The next 5 questions refer to the DSO shown below.

1. (2.00 pts) Which DSO is shown in the picture?

- A) Bullet Cluster
- B) M87
- C) NGC 2623
- D) 152156.48+520238.5

2. (2.00 pts) What is another name for this DSO?

- A) Arp 243
- B) Warm Hot Intergalactic Medium
- C) 2305842+4329.2
- D) The CfA2 Great Wall (Coma Wall)

3. (2.00 pts) Why is star formation prominent in the tails?

- A) The tails contain multiple quasars, which aid in star formation
- B) The tails are rich in WHIM, which helps cool the interstellar gas
- C) Gravitational interactions cause clouds of gas in the tails to be compressed
- D) Gravitational lensing causes the number of visible stars in the tails to increase

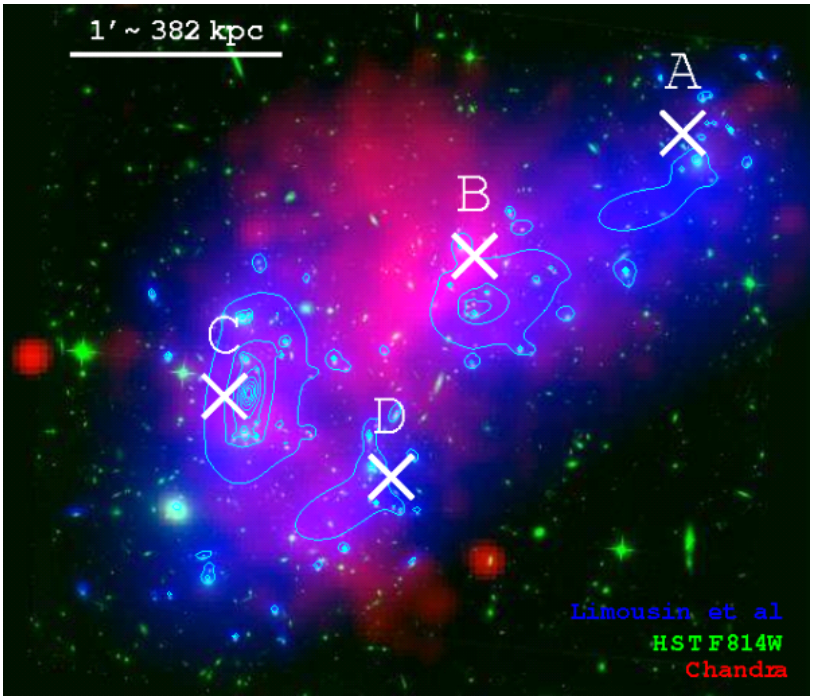
4. (2.00 pts) How does the stellar population at the nucleus of this galaxy compare to the Milky Way's nucleus?

- A) The stellar populations have approximately the same age
- B) There is no way to compare the stellar populations
- C) It has a higher proportion of old stars than the Milky Way
- D) It has a higher proportion of young stars than the Milky Way

5. (2.00 pts) The apparent magnitude is observed to be $m_B = 13.99$. If the galaxy is 77 million parsecs away, what is the B-band absolute magnitude?

- (●) A) -20.4
- ( ) B) -13.3
- ( ) C) 2.4
- ( ) D) 13.3

The next 5 questions refer to the DSO shown below.



6. (2.00 pts) Which DSO is shown in the picture?

- ( ) A) NGC 2623
- (●) B) MACS J0717.5+3745
- ( ) C) GW151226
- ( ) D) 222256.11-094636.2

7. (2.00 pts) What is occurring in this DSO?

- ( ) A) Two galaxies have collided, prompting starburst
- ( ) B) A quasar has formed from a direct-collapse black hole
- (●) C) Four galaxy clusters have collided and merged
- ( ) D) A neutron star merger has produced gravitational waves

8. (2.00 pts) How can we estimate the speed of the objects within the DSO?

- ( ) A) Examine the spectral composition of the gas
- (●) B) Examine the offset between galaxies and gas
- ( ) C) Use Hubble's law to determine the peculiar motions
- ( ) D) Use the Sunyaev-Zel'dovich effect to estimate surface density

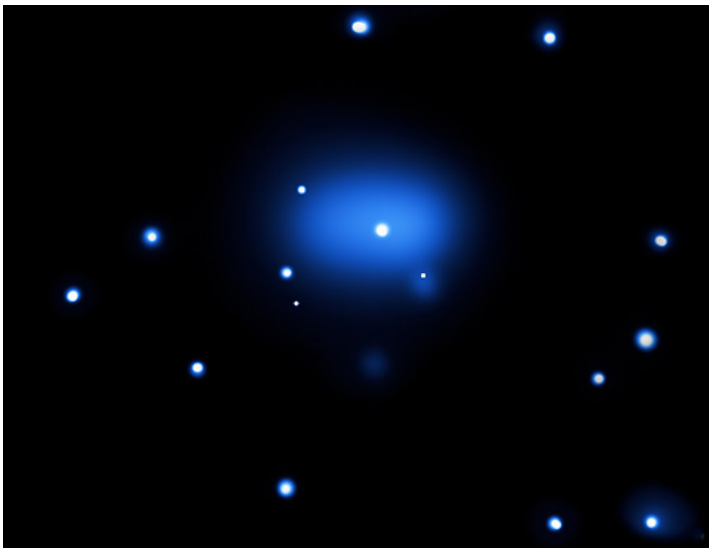
9. (2.00 pts) This DSO lies along a dark matter filament. Which of the following is true about dark matter filaments?

- A) They are rare in the universe, since most dark matter is uniformly distributed across space
- B) Regular matter (galaxies, intergalactic gas, etc) tends to be concentrated in the voids between dark matter filaments
- C) Although there is observational evidence for dark matter filaments, computer simulations of the universe don't show evidence for filaments.
- D) Dark matter filaments tend to connect galaxy superclusters.

10. (2.00 pts)
The redshift of this galaxy is estimated to be $z = 0.5458$. This is a reasonably high redshift, and Hubble's law doesn't really hold. Let's ignore that and try to apply Hubble's law anyway. What is the recessional velocity?

- A) 54,000 km/s
- B) 164,000 km/s
- C) 208,000 km/s
- D) 315,000 km/s

The following 5 questions refer to the DSO shown below.



11. (2.00 pts) Which DSO is shown in the picture?

- A) JKCS 041
- B) NGC 2623
- C) H2356-309
- D) PSS 0955+5940

12. (2.00 pts) Which one of the following is true about the DSO?

- A) It contains more matter than dark matter.
- B) It is one of the farthest galaxy groups to be observed.
- C) It is one of the first quasars to be observed.
- D) It contains one of the most newly formed SMBHs.

13. (2.00 pts) This picture was taken by the Chandra space telescope. What waveband does Chandra observe in?

- A) Visible
- B) X-ray
- C) Infrared

D) Radio

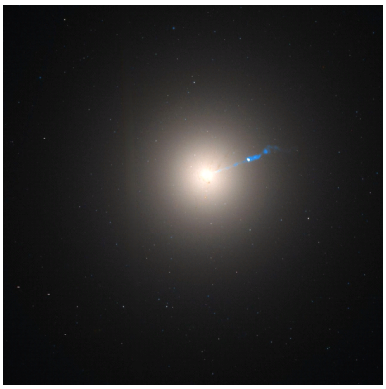
14. (2.00 pts) This object is thought to be at a redshift of around 2. Should you use the relativistic form of Hubble's Law to determine distance?

A) No, the redshift is too low for relativistic corrections to be significant.
B) No, relativistic calculations are not relevant at high redshift.
C) Yes, the object is moving relativistically due to Hubble expansion.
D) Yes, the nonrelativistic form of Hubble's law is only valid within the Milky Way.

15. (2.00 pts)
The light was emitted when the scale factor of the universe was about $a = 0.3$. If the galaxy is currently 10 billion lightyears away, how far was it when the light was emitted? Assume the peculiar velocity is zero.

A) 3 billion lightyears
B) 4.3 billion lightyears
C) 7.7 billion lightyears
D) 33.3 billion lightyears

The following 5 questions refer to the DSO shown below.



16. (2.00 pts) Which DSO is shown in the picture?

A) M87
B) GW151226
C) H2356-309
D) SN UDS10Wil

17. (2.00 pts) What constellation is this DSO located in?

A) Virgo
B) Cassiopeia
C) Taurus
D) Ursa Major

18. (2.00 pts)
The black hole associated with this DSO was imaged by a global array of telescopes, observing in the radio band. Which of the following explains why radio telescopes are typically arranged in an array (rather than a single telescope)?

A) Having multiple collecting dishes helps increase the brightness of the image since radio waves are naturally very weak.
B) The redundancy helps mitigate the effect of earth's atmospheric turbulence on radio-band radiation.
C) The multiple telescopes increase the signal-to-noise ratio since radio waves are spatially stochastic.

- [x] D) The large effective collecting area helps create higher-resolution images since radio waves have such a long wavelength.

19. (2.00 pts)
The black hole has a mass of $6 \times 10^9 M_\odot$. How many AUs away would a star have to be from the black hole to experience the same gravitational acceleration that the earth feels from the sun?

- [ ] A) 1800
- [ ] B) 24300
- [x] C) 77500
- [ ] D) 156900

20. (2.00 pts) What is the escape velocity at a distance twice the Schwarzschild radius from the singularity?

- [ ] A) $0.41c$
- [ ] B) $0.5c$
- [x] C) $0.71c$
- [ ] D) c

The following 4 questions are about star clusters: how we determine their age, how they form, and how they fit into our theory of galactic evolution.

21. (4.00 pts) The Main Sequence Turnoff Point method is often used to determine the age of a star cluster. Explain how this method works.

Expected Answer: You plot the stars on the HR diagram and see where stars are leaving the MS. From the color temperature, you can find estimate the star's mass, and you can estimate the lifespan of the star. Since stars at the turnoff point are beginning to die, we can assume the cluster has the same age.

22. (4.00 pts) The method rests on a few assumptions. Name two of them. For each, why is it a reasonable assumption?

Expected Answer: Sample answers: The star cluster consists of stars of varying masses. Reasonable since if the star-forming cloud is large enough, it should sample evenly across the IMF. Another assumption: stars are born at the same time. Reasonable since the star formation process will proceed quickly until the star-forming gas is used up. So, relative to stellar lifespans, the stars are born at about the same time.

23. (4.00 pts) A star cluster in the Milky Way's halo is determined to be 12 billion years old, while another cluster in the arms is 7 billion years old. Why is this reasonable?

Expected Answer: Halo clusters were formed before the galaxy collapsed into a disk. Clusters in the arms could have formed at any time since there is still a lot of star-forming gas in the arms.

24. (4.00 pts) Do you expect halo clusters to have higher metallicity than clusters in the arms? Justify in terms of astrophysical processes.

Expected Answer: No. Since they are older, there was less time for metals to form and enrich the ISM. So the ISM they were born from was relatively metal-poor.

The next 5 questions are about redshift and Hubble's law.

Galactic redshift is often explained via the Doppler effect. In other words, we imagine that the galaxy is moving through space away from us, and that recessional velocity causes the wavelength to be stretched, like a firetruck siren driving away.

25. (4.00 pts) At low redshift, this explanation works pretty well. But at high redshift ($z > 1$) this explanation breaks some laws of physics. What's the issue?

Expected Answer: If you convert $z > 1$ to a speed, it'll exceed the speed of light, which breaks SR.

26. (4.00 pts) How is this issue resolved?

Expected Answer: It's the expansion of space that incrementally stretches the photon wavelength as it's traveling from there to here. Another way to think about it: the recession of the galaxy can exceed the speed of light because it's not a genuine motion through space, but rather an apparent motion due to the expansion of space.

27. (4.00 pts) What's the risk of using Hubble's law to predict distances for very nearby objects?

Expected Answer: Motion through space (peculiar velocity) might contaminate the redshift. Also, if the objects are gravitationally bound, there is no cosmological expansion. Either answer for full credit.

28. (4.00 pts) Why isn't Hubble's law expected to work for high-redshift (e.g. $z > 2$) objects? Hint: it's for a different reason than the issue in part a.

Expected Answer: Since Hubble's constant might've had a different value in the past, photons that were emitted a long time ago don't experience a constant cosmological redshift. So a simple linear relation doesn't hold anymore.

29. (4.00 pts) We observe a galaxy's $H\alpha$ line at 663.7 nm. Assume that the redshift is due to cosmological redshift. Estimate the distance to the galaxy in Mpc.

Expected Answer: 635,900

The next 4 questions are about the warm-hot intergalactic medium (WHIM).

The WHIM is expected to have an average number density of 5 particles per cubic meter. This is very sparse!

30. (4.00 pts)
Assume that the WHIM is composed entirely of hydrogen. What is the mass density of the WHIM, in grams per cubic centimeter? The mass of a proton is 1.67×10^{-24} g. (You can ignore the electrons since their mass is negligible compared to the protons' mass.)

Expected Answer: $8.35\text{e}{-30}$ g/cm^3

31. (4.00 pts)
The Maxwell-Boltzmann distribution gives the speed distribution of particles at a given temperature. This distribution has an average speed $v = \sqrt{\frac{8kT}{\pi m}}$, where $k = 1.38 \times 10^{-16}$ erg/K is Boltzmann's constant, T is the temperature, and m is the particle mass. Verify that the units for this equation work out (in other words, show that the right-hand-side of the equation has units of velocity). Hint: An erg is a unit of energy equal to 1 g cm^2 / s^2.

Expected Answer: kT has units of energy, which is mass * velocity * velocity. Then we divide out the mass and square root, leaving a velocity.

32. (4.00 pts)
The WHIM has a temperature of 10^6 K. Compute the kinetic energy of a particle moving at the average speed, in ergs. (For partial credit, explain how you would calculate it.)

Expected Answer: $1.757\text{e}{-10}$

33. (4.00 pts)
The WHIM is in thermal equilibrium with the electromagnetic field, which means that it produces photons with roughly the same energy. What is the wavelength of a photon with the energy you calculated above, in nm? Verify that this lies in the ultraviolet/x-ray region, which agrees with observations of the WHIM.

Expected Answer: 11.3 nm

The following 2 questions are about Type 1a supernovae.

34. (4.00 pts)
Suppose the measurement of the peak apparent brightness of a Type Ia supernova had an uncertainty of ± 0.3 magnitudes. What is the corresponding uncertainty in distance? Express your answer as a decimal ratio between the upper and lower error bounds.

Expected Answer: 1.318 (reciprocal 0.759 for half credit)

35. (4.00 pts)

Imagine that you tracked a type Ia supernova and determined its distance. But then, your friend (who works at a gravitational wave lab) says that he measured a gravitational wave "chirp" originating from the supernova. (Let's say that this is in the future, where gravitational wave detectors are much more sensitive than they are today.) Is this information relevant (i.e. should you modify your distance calculation)? Why or why not?

Expected Answer: Yes, the original estimate was probably an underestimate since this was likely a double-degenerate scenario

We hope you enjoyed this exam! If you have any feedback about any of the exams at this tournament, please let us know through this form: https://tinyurl.com/utreg21feedback (https://tinyurl.com/utreg21feedback)