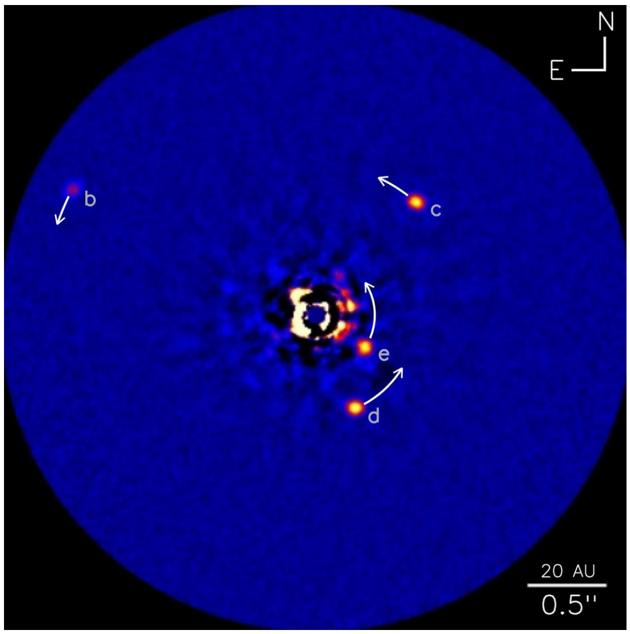
# Science Olympiad
# Astronomy C
# National Event - Wichita State University

May 20, 2023




**Directions:**

- Each team will be given **50 minutes** to complete the exam.
- There are three sections: **§A** (Deep Sky Objects), **§B** (JS9), and **§C** (General Astrophysics).
- Please use the appropriate Image Sheet for each Section, stated in the Section Preamble.
- For significant figures, **use 3 or more in your answers** unless otherwise specified.
- Work will not be graded, only the final answer will be scored.
- The top five tiebreakers, in order, are: Q22, Q9, Q25, Q14, Q23.
- The exam will be posted soon after the competition at https://chandra.si.edu/edu/ and https://www.universeunplugged.org/series/nso-webinars.
- Good luck! And may the stars be with you!

**Written by:**
**The Astronomy A-Team**
Donna Young, Robert Lee, Terry Matilsky, Dhruva Karkada,
Jimmy Ragan, Tad Komacek, et al.

## Section A: Deep Sky Objects

**Use the images in Image/Illustration Set A/B to answer the following questions. Each question or sub-question is worth 1 point, for a total of 55 points.**

1. A solitary Long Period Variable star, also surrounded by dust, is expected to eventually have the same type of stellar core as the object in image 9. Its motions through previous mass ejecta have produced a bow shock.
   (a) What is the name and image number of this object?
   (b) Which light curve shows the pulsations of this object, and what letter on the H-R diagram shows the current evolutionary progress of the star?
2. The light curve in image 29 is produced by the system illustrated in image 6, showing that it undergoes a fairly regular pattern of outbursts, plus anomalies.
   (a) The two main components comprising this system are located on the H-R diagram. What types of objects are the two components and what letters show their locations on the H-R diagram?
   (b) What process within this system is causing the recurring outbursts?
3. What is the previous evolutionary stage of objects that are located at letter E on the H-R diagram in Image/Illustration Set B, and what letter shows the location of the previous stage of these objects?
4. Sometimes light curve behavior changes due to interference from other processes within the system and undergoes radical fluctuations. This is true of symbiotic variable stars.
   (a) What is the image name and number that shows a symbiotic system?
   (b) What part of the system dominates the light curve, and what is the image number that shows the light curve?
5. Large clusters of older, low metallicity Population II stars inhabit specific areas within most galaxies.
   (a) What is the name of and image number of an object that contains a large group of Population II stars?
   (b) A large number of pulsating variables reside in these clusters. What type of variable are they, and what is the number of the image that plots their unique behavior?
   (c) The location of these variables on the H-R diagram is designated by what letter?
6. Which of the following are Population I stars have a similar metallicity to the Sun: RR Lyrae, Classical (Type I) Cepheids, and/or Type II Cepheids?
7. What are two techniques used in establishing the cosmic distance ladder?

8. The object shown in image 8 is 10 times more massive and 15,000 times more luminous than the Sun.
   (a) What is the name and type of object shown in image 8?
   (b) What letter on the H-R diagram denotes the location for this object, and which light curve shows the behavior of this object?
   (c) What feature of this object was used to calculate its distance with minimal error?

9. The object in image 9 was recently observed in the near-ultraviolet by Hubble, which penetrated the dust in this extremely young object allowing a more detailed image of the dense center.
   (a) What is the name and type of object shown in image 9?
   (b) What are the two processes and/or motions that are thought to have produced the shape of this object?
   (c) Identify the red features covering the clover-leaf shaped section.
   (d) The false color red represents the [FeII] line emission. Does this imply the feature contains iron? If so, explain why it is primarily found in the outer layers of the object. If not, why is it red? (Hint: Consider your answer to part (b).)

   The structure of the object can be characterized by three components: a spherical region, an ellipsoidal shell, and a bipolar hourglass structure.
   (e) Draw a cross section of the object. (Hint: The components are listed in no particular order.)
   (f) Label each component with its composition.

10. GW 170817 is a kilonova, a transient event that occurred when two neutron stars merged. The event is illustrated in image 10.
    (a) Which two image numbers show the position and behavior produced by the merger?
    (b) What type of energy (not the electromagnetic component) was produced during this event?

11. Image 20 depicts X-ray radiation from GW 170817. 3.5 years after its initial detection, the level of X-rays detected from it remained at a near constant level rather than continuing to decay.
    (a) What are the two possible explanations for this excess X-ray detection?
    (b) Why do astronomers expect only one of the two explanations will be the primary source of the X-rays?
    (c) How will these two possibilities be distinguished?

12. The object in image 4 is a Type II supernova remnant in the Magellanic Cloud.
    (a) What is the image number that shows the dominant X-ray rings surrounding this object produced by the shock wave from the core collapse?
    (b) At the center of the ring is a smaller X-ray source. What is thought to be producing the smaller X-ray source?

13. The Wolf-Rayet (WR) stage is transitory and highly turbulent. Not many stars have been observed during their rapid transition from the main sequence to Wolf-Rayet objects. This transient evolutionary stage is difficult to determine and categorize.
    (a) What are the two most prominent characteristics of these stars?
    (b) What is the name and image number of a highly unusual WR object caught in this transitory phase?
    (c) This object is highly unusual due to what type of feature?
    (d) What is thought to have caused the feature to form?

14. (a) Identify the object depicted in image 3.
    (b) Which letter on the H-R diagram shows the location of this object and what is the image number that shows its behavior?
    (c) This object should have a negative color index; however, its color index is 0.54. What factors cause this to happen?
    (d) This image uses the false-colors blue, cyan, orange, and red. In general, why are false-color images used in astronomy images?
    (e) The WFC3/UVIS F845M filter was assigned the color red. Given that it is an 11% passband filter with a width of 1000 Angstroms, sketch the system throughput for the filter. (Hint: The x-axis is wavelength (Angstroms) and y-axis is throughput (%).)
    (f) This object is known as a luminous blue variable. Image 31 depicts the variations of well-known LBVs. What empirical relationship can be concluded from this diagram?
    (g) Which area (hatched vs. dotted) represents the quiescent phase and which represents the eruption (maximum) phase?
    (h) Why is the designation of a "quiescent phase" a misnomer?

15. What is thought to be the final evolutionary stage for Wolf-Rayet stars?

16. Observations of the X9 binary system in 47 Tuc is observed and illustrated in image 17.
    (a) What two types of objects comprise the binary system and what is so unusual about the orbital motions of the system?
    (b) The final evolution products for this system could well be very different. What are two possibilities that are thought to be possible?

17. (a) What is the name and specific type of variable star in image 14?
    (b) The light curve that shows the behavior of this object is shown in which image number?

18. (a) What are the image numbers that show multiwavelength and x-ray 3-color composites of a Type Ia supernova event?
    (b) What is the number of the light curve produced by this event?

19. Some core collapse stars have been stripped of their outer envelope of hydrogen and are not designated as Type II events due to spectral differences.
    (a) What is the image number and name of this type of object?
    (b) What occurred for the first time when this object was observed?

20. Sometimes gamma ray pulsars produce extensive filaments that interact with the surrounding interstellar magnetic field.
    (a) What are the image numbers for this type of object, and the cross section of the filament?
    (b) The extensive filament is being produced by what conditions surrounding the pulsar?

21. (a) Which image number depicts BD+30-3639?
    (b) One notable trait of this object is its youth. List two pieces of evidence that support this.
    (c) What specific type of star is located at the center of this object?
    (d) The type of star referenced in part (c) reveals products of what nuclear process on its surface?

## Section B: JS9

**You will use JS9 to answer the following questions. Points are shown for each sub-question, for a total of 28 points.**

22. Supernovae and their remnants are major products of the end points of stellar evolution. Let's explore some of these in detail, using JS9.

    Go to: https://chandra.si.edu/js9/nso/nso.html. You will find 6 clickable observations loaded there for you. Please answer the following questions:

    (a) (4 points) Which of the six observations are supernova remnants?

    (b) (2 points) What is the easiest way to find out when any of these observations were made?

    (c) (4 points) Which two of the remnants have the same prominent feature in their spectra?

    (d) (2 points) What is the energy of this feature and what element produces it?

    (e) (2 points) What is the energy of the most prominent feature of the other(s), and what element produces it?

    (f) (4 points) In one or two sentences, describe what these spectral differences tell us about the nature of supernovae.

    (g) (4 points) By just looking at its image, you can tell that one of the objects is NOT a Type Ia supernova. Which object is this, and how can you tell it is not a Type Ia?

    (h) (2 points) What must happen to a Type Ia progenitor before it will explode?

    (i) (2 points) What type of object becomes a Type II supernova?

    (j) (2 points) What is the most important physical attribute of a star which will determine whether it becomes a supernova at the end of its life?

## Section C: General Astrophysics

**Use the images in Image/Illustration Set C to answer the following questions. Points are shown for each sub-question, for a total of 33 points.**

23. **A changing star.** You're studying a variable star with a period of 280 days and observe that its visual magnitude is varying from 5.7 to 13.1 over the course of this period. You also have access to observations of this star at several other wavelengths, and from this data you are able to conclude that the total luminosity of the star varies much less, by only 1 magnitude.

    (a) (1 point) From the above information, what specific type of variable star is this?

    (b) (2 points) The star's parallax is measured to be 0.004 arcseconds (i.e., 4 milli-arcseconds). What is the distance to this star, in parsecs?

    (c) (2 points) What is the average absolute magnitude of this star?

    (d) (2 points) Considering the observed variation in visual magnitude, what is the ratio of the star's brightest visual apparent luminosity to its dimmest apparent luminosity? Answer as a decimal.

    For the rest of this question, we will adopt a simplified model of this variable star. First, we will assume the luminosity of this star is constant. Further, we will assume that it has a peak wavelength of 600 nm when $m_v = 5.7$, and a peak wavelength of 800 nm when $m_v = 13.1$, and that the star can be modeled as a black body.

    (e) (2 points) What is the effective temperature of the star at 600 nm and 800 nm? Answer in Kelvin.

    (f) (2 points) What is the ratio of the star's radius when $m_v = 13.1$ ($\lambda_{\text{peak}} = 800\text{nm}$) to its radius when $m_v = 5.7$ ($\lambda_{\text{peak}} = 600\text{nm}$)? Answer as a decimal.

X-ray binaries allow us to indirectly observe exotic objects such as neutron stars and black holes. In fact, an x-ray binary provided the first evidence that black holes are not just theoretical constructs – they truly exist in the universe. In the following two sets of questions, we'll study an x-ray binary consisting of a star and a black hole. Note that the questions are independent and the answers do not depend on each other.

24. **Past and future evolution.** The star and the black hole progenitor formed together millions of years ago in a stellar nursery. (*Progenitor* refers to the original star that is now a black hole.)

    (a) (2 points) We measure the mass of the stellar partner to be $40M_\odot$. Explain why we can infer that the progenitor was at least $40M_\odot$ at its birth.

    (b) Being so massive, the progenitor star likely produced radiation pressure strong enough to blow away its outer hydrogen atmosphere during the course of its life. In its later life, the strong stellar winds likely continued, although the surface of the star was likely depleted of hydrogen. Meanwhile, its stellar partner was a main sequence star with a surface temperature around 31,000 K.

i. (2 points) Which spectrum in image 32 depicts the progenitor star in its later life? Explain.

ii. (2 points) Which spectrum in image 32 depicts the partner star during the same time? Explain.

(c) In the future, the stellar partner will likely become a black hole as well.

i. (2 points) What is the fate of this black hole binary system, in the very distant future, according to Newtonian physics? Assume that the black holes interact only with each other.

ii. (2 points) According to our best theories of the universe, in the very distant future the black holes will in-spiral and eventually merge. This implies the orbital energy decreases over time, seemingly violating the law of energy conservation. Where does the orbital energy go?

25. **X-ray emission.** The x-ray spectrum of the accretion disk is shown in image 34. The crosses are the observed data (with error bars), and the solid line is our model. Our model consists of three components: a dominant soft blackbody spectrum around 2 keV (believed to be emission from an optically thick accretion disk), a hard power-law continuum extending to at least 800 keV (believed to be emission from an optically thin, non-thermal corona above the disk), and the reflection of light from the corona off the disk.

(a) (2 points) Explain why a strong x-ray spectrum suggests that the accretor is a black hole or neutron star (as opposed to, e.g., a white dwarf, protostar, main sequence star).

(b) (2 points) Using the energy version of Wien's law ($E_{\text{peak}} = 2.821 k_B T$ where $k_B = 8.617 \times 10^{-5}$ eV/K) estimate the temperature of the optically thick accretion disk in Kelvin. Then use the wavelength version of Wien's Law to show that the peak wavelength is in the x-ray range.

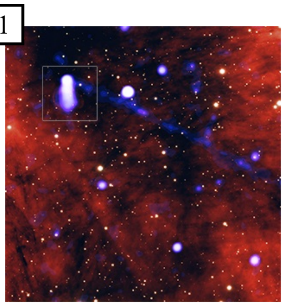
(c) (2 points) Considering that the corona is optically thin (non-thermalized), explain why we can't use Wien's law to estimate its temperature from its radiative peak.

(d) (4 points) Some of the light emitted by the corona is then absorbed by the disk and then re-emitted towards us. The disk is hypothesized to contain a metal which fluoresces under hard x-rays. This means that an inner-shell electron absorbs a high-energy x-ray and is ejected from the atom; an outer-shell electron falls in energy to take its place (emitting a fluorescent photon in the process). Looking at the spectrum and the table shown in image 33, what metal is likely to be fluorescing in the disk? Explain your reasoning. Hint: Planck's constant times the speed of light is $hc = 1241$ nm eV. You can ignore the effects of gravitational redshift.

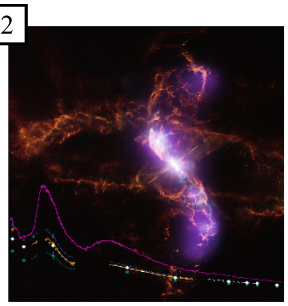
(e) (2 points) Using x-ray telescopes, we observe this system to irregularly alternate between a soft state (described above) and a hard state (where the high-energy x-rays are more intense). Give one plausible explanation for this variability.

# Image/Illustration Set A

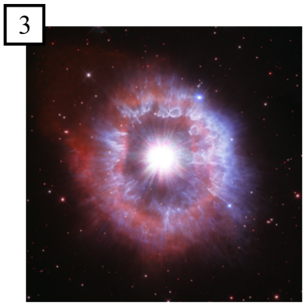
1



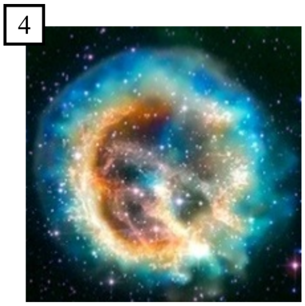
2



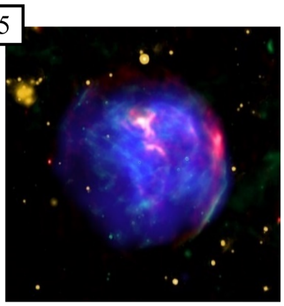
3



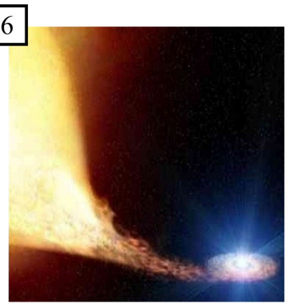
4



5

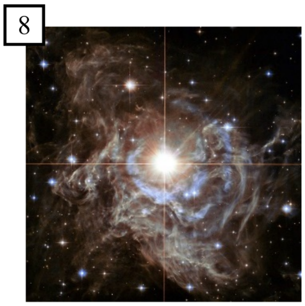


6

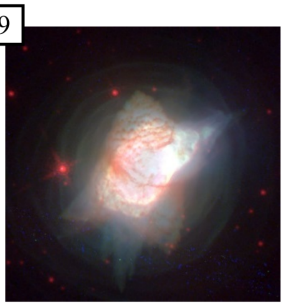


7

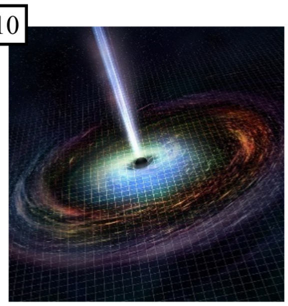
8



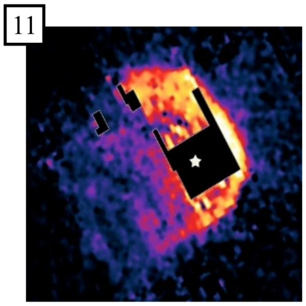
9



10

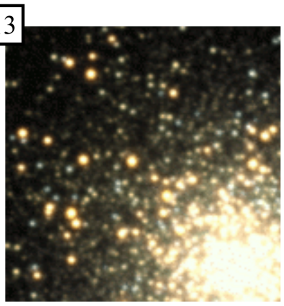


11

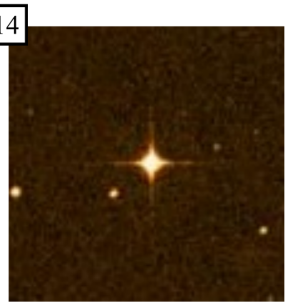


12

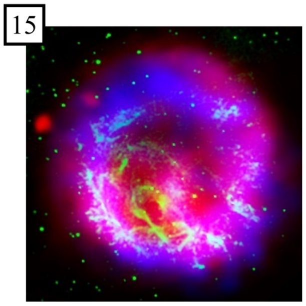
13



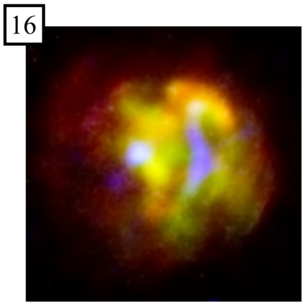
14



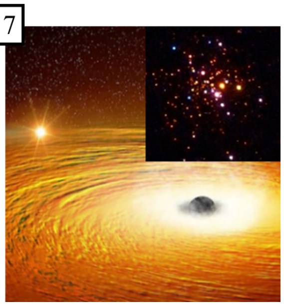
15



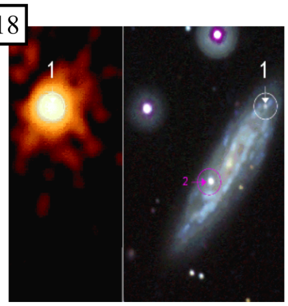
16



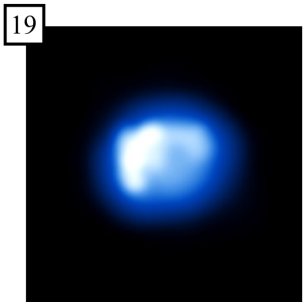
17



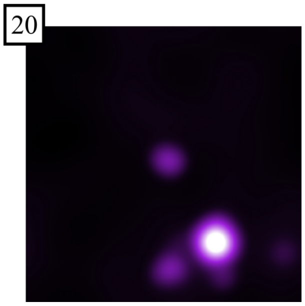
18



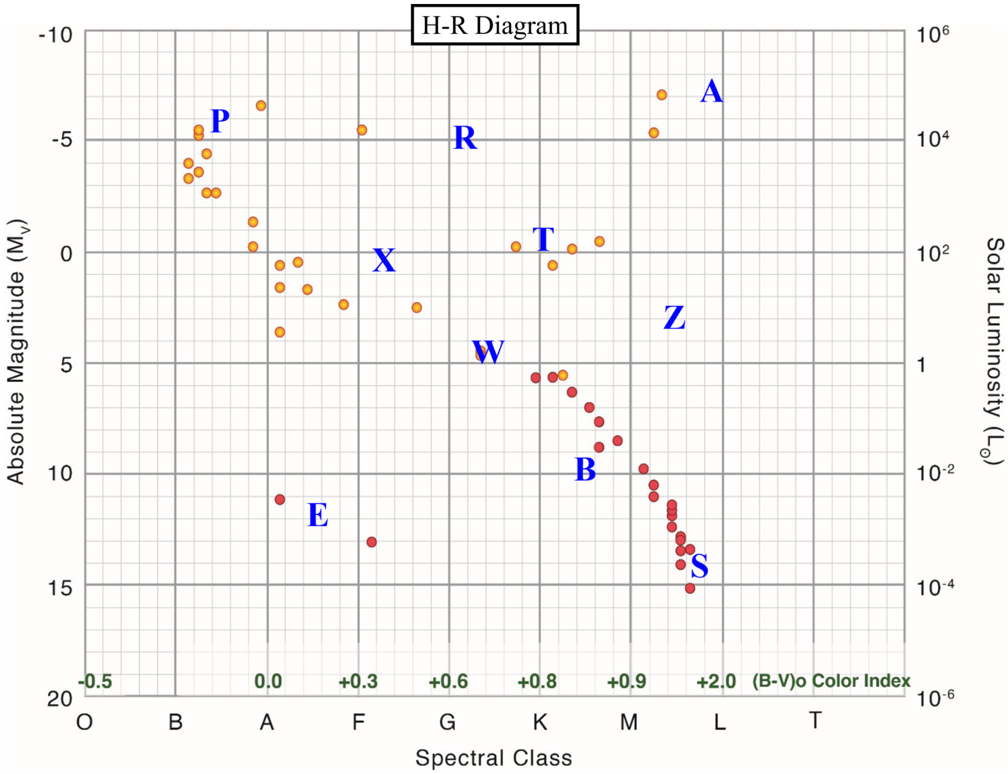

19



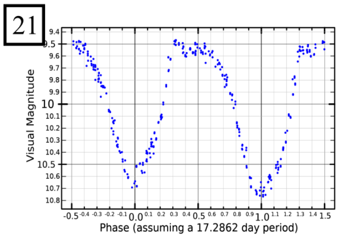
20



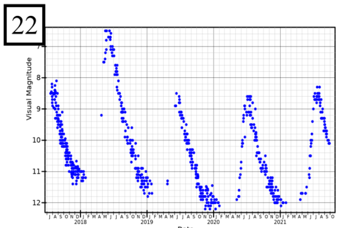
# Image/Illustration Set B



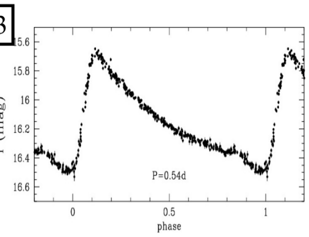

21



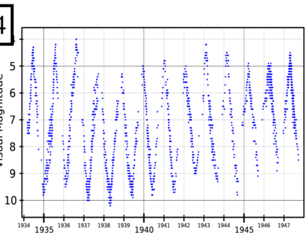

22



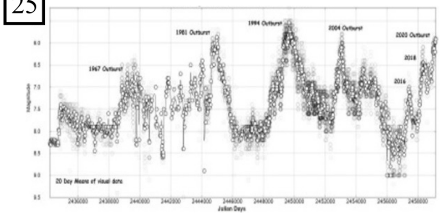

23



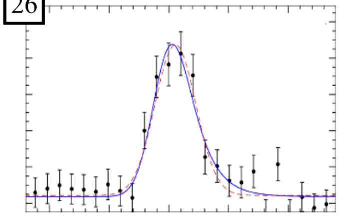

24



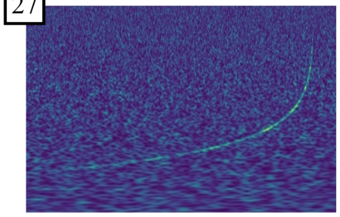

25



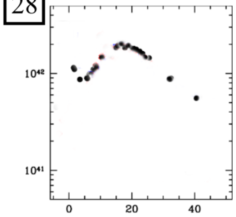

26



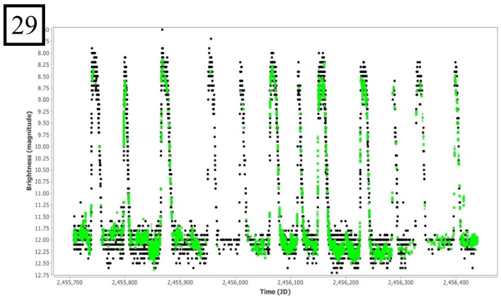
27



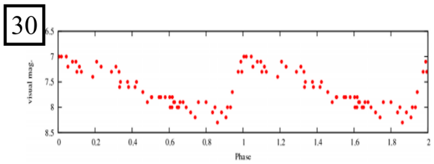
28



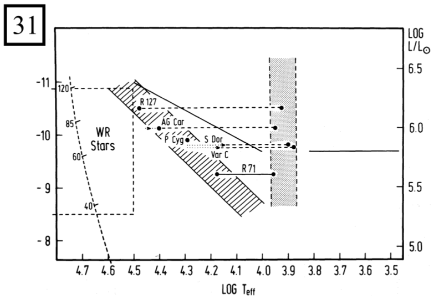

29




30

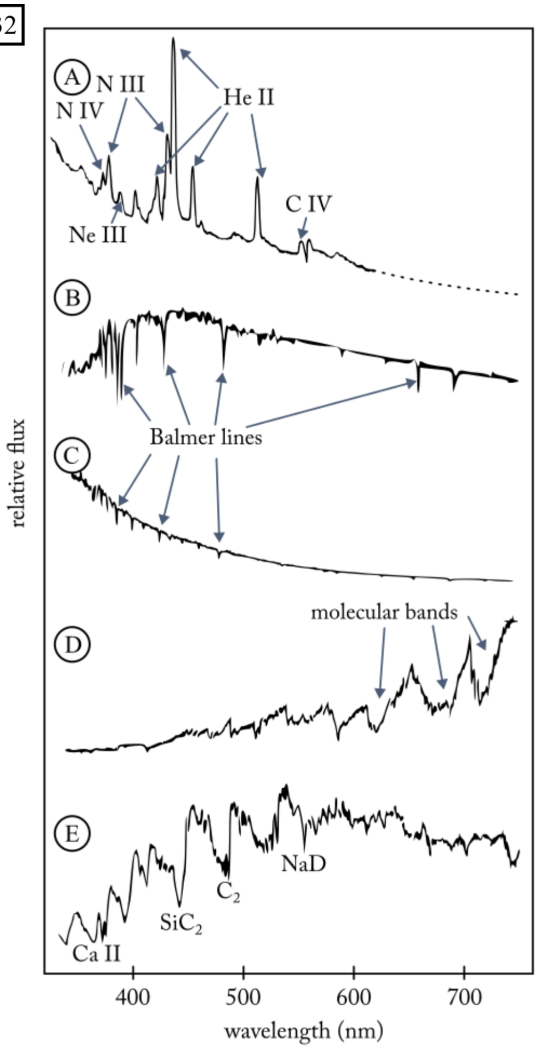



31



# Image/Illustration Set C

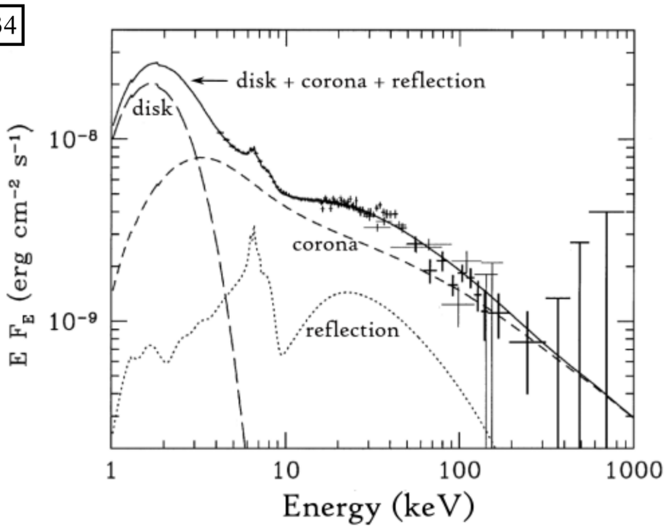
32




33

| Element | Fluorescence line (nm) |
|---|---|
| Carbon | 4.47 |
| Neon | 1.461 |
| Magnesium | 0.9890 |
| Calcium | 0.3359 |
| Titanium | 0.2749 |
| Iron | 0.1936 |
| Zinc | 0.1435 |
| Bromine | 0.1040 |

34



Science Olympiad

Astronomy C

National Event - Wichita State University

May 20, 2023

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 (55 points)

1. (a) R Hydrae, 11
   (b) 24, Z
2. (a) Red dwarf B, white dwarf E
   (b) Mass transfer from accretion disk to white dwarf
3. Red giant (main sequence acceptable), T
4. (a) R Aquarii, 2
   (b) Mira var. (red giant acceptable), 22
5. (a) 47 Tuc, 13
   (b) RR Lyrae, 23
   (c) X
6. Classical (Type I) Cepheids
7. Standard candle, period-luminosity relationship, distance modulus, parallax, spectroscopic parallax, Hubble's law.

   Specific object names, eg. Cepheid variables and type Ia supernovae, were not accepted.
8. (a) RS Puppis, Cepheid variable
   (b) R, 30
   (c) Light echoes from mass ejecta
9. (a) NGC 7027 (Jewel Bug Nebula), Planetary Nebula
   (b) Newer ejecta colliding with older ejecta, binary companions to central star (accretion disk on central star acceptable)
   (c) Dust filaments
   (d) Yes, the environment (low-density gas) and external source of energy (shock) is ideal for [FeII] emission.
   (e) Drawing below.
   (f) Drawing should contain an ellipsoidal shell that is the ionized core, a bipolar hourglass structure that is the photodissociation region, and a spherical region that is the cool, neutral molecular envelope.
10. (a) 12, 27
    (b) Gravitational wave
11. (a) A kilonova afterglow (r-process decay acceptable) or an accretion-powered emission
    (b) It is highly unlikely that both sources of X-rays are equal in magnitude.
    (c) Further observations in X-ray and radio will differentiate the two possibilities. An increase in both implies a kilonova afterglow and a constant (or declining) X-ray emission and lack of radio emission implies an accretion-powered emission.

12. (a) 15
    (b) Isolated neutron star with low magnetic field offset from center
13. (a) Strong stellar winds, unusual spectra
    (b) NaSt1, 7
    (c) 2-trillion-mile pancake shaped disk
    (d) Binary system in the center
14. (a) AG Car
    (b) P, 25
    (c) Interstellar reddening, extinction
    (d) Allow invisible wavelengths to be depicted. Highlight specific spectral lines and/or concentrated regions of particular elements.
    (e) A square wave from 0% to 11% from 8000 to 9000 angstroms.
    (f) The change in effective temperature is larger for more luminous LBVs.
    (g) Hatched is quiescent, dotted is eruption
    (h) It is a misnomer because an LBV becomes much more unstable during its quiescent phase, with its Eddington parameter modified by rotation nearing 1.
15. Supernova Type Ibc
16. (a) White dwarf and black hole, only 2.5 x distance Earth-moon separation
    (b) Form an exotic planet or evaporate
17. (a) W Virginis, Type II Cepheid
    (b) 21
18. (a) 5, 16
    (b) 28
19. (a) 18, 2008D
    (b) The first time a supernova was observed from the beginning of the event
20. (a) 1, 26
    (b) The pulsar caught up with the stalled bow shock causing a particle leak of electrons and positrons
21. (a) 19
    (b) Compact morphology, low ionization state of its HII region, low temperature of the central star, and large ratio of neutral to ionized gas mass
    (c) WC star
    (d) Triple-alpha process

## Section B (28 points)

22. (a) (4 points) CAS-A, Tycho, G292.0+1.8
    (b) (2 points) Look at the FITS header record.
    (c) (4 points) CAS-A and Tycho.
    (d) (2 points) 1.9 keV; Silicon
    (e) (2 points) $\sim 1$ keV; Neon
    (f) (4 points) They can tell us what the progenitor system was like. Whether it was a core-collapse or white dwarf (Type Ia) system.
    (g) (4 points) CAS-A; it has a central object, which means it cannot be a Type Ia system.
    (h) (2 points) The white dwarf must approach/exceed the Chandrasekhar Limit.
    (i) (2 points) A massive star whose core collapses.
    (j) (2 points) The initial mass of the star.

## Section C (33 points)

23. (a) (1 point) Mira variable
    (b) (2 points) 250 (225-275) parsecs
    (c) (2 points) +2.4 (1.5-3.5)
    (d) (2 points) 912.01 (812-1042)
    (e) (2 points) 600 nm: 4830 (4330-5330) K
    800 nm: 3622 (3022-4222)1 K
    (f) (2 points) 1.778 (1.27-2.27)

24. (a) (2 points) The stars formed together, and the more massive star will have the shorter lifespan. Clearly the black hole progenitor was the first to die, so it must have been more massive.
    (b) i. (2 points) A. The evolved progenitor was likely a Wolf-Rayet star (massive, evolved star with strong stellar winds and a hydrogen-depleted surface). WR stars have Doppler-broadened emission lines from ionized nitrogen and carbon (seen in A).
    ii. (2 points) C. From the surface temperature, we know the partner star was a type O star: very hot and very blue with weak Balmer lines.
    (c) i. (2 points) With no external forces, the black holes will orbit forever with unchanging orbital parameters.
    ii. (2 points) General relativity predicts that the system will radiate energy (and angular momentum) in the form of gravitational waves.

25. (a) (2 points) Only very compact accretors have accretion disks with tight enough orbital radii to produce strong X-rays. These X-rays are produced when the accretion disk moves fast and gets very hot. This happens when the orbital radius of the innermost disk becomes very small (kinetic energy is inversely proportional to the orbital radius). The inner disk of larger accretors doesn't reach the necessary orbital speed.
    (b) (2 points) Accept answers between 5-10 million Kelvin. This corresponds to peak wavelengths between 0.29 nm and 0.58 nm. This is in the x-ray range of 0.01 - 10 nm.
    (c) (2 points) Wien's law only applies to blackbody radiation, but the corona is not a blackbody. Specifically, since the plasma is optically thin, it cannot efficiently thermalize, meaning it has no well-defined temperature.
    (d) (4 points) We want to look for spectral features in the reflection spectrum. It shows an emission peak at around 6.5 keV, followed by a wider absorption notch. This signals fluorescence: a wide absorption notch for the ionizing photons, and a sharp lower-energy emission peak (the fluorescence line) for the subsequent electron transition. Using $E = hc/\lambda$ with the given value of $hc$ and $E \approx 6500$ eV, we get $\lambda \approx 0.191$ nm. Referencing the table, we see that the metal is likely iron.
    (e) (2 points) Possible answers: Disk instability causing coronal flares (dwarf nova). Outbursts from the partner star, causing higher accretion rates. Onset of hard relativistic jets. Do not accept answers that assume a white dwarf or neutron star accretor (e.g. pulsars, very strong magnetic fields, cataclysmic variables, etc).