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 lines 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) Feel free to take apart the test and staple it back together at the end!
7) Good luck! And may the stars be with you!
Section A: Use the Image/Illustration Set to answer the following questions. Each sub-question in this section is worth one point.

1. Image 1 shows the Bullet Cluster.
   (a) What part of the electromagnetic spectrum was this image taken in?
   (b) What do the blue regions correspond to?
   (c) How was the matter in the blue regions detected?
   (d) Which other image shows this cluster?

2. Image 2 shows part of M87.
   (a) What part of M87 does this image show?
   (b) What part of the electromagnetic spectrum was this image taken in?
   (c) Which image shows a zoomed-in radio observation of this region?
   (d) What type of astronomical object is shown in the image from part (c)?

3. (a) Which two images show spectra that are evidence for large filaments of hot intergalactic gas?
   (b) One of these spectra is of H2356-309. Which spectra is from this object?
   (c) What types of objects were these spectra taken of?

4. Image 3 shows the most distant galaxy cluster observed, which lies at a redshift of 1.9.
   (a) What is the name of this galaxy cluster?
   (b) Observations at which two parts of the electromagnetic spectrum were superimposed to make image 3?

5. Image 4 shows the first quasar ever discovered.
   (a) What is the name of this object?
   (b) What part of the electromagnetic spectrum was image 4 taken in?
   (c) Another image shows a zoom-in on image 4 taken in multiple wavelengths. Which image is this?
   (d) What region of the object is shown in this image?

6. (a) Which image shows gamma-ray-burst GRB 150101B?
   (b) What part of the electromagnetic spectrum was this image taken in?
   (c) A binary system consisting of which type of objects merged to form this gamma-ray-burst?
   (d) What type of non-electromagnetic “radiation” was detected from this object?

7. (a) Which image contains the furthest Type Ia supernova ever detected?
   (b) What is the name of this object?
   (c) What redshift is this object at?
8. (a) Which two images show the massive galaxy cluster MACSJ0717.5+3745?
   (b) How many galaxies merged to form this cluster?

9. (a) Which two images show PSS 0133+0400 and PSS 0955+5940?
   (b) What type of objects are these?
   (c) These two objects are parts of a survey to measure distances. What two parts of the electromagnetic spectrum are used to measure distances to these objects?

10. (a) Which image shows the detection of the second gravitational wave event?
    (b) What two kinds of astronomical objects merged to cause this event?

11. (a) Which image shows an optical-wavelength observation of GOODS-S 29323?
    (b) Which image shows the accompanying X-ray observation of this object?
    (c) What type of object is forming in the center of both of these images?

12. (a) Which image shows NGC 2623?
    (b) How did this object form?
    (c) What part of the electromagnetic spectrum is this object abnormally bright in?

13. (a) Image 16 shows a system of galaxy clusters. Which object is this?
    (b) The blue shows X-ray observations. Emission from which part of the electromagnetic spectrum is shown by the pink colors in the image?
    (c) What process are these interacting galaxy clusters undergoing?
    (d) Some of the galaxies in the image appear distorted. Why is this?
Section B: Each sub-question in this section is worth two points, unless otherwise noted.

Many of the interesting phenomena studied by astronomers have direct ties to stars and their life cycles, so that’s where we’ll begin. All main sequence stars begin their lives by fusing hydrogen into helium. As a main sequence star burns through its supply of H and the pressure inside decreases, gravity begins to compress the core, converting gravitational potential energy to heat. Eventually it gets hot enough for He atoms to fuse into carbon, and the process repeats itself. Before the process of nuclear fusion was understood, scientists like Kelvin and Helmholtz tried to explain the energy production of stars purely as a result of this conversion of gravitational potential energy into heat.

14. Why does hydrogen fuse at a lower temperature than helium?

15. (a) Newton’s law of gravitation states that the force of gravity between two bodies is given by \( F_g = \frac{GMm}{R^2} \). Since force is the derivative of potential, we have that the gravitational potential between two objects is \( U = -\frac{GMm}{R} \). By considering how a sphere of radius \( r \) interacts with a shell of radius \( dr \), derive that the potential energy of a self gravitating sphere is

\[
U = -\frac{16}{15}\pi \rho^2 GR^5 = -\frac{3GM^2}{5R},
\]

where \( \rho \) is the average mass per unit volume (the first expression for \( U \) becomes the second when one applies the fact that \( M = \frac{4}{3}\pi R^3 \rho \)).

(b) Suppose the sun radiates energy at a rate of \( P = 3.86 \times 10^{26} \) Watts. How far, radially, would the sun need to contract in one year to maintain this amount of power? State your answer in meters.

(c) If we assume the sun would maintain this rate of collapse as it shrinks, how long, in years, would it take before the its radius becomes less that that of its Schwarzschild radius (which is given by \( r_s = \frac{2GM}{c^2} \))? 

For the stars with cores that don’t get hot enough to fuse carbon, their cores continue to collapse, and the outer layers expand until the star enters a second red giant phase. At this point, the star loses large amounts of mass as a planetary nebula forms around it, and the core becomes a white dwarf.

16. (a) Briefly explain why some stars’ cores get hot enough to fuse carbon and some don’t.

(b) What prevents white dwarfs from continuing to collapse in on themselves?

(c) Consider a white dwarf with mass equal to 0.5 times that of the Sun, and radius equal to 0.01 times that of the Sun. How many times stronger is the force of gravity on the surface of this white dwarf than on Earth?

(d) Suppose the outer layer of the white dwarf from the previous question is at a temperature of \( 10^4 \) K. What is the star’s luminosity, in Solar luminosities?

(e) What would its apparent brightness be if it were 1 astronomical unit away from the Earth, in W/m\(^2\)?

White dwarfs radiate away their internal energy very slowly, in fact some of the oldest ones have been around for about \( 10^{10} \) years! They’re extremely common too, it’s a wonder we don’t see them everywhere we look...
The fact that the night sky is dark at visible wavelengths, and not uniformly bright with starlight is known as Olbers’ Paradox. The paradox is that, if the universe is infinite (which it may or may not be; for the purposes of this problem assume that it is at least big enough to be practically infinite) and has some overall average density of stars in it, we should find that, in any direction we look, our line of sight will eventually hit a star. Consequently, the entire night sky should be awash with starlight.

One might think that the inverse square law for brightness resolves the paradox—that the light from distant stars is so dim, that it doesn’t contribute much to the picture we see from earth. But this is not the case. Consider a spherical shell of space a distance \( r \) from Earth with thickness \( dr \). The number of stars in the shell is proportional to the volume, which is proportional to \( r^2 \), so even though the light that reaches us from those stars is fainter by \( \frac{1}{r^2} \), the two effects cancel each other out. We expect to receive equal amounts of light from regions at all distances from us.

17. (a) To dissect this paradox it is helpful to first examine a simpler analogy. Suppose you are standing in the middle of an infinite forest where the average radius of a tree is \( R = 1 \) meter and the number density of trees is 0.005 trees per square meter. If you fire an arrow in a random direction, how far away (in meters), on average, will it travel before it strikes a tree? Hint: start by finding the angular size of a tree \( r \) units away from the archer. (4 points)

(b) Now for the 3D case. Suppose you are in an infinite universe in which the average density of stars is \( n = 10^9 \) stars per cubic megaparsec and the average stellar radius is that of the Sun: \( R = 7 \times 10^8 \) meters. How far could you see (in megaparsecs), on average, before your line of sight meets a star? (4 points)

(c) Heinrich Olbers tried to resolve the paradox by postulating that distant stars are blocked from view by interstellar matter which absorbs starlight. Why doesn’t this explanation resolve the paradox?

(d) Another explanation might be that the number density and or luminosity of stars might not be the same everywhere in the universe. Why might a cosmologist dislike this explanation?

(e) Something Olbers missed is that, due to the expansion of the Universe, light from distant stars is redshifted. How fast, in terms of the speed of light, must a distant star be receding from us for any visible light it emits to be redshifted out of the visible range (400-700nm)? The doppler relation is given by \( \frac{f_{\text{source}}}{f_{\text{receiver}}} = \sqrt{\frac{1+\beta}{1-\beta}} \), where \( \beta = \frac{v}{c} \).

(f) Considering only the motion of the star due to the expansion of the Universe, and using the velocity you found in the last question, how far away must that star be, in megaparsecs?

(g) If we ignore redshift and assume that the light from even the most distant stars will eventually reach us, we return to the original paradox. But there is one fact that definitively resolves the paradox that we’ve yet to address. What is it?
Answer Page: Section A (1 point each)

1. (a) ________________________________ (b) ________________________________
   (c) ________________________________ (d) ________________________________
2. (a) ________________________________ (b) ________________________________
   (c) ________________________________ (d) ________________________________
3. (a) ________________________________ (b) ________________________________
   (c) ________________________________
4. (a) ________________________________ (b) ________________________________
5. (a) ________________________________ (b) ________________________________
   (c) ________________________________ (d) ________________________________
6. (a) ________________________________ (b) ________________________________
   (c) ________________________________ (d) ________________________________
7. (a) ________________________________ (b) ________________________________
   (c) ________________________________
8. (a) ________________________________ (b) ________________________________
9. (a) ________________________________ (b) ________________________________
   (c) ________________________________
10. (a) ________________________________
Answer Page: Section B (2 points each, unless noted)

14. 

15. (a) 

(b) 

(c) 

16. (a) 

(b) 

(c) 

(d) 

(e) 

Solar luminosities 

Watts/meter$^2$

17. (a) 

(b) 

(c) 

(d) 

(e) 

times the speed of light 

(f) 

(g) 

Use the bottom of the page as extra space to write answers:
Answer Page: Section A (1 point each)

1. (a) Optical  
   (b) Dark matter  
   (c) Gravitational lensing  
   (d) 19

2. (a) Core  
   (b) X-ray  
   (c) 8  
   (d) Black hole

3. (a) 9,10  
   (b) 9  
   (c) Quasars

4. (a) JKCS041  
   (b) Optical, X-ray

5. (a) 3C 273  
   (b) Radio  
   (c) 14  
   (d) Jet

6. (a) 12  
   (b) X-ray  
   (c) Neutron stars  
   (d) Gravitational waves

7. (a) 17  
   (b) SN UDS10Wil  
   (c) 1.7-2.1

8. (a) 5, 15  
   (b) 4

9. (a) 6, 13  
   (b) Quasars  
   (c) UV and X-ray

10. (a) 20

11. (a) 7  
    (b) 18  
    (c) Supermassive black hole

12. (a) 11  
    (b) Galaxy merger  
    (c) Infrared

13. (a) MACS J1149.5+2233  
    (b) Radio observations  
    (c) Merger  
    (d) Gravitational lensing
14. Hydrogen has less charge / fewer protons. The Coulomb force between two H nuclei is less than that between two He nuclei.

15. (a) \(-\int_0^\infty \frac{G(4/3\pi\rho r^3)(4\pi\rho r^2)}{r} dr\). One point for writing an integral with the correct limits.
   One point for a correct integrand.
   (b) 37.3 meters. Accept answers from 10-100. meters
   (c) 1.88 \times 10^7 years. Accept 10-30 million. years

16. (a) The cores of more massive stars can get hotter than those with less mass.
   (b) Electron degeneracy pressure.
   (c) 138,900 times stronger. Accept 100,000-180,000.
   (d) 9.12 \times 10^{-4} Solar Luminosities (Accept 8.5 – 9.5 \times 10^{-4}) Solar luminosities
   (e) 1.2 Watts per square meter. Accept 0.7-1.7. Watts/meter^2

17. (a) 100 meters. Accept only this value. meters (4 points)
   (b) 6.2 mega parsecs. Accept 5.7-6.7. megaparsecs (4 points)
   (c) The light from the hidden stars would heat the interstellar matter until it was as hot and bright as the stars themselves.
   (d) It violates the cosmological principle. Where we are in the Universe isn’t inherently special.
   (e) 0.5c. Accept 0.4-0.6c. times the speed of light
   (f) 2175 mega parsecs. Accept 2000-2300. megaparsecs
   (g) The Universe isn’t infinitely old. Light from distant stars hasn’t had time to reach us.

Use the bottom of the page as extra space to write answers: