

2020
YALE UNIVERSITY



Astronomy C

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Do Not Write
On This Exam

Directions:

Each sub-question is worth two points. Partial, integral credit will be given for sub-questions with multiple parts. Only the answer sheet will be scored. Computational problems will accept a range of numbers. Questions? Email me at ashernoel@college.harvard.edu!

Good Luck!

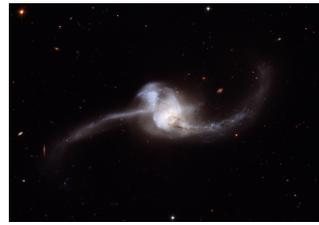
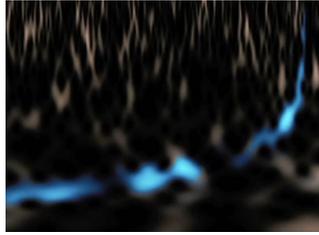
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Question 1: DSOs 1

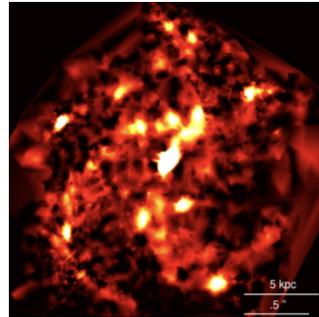
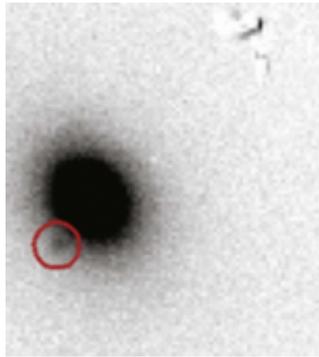
1. For the following ten images, identify the:

(a) DSO & the meaning of "GW"



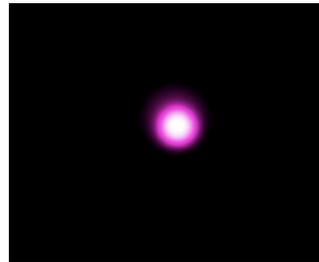
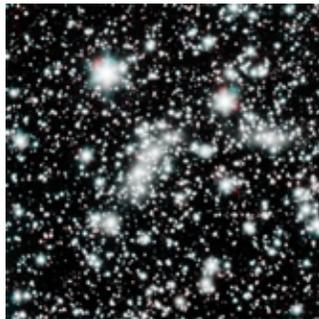
(f) DSO & the meaning of "NGC"

(b) DSO & date of discovery in UT



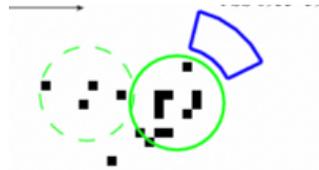
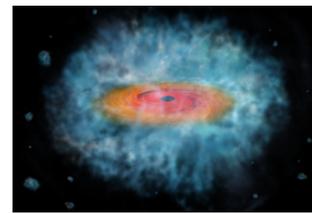
(g) DSO & meaning of the acronym in the DSO's name

(c) DSO & wavelength



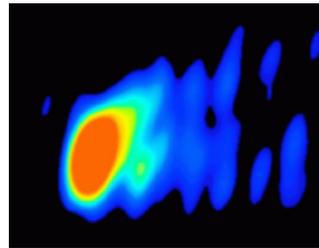
(h) DSO & wavelength

(d) DSO & redshift



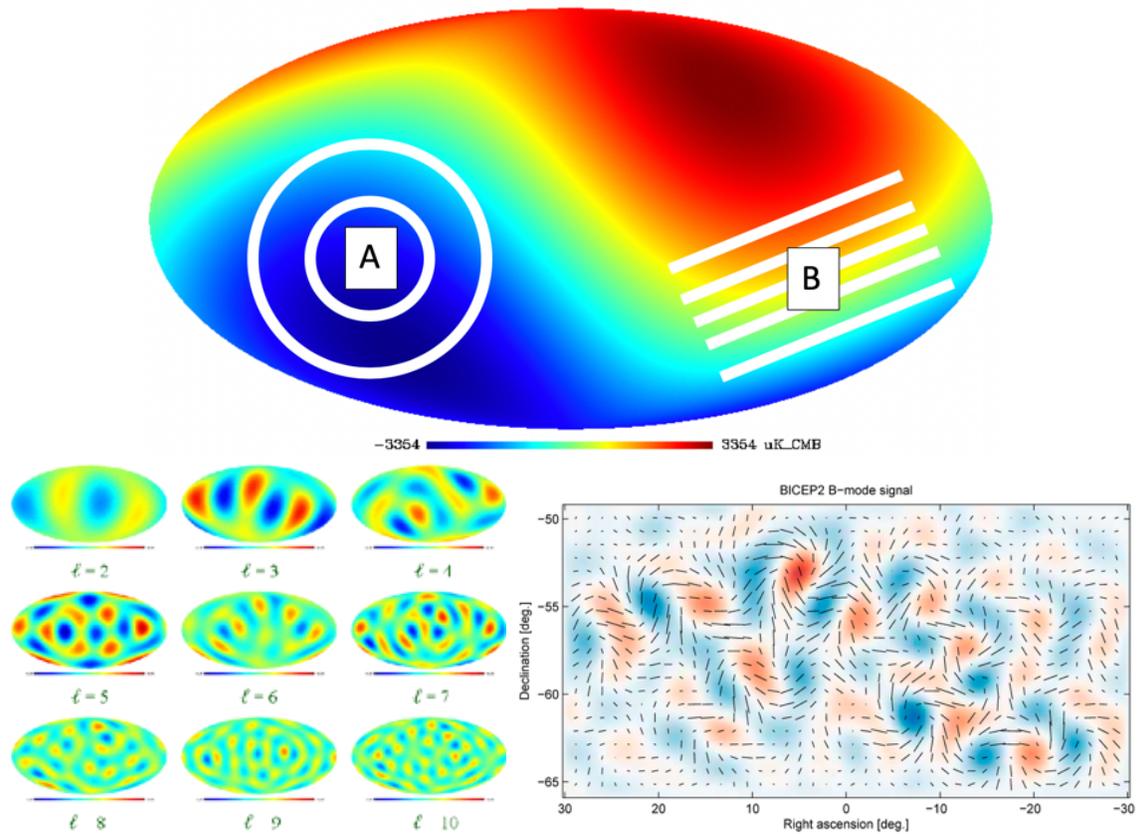
(i) DSO & meaning of "Quasar"

(e) DSO & sub-type of AGN that this illustrates.



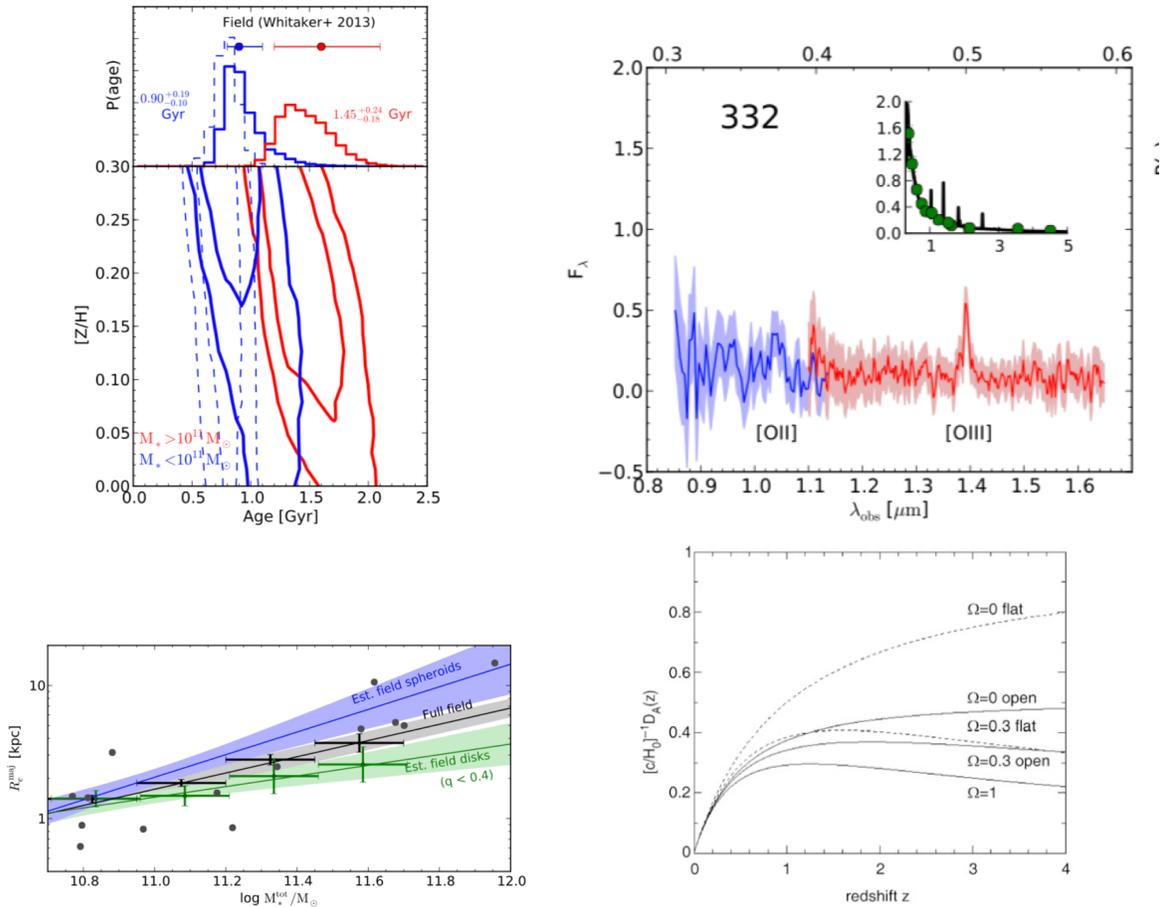
(j) DSO & spin of black hole as viewed from Earth.

Question 2: Cosmic Microwave Background



2. The following questions refer to the Cosmic Microwave Background (CMB):
- If the universe contains approximately 10^{23} stars, why is the night sky dark?
 - What does the CMB suggest about the isotropy and homogeneity at large scales? Why?
 - Is the bar pattern in the top image around B isotropic? Homogeneous? Why?
 - Before decoupling, how did photons and electrons maintain thermal equilibrium?
 - How did recombination cause decoupling?
 - What is shown in the bottom left?
 - Why would astronomers use the technique in the bottom left instead of a correlation function?
 - What is shown in the bottom right?
 - What is thought to have caused this? At what epoch did these originate?

Question 3: JKCS 041 in Depth



3. The following questions relate to the DSO JKCS041

- Using the spectrum above, what is the redshift of the JKCS041?
- At least how many galaxies are identified within this cluster?
- What does the image in the top left suggest about the relative ages of galaxies of different masses?
- What does (c) suggest about galaxy formation in general?
- Use the image in the bottom left to calculate the angular-diameter distance to this DSO in a flat universe dominated by dark energy, in megaparsecs.
- Calculate the luminosity-distance to this DSO, in megaparsecs.
- How does the spectra evidence that the object is undergoing star formation?
- Would you expect this object to be plotted in the green, black, or blue part of the image in the bottom right? Why?
- What are two ways that galaxy clusters quench star formation?

Question 4: The End of Recombination

4. Use the following relations and data to answer the following questions about the epoch of photon decoupling:

$$T = T_0(1 + z) \quad (1)$$

$$\rho_0 = \rho_{b,0}(1 + z)^3 \quad (2)$$

$$M_J \approx \left(\frac{5kT}{\mu G m_H} \right)^{3/2} \left(\frac{3}{4\pi\rho} \right)^{1/2} \quad (3)$$

$$H(t) = \frac{\dot{a}}{a} \quad (4)$$

$$\left(\frac{\dot{a}}{a} \right)^2 = \frac{8\pi G\rho}{3} + \frac{\Lambda}{3} - \frac{\kappa c^2}{a^2} \quad (5)$$

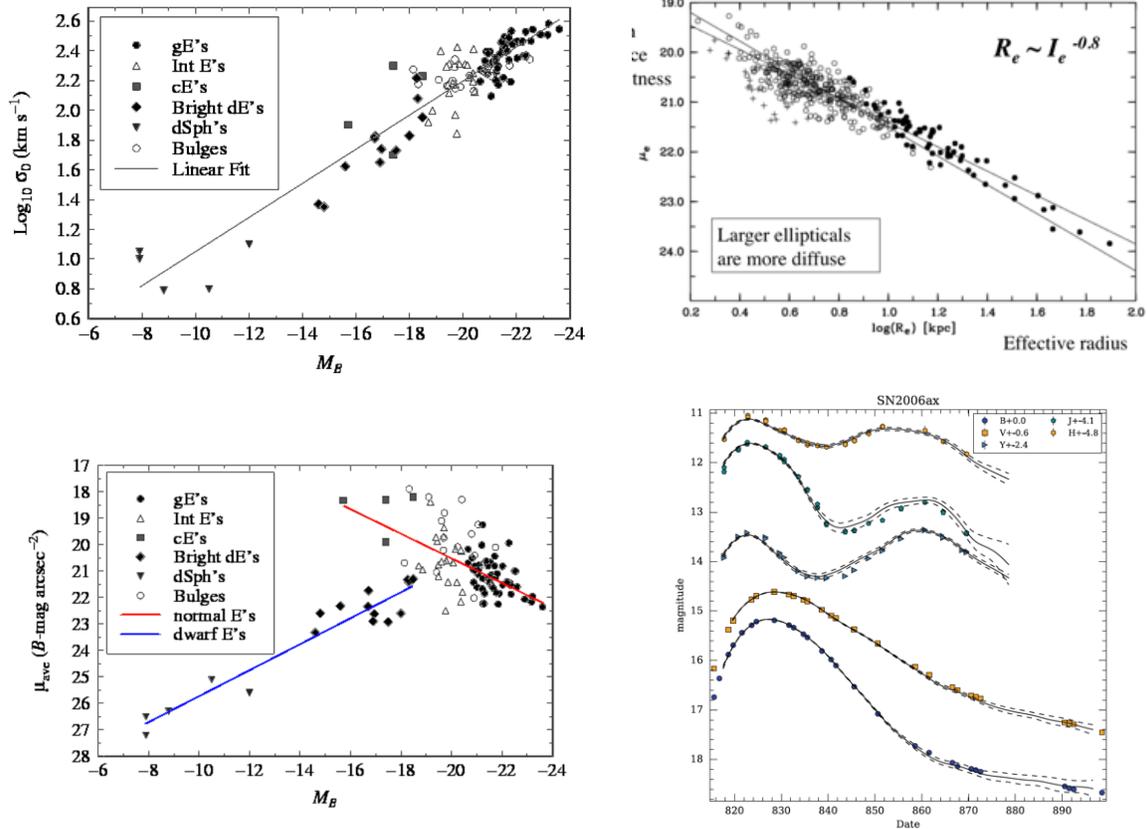
Parameter	Value
H_0	70 km s ⁻¹ Mpc ⁻¹
μ	0.64
k	$1.38 \times 10^{-23} \text{m}^2 \text{kg s}^{-2} \text{K}^{-1}$
m_H	$1.67 \times 10^{-27} \text{kg}$
$T_{\text{decoupling}}$	2970K
$T_{\text{recombination}}$	4000K
a_0	1
κ	0
Λ	0
$\Omega_{b,0}$	0.04

- What is the temperature of the Cosmic Microwave Background T_0 ?
- Calculate the redshift at the epoch of decoupling.
- At high redshifts, can information travel faster than c ? Why or why not?
- What famous equation is shown in equation 5?
- What is a commonly referred to as?
- What is Λ commonly referred to as?
- According to the data, what is curvature of the universe?
- Using the data and equation 5, calculate the present critical density.
- Calculate the present baryonic mass density.
- Calculate the baryonic mass density at the epoch of decoupling.
- Calculate Jeans' mass at the epoch of decoupling.
- What structures have masses that resemble the value obtained in (c)?
- What does this suggest about galaxy formation?

Question 5: Reference Warm-Up

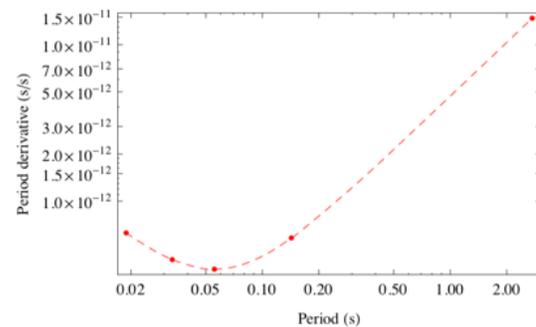
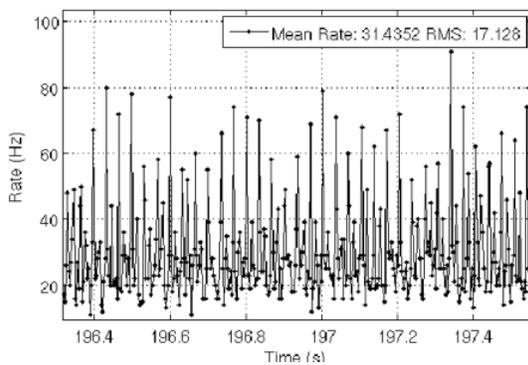
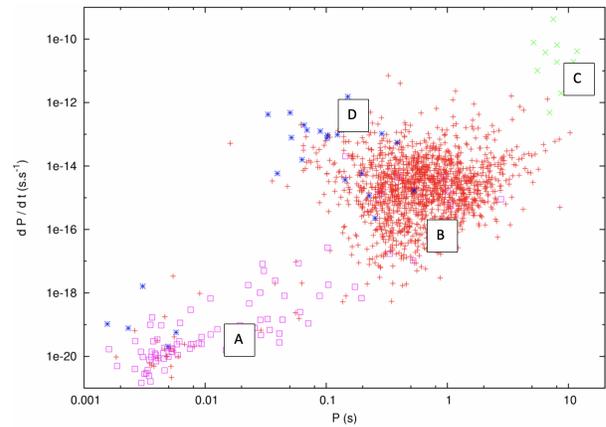
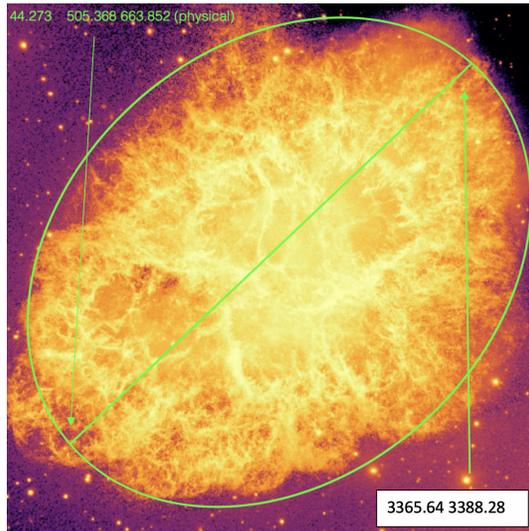
5. This question should serve as a good warm-up for the partner who does not start with DSOs. An essential component of any binder, whether physical or on a laptop, is quickly accessible reference information. For each of the following, write the correct number or equation on the corresponding part of the answer sheet. A range of answers will be accepted for the ambiguous values.
- (a) The questions here overlapped with another test. The answers remain in the key, but both questions and answers will not appear in future tests.

Question 6: Dwarf Elliptical NSO1



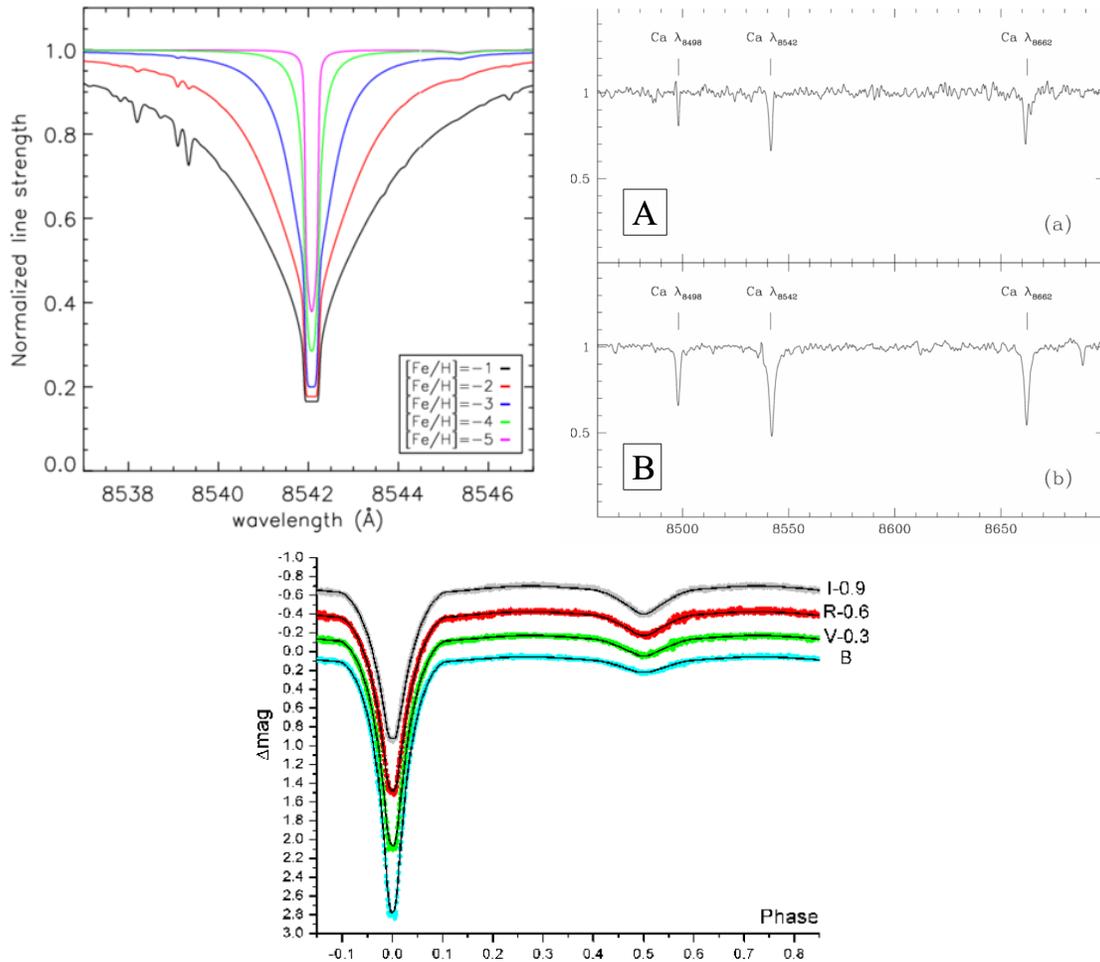
6. Galaxy NSO1 is a dwarf elliptical (dE) galaxy. The light curve of a type Ia supernova detected originating from this galaxy is shown in the image in the bottom right.
- Find the distance to NSO1, in megaparsecs.
 - NSO1 is observed to have an apparent B-band magnitude of 15.23. Calculate its B-band absolute magnitude.
 - What relation is shown in the top left? Using this, find NSO1's dispersion velocity.
 - What relation is shown in the top right? Using this and the image in the bottom left, estimate NSO1's effective radius.
 - Given that the mass of dE's ranges from 10^7 to 10^9 M, estimate the maximum escape velocity of NSO1 in m/s.
 - Estimate the typical expansion velocity of a supernova in m/s.
 - Use your previous answers to explain the evolution of ancient, gas-poor systems such as dEs.

Question 7: The Crab Nebula



7. The following questions ask about the crab nebula and pulsar. Assume the central compact object (CCO) has a mass of $1.4M_{\odot}$ and a radius of 10 km.
- Use the JS9 image in the top left and the conversion of $0.001''/\text{pix}$ to determine the length of the longer diameter in meters if the nebula is 2,000 pc away.
 - The expansion velocity in the long direction is 1450 km s^{-1} . Calculate the age of the pulsar.
 - It is found that there is a slight peak in the remnant's X-ray flux at 849 eV (not shown above). What element causes this?
 - Determine the period, in seconds.
 - Determine the period derivative using the image in the bottom right, in s s^{-1} , to the nearest 5×10^{-13} .
 - Calculate the spin-down luminosity, in L_{\odot} .
 - (1 point) Calculate the Eddington luminosity of the pulsar, in L_{\odot} . (1 point) Why does it make sense that the spin down luminosity is larger?
 - What type of magnetobremstrahlung radiation dominates in the optical?
 - Which letter on the $P - \dot{P}$ diagram in the upper right represents where one would expect to find the CCO?

Question 8: A Metallic Binary



8. The proton-proton chain converts 0.7% of rest mass into energy. Consider an eclipsing binary system with two stars of $M = 0.084M_{\odot}$ and $L = 1.72 \times 10^{22}W$.
- What is the inclination of the system as viewed from Earth, in degrees?
 - What is the luminosity of the system at maximum, in L_{\odot} ?
 - Calculate the total energy released inside star A via the conversion of hydrogen to helium, in joules, assuming a pure hydrogen composition and that the entire star participates in hydrogen fusion.
 - Use your previous answer to calculate star A's main sequence lifetime, in years.
 - The first image in the upper left shows the Ca II triplet at different metallicities and the second shows the Ca II for stars A and B. Which star - A or B - has the lower metallicity?
 - (4 points) Explain *why* and *how* a higher metallicity affects radius and temperature.
 - Which star - A or B - is obscured from view during the primary minimum?
 - Calculate the ratio of the temperature of A to the temperature of B using observations in the I-band.

Answer Sheet A: Questions 1-4

Team Number: _____

Team Name: _____

Team Members: _____

- 1. (a) _____
(b) _____
(c) _____
(d) _____
(e) _____
(f) _____
(g) _____
(h) _____
(i) _____
(j) _____
- 2. (a) _____

(b) _____

(c) _____

(d) _____

(e) _____

(f) _____

(g) _____

(h) _____
(i) _____
- 3. (a) _____
(b) _____
(c) _____

(d) _____

(e) _____

(f) _____

(g) _____

(h) _____

(i) _____

4. (a) _____

(b) _____

(c) _____

(d) _____

(e) _____

(f) _____

(g) _____

(h) _____

(i) _____

(j) _____

(k) _____

(l) _____

(m) _____

Answer Sheet B: Questions 5-8

5. (a) _____
(b) _____
(c) _____
(d) _____
(e) _____
(f) _____
(g) _____
(h) _____
(i) _____
(j) _____

6. (a) _____
(b) _____
(c) _____
(d) _____
(e) _____
(f) _____
(g) _____

7. (a) _____
(b) _____
(c) _____
(d) _____
(e) _____
(f) _____
(g) _____
(h) _____
(i) _____

8. (a) _____
(b) _____
(c) _____
(d) _____
(e) _____
(f) _____

(g) _____
(h) _____