Science Olympiad
Science Olympiad National Tournament 2025
May 23-24, 2025

Reach for the Stars B Answer Key

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Question 1 (30 points)

a. [1 pt] Mira / Omicron Ceti

b. [1 pt] Sirius / Alpha Canis Majoris

c. [1 pt] Image 26

d. [1 pt] Asymptotic Giant Branch

e. [2 pts] 8 $M_\odot$, 20 $M_\odot$

f. [1 pt] Image 22

g. [1 pt] Planetary nebula

h. [1 pt] Pulsar

i. [1 pt] SS Cygni

j. [2 pts] Type II; Type I

k. [1 pt] Image 6

l. [1 pt] Image 33

m. [1 pt] Image 23

n. [1 pt] Type Ia

o. [2 pts] Red dwarf; white dwarf

p. [1 pt] Cygnus X-1

q. [1 pt] Instability strip

r. [1 pt] Image 34

s. [1 pt] Image 18

t. [2 pts] Image 12; Image 8

u. [1 pt] X-ray

v. [1 pt] Image 7

w. [1 pt] Long-period variable / Mira variable

x. [1 pt] Image 20

y. [2 pts] NGC 6543 / Cat's Eye Nebula; Image 14

Question 2 (15 points)

a. [1 pt] HR Diagram

b. [2 pts] X: Temperature in kelvin; Y: Luminosity in Solar units

c. [1 pt] I

d. [1 pt] K

e. [1 pt] J

f. [1 pt] C

g. [1 pt] M

h. [1 pt] J

i. [1 pt] F

j. [5 pts] D -> J -> H -> K -> E -> C -> F

Question 3 (22 points)

a. [3 pts] A: Sirius (+1); B: RR Lyrae (+1); C: SN 1604/Kepler's SNR (+1)

b. [3 pts] A: Star/binary system (+1); B: Star/variable (+1); C: Supernova remnant/type Ia supernova (+1)

c. [1 pt] Apparent

d. [2 pts] No (+1), because if they are all at different distances, their apparent magnitudes could look the same even with different absolute magnitudes (+1)

e. [3 pts] A, B, C (+1 for A before B, +1 for A before C, +1 for B before C)

f. [1 pt] An object or event that always has the same absolute magnitude, and thus once identified can be used to benchmark astronomical distances regardless of its brightness

g. [3 pts] A: parallax (+1); B: distance modulus (+1); C: distance modulus (+1)

h. [6 pts] Answers for sub-parts:

   (i) [2 pts] Object C (+1), since a Type Ia supernova would be expected to decrease by that much over a month (+1).

   (ii) [2 pts] Object A is a main-sequence star and thus shouldn't show variability (+1); Object B does vary in brightness, but not as much as magnitude +2 based on its light curve (+1)

   (iii) [2 pts] Any answers are acceptable here so long as they account for Objects A and B diminishing in brightness as explained. Potential answers include: the objects are getting further away, a large opaque cloud has passed between us and the object(s), the objects were misidentified or observations were incorrect somehow, etc.

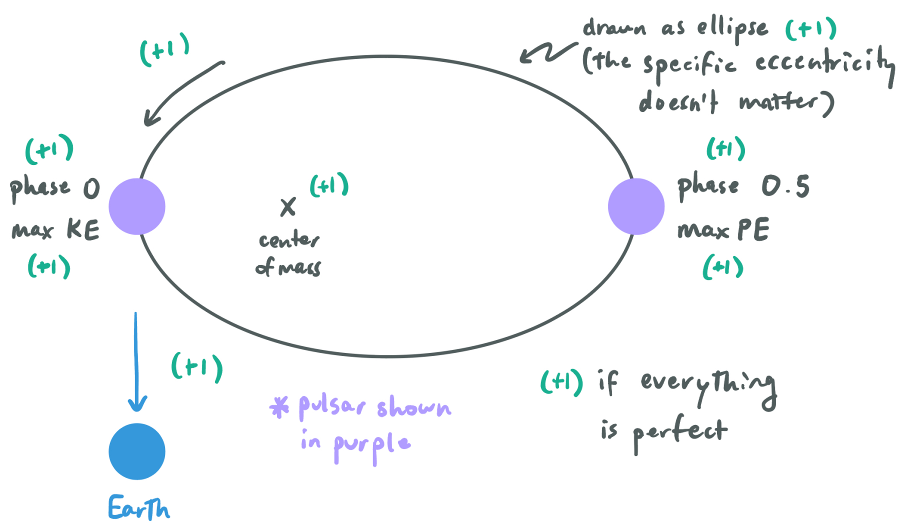
Question 4 (20 points)

a. [1 pt] Neutron star.

b. [2 pts] Redshift and blueshift refer to the Doppler effect as observed in light waves. Redshift occurs when light waves are stretched to longer wavelengths (+0.5). Blueshift occurs when light waves are compressed to shorter wavelengths (+0.5). When the pulsar is moving towards Earth, its light is blueshifted (+1).

c. [2 pts] The Hulse-Taylor pulsar contains two massive compact objects that are orbiting very closely to each other at high speeds. As a result, scientists can use this system to experimentally test general relativity (+2), which Einstein published in 1915. Students got 1 point if they mentioned that it was the first binary pulsar system ever discovered.

d. [9 pts] Orbits should look approximately like this:



Some notes about the diagram:

- Notice how the shape of the radial velocity curve indicates that the orbit is an ellipse. If the orbit was perfectly circular, then the curve would look like a sine wave.
- From Kepler's first law, we know that the center of mass is at one of the *foci* of the ellipse, *not* in the center.
- Since the plot is symmetric around phase = 0, we know the direction to Earth is parallel to the minor axis.

- Since the fastest speed is negative (moving towards us), the direction to Earth must also be pointing in the same direction as the velocity vector of the pulsar when it is at periapsis.
- At periapsis, the speed is highest (so phase = 0) and kinetic energy is maximized. Similarly, at apoapsis, phase = 0.5 and potential energy is maximized.

Rotations, reflections, etc. of this drawing are given full credit as long as the relative orientations, shapes, etc. are consistent. I encourage looking at this radial velocity simulator to build more intuition for this (note: their convention is such that moving away is negative velocity).

e. [5 pts] From the figure, we can read that the maximum negative velocity is approximately -320 km/s and the maximum positive velocity is approximately $+80$ km/s. From the previous part, we know that these occur at periapsis and apoapsis, respectively.

From conservation of angular momentum, we know that at periapsis and apoapsis, $m|v_p|d_p = m|v_a|d_a$, where the $|v|$ represents the speed at that point and d is the distance from the pulsar to the center of mass of the system. We know that $|v_p/v_a| \approx |-320/80| \approx 4$. So, $d_a/d_p \approx 4$. Now, using the hint:

$$\begin{aligned} e &= \frac{d_a - d_p}{d_a + d_p} \\ &\approx \frac{4d_p - d_p}{4d_p + d_p} \\ &\approx \frac{4-1}{4+1} \\ &\approx \frac{3}{5} \end{aligned}$$

f. [2 pts] The circular orbit has higher angular momentum than the elliptical orbit. For a two-body system with fixed semi-major axis a, the orbital angular momentum is proportional to $\sqrt{1-e^2}$ where e is the eccentricity. For a circular orbit, $e = 0$ and the factor becomes 1 (maximum possible value). For the elliptical orbit with $e > 0$, this factor must be less than 1.

Question 5 (18 points)

a. [1 pt] Betelgeuse / Alpha Orionis

b. [2 pts] It occurred without precedent (+1) and at a much higher degree that previous events (+1)

c. [3 pts] Stars about to go supernova undergo collapse (+1) which leads to a drastic decrease in luminosity (+1); astronomers considered the time frame unlikely as it was unaccompanied by other evidence (+1)

d. [4 pts] Answers for sub-parts:

   (i) [1 pt] Accept 725 nm – 775 nm

   (ii) [2 pts] Accept 3500 K – 4000 K (+1); Wien's Law (+1)

   (iii) [1 pt] They are nearly identical in value

e. [4 pts] By the Stefan-Boltzmann Law (+1), this implies that the luminosity of the star remained relatively consistent throughout the dimming (+1). This invalidates the supernova theory (+1), as such an event would require the star's dimming to be the result of a drop in luminosity (+1).

f. [4 pts] Full points awarded for taking into account that:

   (i) [1 pt] Temperature remaining unchanged

   (ii) [1 pt] Luminosity & radius unchanged

   (iii) [1 pt] Dimming lasted only a few months

   (iv) [1 pt] Other dimming events occurred which were minor in comparison

Question 6 (20 points)

a. [1 pt] No (+0.5). Pulsars are rapidly rotating neutron stars, and neutron stars only form from the collapse of very massive stars (typically greater than 8 solar masses). The Sun, with only 1 solar mass, is not massive enough to undergo core collapse to form a neutron star. Instead, the Sun will eventually exhaust its nuclear fuel, shed its outer layers to form a planetary nebula, and leave behind a white dwarf remnant (+0.5).

b. [2 pts] Pulsars have extremely strong magnetic fields. Charged particles are accelerated along the magnetic field lines and emit beams of electromagnetic radiation from the magnetic poles of the neutron star (+1). There are a couple of different categories of pulsars, and we gave credit for any valid explanation. But, in order to get this point, students have to describe some sort of mechanism beyond just saying "pulsars spin quickly".

   Why do we not see a continuous signal from the pulsar? As the neutron star rotates, these beams sweep across space like a lighthouse. We observe "pulses" because we only detect the radiation when the beam is pointed directly toward Earth during each rotation. The pulsar is still emitting radiation even when we don't see a signal from it; it's just that the radiation isn't pointed towards us. The time between pulses is the rotation period of the neutron star (+1).

c. [1 pt] The simplest thing is to observe the same region of the sky with a different telescope (+1). This doesn't rule it out for sure, but if the signal still appears with the different telescope, then it is much less likely that it's an instrumentation artifact. Students also got points for answers like "change the parts in the original telescope and see if the signal still appears“.

d. [1 pt] It would be highly improbable for multiple alien civilizations to be transmitting nearly identical signals simultaneously from different parts of the galaxy. And, even if there were two groups of aliens trying to communicate with each other, the liklihood that Earth would be in their "line of sight“ is very small.

e. [2 pts] According to Einstein's general theory of relativity, a binary system of compact objects (like neutron stars) loses energy by emitting gravitational waves. This means the period of the signal produced by the binary system *decreases* with time (+1). However, pulsar periods are observed to *increase* with time (+1).

f. [3 pts] Since P is proportional to $\rho^{-1/2}$:

$$\frac{P_{\mathrm{NS}}}{P_{\mathrm{WD}}} = \left(\frac{\rho_{\mathrm{WD}}}{\rho_{\mathrm{NS}}}\right)^{1/2} = \left(\frac{1}{10^8}\right)^{1/2} = 10^{-4} \Rightarrow P_{\mathrm{NS}} = 10^{-4} P_{\mathrm{WD}}$$

From the problem statement, we know that P_{WD} is 10^2 to 10^3 seconds. So, the lower bound of P_{NS} will be $10^{-4} \times 10^2 = 10^{-2}$ seconds. The upper bound will be $10^{-4} \times 10^3 = 10^{-1}$ seconds (+2 for getting both correct, +1 for finding the ratio 10^{-4} or 10^4 but not getting the final numbers correct, +0.5 for an attempt generally involving proportions). Neither mechanism fully explains pulsar periods because white dwarf oscillations are too slow, and neutron star oscillations are too fast for the slower pulsars (+1).

g. [4 pts] We start with the equation given in the problem statement:

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

Imagine a point traveling around the equator of an object. Its speed will be distance divided by time. The distance is the circumference, and the time is the period (how long it takes to rotate around once). So, $v = 2\pi R/P$. Making this substitution (+1) gives:

$$\begin{aligned} \frac{(2\pi R/P)^2}{R} &\leqslant \frac{GM}{R^2} \\ \frac{4\pi^2 R}{P^2} &\leqslant \frac{GM}{R^2} \\ \frac{4\pi^2 R^3}{GP^2} &\leqslant M \end{aligned}$$

Right now, we have things in terms of mass. However, we want things in terms of density, which is mass divided by volume (i.e., $\rho = M/V$). For a sphere, $M = \rho V = \rho \times \frac{4}{3}\pi R^3$. Making this substitution (+1) gives:

$$\begin{aligned} \frac{4\pi^2 R^3}{GP^2} &\leqslant M \\ \frac{4\pi^2 R^3}{GP^2} &\leqslant \rho \times \frac{4}{3}\pi R^3 \\ \frac{4\pi^2}{GP^2} &\leqslant \rho \times \frac{4\pi}{3} \\ \rho &\geqslant \frac{3\pi}{GP^2} \end{aligned}$$

Students automatically get +1 point for attempting. If students simplify the algebra perfectly, then they get an additional +1 point, for a total of 4 points for this part.

h. [2 pts] When a star rotates rapidly and flattens into an oblate spheroid, the equatorial radius becomes larger than it would be for a sphere of the same mass. Since the centripetal acceleration scales as v^2/R and v is proportional to R for rigid rotation, the centripetal force requirement increases with the larger equatorial radius. To maintain gravitational binding against this increased centripetal force, a *higher minimum density is required.*

i. [4 pts] For a typical neutron star, $M \approx 3 \times 10^{30}$ kg (1.5 solar masses) and $R \approx 10^4$ m. So,

$$
\begin{aligned}
\rho_{\mathrm{NS}} &= \frac{M}{\frac{4}{3}\pi R^3} \\
&= \frac{3 \times 10^{30}}{\frac{4}{\cancel{3}}\cancel{\pi}(10^4)^3} \\
&\approx 10^{18} \text{ kg/m}^3 \text{ (+1 point)}
\end{aligned}
$$

The fastest pulsars rotate with periods of on the order of 0.001 seconds. From part (f), we can estimate the minimum density needed to sustain the fastest periods pulsars show.

$$
\begin{aligned}
\rho_{\min} &= \frac{3\pi}{GP^2} \\
&= \frac{3\pi}{7 \times 10^{-11} \times (10^{-3})^2} \\
&= \frac{3\pi}{7} \frac{1}{10^{-11} \times (10^{-3})^2} \\
&\approx 10^{17} \text{ kg/m}^3 \text{ (+1 point)}
\end{aligned}
$$

You can get slightly different values (e.g., the neutron star density could easily be calculated to be 10^{17} kg/m^3) and it would still get full credit. The point is just to show that the density of a neutron star is comparable to (or maybe even a little higher) than the density required for the pulsars with the shortest (i.e., most difficult) periods. If they can handle the pulsars with the shortest periods, then they can handle the ones with longer periods too. Students automatically get +1 point for attempting. Correctly interpreting the values gives the last point (+1) for this part. More information can be found here or towards the end of Chapter 16 of An Introduction to Modern Astrophysics.

Question 7 (35 points)

a. [5 pts] Example goal: Perform observations of both low- and high-energy activity and events in the accretion disks of stellar- and intermediate-mass black holes.

b. [6 pts] Example science requirements:

   (i) [2 pts] The mission shall be able to detect low-energy infrared and optical events, as well as high-energy x-ray and gamma-ray events.

   (ii) [2 pts] The mission shall be able to detect gravitational wave and/or gamma-ray-burst signals from black hole merger events.

   (iii) [2 pts] The mission shall be able to resolve both short-term outburst activity and long-term disk evolution processes.

c. [6 pts] Example engineering requirements:

   (i) [2 pts] The mission shall conduct observations between photon energies of 0.1 meV and 100 keV.

   (ii) [2 pts] The mission shall be able to detect transient "chirp" signals lasting no less than 0.1 seconds at frequencies up to 512 Hz.

   (iii) [2 pts] The mission shall be able to maintain exposures for as short as 1 second or as long as 12 hours.

d. [12 pts] For every requirement addressed, competitors receive **3 points**, with **3 points** extra applied for completion

e. [6 pts] Free space – anything creative, expressive, or unique counts for full credit and fits here!