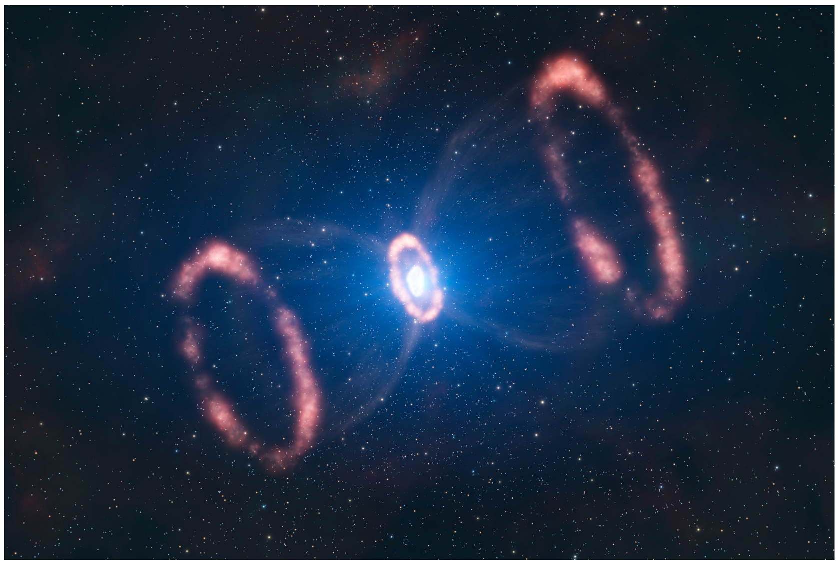
Science Olympiad
National Tournament

May 23-24, 2025

Reach for the Stars – Division B



Directions:

- This exam consists of **7 questions** worth **160 points** in total. Partial credit will be considered. There is no penalty for incorrect answers.
- You are allowed to bring in **two 8.5"×11" sheets of paper** with information on both sides.
- The use of calculators or AI tools (e.g. ChatGPT) is expressly forbidden.
- In the event of a tie, placement will be determined by cumulative score on the following questions, in order: **Q1, Q7, Q6, Q5, Q4, Q3, Q2**.
- This exam will be posted online after the competition at https://chandra.si.edu/edu/ and https://www.universeunplugged.org/series/nso-webinars.
- A survey will be available afterward about your experience with the exam and the event generally. We encourage you to take it to help us improve the event for next year!
- Above all else, just believe!

Written by:

The Reach for the Stars A-Team

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Question 1: See What You Can Find [30 pts.]

For each of the questions below, refer to ***both pages*** of the attached Image Sheet where prompted. All questions are worth **1 point** unless otherwise specified.

a. [1 pt] What is the name of the red giant star in Image 13?

b. [1 pt] What is the name of the star system depicted in Image 2?

c. [1 pt] Which image depicts the constellation Orion?

d. [1 pt] What stage of evolution on the H-R Diagram is the object in Image 4 in?

e. [2 pts] White dwarfs generally result from the deaths of stars under ______ $M_\odot$, while neutron stars result from the deaths of stars between that and ______ $M_\odot$.

f. [1 pt] Which image depicts the constellation which contains SS Cygni?

g. [1 pt] What type of object is depicted in Image 9?

h. [1 pt] The diagram in Image 3 depicts a binary system of one neutron star and one ______.

i. [1 pt] Image 10 depicts the behavior of which object?

j. [2 pts] In Image 29, the solid line represents a ______ event, while the dashed line represents a ______ event.

k. [1 pt] Which image depicts a a gamma-ray outburst in a Type II supernova remnant?

l. [1 pt] Which image depicts the behavior of the brightest star in Orion?

m. [1 pt] Which image depicts the constellation which contains the Cat's Eye Nebula?

n. [1 pt] The most recently-observed supernova in the Milky Way was of what type?

o. [2 pts] The behavior depicted in Image 31 is produced by a binary system of a main-sequence ______ star and a post-main-sequence ______ star.

p. [1 pt] What is the name of the object depicted in Image 17?

q. [1 pt] What stage of evolution on the H-R Diagram is an RR Lyrae variable in?

r. [1 pt] Which image depicts the behavior of the first observed gravitational wave signal?

s. [1 pt] Which image depicts the constellation containing the object in Image 15?

t. [2 pts] Which image depicts a Hubble observation of the remnant SN 1604? Which image depicts this same region in infrared?

u. [1 pt] The first widely-acknowledged black hole candidate is also a high-mass ______ binary.

v. [1 pt] Which image depicts a radio observation of the compact remnant of SN 1987A?

w. [1 pt] What type of variable star is depicted in Image 30?

x. [1 pt] Which image depicts the constellation containing the object in Image 28?

y. [2 pts] Image 16 depicts which object? Which image depicts the central compact remnant of this object in x-ray?

Question 2: The Stellar Circle of Life [15 pts.]

Image 32 is a graphical representation of various stages in the life cycle of a star. For all questions in this section, refer to Image 32.

a. [1 pt] What type of diagram is depicted in Image 32?

b. [2 pts] Which values are plotted on the x and y axes of this diagram? Include units.

c. [1 pt] Which letter on this diagram best matches the location of the Sun?

d. [1 pt] Which letter on this diagram best matches the location of Alpha Orionis?

e. [1 pt] Which letter on this diagram best matches the location of Omicron Ceti?

f. [1 pt] Which letter on this diagram best matches the location of Sirius B?

g. [1 pt] Which letter on this diagram best matches the location of the donor star of SS Cygni?

h. [1 pt] Which letter on this diagram corresponds to the next phase in the Sun's life?

i. [1 pt] Which letter on this diagram corresponds to the final phase of the Sun's life?

j. [5 pts] Sort the following letters into chronological order for the life cycle of the star Sirius A: **C, D, E, F, H, J, K**

Question 3: Climbing the Ladder [22 pts.]

Astronomers may use many different means of measuring an object's distance, depending on how far away they think an object might be. This principle is known as the **"Cosmic Distance Ladder"**. Below are images representing three objects, each of which is featured in the rules this year.

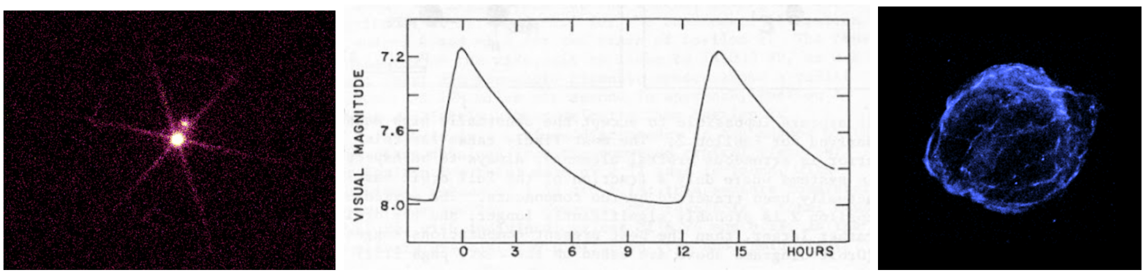

Figure 1: Object A (left), Object B (center), and Object C (right)

a. [3 pts] Identify the names of objects A, B, and C.

b. [3 pts] What types of objects (star, nebula, etc.) are A, B, and C? Identify each one.

Assume, for the sake of this question, that all three objects appear **exactly as bright as one another** in the night sky, and are being observed **at their brightest moment in time**.

c. [1 pt] While an object's brightness at exactly 10 parsecs is its "*absolute magnitude*", its brightness at whatever distance you are observing it is known as its "__________ *magnitude*".

d. [2 pts] Can we be sure that all 3 objects have the same absolute magnitude? Why or why not?

e. [3 pts] Given the assumptions above, order objects A, B, and C from closest to furthest away.

Due to differences in their distances, we need different methods to determine how far away each object is. We will consider **stellar parallax** and **the distance modulus** for a **standard candle**.

f. [1 pt] What is a "standard candle"?

g. [3 pts] Based on your answer to part e, identify which methodology (parallax or distance modulus) is most appropriate for each object.

h. [6 pts] To your astonishment, only one month after your initial observation of objects A, B, and C, each object has decreased in brightness by **magnitude +2**!

(i) [2 pts] In which object would such a decrease in brightness **not** be surprising? Why not?

(ii) [2 pts] Why would this be so unexpected in the other two objects?

(iii) [2 pts] For these two objects, provide at least two theories for what might be happening. *Note: these explanations need not be reasonable or even possible in real life – so long as they would explain such unexpected behavior, they are fair game!*

Question 4: Circular Reasoning [20 pts.]

Many of the objects in the rules are part of binary systems, like SS Cygni or Mira. In 1974, Russell Alan Hulse and Joseph Hooton Taylor Jr. discovered the first ever pulsar in a binary system.

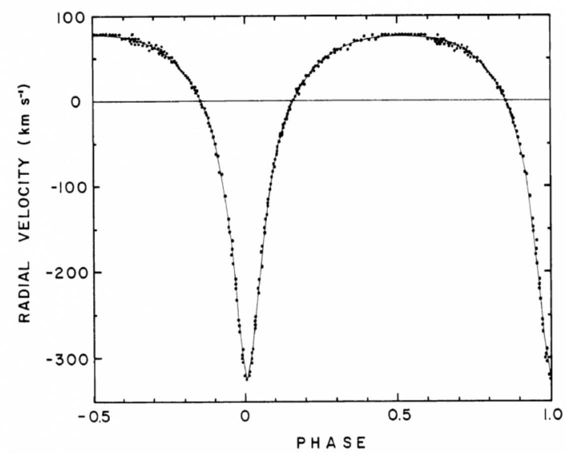

Figure 2: Radial velocity of the Hulse-Taylor pulsar. When the radial velocity is negative, the pulsar is moving towards us; when it is positive, the pulsar is moving away.

a. [1 pt] In addition to the pulsar, what other type of object is in the Hulse-Taylor binary system?

b. [2 pts] Briefly explain what redshifted and blueshifted mean in astronomy. When the pulsar is moving towards Earth, do we say that its light is redshifted or blueshifted?

c. [2 pts] Astronomers have discovered many pulsars and binary systems. Why was discovering a pulsar in a binary system with a compact object particularly notable and useful for astrophysics?

d. [9 pts] On the answer sheet, sketch a diagram of the Hulse-Taylor pulsar's orbit around the system's center of mass. Please include:
- an arrow indicating the direction toward Earth
- an arrow indicating the direction (clockwise or counterclockwise) that the pulsar orbits
- the position of the center of mass
- the positions in the orbit corresponding to phase = 0 and phase = 0.5
- the positions in the orbit corresponding to maximum kinetic energy and potential energy

Note: the arrows can be in any direction as long as your diagram is consistent overall.

e. [4 pts] Using only the information in Fig. 2, estimate the eccentricity, e, of the orbit. Show your work and explain the physics of what you are doing; the process is much more valuable to us than the exact value. *Hints:* $e = (d_a - d_p)/(d_a + d_p)$*; angular momentum is conserved.*

f. [2 pts] Suppose you magically created a "replica" of this binary system where the objects and semi-major axis are the same. However, the orbit in the new system is perfectly circular instead of elliptical. Which system has the higher angular momentum? Explain.

Question 5: Burning Out or Fading Away? [18 pts.]

In late 2019, one of the stars on this year's rules underwent an irregular dimming event. This event, in which the well-studied star unexpectedly diminished in brightness by more than magnitude +1.

a. [1 pt] Identify the star described above.

b. [2 pts] This star has dimmed many times before. Why was this particular event so notable?

c. [3 pts] At the time, one popular theory was that this star was on the verge of a supernova. How could the dimming have indicated this 'imminent event', and why astronomers dispute it?

The plots below depict the spectrum of this star in the middle of this dimming event.

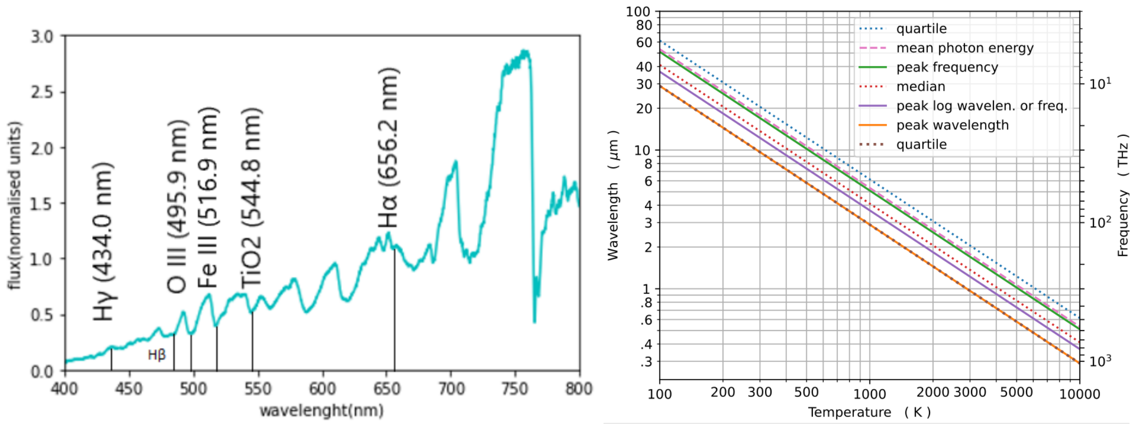

Figure 3: Spectrum of star (left); relation of stellar temperature to spectral parameters (right)

d. [4 pts] Prior to this event, this star was known to have a surface temperature of **∼3600 K**.

   (i) [1 pt] What wavelength did this star's spectrum peak at at time of dimming?

   (ii) [2 pts] What surface temperature does this correspond to? Which physical law describes this relationship?

   (iii) [1 pt] How does this compare to the prior observed temperature of the star?

e. [4 pts] Assuming no major change in other intrinsic physical properties (e.g. radius, mass, etc.), what does this data imply about the luminosity of this star over the course of its dimming period? Does this validate or disprove the "imminent supernova" theory? Explain.

f. [4 pts] Propose at least one alternative theory that might explain this dimming event. Be sure to account for your temperature observations, known constant values, the time frame of the dimming, and the preceding and succeeding behavior of the star.

Question 6: Lighthouses of the Universe [20 pts.]

In 1967, Jocelyn Bell detected mysterious radio signals arriving every 1.337 seconds. Scientists thought through many possibilities before concluding that the signals come from rapidly rotating neutron stars called pulsars. Most pulsars have periods between 0.001 and 10 seconds.

a. [1 pt] Do astronomers believe the Sun will eventually become a pulsar? Why or why not?

b. [2 pts] Explain the mechanism through which pulsars emit radiation and we observe it. Why do we see "pulses" separated by some amount of time instead of a constant signal?

c. [1 pt] At first, Bell thought that the signal might be an artifact of the specific telescope she was using. Describe one thing you could do to see if the signal is an instrumentation artifact.

d. [1 pt] Bell briefly considered the possibility that the signals came from aliens trying to communicate with Earth. However, she later discovered a second signal in a completely different region of the sky. Explain why this discovery made aliens a less likely source of the signals.

e. [2 pts] One way of producing a predictable signal is through a binary system. A binary system of neutron stars could orbit physically close enough to produce rapid enough pulses. However, this possibility is ruled out by Einstein's general theory of relativity. Explain why.

f. [3 pts] Another way to produce these pulses is through oscillations in a star. The oscillation period, P, is proportional to $\rho^{-1/2}$, where ρ is the density of the star. Given that white dwarfs oscillate with periods of 10^2 to 10^3 seconds and neutron stars are 10^8 times denser, estimate the oscillation period for neutron stars. Explain why neither white dwarf nor neutron star oscillations can completely account for typical pulsar periods.

g. [4 pts] The last way to produce pulses like this is through rapid rotation. For a rotating star to remain intact, the gravitational force holding the star together must exceed the centripetal force required to rotate that quickly. Starting with

$$\frac{v^2}{R} \leqslant \frac{GM}{R^2}$$

derive an expression for the minimum density ($\rho_{\min}$) required for a star with rotation period P to remain intact. Express your answer in terms of only P, G, and dimensionless constants, like π. Assume that the object is a perfect sphere with volume $\frac{4}{3}\pi R^3$.

h. [2 pts] When a star rotates rapidly, it flattens at the poles and bulges at the equator. If our star is modeled as this flattened spheroid instead of a perfect sphere, does $\rho_{\min}$ increase or decrease compared to your answer from the previous part?

i. [4 pts] With your answer from part (g), use order-of-magnitude estimation to show that rotating neutron stars can accommodate the range of periods that pulsars exhibit. $1\ M_\odot \approx 2 \times 10^{30}$ kg, $G \approx 7 \times 10^{-11}$ N$\cdot$ m^2/kg^2, and neutron stars have a radius of about 10^4 m.

Question 7: Mission Makeover – Space Edition [35 pts.]

It is the summer of 2040, and in a couple of months the astronomical community will celebrate the 25th anniversary of the first signal detection of gravitational waves, named GW150914. In the intervening decades since the discovery, further study has revealed that the black hole merge event which produced this signal left behind a massive, highly-active, singular merged black hole.

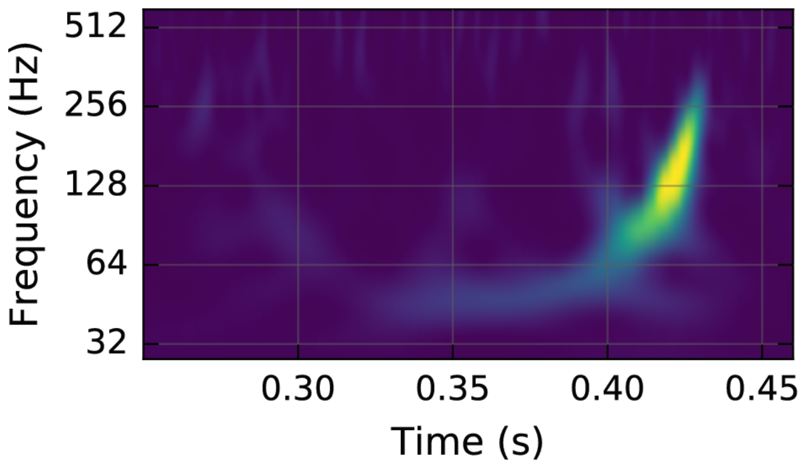

Figure 4: The "chirp" of GW150914, a.k.a. the moment at which the two black holes within the binary merged

As part of the celebration, and in honor of the work to be done in the field of black hole research, NASA Science Mission Directorate has issued the following call for proposals to study the results of black hole merging events:

> *"In accordance with burgeoning needs within the astrophysical community, we are issuing a call for mission proposals to design an Earth-orbiting space telescope that will be used to study accretion effects and energetic activity in the disk environments of post-merger black holes, such as those which produced the famous GW150914 signal."*

Seeing the need for such a mission, and being yourself interested in continuing to study **activity in the disk environment around post-merger objects**, you set about designing a mission proposal which would enable such science to take place.

Using your knowledge of existing missions, as well as the science of **late-stage stellar evolution and black holes**, your job is to:

a. [5 pts] Define your overall **Mission Goal** – In a sentence, what would your observatory do?

b. [6 pts] Identify **three key Science Requirements** driving your mission's design, namely:
   (i) [2 pts] Observational **wavelength regimes** to conduct science in (*"What wavelengths will the phenomena I study be best observed in?"*)
   (ii) [2 pts] Means of identifying **post-merger candidates** for study (*"How will the mission identify black holes formed from a merger?"*)
   (iii) [2 pts] Time-resolvable **targets** of observation (*"What sorts of activity will we be trying to study in these black holes?"*)

   *Hint: Science requirements are driven by the mission goal – they are your way of ensuring the science you end up doing aligns with what you set out to study (in this case, accretion and energetic activity in the disks of **post-merger black holes**).*

c. [6 pts] Identify **one key Engineering Requirement** for each **Science Requirement**, namely:
   (i) [2 pts] Wavelength capacity (*Hint: This is a length or energy range*)
   (ii) [2 pts] Signal sensitivity (*Hint: This is a frequency and time duration limit*)
   (iii) [2 pts] Minimum & maximum exposure durations (*Hint: These are durations of time*)

   (*Hint: Engineering requirements are driven by science requirements – they are your way of ensuring the **design** of the mission will meet the **needs of the scientists** who will use it*)

d. [12 pts] Based on the goal/requirements you identified, design an observatory! You have total freedom, so long as you meet **all Science/Engineering Requirements**. You may consider:
   (i) Orbital Configuration
   (ii) Onboard Instruments (the "science payload")
   (iii) Power & Electronics
   (iv) Communication & Data Handling
   (v) Anything else you find relevant, fascinating, cool, etc.

   You may focus your attention on any or all of these areas, but none is explicitly necessary – your design will primarily be graded on its **feasibility** and the degree to which it meets the **Science and Engineering Requirements** you specified.

e. [6 pts] Bonus points for **creativity**! This is a loose category, and could encompass novel approaches to old ideas, a fun mission name or patch, a sketch of the observatory, non-requirements-based capabilities, or anything else to help it stand out and draw attention. Remember: NASA is funding your mission, and NASA's money comes from the general public, so make your mission something people would want to support, whether or not they are scientists themselves. Have fun, get creative, and enjoy making something brand new!