Team Number: _____________

Team Name: ________________________________

Instructions:
1) Please turn in all materials at the end of the event.
2) Do not forget to put your team name and team number at the top of all answer pages.
3) Write all answers on the answer pages. Any marks elsewhere will not be scored.
4) Do not worry about significant figures. Use 3 or more in your answers, regardless of how many are in the question.
5) Please do not access the internet during the event. If you do so, your team will be disqualified.
6) Good luck! And may the stars be with you!
Section A: Use Image/Illustration Set A to answer Questions 1-17. An H-R diagram is shown in Image 21. Each sub-question in this section is worth one point.

1. (a) What is the name of the object shown in Image 3?  
   (b) What type of object is it?  
   (c) Which letter on Image 21 (the H-R diagram) shows the location of this object?  
   (d) Which image displays the behavior of this object?  
   (e) What is the classification for the variability that this object shows?

2. (a) What is the name of the object shown in Image 15?  
   (b) What type of object is it?  
   (c) Which image shows a wide field view that contains this same object?

3. (a) Which image shows AG Carinae?  
   (b) Which letter on the H-R diagram shows the most probable location of AG Carinae?  
   (c) What is this region of the H-R diagram called?  
   (d) Which image shows the behavior of AG Carinae?  
   (e) This star is in transition between which two stages?

4. (a) What is the name of the object indicated by the arrow in Image 10?  
   (b) What type of object is this?  
   (c) What type of event produced this object?

5. (a) What is the name of the object in Image 20?  
   (b) What type of object is this?  
   (c) Which wavelength range was this image taken in?

6. (a) A star transitioning from location S to X on the H-R diagram will pass through what specific region?  
   (b) Which image shows the behavior of a star that is evolving through this region?

7. (a) What is the name of the object shown in Image 1?  
   (b) What type of object is this?  
   (c) What do the circles represent?  
   (d) Why is drawing these circles useful?  
   (e) Which image shows this object in radio wavelengths?

8. (a) Which letter(s) on the H-R diagram represent star(s) that will not go through Type II supernova events?

9. (a) Which image shows the Jellyfish nebula?
(b) What is the official name of this object?
(c) What is interesting about the stellar core in this object?

10. (a) Which object is shown on the cover page?
(b) Which image shows the detection of this object?
(c) Which image shows the current structure of the material ejected from the star thousands of years ago?
(d) What is the color of the line in Image 25 that represents the light curve of this object?

11. (a) What is the name of the object that shares a name with the instability strip it occupies?
(b) Which image shows this object?
(c) Which image shows the behavior of this object?

12. (a) Images 2 and 16 contain what type of object?
(b) What are the dominant wavelengths produced by the objects in Images 2 and 16?
(c) What is the reason for the difference in the brightest wavelengths for these objects?

13. Image 5 shows the field around a massive star. A different image shows an illustration of this star.
   (a) What is the name of this star?
   (b) What is the number of the image that shows an illustration of this star?
   (c) What type of star is this?
   (d) Which image shows the motion of this object?

14. (a) What object is illustrated in Image 4?
(b) What was extraordinary about the radiation output of this object after the initial event?
(c) What is thought to be the reason for the unusual radiation detected?
(d) What color is the line in Image 25 that represents the light curve for this object?

15. (a) Which image shows a supernova remnant in the infrared?
(b) What is the name of this object?
(c) What is the most probable type of stellar core at the center of this object?

16. (a) What is the number of the image that contains a gamma ray binary?
(b) What is the name of this object?
(c) Why is this system rare?

17. (a) What is the name of the object in Image 11?
(b) Which image shows the behavior of this object?
(c) What bizarre behavior is exhibited by the stellar core?
(d) Due to this behavior, what specific type of object is it thought to be?
Section B: Each sub-question in this section is worth 2 points.

18. A star you’ve been watching for some time went supernova! You and your research team carefully observe the supernova event for 30.0 days, and measure the average flux from the event (at Earth) to be $2.00 \times 10^{-6}$ W·m$^{-2}$.

(a) If the supernova is $2.00 \times 10^4$ lightyears away, how much energy, in Joules, was released via photons over the course of your measurement period?

(b) The mass of the progenitor was 20 M$_\odot$, and the supernova left behind a 1.8 M$_\odot$ neutron star. The rest of the mass was blown away as ejecta; the effective (average) velocity of the ejecta relative to the remnant is measured to be 5000 km/s. What is the total kinetic energy, in Joules, of the ejecta?

(c) At the beginning of the star’s collapse, the star’s core begins to fall in on itself. Explain how this core collapse results in the outwards force that pushes away the star’s atmosphere, causing it to be ejected outwards.

(d) Your theorist friend says, “A star of that mass and metallicity should’ve produced $10^{46}$ J of energy.” What percentage of this total energy comes from the sum of the kinetic energy of the ejecta and the photon luminosity of the event? Is your friend’s claim reasonable? Explain.

19. Geminga was discovered by NASA’s SAS-2 satellite around 1974, but its identity as a pulsar wasn’t determined until around 1992.

(a) What discovery about Geminga led scientists to conclude that it was a pulsar?

(b) What interesting property of Geminga posed a challenge to existing pulsar models?

(c) Which image on Image/Illustration Set A represents Geminga?

(d) In the first day or so of a neutron star’s existence, the following reactions occur:

$$n \rightarrow p^+ + e^- + \bar{\nu}_e \quad p^+ + e^- \rightarrow n + \nu_e.$$  

What is the name of this process, and what effect does it have on the neutron star?
Observe the following graph about a neutron star.

(e) What does the general trend in the data say about the neutron star’s angular velocity? What might be causing this?

(f) What is the name of the phenomenon seen at \( t \approx 28 \)?

(g) In October 2017, astronomers around the world announced the detection of the merger of two neutron stars, which was observed in August. What was special about this detection? What are some important aspects/implications from this event?
20. Use the Type I Cepheid period-luminosity relationship \( M_v = -2.43(\log_{10}P - 1) - 4.05 \) for the following questions.

(a) A Type I Cepheid in a nearby galaxy is determined to have a variability period of 10 days. What is its absolute visible magnitude?

(b) What is the visible luminosity of this Cepheid, in Solar luminosities?

(c) The apparent magnitude of this Cepheid is 6. What is the distance to this Cepheid, in kiloparsecs?

(d) Are Type II Cepheids brighter or dimmer than Type I Cepheids? Why is this?

21. The most current estimate of Hubble’s constant is 70.0 km/s/Mpc and was established in October 2017.

(a) What measurement enabled this calculation of Hubble’s constant?

(b) Use this estimate of Hubble’s constant to calculate the radius of the Hubble sphere (in units of Gpc), beyond which objects recede faster than the speed of light.

(c) Use this estimate of Hubble’s constant to calculate the Hubble time, in units of Gyr.

22. Star A and Star B orbit one another in a binary star system that is 10 parsecs away. Star A has the mass, radius, and luminosity equal to that of the Sun. Star B has a mass of 0.5 Solar masses. The binary system is non-eclipsing.

(a) The orbital period of this binary system is 1 year. What is the semi-major axis of this binary system, in AU?

(b) Assuming that stellar mass and luminosity are related as \( L \propto M^4 \), what is the luminosity of Star B, in Solar luminosities?

(c) What is the apparent magnitude of this binary star system?

(d) The effective temperature of Star B is 3,500 K. Use the Stefan-Boltzmann law to calculate its radius, in Solar radii.
H-R Diagram

Absolute Magnitude ($M_\odot$) vs. Spectral Class

Solar Luminosity ($L_\odot$)

Image/Illustration Set A Page 2
Answer Page: Section A

1. (a) __________________________ 10. (a) __________________________
   (b) __________________________  (b) __________________________
   (c) __________________________  (c) __________________________
   (d) __________________________  (d) __________________________
   (e) __________________________  

2. (a) __________________________ 11. (a) __________________________
   (b) __________________________  (b) __________________________
   (c) __________________________  (c) __________________________

3. (a) __________________________ 12. (a) __________________________
   (b) __________________________  (b) __________________________
   (c) __________________________  (c) __________________________
   (d) __________________________  (d) __________________________
   (e) __________________________  

4. (a) __________________________ 13. (a) __________________________
   (b) __________________________  (b) __________________________
   (c) __________________________  (c) __________________________
   (d) __________________________  

5. (a) __________________________ 14. (a) __________________________
   (b) __________________________  (b) __________________________
   (c) __________________________  (c) __________________________
   (d) __________________________  

6. (a) __________________________ 15. (a) __________________________
   (b) __________________________  (b) __________________________
   (c) __________________________  

7. (a) __________________________ 16. (a) __________________________
   (b) __________________________  (b) __________________________
   (c) __________________________  (c) __________________________
   (d) __________________________  

8. _____________________________ 17. (a) __________________________

9. (a) __________________________  (b) __________________________
   (b) __________________________  (c) __________________________
   (c) __________________________  

   (d) __________________________  

Answer Page: Sections B and C

18. (a) ________________________________ Joules
(b) ________________________________ Joules
(c) ________________________________
(d) ________________________________

19. (a) ________________________________
(b) ________________________________
(c) ________________________________
(d) ________________________________
(e) ________________________________
(f) ________________________________
(g) ________________________________

20. (a) ________________________________ Solar luminosities
(b) ________________________________ Kiloparsecs
(c) ________________________________
(d) ________________________________

21. (a) ________________________________ Gigaparsecs
(b) ________________________________ Gyr
(c) ________________________________

22. (a) ________________________________ AU
(b) ________________________________ Solar luminosities
(c) ________________________________
(d) ________________________________ Solar radii
Answer Page: Section A

1. (a) Alpha Orionis/Betelgeuse
   (b) Red supergiant
   (c) W
   (d) 24
   (e) Semiregular

2. (a) NGC 6357
   (b) Star formation region
   (c) 6

3. (a) 12
   (b) N
   (c) S Doradus instability strip
   (d) 23
   (e) LBV to Wolf-Rayet

4. (a) M82 X-2
   (b) Pulsar
   (c) Type II Supernova

5. (a) NGC 7822
   (b) Star formation region
   (c) Infrared

6. (a) Cepheid instability strip
   (b) 28

7. (a) Circinus X-1
   (b) X-ray binary
   (c) Light echoes
   (d) Calculating the distance
   (e) 13

8. B,H

9. (a) 17
   (b) IC 443
   (c) Pulsar jet direction different from pulsar direction

10. (a) SN 1987A
    (b) 19
    (c) 8
    (d) Red

11. (a) S Doradus
    (b) 18
    (c) 22

12. (a) Pulsars
    (b) 16- Gamma, 2- Radio
    (c) Different spin orientations

13. (a) HR 5171A
    (b) 14
    (c) Yellow hypergiant
    (d) 26

14. (a) ASASSn-15lh
    (b) Increase in UV only
    (c) Tidal disruption by black hole
    (d) Black

15. (a) 7
    (b) W49B
    (c) Black hole

16. (a) 9
    (b) DEM L241
    (c) Companion survived stellar collapse

17. (a) RCW 103
    (b) 27
    (c) Slowest spinning neutron star
    (d) Magnetar
Answer Page: Sections B and C

18. (a) \(2.33 \times 10^{42} \left(10^{41} - 10^{43}\right)\) Joules
(b) \(4.52 \times 10^{44} \left(10^{43} - 10^{45}\right)\) Joules
(c) 1 Point for mentioning any of:
   - Inner core collapses, causing high density.
   - Inner core rebounds, causing a shock wave.
   - The shock wave stalls, with neutrinos building up behind shock wave.
   - Neutrinos push shock wave outward, causing explosion.
(d) 0.1 – 10 % Yes. 99% of the energy is carried away in the form of neutrinos.

19. (a) The detection of X-ray pulsations
(b) The lack of radio emission, despite strong gamma-ray and X-ray emissions
(c) 16
(d) URCA process. It cools the initially hot neutron star very quickly.
(e) It is gradually slowing down. Magnetic dipole radiation carries away rotational energy.
(f) Glitch
(g) 1 Point for any of the following:
   - Both gravitational waves and EM radiation were observed.
   - It supports the hypothesis that neutron star mergers lead to r-process metals.
   - It supports the hypothesis that mergers cause short GRBs
   - It supports the hypothesis that gravitational waves travel at the speed of light
   - It can be used to improve the measurement of \(H_0\).

20. (a) -4.05
(b) 3,564 (3,000 - 4,000) Solar luminosities
(c) 1.02 (0.5-1.5) Kiloparsecs
(d) Dimmer, they are older and lower-mass

21. (a) Concurrent measurement of gravitational waves with LIGO and EM signal
(b) 4.29 (3.3 - 5.3) Gigaparsecs
(c) 14.0 (13.5 - 14.5) Gyr

22. (a) 1.15 (1 - 1.3) AU
(b) 0.0625 (0.06 - 0.065) Solar luminosities
(c) 4.76 (4.66 - 4.86)
(d) 0.681 (0.6 - 0.8) Solar radii