Science Olympiad
Astronomy C
BEARSO Invitational

October 10, 2020

Directions:

- Do **not** open the test until told to start!
- Each team will be given **50 minutes** to complete the test.
- There are three sections: **Section A** (Deep-Sky Objects), **Section B** (General Knowledge), and **Section C** (Calculations).
- Write **all answers on the lines on the answer pages**. Any marks elsewhere will not be scored. And make sure to include your **team name** and **team number** at the top of all answer pages.
- Feel free to take apart the test, so long as it is restapled before it is turned in.
- Do not worry about significant figures. Just make sure to use 3 or more in your answers.
- Ties will be broken by comparing points earned on the following sections/questions, in order: Section C, Section A, §C1, . . . , §C4, §A1, . . . , §A12, §B1, . . . , §B5.
- Good luck! And may the stars be with you!

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Feedback? **Test Code**: *2021BEARSO-AstronomyC-Comet*

Section A: Deep-Sky Objects

Use the Image Sheet to answer the following questions. Points are shown for each question or sub-question, for a total of 68 points.

1. (a) (1 point) What type of event is depicted in image 7?
   (b) (1 point) What type of object was likely produced by this event?
   (c) (1 point) This event was observed at which two locations?
   (d) (3 points) To the nearest order of magnitude, how much energy was emitted by the event, in joules?
   (e) (2 points) To the nearest order of magnitude, how much of the emitted energy passed through Earth, in joules?

2. (a) (1 point) What DSO is depicted in image 2?
   (b) (1 point) What type of event is this?
   (c) (2 points) Located 1".5 to the top right of the DSO is what type of object?
   (d) (2 points) How could this object have affected the DSO measurements?

3. (a) (1 point) Which image depicts MACS J0717.5+3745?
   (b) (1 point) What wavelength(s) is the image taken in?
   (c) (2 points) This galaxy cluster consists of four separate clusters colliding together, one of which is moving at a very high speed. How fast is it moving, in $\mathrm{km\,s^{-1}}$?

4. (a) (1 point) What DSO is depicted in image 9?
   (b) (1 point) What wavelength(s) is this image taken in?
   (c) (1 point) What type of object is this DSO?
   (d) (3 points) Astronomers have proposed two main solutions to the formation of early SMBHs, what are they?

5. (a) (1 point) What DSO is depicted in image 11?
   (b) (1 point) What do the green contours in the image represent?
   (c) (2 points) What specific phenomena was used to measure the green contours?

6. (a) (1 point) What DSO depicted in image 5?
   (b) (1 point) What is the mass of this object, in solar masses?
   (c) (2 points) What specific type of object is this DSO?
   (d) (3 points) Explain the main physical process that makes these objects so bright? Where does this energy come from?

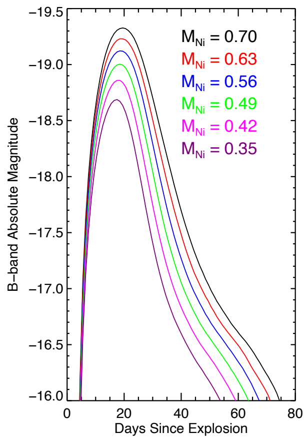
7. (a) (1 point) Which image depicts NGC 2623?
   (b) (1 point) What wavelength is the image taken in?
   (c) (2 points) What do observations in this wavelength reveal about this object?
   (d) (2 points) What specific type of galactic nucleus is NGC 2623?

8. (a) (1 point) What DSO is depicted in image 8?
   (b) (1 point) Which wavelengths are shown by the colors blue and orange in the image?
   (c) (2 points) The central orange feature is generated through what process?
9. (a) (1 point) Which image depicts PSS 0955+5940?
   (b) (1 point) What is the redshift of PSS 0955+5940?
   (c) (2 points) How were astronomers able to determine the distances to these high redshift quasars?
10. (a) (1 point) Image 4 shows observational data of what DSO?
    (b) (3 points) Since observations of the DSO have low signal-to-noise spectra, how were astronomers able to discern features from it?
    (c) (1 point) The shadowed regions at 22.25 Å show the location of what absorption line?
    (d) (1 point) What was this absorption line used to discover?
11. (a) (1 point) Image 16 shows an artist impression of which DSO?
    (b) (2 points) A bright light depicted in the top left. What type of object is this and what is its designation?
    (c) (1 point) What is the relationship between the object and the DSO?
    (d) (2 points) How does the object affect the significance of the DSO's discovery?
12. (a) (1 point) Which image depicts JKCS 041?
    (b) (1 point) What wavelength(s) is the image taken in?
    (c) (2 points) What does it mean for a galaxy to be quiescent and how many cluster members are quiescent?
    (d) (3 points) "Comparing the quiescent members of JKCS 041 to a large sample of coeval field galaxies, we find that the distribution of projected axis ratios suggests a lower fraction of disk-like systems among quiescent galaxies in the cluster" (Newman et al. 2014). Using your knowledge of galaxy evolution, explain why this observation makes sense.

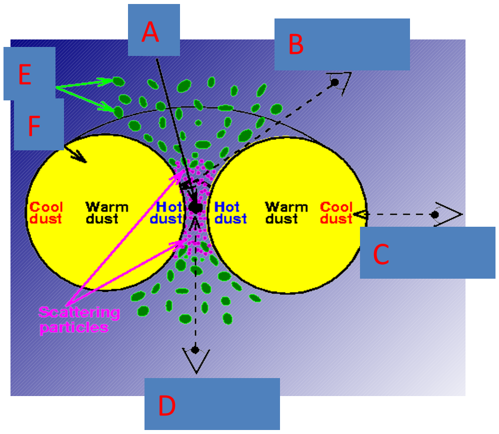
Section B: General Knowledge

Points are shown for each question or sub-question, for a total of 48 points.

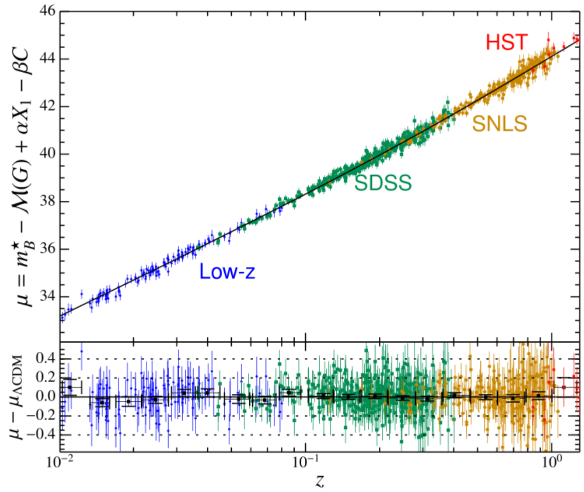
1. (9 points) The figure below shows how light curves of Type Ia supernovae depend on the mass of Nickel synthesized in the explosion, from Kasen & Woosley (2007).
   (a) (2 points) What element is the end result of the decay of Nickel-56?
   (b) (3 points) How do the width and luminosity of Type Ia supernovae depend on the amount of Nickel synthesized?
   (c) (4 points) What physical process causes the dependence of the width of the peak of the light curve with varying nickel content? Explain in 1-2 sentences.



2. (8 points) A labeled schematic of a quasar is shown below.
   (a) (2 points) Locations B-D show possible viewing angles of this quasar. Which viewing angle (B-D) would appear the "quietest" in radio wavelengths?
   (b) (2 points) At which viewing angle (B-D) would this object appear to be a blazar?
   (c) (2 points) Which location (A-F) shows the accretion disk surrounding the central compact object?
   (d) (2 points) What is the nature of the central compact object?



3. (12 points) The top panel of the plot below shows the measured distance modulus of galaxies from various observatories as a function of redshift. The bottom panel shows the deviation of the distance modulus from that expected from standard Lambda-CDM cosmology.



   (a) (3 points) What is the slope of the line, in distance modulus per redshift?

   (b) (3 points) What is the slope of the line when converting distance modulus to distance and redshift to radial velocity, in Mpc km^{-1} s^{-1}?

   (c) (2 points) How is this slope related to Hubble's constant?

   (d) (4 points) There is a deviation between the measured distance modulus and that expected from Lambda-CDM at high redshift. What causes this deviation?

4. (10 points) Match the term to the type of astronomical object.

   (a) (2 points) A compact object approximately the size of a large city.

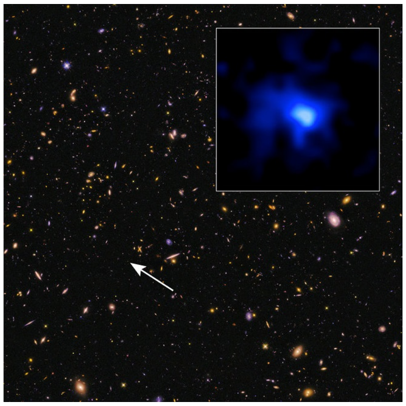
   (b) (2 points) Plasma that contains approximately 50% of the baryonic matter in the observable universe.

   (c) (2 points) Supernova caused by the thermonuclear detonation of a white dwarf star.

   (d) (2 points) A galaxy with a quasar-like nucleus and highly-ionized emission lines but that looks like a normal spiral galaxy in visible light.

   (e) (2 points) An AGN with its jet directed toward the observer.

5. (9 points) The CANDELS survey is the largest observing project in the history of the Hubble Space Telescope.



   (a) (2 points) The infrared instrument used for this survey was installed during Hubble's last servicing mission in 2009. What instrument is this?

   (b) (2 points) Which HST instrument was used to take the visible wavelength observations of CANDELS?

   (c) (2 points) What was the minimum redshift that CANDELS probed beyond?

   (d) (3 points) The image on the right shows the most distant galaxy observed during the CANDELS survey. What redshift does this galaxy lie at?

Section C: Calculations

Points are shown for each question or sub-question, for a total of 84 points.

1. (27 points) For any body balanced between gravitational collapse and radiation pressure, there is an upper limit to its luminosity called the **Eddington luminosity** L_{Edd}. The Eddington luminosity of a star of mass M and opacity κ is given by

$$L_{Edd} = \frac{4\pi GMc}{\kappa}$$

(a) (4 points) This equation can be simplified into the form

$$L_{Edd} = k\left(\frac{M}{M_\odot}\right)\mathrm{L}_\odot$$

where $\frac{M}{M_\odot}$ is the star's mass in solar masses and k is a constant. Find k. Assume the star is composed of ionized hydrogen, whose opacity is given by $\kappa = \frac{\sigma_T}{m_p}$, where $\sigma_T = 6.652 \times 10^{-29}\,\mathrm{m}^2$ is the Thomson scattering cross-section for the electron, and $m_p = 1.673 \times 10^{-27}\,\mathrm{kg}$ is the mass of the proton.

(b) (2 points) Calculate the Eddington luminosity of the sun, in solar luminosities. Is this smaller or larger than the Sun's actual luminosity?

(c) (9 points) Luminous Blue Variables are stars that sometimes exceed their Eddington limit during their outburst states. η Carinae is a star famous for its "Great Eruption" in the 19th century, where it brightened up to magnitude -0.8, becoming the second brightest star in the night sky at the time. It has since dimmed back to an apparent magnitude of 4.3.

i. Assuming that η Carinae's current luminosity is $5.0 \times 10^6\,\mathrm{L}_\odot$, calculate its luminosity during the outburst state, in solar luminosities.

ii. Assuming that η Carinae had a mass of $150\,\mathrm{M}_\odot$ at the time of the outburst, what was its Eddington luminosity, in solar luminosities?

iii. There is a cloud of gas surrounding η Carinae that is so prominent we have named it the Homunculus Nebula. Connect this with the star's Great Eruption and the Eddington luminosity.

(d) (12 points) The following data is given for the quasar 152156.48+520238.5.

Object name (J2000)	$\log(L_{Bol})$ $\mathrm{erg\,s^{-1}}$	$\log(M_{BH})$ $\mathrm{M}_\odot$	L_{Bol}/L_{Edd}
152156.48+520238.5	48.2	9.8	2.09

i. Calculate the quasar's bolometric luminosity, in solar luminosities.

ii. Calculate the quasar's Eddington luminosity, in solar luminosities.

iii. What is the calculated Eddington ratio (L_{Bol}/L_{Edd})? Is this consistent with the one given in the table?

iv. Not many objects can sustain a super-Eddington luminosity. Explain why, and why an active galactic nucleus might be able to. *Hint: what are AGNs powered by?*

2. (31 points) We observe a star orbiting within a certain galaxy with redshift z = 0.00300 and angular radius 5.00′; the star is orbiting 2.50′ from the galaxy's center. Assume the galaxy is circular and that we are viewing it edge-on (i = 90°); assume also that the star's orbit is circular, and at the time we are viewing this star, its apparent separation from the galaxy center is maximum.
   (a) (4 points) What is the distance to this galaxy, in Mpc? Use $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.
   (b) (3 points) What is the physical radius of this galaxy, in pc?
   (c) (2 points) What is the physical orbital radius of the star, in pc?
   (d) (4 points) After taking the spectrum of this star, we find that its H-alpha line ($\lambda_0 = 656.281\,\mathrm{nm}$) is centered at 658.416 nm. Find this star's recessional velocity with respect to Earth, in $\mathrm{km\,s^{-1}}$.
   (e) (4 points) Find this star's orbital velocity with respect to the galaxy, in $\mathrm{km\,s^{-1}}$.
   (f) (4 points) Find the galaxy's mass interior to the star's orbital radius, in $\mathrm{M_\odot}$.
   (g) (4 points) Assuming the galaxy has a spherical uniform mass distribution, find its total mass, in $\mathrm{M_\odot}$.
   (h) (3 points) There are an estimated 70 billion stars in this galaxy. Assuming that each star is sunlike on average, estimate this galaxy's mass to light ratio, in $\mathrm{M_\odot\,L_\odot}^{-1}$.
   (i) (3 points) Compared to the composition of a typical galaxy, does this galaxy have more or less dark matter?

3. (8 points) Gravitational lensing is a well-known phenomenon of general relativity that astrophysicists use for weighing galaxies, detecting exoplanets, and more. The angle of deflection of light for a massive body is given by
$$\theta = \frac{2R_s}{r}$$
where r is the impact parameter (the distance of closest approach from the light ray to the center of the lensing object) and R_s is the object's Schwarzschild radius.
   (a) (4 points) Find the maximum angle of deflection for a photon passing near the sun, in arcseconds.
   (b) (4 points) Find the maximum angle of deflection for a photon passing near Jupiter, in arcseconds.

4. (18 points) The **Friedmann equation** is a fundamental equation of modern cosmology and describes the expansion of an isotropic, homogeneous universe (which is a good approximation on large scales). While this equation is accurate in the context of general relativity, some of its components can also be understood with classical Newtonian gravity.

$$H^2 = \frac{8\pi G}{3}(\rho_m + \rho_r) - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

Here, H is the Hubble constant, which describes the universe's expansion rate; a is the scale factor, which describes the universe's size; ρ_m is the matter density, ρ_r is the relativistic particle (photons, neutrinos, etc) mass density, k is a coefficient that describes the universe's curvature (closed, flat, or open), and Λ is the cosmological constant (dark energy). These four components govern the expansion of the universe.

(a) (5 points) Derive an expression for the critical density ρ_c of the universe, which is the density required of a flat ($k = 0$) universe. *Hint: Matter density, relativistic particle density, and dark energy all contribute to the universe's density, so you can rewrite the Friedmann equation as*

$$H^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2}$$

(b) (4 points) Compute the critical density for the universe today, in $\mathrm{kg\,m^{-3}}$. Use $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

(c) (4 points) Using part the answer to part (b), estimate the baryonic mass density of the universe. Give your answer in hydrogen atoms per cubic meter.

(d) (5 points) The actual density of the universe (as measured by instruments like WMAP) is quite close to the critical density. A universe that is initially even just slightly closed or open will rapidly diverge from flatness; the fact that the universe today is flat (or nearly flat) seems like a remarkable coincidence. How do cosmologists explain this, besides using the anthropic principle?