt]** is given for mentioning habitable temperature range of 273 K to 373 K.)

2. (a) [4 pts] $T = 6100\,\text{K}$ [5800, 6400]

   (b) [4 pts] $d = 1400\,\text{pc}$ [880, 1800]

3. [4 pts] $\tau \cong 3 \times 10^7$ yr (Full credit for right order of magnitude) **[3 pts]**. No, there would not be enough time for life to form **[1 pt]**.

4. (a) [3 pts] $d = 800\,\text{pc}$ (exact)

   (b) [3 pts] The star must be located (angularly) near the line connecting Earth during April and October (near the vernal equinox). Thus, the star does not undergo any parallax effect.

5. (a) i. [3 pts] $2R_\star(1+k)$

   ii. [3 pts] $\theta = 2\sin^{-1}(R_\star(1+k)/a)$

   iii. [3 pts] $t_{\text{IV}} - t_{\text{I}} = (P/2\pi)\theta$

   iv. [4 pts] $t_{\text{III}} - t_{\text{II}} = (P/\pi)\sin^{-1}(R_\star(1-k)/a)$

   (b) i. [3 pts] $\delta = k^2(1 - I_{\text{p}}/I_\star)$

   ii. [2 pts] $\delta = k^2$ (**[1 pt]** is given for correctly applying $I_{\text{p}} \ll I_\star$)

   (c) i. [3 pts] Stars don't have uniform disk intensities, rather they are brighter towards the center, which is why more light is blocked as the planet moves closer to the center of the star and less as the planet moves away **[2 pts]**. This phenomenon is called limb darkening **[1 pt]**. Alternatively, partial credit given for stellar curvature or non-linear change in area **[1 pt]**.

   ii. [5 pts] $R_\star/a = 0.1943$ [0.1936, 0.1948]

   (d) i. [4 pts] $M_{\text{p}}/M_\star^{2/3} = 0.001\,011\,\text{M}_\odot{}^1$ [0.000941, 0.001075]

   ii. [4 pts] Use luminosity, spectral type, and over observable properties

6. (a) [3 pts] Higher-velocity **[1 pt]**. They require a larger gravitational force to hold them in orbit **[2 pts]**.

   (b) [3 pts] $F_{\text{net}} - F_c = \frac{GM_\star m}{r^2} + \frac{GM_{\text{p}} m}{(r-R_{\text{p}})^2} - \frac{mv^2}{r}$

   (c) [4 pts] $r_{\min} = 2.6 \times 10^{11}$ m. Half credit given for $r = 7.9 \times 10^{11}$ m and $r = 4.2 \times 10^{11}$ m.

   (d) [4 pts] The inner radius is unchanged **[1 pt]**. A numerical (evaluating at least three values for N at varying magnitudes) or analytic approach with sufficient justification is accepted **[3 pts]**.

   (e) [5 pts] $w = r_{\max} - r_{\min} = 4.4 \times 10^{11}$ m