Science Olympiad
Golden Gate Invitational
February 11, 2024

Astronomy C

<u>Directions:</u>

- Each team will be given **50 minutes** to complete the test.
- There are three sections: **§A** (Stellar Formation), **§B** (Exoplanets), and **§C** (JS9 Time!).
- For calculation questions, **use 3 or more sig. figs. in your answers** unless otherwise specified.
- Work will not be graded, only the final answer will be scored.
- The use of AI tools (e.g. ChatGPT) are expressly forbidden.
- Tiebreakers, in order: §A, §B3, §B2, §C.
- Good luck! And may the stars be with you!

Written by: The Astronomy A-Team
Tad Komacek, *tkomacek@gmail.com*; **Connor Todd**, *cepheidwatch@gmail.com*
Terry Matilsky, *matilsky@physics.rutgers.edu*; **Robert Lee**, *robertyl@ucla.edu*

Feedback? Test Code: *2024GGSO-AstronomyC-Ecliptic*

Section A: Stellar Formation

This section consists of multiple choice and short answer questions about stellar formation and associated deep-sky objects. Unless otherwise specified, each question is worth 2 points, for a total of 70 points.

1. [1 pt] Where does star formation occur?
   A. Stellar nurseries
   B. Debris disks
   C. OB associations
   D. Stellar remnant fields

2. Protostars form through the collapse of gas clouds. Which of the following best describes the chronological order of their formation?
   I. Accretion
   II. Isothermal
   III. Adiabatic

   A. I, II, III
   B. II, III, I
   C. III, II, I
   D. III, I, II

3. As a gas cloud collapses, subregions of the cloud begin to satisfy the Jeans criterion and collapse independently from each other and the cloud as a whole. What is this process known as?
   A. Fragmentation
   B. Eddington collapse
   C. Kelvin-Helmholtz contraction
   D. Separation

4. Taken by NIRCam on the James Webb Space Telescope, Image 2 depicts the Cosmic Cliffs, a young, star-forming region in the Carina Nebula. What type of object is the Carina Nebula?
   A. Reflection nebula
   B. Dark nebula
   C. Emission nebula
   D. Planetary nebula

5. How were these orange, gaseous "cliffs" formed?
   A. Dark pillars of dense, cold gas—known as Bok globules—have slowly expanded over millions of years to form this landscape.
   B. The "cliffs" are a breakaway segment of a cosmic filament energized by the supernovae of short-lived, massive stars.
   C. Hot, ionized gas expelled from a cluster of "Population I" stars have coalesced, restarting the stellar life cycle.
   D. Intense ultraviolet radiation from young stars in the core of the nebula have carved away the dust.

6. Embedded in the dust, JWST's MIRI discovers a low-mass star with a surface temperature of 4000 K and a high lithium abundance. This object is most likely a
   A. Brown dwarf
   B. FU Orionis star
   C. Herbig Ae/Be star
   D. T Tauri star

7. Identify the object in Image 3.
   - A. AB Aurigae
   - B. 2M 1207
   - C. HD 169142
   - D. TRAPPIST-1

8. The protoplanetary disk of this object is viewed at what inclination?
   - A. 0°
   - B. 30°
   - C. 60°
   - D. 90°

9. Image 6 depicts the spectra of the object. What are the units of the x-axis?
   - A. Microns (µm)
   - B. Langley (Ly)
   - C. Nanometers (nm)
   - D. Angstroms (Å)

10. Which emission line is shown in Image 6.
    - A. H-alpha
    - B. [SII]
    - C. [OIII]
    - D. 21-cm

11. The shape of the spectral feature also includes a small, blueshifted absorption line. This suggests the existence of what physical phenomenon?
    - A. Reverse shock
    - B. Stellar wind
    - C. Recombination
    - D. Circumstellar disk

---

12. Which of the following best characterizes moving right and down the H-R diagram?
    - A. Increasing temperature, increasing luminosity
    - B. Increasing temperature, decreasing luminosity
    - C. Decreasing temperature, increasing luminosity
    - D. Decreasing temperature, decreasing luminosity

13. The lifespan of a star is primarily dependent on its ______.
    - A. formation site (e.g. globular cluster, open cluster)
    - B. initial mass
    - C. Kelvin-Helmholtz timescale
    - D. metallicity (e.g. population I vs. II)

14. The vast majority of all stars are
    - A. Main sequence stars
    - B. Neutron stars
    - C. Red giants
    - D. White dwarfs

15. [3 pts] Stars are in hydrostatic equilibrium when there is a balance between ______ and ______. (Select two answers)
    - A. neutron degeneracy
    - B. convection
    - C. radiation
    - D. self-gravity
    - E. buoyancy
    - F. thermal pressure

16. You've identified an O-type, an F-type, and an M-type star. Which star has the greatest stellar radius?
    - A. O
    - B. F
    - C. M
    - D. Not enough information provided

---

17. How far is Beta Pictoris from Earth?
    A. 19.4 pc
    B. 30.1 pc
    C. 56.8 pc
    D. 95.7 pc
18. In what wavelength does Image 4 depict Beta Pictoris in?
    A. Infrared
    B. Visible
    C. Ultraviolet
    D. X-ray
19. What do the two features jutting out to the top left and bottom right of Beta Pictoris in Image 4 represent?
    A. Bipolar jets
    B. Debris disk
    C. Diffraction spikes
    D. Herbig-Haro objects
20. Which letter best corresponds to the closest location on the H-R diagram (Image 1) to Beta Pictoris?

---

21. Identify the object in Image 7.
    A. V830 Tau
    B. Luhman 16
    C. TW Hya
    D. 2M 1207
22. Roughly how old is this object?
    A. 1 Myr
    B. 10 Myr
    C. 100 Myr
    D. 1 Gyr
23. If the size of each image is $1' \times 1'$, what is the proper motion of the object?
    A. $1.5''/\text{yr}$
    B. $2''\,\text{yr}^{-1}$
    C. $2.5''\,\text{yr}^{-1}$
    D. $3''\,\text{yr}^{-1}$

---

24. Young stellar objects (YSOs) exhibit mass loss through a common mechanism. Which of the following statements most accurately describe it?
    A. An excess of thermal energy, generated through viscous accretion, ionize gas and form an energetic stellar wind from the YSO surface.
    B. By conservation of angular momentum, a rotating disk or torus forms about the YSO and forcing outflowing gas to escape through the poles.
    C. Highly collimated jets are powered by the action of magnetic fields generated by radiative processes within the YSO.
    D. Rapid rotation of YSOs generate significant centrifugal forces that expel mass from their stellar surface into their circumstellar disk.
25. Image 5 depicts HH 7–11, which is a set of Herbig-Haro objects formed as a consequence of the mechanism described in the previous question. What telescope took this image?
    A. Chandra
    B. Spitzer
    C. James Webb
    D. Hubble

Use the following abstract[1] to answer the next four (4) questions.

> Absorption-line radial velocities have been measured for about 50 T Tauri stars on 34 Å mm^{-1} spectrograms of the 5850 Å–6700 Å region; the standard deviation of the velocity from an average plate is 4 km s^{-1}. Only emission lines were measurable in about 10 other stars. The scatter of the absorption velocities with respect to the molecular cloud velocities is small, but the true dispersion is concealed by errors of measurement; an upper limit on the intrinsic dispersion of about 3 km s^{-1} is estimated. Single spectrograms of three stars do show larger velocity discrepancies, and require further investigation. One fairly well-observed star (RY Tau) may be a single-line spectroscopic binary. The number of large residuals is about as expected if the proportion of spectroscopic binaries in the sample is the same as is found among F3-G2, IV and V stars near the Sun. The T Tauri velocities in the mean indicate no systematic radial motion of stars with respect to the molecular clouds. Velocities from emission lines on the average seem to agree with those from the absorption-line spectra, but there is a substantial scatter. The displacement of the absorption reversal in Ha, with respect to the stellar velocity, ranges between about −300 and 60 km s^{-1} in different stars, with a frequency peak near −80 km s^{-1}. Although a few mildly positively shifted reversals do occur in the sample, no "reversed P Cygni" structure of the YY Orionis type is seen at any star, including YY Ori itself. The spectral types of these stars range from G to M4. With a few exceptions, they are mostly of luminosity class V. A few T Tauri stars are observed to lie outside cloud boundaries, but it is not yet clear how they have escaped.

26. Why were emission lines not used to determine the radial velocity of the stars?
27. The author indicates there are large velocity discrepancies for three stars. How is this justified?
28. [4 pts] What key assumption does the justification make? Do you agree or disagree with the validity of this assumption? Support your claim.
29. [3 pts] At the discovery of T Tauri stars, it was not known where they fell in the sequence of stellar evolution. Explain how the abstract supports or refutes the claim that T Tauri stars are pre-main-sequence stars.

For the next four (4) questions, refer to Image 11[2], which depicts a cooling curve for M dwarfs (blue), brown dwarfs (green), and extrasolar giant planets (red). Magenta and brown circles indicate the times when deuterium fusion ends and grain formation begins, respectively.

30. Over which region would we be unable to determine the stellar mass even if the age and luminosity of the star was known?
31. What is the primary difference between M dwarfs and brown dwarfs?

Theo is an astronomer interested in studying systems with Jovian-mass planets orbiting M dwarfs.

32. Theo discovers an exoplanet with around the same mass as Jupiter orbiting a 0.2 $M_\odot$ star that are both 1 Myr old. What is the ratio of luminosity between the brighter and the dimmer object?
33. [3 pts] Theo has cataloged a set of these systems that have been discovered with the direct imaging method. Identify two selection effects supported by information in the figure and describe how they affect the observed system population.

[1] GH Herbig (1977)
[2] JA Caballero (2018)

Section B: Exoplanets

This section consists of extended questions about exoplanets with short answer and calculation sub-questions. Points are shown for each question or sub-question, for a total of 85 points.

1. [18 pts] **What's That Exoplanet?**

   Image 8 shows emission spectra of the dayside (top) and nightside (bottom) of the planet WASP-121b. Use these spectra to answer the following questions.

   (a) [2 pts] The y-axis of each plot is the ratio of the flux received from the planet relative to that of the host star, in ppm. What is the maximum ratio of the flux of the planet's dayside to the star, without units?

   (b) [2 pts] Which of the models shown (colored lines) best matches the observed data for the dayside and nightside hemisphere together? Just state the name of the model from the legend. Note that there are two reductions of the data with slightly different methods, shown by the black and grey points—your answer should be independent of the data reduction method used.

   (c) [2 pts] There is a decrease in flux from the planet's nightside (around a wavelength of 1.4 μm) right around where there is a peak in the flux from the planet on the dayside. What molecular species absorbs infrared radiation in this trough on the nightside hemisphere?

   (d) [4 pts] What is different about the dayside and nightside of the planet that causes there to be a peak on the dayside yet a trough in flux on the nightside near 1.4 μm?

   (e) [4 pts] Estimate the effective temperature of the planet's dayside, assuming is it a blackbody with a flux equal to the peak flux observed in the waveband. Note that the planet's radius is 1.75 Jupiter radii, and the host star's radius is $1.52\,R_\odot$ and the host star's effective temperature is 6776 K.

   (f) [2 pts] What is the letter that corresponds to the closest location on the H-R diagram (Image 1) to the host star in this system?

   (g) [2 pts] From your answers above, state what class of exoplanet WASP-121b is. Be specific.

2. [16 pts] **Extrasolar Expedition**

   Image 9 shows the face-on view of a nearby planetary system. Image 10 shows a plot of the radius vs. incident flux of the planets in this system. Use these figures to answer the following questions.

   (a) [2 pts] What planetary system is this?

   (b) [2 pts] By which method was this system discovered?

   (c) [1 pt] What is the acronym of the observational survey that discovered this planet?

   (d) [2 pts] What is the letter that corresponds to the closest location on the H-R diagram (Image 1) to the host star in this system?

   (e) [2 pts] What is shown by the region that is shaded gray in Image 9?

   (f) [3 pts] Which two planets in this system have a level of incident flux that is between that of Venus and Mars, and similar to Earth?

   (g) [4 pts] Which of these two planets do you think is more likely to have surface liquid water? Why do you think this planet is more likely to be habitable?

3. [9 pts] **Going the Distance**

Your lab is observing a star that moves through a total angular distance of 0.0163 arcseconds over a six-month observation period. Over this timeframe, it maintains a steady visual brightness of magnitude +9.27. Your database indicates that this star is known to have a bolometric correction factor of -0.176.

(a) [2 pts] What is the parallax angle of this star in milliarcseconds?

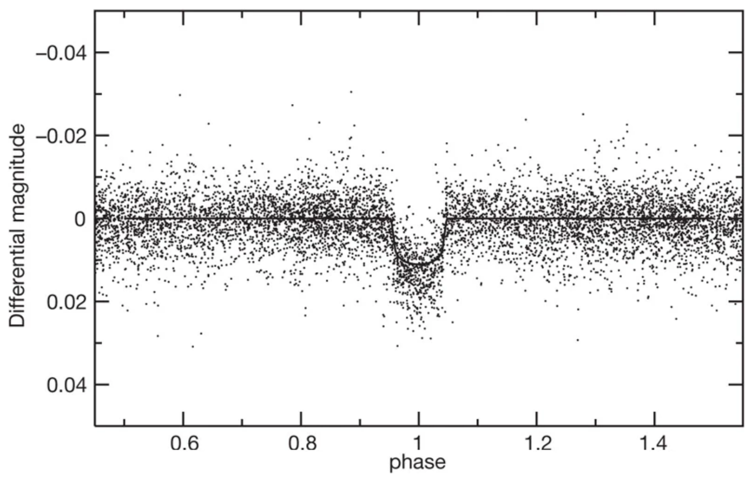
(b) [2 pts] What is the distance to this star in parsecs?

(c) [2 pts] What is the absolute visual magnitude of this star?

(d) [3 pts] What is the approximate luminosity of this star in $L_\odot$?

4. [18 pts] **Getting Into Your Orbit**

The figure below depicts the behavior of a single exoplanet in orbit around the star described in Question 3. Over the course of your six months of observation, the portion of time corresponding to a negative differential magnitude in the normalized data trendline lasted for, on average, 3 hours and 20 minutes. You may assume that the data drawn from this plot represents a system in a perfectly-circular orbit viewed edge-on.



Additionally, Image 12 depicts several modeled spectra of the atmosphere of this exoplanet, each one derived from various effective temperature models of the planet. For the purpose of this question, assume that the most accurate temperature model is the top-line spectrum and that the exoplanet is partially absorptive with an albedo $\alpha = 0.22$.

(a) [1 pt] What method of exoplanet detection was used to produce the data in the figure above?

(b) [3 pts] Based on the figure above, what is the total orbital period of this exoplanet around its parent star?

(c) [2 pts] What is the effective surface temperature of this exoplanet in degrees Kelvin?

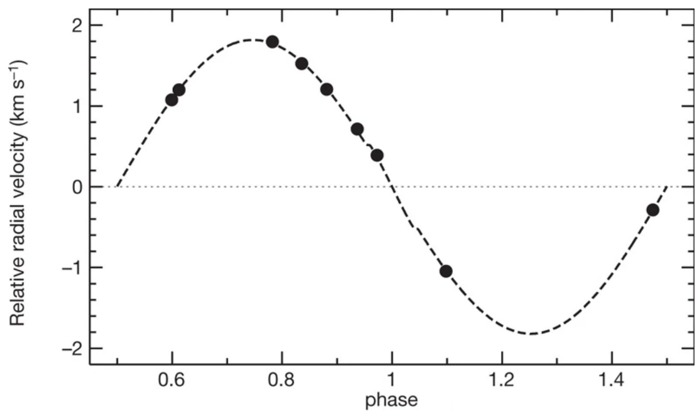
(d) [4 pts] What is the surface flux density in watts per square meter, or "Solar constant", experienced by this exoplanet at its surface?

(e) [5 pts] Using the equations for intensity of stellar radiance at its surface and the inverse square law of flux density, derive an expression of the surface flux density of a star as a function of its luminosity, $L_\star$, at a distance of a circularly-orbiting planet's semi-major axis, a. Use this equation, along with the value for luminosity determined in Question 3(d), to determine the semi-major axis in meters of this exoplanet's orbit (if you were unable to determine the star's luminosity in Question 3(d), you may substitute with a value of $2.68\,L_\odot$).

(f) [3 pts] What is the orbital velocity of this exoplanet in meters per second?

5. [24 pts] **Building Character**

The figure below depicts a modeled observation of this same exoplanetary system, this time with a normalized trendline of the radial velocity of the parent star that follows the same timeframe as the magnitude plot in Question 4. This plot was produced by observations of this same exoplanet by a separate research team at the same time as the magnitude plot.



(a) [1 pt] What method of exoplanet detection was used to produce the data in the figure above?

(b) [3 pts] What is the maximum magnitude of the velocity of the parent star in this system, in meters per second? At what point in the exoplanet's orbit, geometrically-speaking with respect to the Earth, does this occur?

(c) [5 pts] Using the equations for Kepler's third law of motion and orbital velocity, derive an expression of the mass of the central star in a circular planetary system as a function of the radial velocities of the star, $v_\star$, and planet, v_p, as well as the planet's period, T, and semi-major axis, a. Assume the planet's mass IS NOT negligibly small in comparison with its parent star. Use this equation, along with all values derived in the questions given above, to calculate the mass of the central star in this planetary system in Solar units (if you were unable to determine values for the planet's period and semi-major axis, you may use values of 8.12×10^4 s and 3.03×10^9 m, respectively).

(d) [3 pts] What is the mass of this exoplanet in kilograms? Was the assumption that its mass was not negligibly small in comparison with its parent star appropriate?

(e) [3 pts] Over time, your lab improved its detection capabilities, and determined via astrometric analysis that the parent star has a mean radius of 5.03×10^8 m. What is the mean radius of this exoplanet in meters?

(f) [2 pts] What is the density of this exoplanet in grams per cubic centimeter?

(g) [2 pts] What is the effective temperature of the parent star in degrees Kelvin?

(h) [5 pts] Describe in words what type of star and exoplanet most likely compose this system, given the values determined above. Are you confident in these measurements? What is most likely the primary source of error in the final values?

Section C: JS9 Time!

For this section, teams will be called up to a station to use the provided JS9 imaging software. Each team may send one or both competitors and will be given 10 minutes to complete all 10 questions in this section. Competitors will only be able to view and answer these questions in the allotted time. Points will be shown for each question, for a total of 25 points.

Science Olympiad
Golden Gate Invitational
February 11, 2024

Astronomy C JS9 Image Analysis

Directions:

- Do not open until prompted.

Section C: JS9 Time!

For this section, use the provided JS9 imaging software at the station to answer the questions. Competitors will only be able to view and answer these questions in the allotted 10 minutes. Points are shown for each question, for a total of 25 points.

Setup Instructions

- Go to chandra.cfa.harvard.edu/js9
- Select the button on the right with the text `[The Unofficial Chandra Archive Search Page]`. A pop-up should appear.
- In the `[Object Name]` box, enter "`SN 1604`" and select `[Search]`.

1. [2 pts] How many observations are listed?
2. [3 pts] Load the data from `ObsID` 116 by dragging its link under `Title` and dropping it onto the JS9 window. What date did the observation start? What date did it end?

To adequately see the remnant, make sure that `[Scale > log]` is selected; you may also need to adjust the contrast and bias by holding down left click and moving up/down and left/right, respectively. Set a circular region and move it to encompass the entire remnant. This region will be used for the next four (4) questions.

3. [2 pts] About how many pixels is the radius of the remnant?
4. [2 pts] What does this correspond to in arcseconds on the sky?
5. [3 pts] Do an energy spectrum by using `[Analysis > Energy Spectrum]` and describe the results in one or two sentences.
6. [3 pts] Perform a light curve on the observation with `[Analysis > Light Curve]`. (Be sure to use the light curve routine listed under "`NSO Analysis`".) This may take a moment. Does the light curve show any statistically significant variability or not? Explain why your answer might be expected.

Switch to the default observation (which is another supernova remnant, Cas-A) with `[File > casa.fits]`. Set another circular region to encompass Cas-A. This region will be used for the next three (3) questions.

7. [2 pts] What is its radius in pixels?
8. [2 pts] What does this correspond to in arcseconds on the sky?
9. [3 pts] Do an energy spectrum. Is your result significantly different from SN 1604? What does this tell you about the nature of the two objects?
10. [3 pts] What are three possible reasons why one of the objects appears significantly larger in the sky than the other?

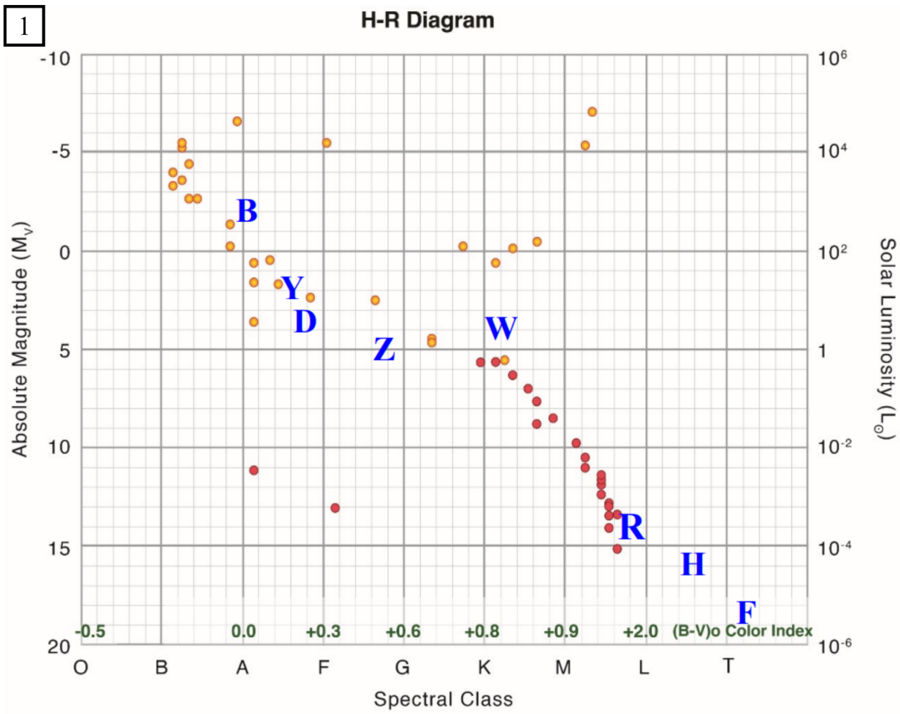
Science Olympiad
Golden Gate Invitational
February 11, 2024

Astronomy C Image Sheet

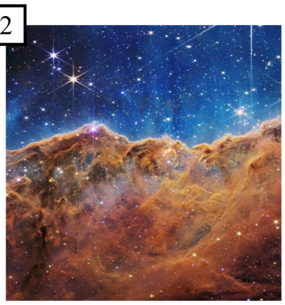
Directions:

- Do not open until the test begins.

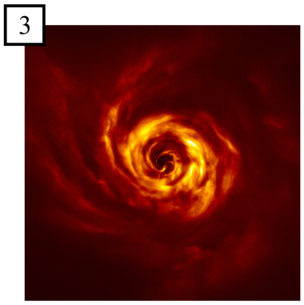
1


H-R Diagram
Absolute Magnitude (M_V)
-10
-5
0
5
10
15
20
Solar Luminosity ($L_\odot$)
10^6
10^4
10^2
1
10^{-2}
10^{-4}
10^{-6}
B
Y
D
Z
W
R
H
F
-0.5
0.0
+0.3
+0.6
+0.8
+0.9
+2.0
(B-V)o Color Index
O B A F G K M L T
Spectral Class

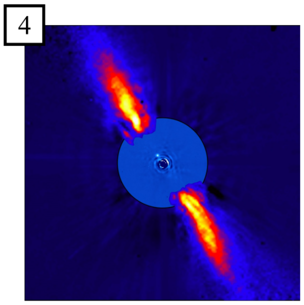
2



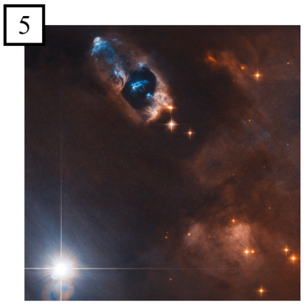
3



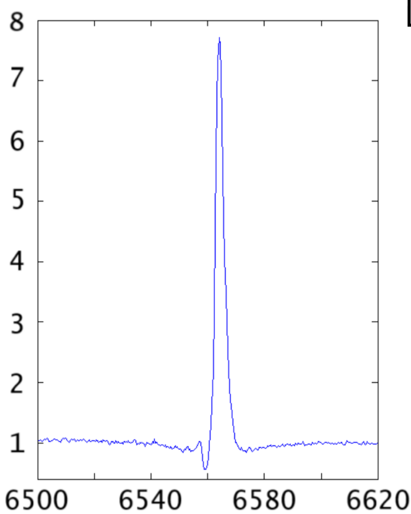
4



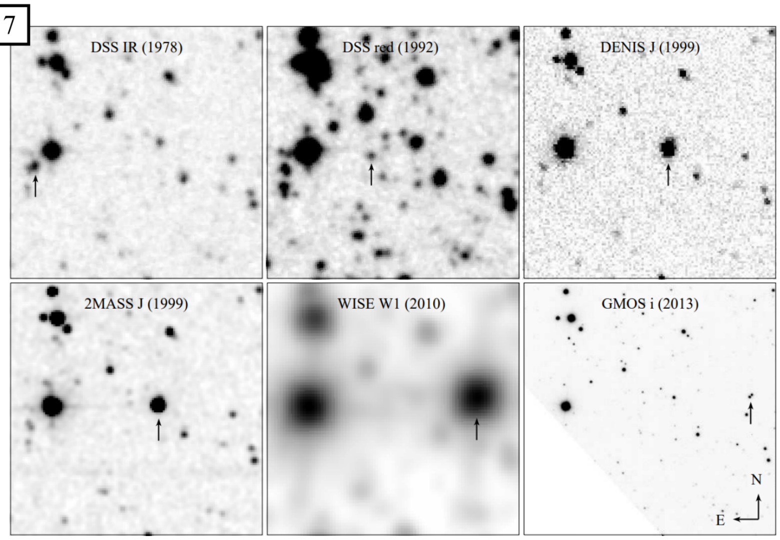
5



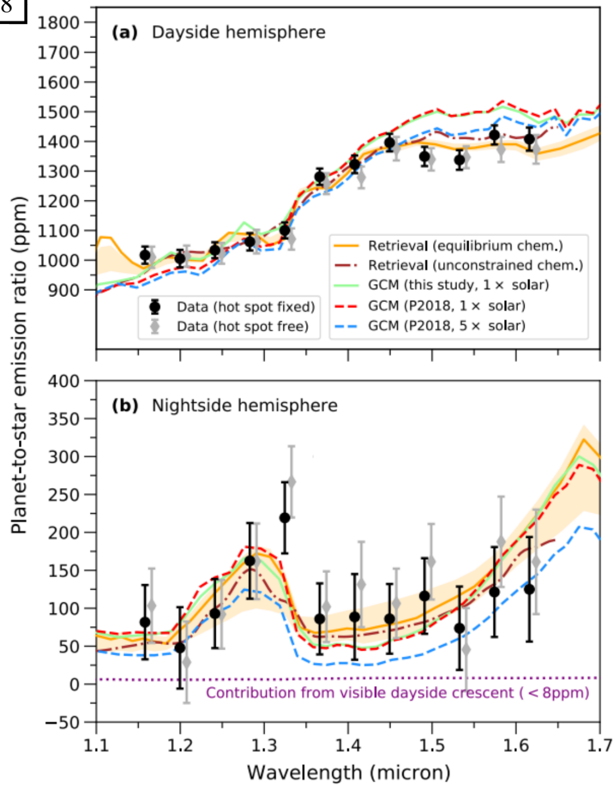
6


8
7
6
5
4
3
2
1
6500
6540
6580
6620

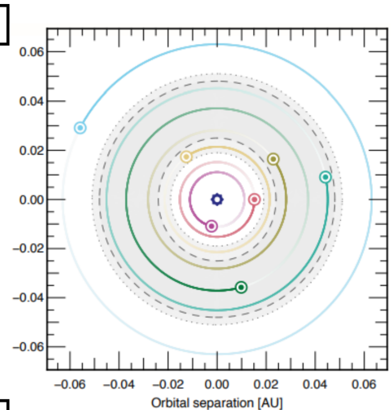
7


DSS IR (1978)
DSS red (1992)
DENIS J (1999)
2MASS J (1999)
WISE W1 (2010)
GMOS i (2013)
N
E

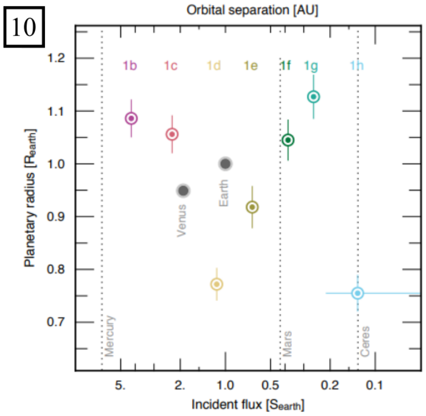
8


(a) Dayside hemisphere
Planet-to-star emission ratio (ppm)
Retrieval (equilibrium chem.)
Retrieval (unconstrained chem.)
GCM (this study, 1 × solar)
GCM (P2018, 1 × solar)
GCM (P2018, 5 × solar)
Data (hot spot fixed)
Data (hot spot free)
(b) Nightside hemisphere
Contribution from visible dayside crescent (< 8ppm)
Wavelength (micron)

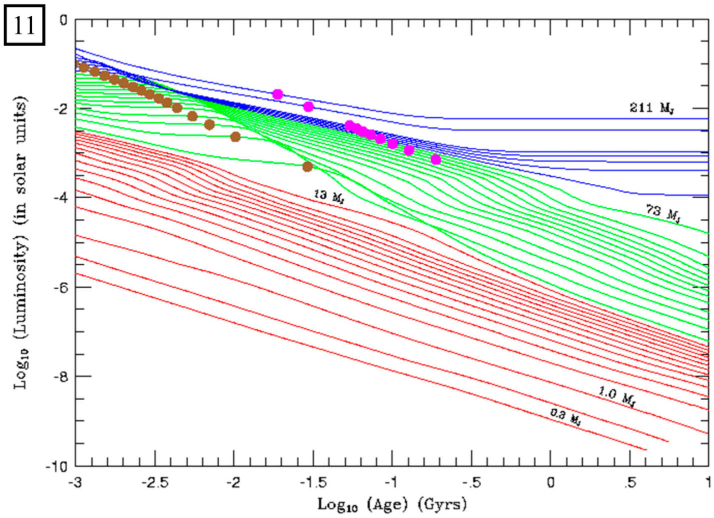
9


Orbital separation [AU]

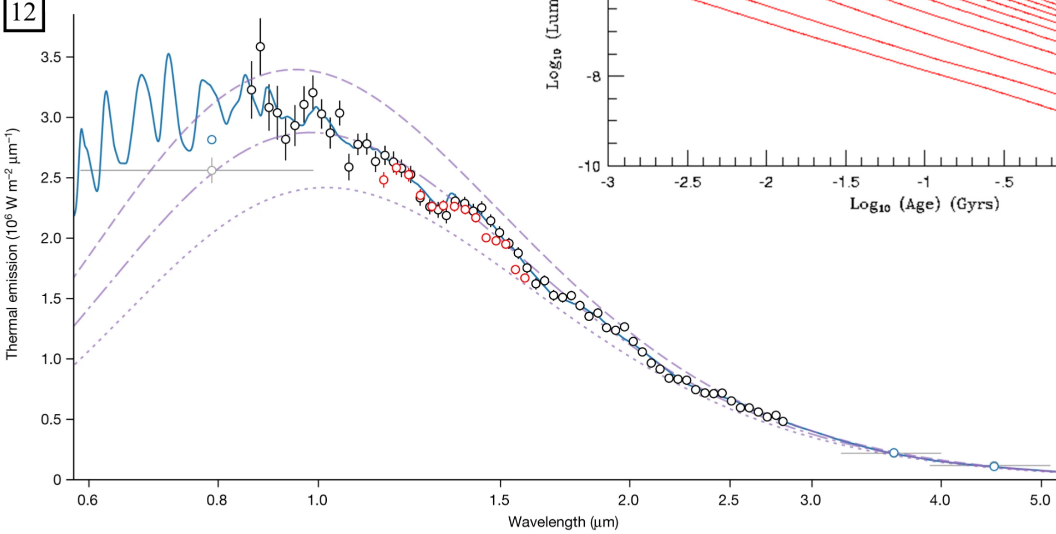
10


1b
1c
1d
1e
1f
1g
1h
Venus
Earth
Mercury
Mars
Ceres
Planetary radius [R_earth]
Incident flux [S_earth]

11


211 M_J
13 M_J
73 M_J
1.0 M_J
0.3 M_J
Log10 (Luminosity) (in solar units)
Log10 (Age) (Gyrs)

12


Thermal emission (10^6 W m^-2 μm^-1)
Wavelength (μm)

Science Olympiad
Golden Gate Invitational
February 11, 2024

Astronomy C Answer Sheet

Team Name and Number: ______________________________

Participant Name(s): ______________________________

Total Score: _____ / 180 **Rank:** _____

Directions:

- Read the directions on the test cover.

Section A (70 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. ______

26. ______

27. ______

28. ______

29. ______

30. ______

31. ______

32. ______

33. ______

Section B (85 points)

1. (a) __________
   (b) __________
   (c) __________
   (d) __________
   (e) __________
   (f) __________
   (g) __________
2. (a) __________
   (b) __________
   (c) __________
   (d) __________
   (e) __________
   (f) __________
   (g) __________

3. (a)

(b)

(c)

(d)

4. (a)

(b)

(c)

(d)

(e)

(f)

5. (a)

(b)

(c)

(d)

(e)

(f)

(g)

(h)

Section C (25 points)

1.

2.

3.

4.

5.

6.

7.

8.

9.

10.

Science Olympiad
Golden Gate Invitational
February 11, 2024

Astronomy C Answer Key

ANSWER KEY ANSWER KEY
ANSWER KEY ANSWER KEY
ANSWER KEY ANSWER KEY
ANSWER KEY ANSWER KEY
ANSWER KEY ANSWER KEY
ANSWER KEY ANSWER KEY
ANSWER KEY ANSWER KEY
ANSWER KEY ANSWER KEY

Section A (70 points)

1. A	2. B	3. A	4. C	5. D
6. D	7. A	8. B	9. D	10. A
11. B	12. D	13. B	14. A	15. DF
16. D	17. A	18. A	19. B	20. D or Y
21. B	22. D	23. A	24. B	25. D

26. They were only measurable in 10 stars.

27. They may be spectroscopic binaries.

28. [4 pts] This proportion of spectroscopic binaries is expected in the sample given the population of F3-G2, IV and V spectral type stars near the Sun.

    Agree: The proportion of binary systems are largely determined by the formation dynamics of a local population. In this case, both the set of T Tauri stars and stars near the Sun were formed through a molecular cloud.

    Disagree: T Tauri stars also include K and M class stars and are not subgiant (IV) stars. The reference population of stars does not accurately represent the population of the 50 T Tauri stars. Alternatively, the proportion may also vary with time.

    Other valid justifications are accepted.

29. [3 pts] It supports the claim. The radial velocities reveal "no systematic radial motion of stars with respect to the molecular clouds" which is expected if T Tauri stars were recently formed, as they have not had the time for dynamics to diverge from their progenitor cloud.

30. The blue (M dwarf) region with many overlapping lines (from roughly 10^{-3} Gyr to 10^{-1} Gyr). Alternatively, the bottom left region with no lines.

31. Fusion of hydrogen. Half credit for only mentioning fusion as brown dwarfs can fuse deuterium. Alternatively, higher surface temperature or lower decrease in luminosity with age.

32. Slightly higher than 10,000.

33. [3 pts] Younger systems (1) are more luminous and (2) have a greater contrast ratio, so the system population will be biased towards them. Partial credit given for wider separation.

Section B (85 points)

1. (a) [2 pts] $(1.4 \pm 0.1) \times 10^{-3}$
   (b) [2 pts] Retrieval (equilibrium chemistry)
   (c) [2 pts] water vapor, H_2O
   (d) [4 pts] The dayside temperature profile increases with height, the nightside temperature profile decreases with height
   (e) [4 pts] 3000–4500 K
   (f) [2 pts] Z or D
   (g) [2 pts] Ultra-hot Jupiter

2. (a) [2 pts] TRAPPIST-1
   (b) [2 pts] Transit
   (c) [1 pt] TRAPPIST
   (d) [2 pts] R
   (e) [2 pts] Habitable zone (surface liquid water stable)
   (f) [3 pts] d, e
   (g) [4 pts] e. The host star is a late M dwarf, so more incident radiation is absorbed rather than scattered compared to planets around Sun-like stars. As a result, lower incident fluxes than Earth are better for habitability.

3. (a) [2 pts] 8.15 mas
   (b) [2 pts] 123 pc
   (c) [2 pts] +3.83
   (d) [3 pts] 2.73 $L_\odot$

4. (a) [1 pt] Transit
   (b) [3 pts] $(1.35 \pm 0.15) \times 10^5$ s
   (c) [2 pts] (3050 ± 150) K
   (d) [4 pts] $(2.55 \pm 0.50) \times 10^7$ W m^{-2}
   (e) [5 pts] Equation: $S = L_\star/(4\pi a^2)$; $(1.72 \pm 0.08) \times 10^9$ m
   (f) [3 pts] $(8.15 \pm 1.35) \times 10^4$ m s^{-1}

5. (a) [1 pt] Radial velocity
   (b) [3 pts] $(1.85 \pm 0.05) \times 10^3$ m s^{-1}; occurs when exoplanet is at greatest radial distance from star when viewed from Earth
   (c) [5 pts] Equation: $M_\star = 4\pi^2 a^3/[GT^2(1 + v_\star/v_\mathrm{p})]$; (0.087 ± 0.031) $M_\odot$ if using calculated answers, (1.17 ± 0.05) $M_\odot$ if using given answers
   (d) [3 pts] $(4.350 \pm 0.031) \times 10^{27}$ kg if using above answers, $(5.55 \pm 0.55) \times 10^{28}$ kg if using given answers; it was appropriate, as the exoplanet is a significant portion of the total mass of the system
   (e) [3 pts] $(5.00 \pm 0.50) \times 10^7$ m
   (f) [2 pts] (8.85 ± 2.65) g cm^{-3} if using above answers, $(116 \pm 44) \times 10^{28}$ g cm^{-3} if using given answers
   (g) [2 pts] (8705 ± 20) K
   (h) [5 pts] Star is low-mass and low-radius but relatively hot, possibly a white dwarf. Planet is high-density and high-radius, likely a near-brown-dwarf. Such an orbital configuration is very unlikely—the error is likely due to the initial assumptions of a circular orbit perfectly aligned at 90° inclination, which overestimates the planetary mass and all derivative values.

Section C (25 points)

1. [2 pts] 11
2. [3 pts] The observation started 2000-06-30 and ended 2000-07-01 which can be found in the header.
3. [2 pts] ~ 250 pixels [210, 280]
4. [2 pts] $\sim 125''$ [110, 140]
5. [3 pts] Strong emission at $\sim 900\,\text{eV}$, $\sim 1850\,\text{eV}$, and a smaller peak at $\sim 2400\,\text{eV}$.
6. [3 pts] The count rate is constant with random fluctuations consistent with count statistics. No short-term variability is expected from an extended object such as a SNR.
7. [2 pts] ~ 350 pixels [290, 400]
8. [2 pts] $\sim 175''$ [140, 200]
9. [3 pts] Yes, they are two different types of supernovae.
10. [3 pts] The larger object can be closer, older, or expanding with a greater velocity. Or a combination of the above.