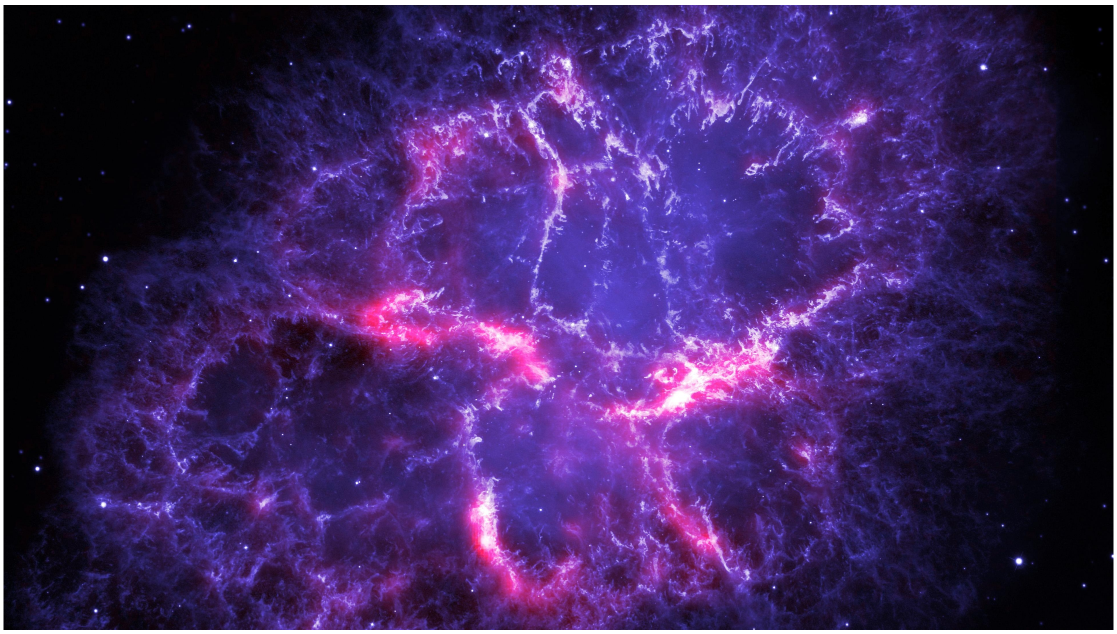
Science Olympiad
Boyceville Invitational
December 7, 2024

Astronomy C



Directions:

- Each team will be given **50 minutes** to complete the exam.
- There are four sections: **§A** (General Knowledge), **§B** (JS9), **§C** (DSOs), and **§D** (Astrophysics).
- **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: §A6–8, §C1–10, §D1, §C13, §B, §A.
- After the tournament, the exam will be available online at `robertyl.com/scioly`
- Good luck! And may the stars align for you.

Written by: The Astronomy A-Team
Rio Sessions, *rio.sessions@student.nmt.edu*
Chris John, *cjohn@berkeley.edu*
Robert Lee, *robertyl@ucla.edu*

Section A: General Knowledge

This section consists of a mix of multiple choice and free-response questions about general astronomy concepts. Each question is worth 2 points, for a total of 40 points.

1. A main-sequence star of $2\,M_\odot$ will eventually evolve to become which of the following?
   A. Red dwarf
   B. Red giant
   C. Red supergiant
   D. Brown dwarf

2. At what point does a star leave the main sequence?
   A. When it initiates hydrogen burning.
   B. When it runs out of hydrogen fuel.
   C. When it initiates helium burning.
   D. When it runs out of helium fuel.

3. A pre-main sequence star typically has a spectral class that is ____ than it will be when the star reaches the main sequence.
   A. Bluer
   B. Redder
   C. Brighter
   D. Dimmer

Two stars, A and B, have apparent magnitudes $m_A = 5$ and $m_B = 8$.

4. Which of these stars appears brighter from Earth?
   A. Star A
   B. Star B
   C. They have the same brightness.
   D. Not enough information.

5. Which of these stars is intrinsically brighter?
   A. Star A
   B. Star B
   C. They have the same brightness.
   D. Not enough information.

An H–R diagram is shown in Image 1.

6. Order these points by increasing temperature (coldest object first).

7. All of these points fall roughly on the evolutionary track of a $1\,M_\odot$ star. Arrange these points in order of the lifetime of this star.

8. At which one of these points on this track would the $1\,M_\odot$ star be shedding its envelope?

Consider the object in Image 4, which was taken in the optical band.

9. What is the term for the dark region indicated in this image?
   A. Absorption nebula
   B. Diffuse nebula
   C. Emission nebula
   D. Reflection nebula

10. This object primarily obscures light from which of the following regions of the EM spectrum?
    A. Radio
    B. Microwave
    C. Infrared
    D. Optical

11. Obscuring light in this band implies that the dust particles in the nebula are (on order) how large?
    A. 500 nm
    B. 100 µm
    C. 50 mm
    D. 10 m

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12. A protostar that forms with a mass of less than ________ is likely to become a brown dwarf.
    - A. $0.008\,M_\odot$
    - B. $0.08\,M_\odot$
    - C. $0.8\,M_\odot$
    - D. $8\,M_\odot$

13. What key process in stars are objects below this mass unable to complete?

14. A very young brown dwarf primarily generates energy through which of the following reactions?
    - A. p–p chain hydrogen fusion
    - B. CNO cycle hydrogen fusion
    - C. Deuterium fusion
    - D. Helium fusion

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15. Which of the following planets is most easily detected using the radial-velocity method?
    - A. Neptune-like
    - B. Hot Jupiter
    - C. Terrestrial
    - D. Sub-Neptune

16. List two key properties of this planet type that make it easier to detect with radial velocity.

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17. The mass of a Super-Earth planet falls in what mass range?
    - A. Less massive than Earth
    - B. More massive than Earth, less massive than ice giants
    - C. More massive than ice giants, less massive than Jupiter
    - D. More massive than Jupiter

18. We can get a general idea of the elemental composition of an exoplanet based on the elemental composition of its star. Why would the composition of these objects be linked?

Taken by JWST, Image 5 displays an intense process of stellar evolution.

19. What is the term for the object in this image?
    - A. Circumstellar disk
    - B. Relativistic jet
    - C. Stellar wind
    - D. Herbig–Haro object

20. Briefly (1–2 sentences) describe the process occurring at the “ends” of the objects (indicated by arrows) that cause them to emit light.

Section B: JS9

This section consists of a lab using the JS9 imaging software. Unless otherwise specified, each question is worth 2 points, for a total of 15 points.

On the provided laptop, JS9 should be open, showing **a white dot in the middle of a black screen**. If you do not see this, or need the file re-opened, raise your hand.

For questions 1-3, do not add a region to perform this analysis!
This object dominates the image, so adding regions will be time-consuming and unnecessary.

1. Run `[Analysis > Server-side Analysis: Energy Spectrum]`.

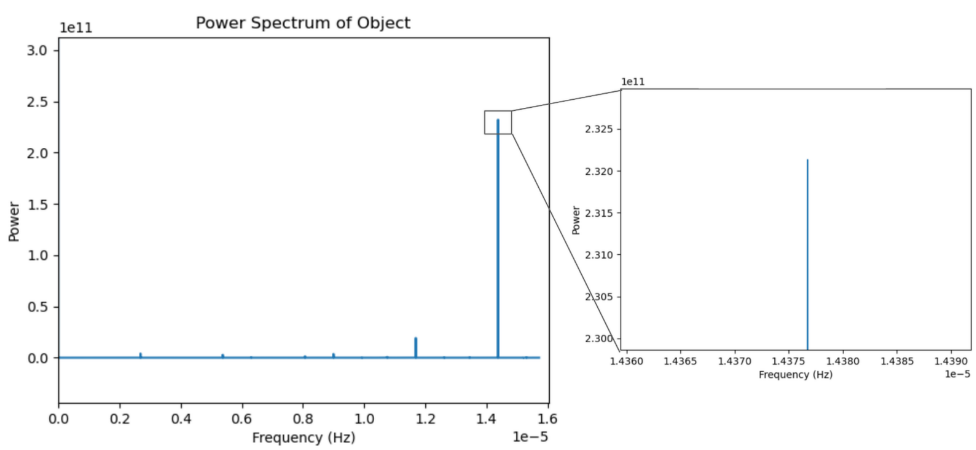
   What major spectral features does this object exhibit? Briefly describe these, and give the wavelengths of any peaks.

2. The lowest energy (farthest left) spectral line is a Neon line, and has a natural width of 0.24 eV. By what factor has this line been broadened?
   (Note: The number that we get will be off, because of the reality of analyzing this raw spectral data. However, it won't be a bad estimate.)

3. This object is a protostar. What is the most likely reason for the broadening of these lines?

This object also has an interesting light curve!

4. The power spectrum of this object is given below. Estimate this object's period, in hours. Be careful with the x–axis—notice that it is scaled by 1×10^{-5}.
   (Hint: Remember the power spectrum x-axis is a frequency, so take its reciprocal to get the period.)



5. What is the exposure of this image, in hours? How does the object's period compare with the exposure?
   (Hint: The FITS header beckons...)

6. [3 pts] Encircle the bright central point in a region, with `[Regions > circle]`. Use `[Analysis > Server-side Analysis: Light Curve]` to generate this object's light curve.

   Roughly sketch the resulting waveform. Label the y-axis with the amplitude of any major peaks, and the background.

7. List one mechanism that can result in periodic emission from a protostar.

Section C: Deep-Sky Objects

This section consists of a mix of multiple choice and free-response questions about this year's DSOs. Unless otherwise specified, each question is worth 2 points, for a total of 45 points.

Match the following ten (10) statements with the corresponding deep-sky object in the list below. Each choice may be used once, more than once, or not at all.

A. Orion Nebula	F. TOI-270d
B. HD 80606b	G. WD 1856+534
C. WASP-121b	H. 55 Cancri
D. LTT 9779b	I. Kepler-62
E. K2-18b	J. AU Microscopii

1. This Messier object contains an open cluster, notable for its four young OB stars.
2. A red dwarf with two confirmed Neptune-like planets detected by TESS.
3. Hubble detected a stratosphere (i.e. an atmospheric layer with a temperature inversion) in this ultra-hot Jupiter.
4. This binary system is located just 41 light-years away, with its primary star named after the astronomer who placed the Sun at the center of the universe.
5. JWST detected methane, carbon dioxide, and water vapor in the atmosphere of this planet, which resides in a system with two other confirmed planets.
6. A planetary system with five confirmed exoplanets with the innermost one being a super-Earth.
7. A highly eccentric gas giant in the constellation Ursa Major.
8. Image 2 depicts the spectra of this object.
9. This object is part of a triple star system.
10. A high albedo planet with a G-type main sequence host star.
11. The central region of 30 Doradus is shown in Image 6.
    (a) What process formed the cavity in the bottom left of the image?
    (b) [3 pts] Is the blue star in the cavity younger or older than the stars in the colored regions. Explain your answer.
    (c) What instrument produced this image?
12. WASP-17b is a gas giant tidally locked to its host star.
    (a) Explain what it means to be "tidally locked." Give an example of this occurring in the Solar System.
    (b) What type of silicate was discovered in its atmosphere?
    (c) What observational technique was used to make this discovery?
13. Image 3 shows two light curves.
    (a) Name the wavelengths these two curves are observed in.
    (b) What type of event is occurring in this light curve?
    (c) A typical simplification in the analysis of these curves leads to the bottom of the curve being flat. Give two possible reasons why we don't observe this.
14. Image 7 highlights a star found in the southern hemisphere, located less than 11 light-years from Earth.
    (a) Identify this star.
    (b) A planet was detected orbiting about this star. What method was used to do so?
    (c) What property of the star impacted the validity of the exoplanet's detection?

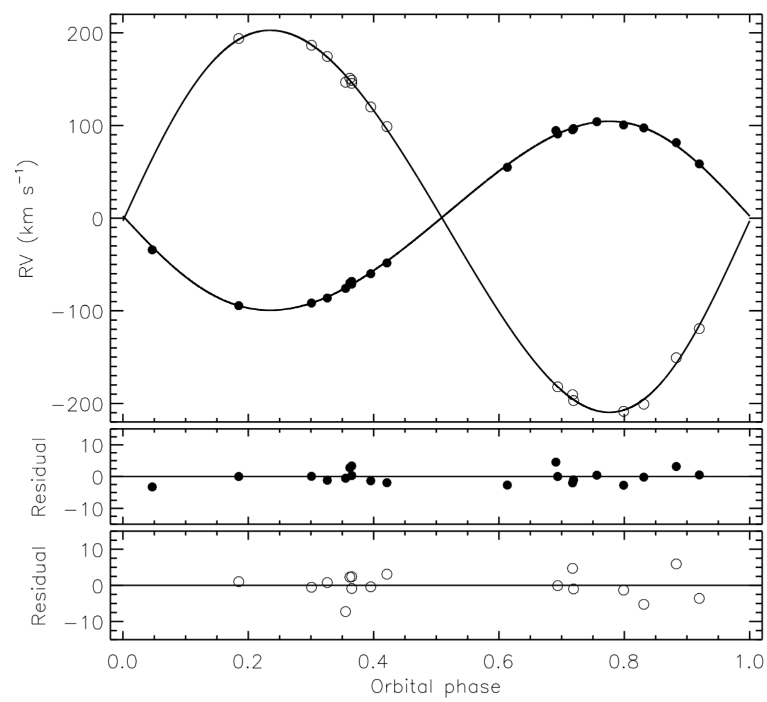
Section D: Astrophysics

This section consists of astrophysics calculations and free-response questions. Points are shown for each sub-question, for a total of 40 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.

Conversions and constants you may find helpful:

$1\,\text{au} = 1.496 \times 10^{11}\,\text{m}$	$1\,\text{R}_\odot = 6.957 \times 10^{8}\,\text{m}$	$G = 6.674 \times 10^{-11}\,\text{N}\,\text{m}^2\,\text{kg}^{-2}$
$1\,\text{ly} = 9.461 \times 10^{15}\,\text{m}$	$1\,\text{M}_\odot = 1.989 \times 10^{30}\,\text{kg}$	$b = 2.898 \times 10^{-3}\,\text{m}\,\text{K}$
$1\,\text{pc} = 3.086 \times 10^{16}\,\text{m}$	$M_\odot = +4.74$ (Abs. mag.)	$\sigma = 5.670 \times 10^{-8}\,\text{W}\,\text{m}^{-2}\,\text{K}^{-4}$

1. **Binary Stars.** You come across a binary star system containing two main-sequence stars: **A** and **B**. As a generally lucky astronomer, you assume the system is approximately edge-on and measure the radial-velocity of the system over some time, as seen below. Assume star **A** is more massive than star **B**, and all orbits are circular.



   (a) [2 pts] This system has a parallax of 0.001″; how far away is it, in light-years?

   (b) [2 pts] Is the binary system moving relative to the observer? Why or why not?

   (c) [2 pts] What does our assumption—that the system is viewed edge-on—allow us to conclude?

   (d) [3 pts] Given the period of the stars is 3 days, find the radius of each star's orbit from the center of mass of the system, in meters.

   (e) [3 pts] Find the mass of the entire binary system, in solar masses.

   (f) [2 pts] Find the mass of star **A**, M_A, and star **B**, M_B, individually in solar masses.

2. **A Little Shifty.** Continuing with the same scenario as the previous question, after more careful observation, you estimate that one of the stars has a surface peak wavelength emission at 300 nm.
   (a) [2 pts] What is the surface temperature of the star, in Kelvin?
   (b) [2 pts] Identify the spectral type and subclass of this star. *(Hint: It's a letter, then a number.)*
   (c) [1 pt] Which star is more likely to have this surface temperature?
   (If you couldn't derive the masses of the stars, assume $M_A = 6\,M_\odot$ and $M_B = 2\,M_\odot$.)
   (d) [2 pts] What parts of the orbital phase in the radial-velocity curve (from question 1) should we observe the stars to get the most accurate surface temperature estimates?
   (e) [3 pts] Another astronomer makes an observation and finds the star has a peak wavelength 0.04 nm less than the original 300 nm, which is your (perfectly accurate) measurement. What was the radial velocity (in $\mathrm{km\,s^{-1}}$) of the star at this time? Is it moving towards or away from Earth?
   (f) [2 pts] Assuming your measurement was made at the optimal time, how long after your observation (in days) was their observation made? As a reminder, the total orbital period is 3 days.
   (Note: There are multiple valid answers, but you need only list one of them.)

3. **Resolution!** A planet that was previously thought to have orbited a single host star is found to be orbiting a very compact set of binary stars.
   (a) [2 pts] If the planet was discovered using direct imaging, what common tool would have been used to blot out the central stars?
   (b) [3 pts] If the diameter of your space telescope is 10 meters and you are observing the system at a wavelength of 10 micrometers, what is the limiting angular resolution of your telescope (by diffraction), in radians?
   (c) [2 pts] The wavelength used by the telescope in part (b) is often used for direct imaging. Why?
   (d) [3 pts] The stars have an absolute magnitude of +1 and +4, respectively. When viewed together, what is their combined absolute magnitude?
   (e) [4 pts] In the far future, astro-neers land and settle on this planet. They find it orbits at a distance of 7 au and is tidally locked to its host stars. More importantly, it lacks an atmosphere!
   So, they construct a bio-dome 2 km in diameter at the planet's substellar point. The shell of the bio-dome is designed to replicate the thermal properties of Earth, having a bond albedo of 0.3 and an emissivity of 0.9. For simplicity, we'll assume the bio-dome is an opaque hemisphere.
   (Note: Use +4.74 for the absolute magnitude of the Sun.)
   What is the temperature in the bio-dome, in Celsius? Is it habitable?