Harvard Undergraduate Science Olympiad Invitational 2020

Astronomy C
EXAM BOOKLET and ANSWER SHEET

Directions:

- Each sub-question in Q1-7 is worth two points. Q8-10 are worth an ambiguous number of 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.
- Ties will be broken by comparing the points scored on the last sub-questions.
- Questions? Email us at awli@college.harvard.edu or ashernoel@college.harvard.edu!
- **Feedback Form Code (for use in HUSO iOS app):** HubbleFlowNMT12

Names:____

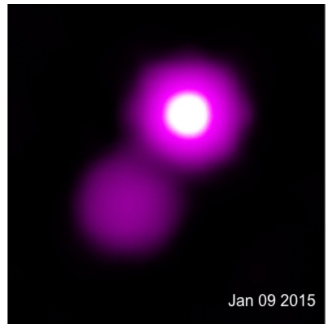
School name: ________________________ Team #:______

Score: ____

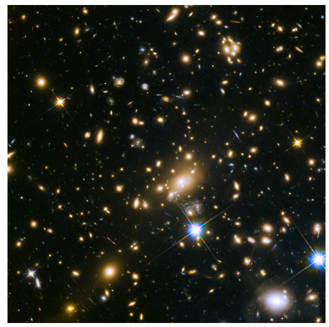
Question 1: DSOs 1

1. For the following ten images, identify the:

(a) DSO & the wavelength of the red jets

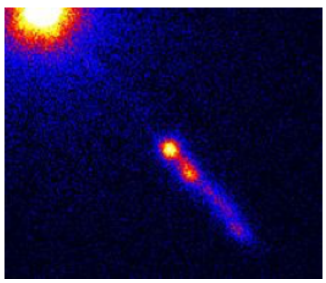


(f) DSO & host galaxy

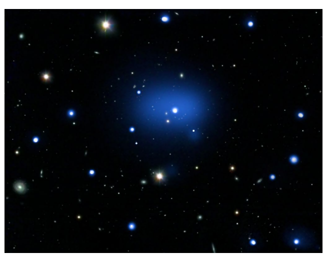


(g) DSO & the year of its discovery.

(b) DSO & the constellation it resides within.

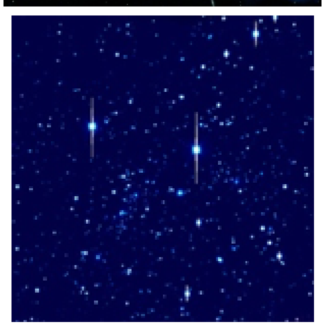


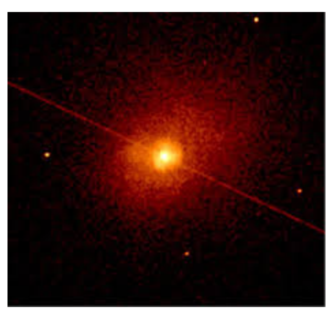
(c) DSO & wavelength



(h) DSO & Hubble type

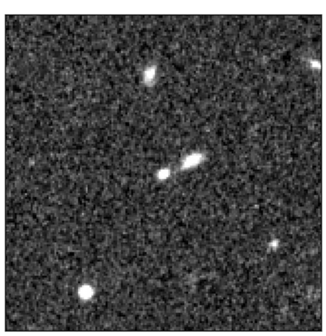
(d) DSO & significance .





(i) DSO & intervening medium

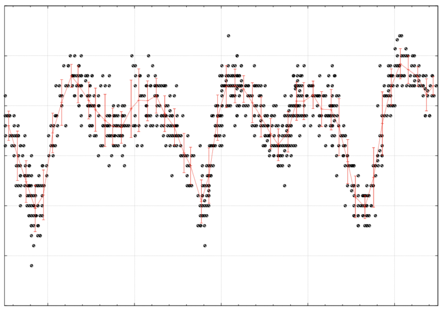
(e) DSO & redshift.



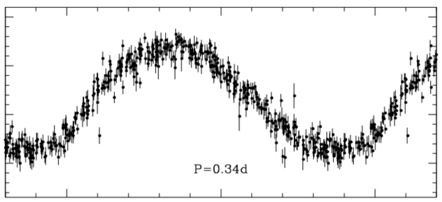
(j) DSO & telescope.

Question 2: Light Curves

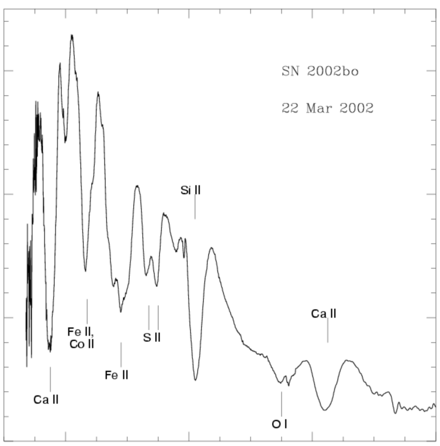
3. Answer the following sub-questions about the associated image to the left.



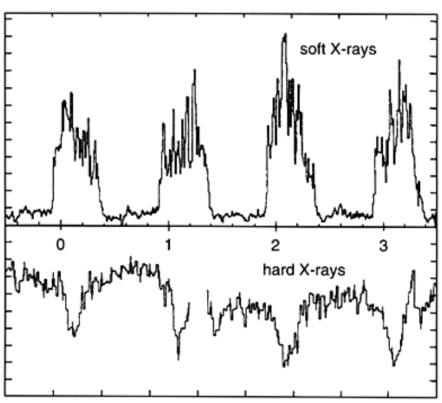
(a) Identify the type of Cepheid variable.
(b) The ionization of what atom drives its radial pulsations?



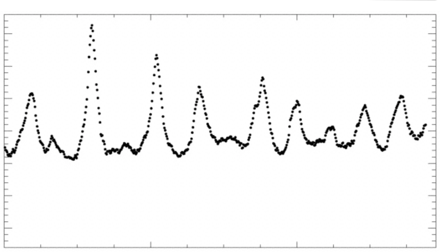
(c) Identify the type of RR Lyrae variable.
(d) What is this object's absolute visual magnitude?



(e) Identify the type of supernova shown at maximum.
(f) What are possible resulting central compact objects?



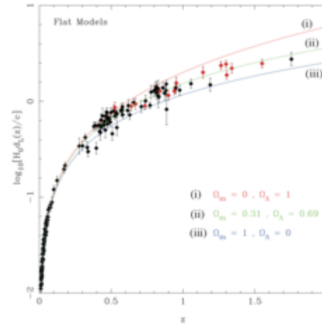
(g) Identify the type of cataclysmic variable (CV).
(h) What distinguishes this type of system from other CVs?

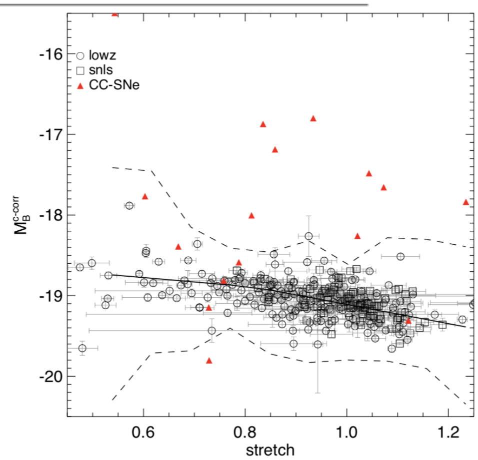


(i) Identify the type of non-radially pulsating variable.
(j) What causes the observed luminosity fluctuations?

Question 3: SN UDS10Wil in Depth

UT Date	MJD	Filter	Exposure Time	Flux (counts s^{-1})	Vega Mag
2010 Nov. 08.8	55508.1	F814W	3517.0	0.143 ± 0.054	27.635 ± 0.413
2010 Nov. 11.2	55511.2	F160W	1605.8	0.517 ± 0.074	25.221 ± 0.156
2010 Nov. 11.2	55511.2	F125W	955.9	0.698 ± 0.096	25.535 ± 0.149
2010 Dec. 28.0*	55557.4	F814W	3817.0	−0.063 ± 0.041	...
2010 Dec. 30.7*	55560.7	F160W	1705.9	1.22 ± 0.079	24.290 ± 0.070
2010 Dec. 30.8*	55560.8	F125W	955.9	1.403 ± 0.102	24.776 ± 0.079
2011 Jan. 12.6	55573.6	F160W	3617.6	0.901 ± 0.063	24.616 ± 0.076
2011 Jan. 12.8	55573.8	F125W	3617.6	0.759 ± 0.062	25.443 ± 0.089
2011 Jan. 13.6	55574.6	F850LP	1994.0	−0.018 ± 0.035	...
2011 Jan. 23.4	55584.3	F160W	3667.6	0.780 ± 0.061	24.774 ± 0.085
2011 Jan. 23.4	55584.4	F125W	3867.6	0.535 ± 0.059	25.823 ± 0.118
2011 Feb. 04.2	55596.1	F160W	3767.6	0.441 ± 0.061	25.392 ± 0.150
2011 Feb. 04.2	55596.1	F125W	3717.6	0.437 ± 0.062	26.043 ± 0.154
2011 Feb. 16.1	55608.1	F160W	4973.5	0.309 ± 0.058	25.779 ± 0.205
2011 Feb. 16.3	55608.2	F125W	4973.5	0.183 ± 0.057	26.989 ± 0.337
2011 Jan. 12.7	55573.7	G141	39088.0	(grism obs)	...



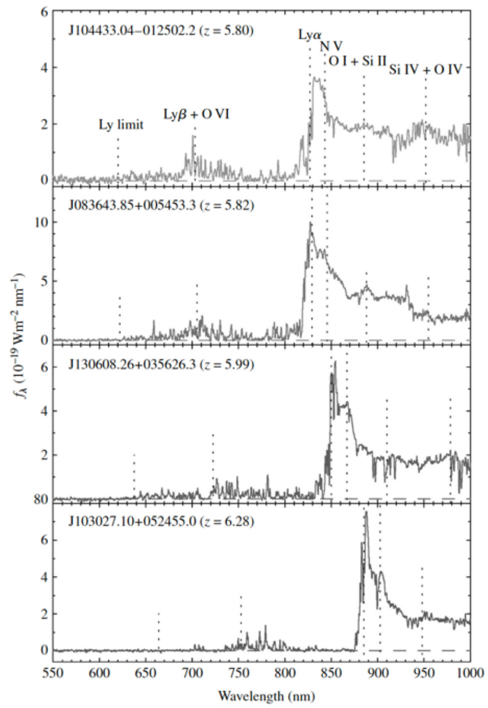


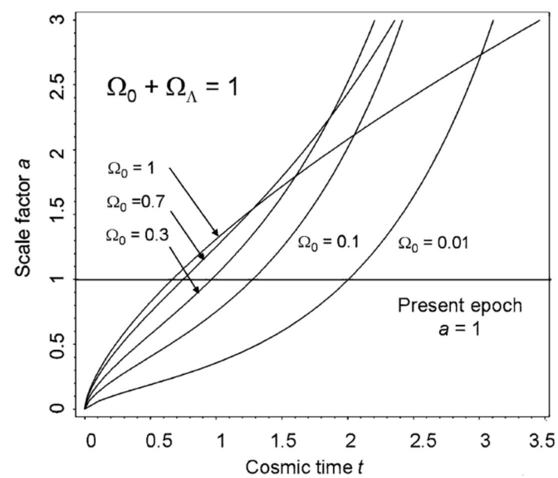
3. The following questions relate to SN UDS10Wil, which had a B-band absolute magnitude of -19.3:
   (a) What is the redshift of this supernova?
   (b) Calculate the scale factor for the universe at the time of the supernova.
   (c) What drove the expansion of the universe during this time?
   (d) Use the table to estimate the peak Vega apparent magnitude.
   (e) The following fit to calculate is used to calculate the corrected apparent magnitude:

$$m_{corr} = m_B^* + \alpha \times (s - 1) - \beta \times C$$

   where $\alpha = 1.367, \beta = 3.179$, and $C = -0.071$. Use the lower image to estimate the SIFTO stretch parameter.
   (f) Use the fit to calculate the corrected apparent magnitude.
   (g) Calculate the proper distance to the object, in megaparsecs.
   (h) Using your answers in (a) and (d), which model in the top right image is predicted by the supernova?
   (i) What is the predicted energy density of matter by the model that best fits the SN, in MeV/m3?
   (j) Would you expect to find to find H I, S II, and/or H II lines in the DSO's spectrum?
   (k) What is the theoretical maximum mass of the progenitor? Why?

Question 4: The Dark Ages





4. After decoupling, this universe was dominated by opaque, neutral hydrogen. In cosmological history, this period of time is referred to as the "Dark Ages."

   (a) What is the qualitative difference between the lyman-alpha forest of quasars at low and high redshifts?

   (b) What transition produces the Lyman-alpha forest?

   (c) Dense neutral hydrogen is opaque to the Lyman-alpha forest. Estimate the redshift of re-ionization, the end of the "Dark Ages."

   (d) Calculate the size of the universe at re-ionization as a fraction of its current size.

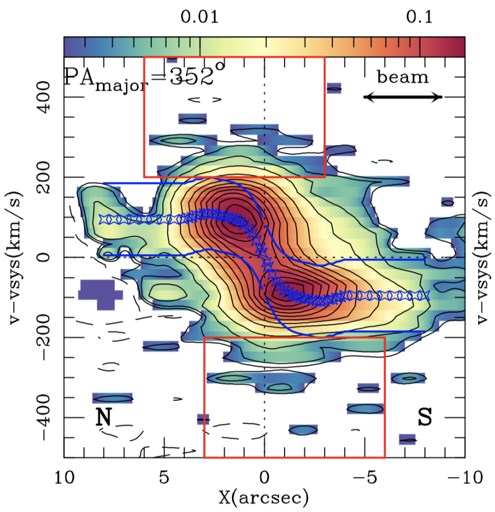
   (e) Using image E, $\Omega_m = 0.3$, and a Hubble constant from Planck of 67.7 km/s/Mpc, estimate the age of the universe at re-ionization.

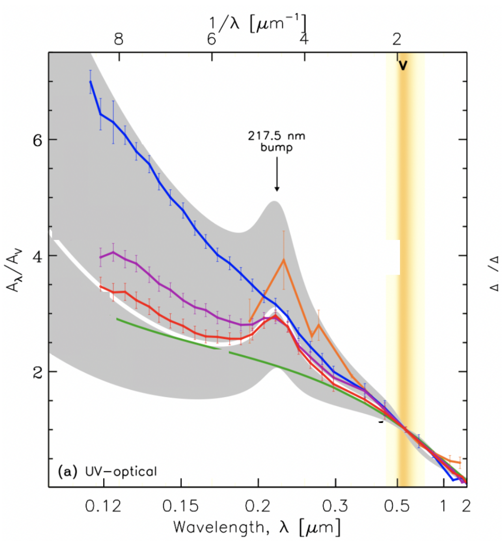
   (f) What does (e) suggest about galaxy formation?

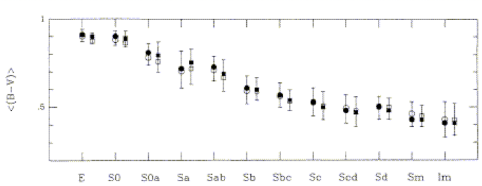
   (g) What does (e) suggest about the existence of hot or dark matter? Why?

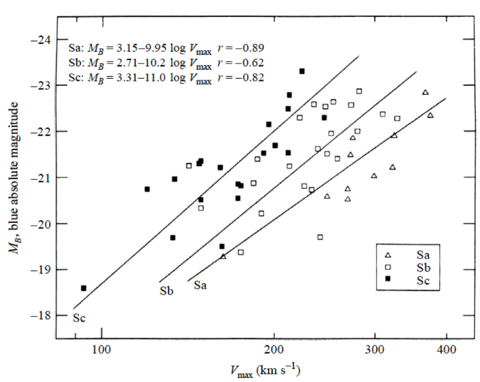
   (h) What does (e) suggest about the validity of the ΛCDM model? Why?

Question 5: NGC 1614









6. NGC 1614 is a spiral galaxy undergoing an extreme starburst. Hubble observes it to have an apparent magnitude m_v of 12.91 and a $B-V$ color index of 0.51

   (a) What is NGC 1614's maximum rotational velocity - 275 or 2750 km/s?

   (b) What is one possible cause of the bump in the extinction curve at 217.5 nm?

   (c) What is NGC 1614's Hubble type - Sa, Sb, or Sc?

   (d) Calculate NGC 1614's absolute B-band magnitude M_B.

   (e) Calculate NGC 1614's absolute visual magnitude M_V.

   (f) Use the fact that $M_{B,sun} = 5.47$ to find the B-band luminosity of NGC 1614 in $L_\odot$.

   (g) Use the following two equations to find the extinction at 0.15 microns $A_{0.15}$.

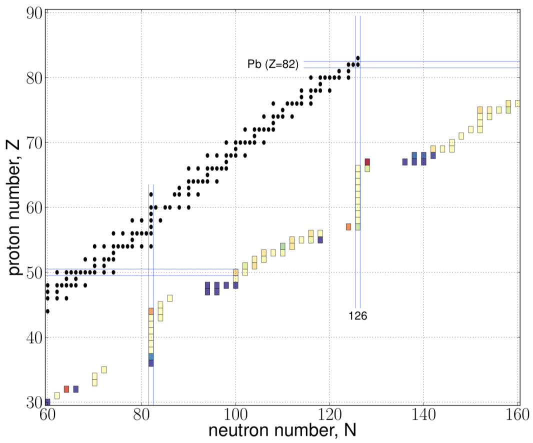
$$L_{B,host}(L_\odot) = 10^{9.9}\text{SFR}_{starb}^{0.94}$$
$$10^{A_{0.15}} = 250 \times \text{SFR}_{starb}^{2.2}$$

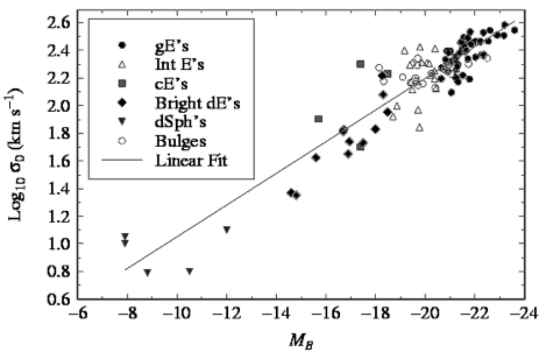
   (h) What is the color of the curve that represents the absolute extinction for NGC 1614 - orange, purple, white, or green?

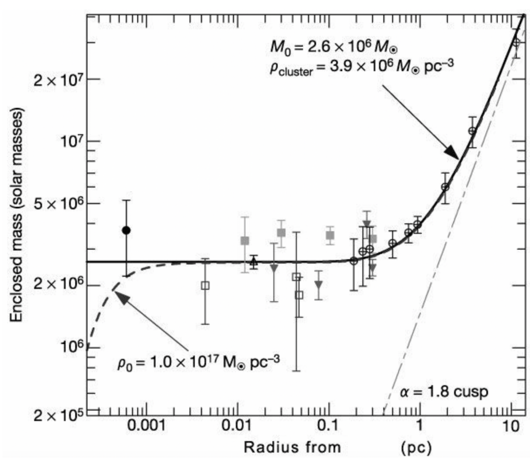
   (i) Use this curve to calculate the starburst's V-band extinction A_V.

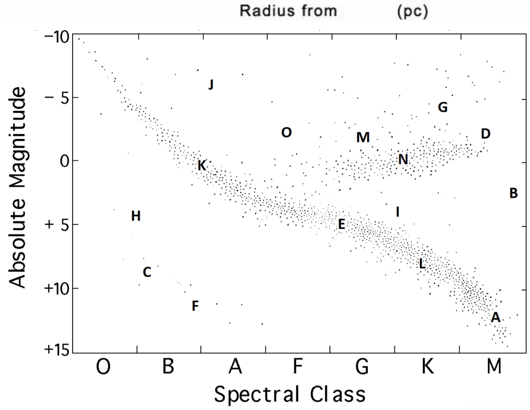
   (j) Use your previous answers and $A_V = 1.24$ for the Milky Way to calculate the distance to NGC 1614 in megaparsecs.

Question 6: Rapid Recall



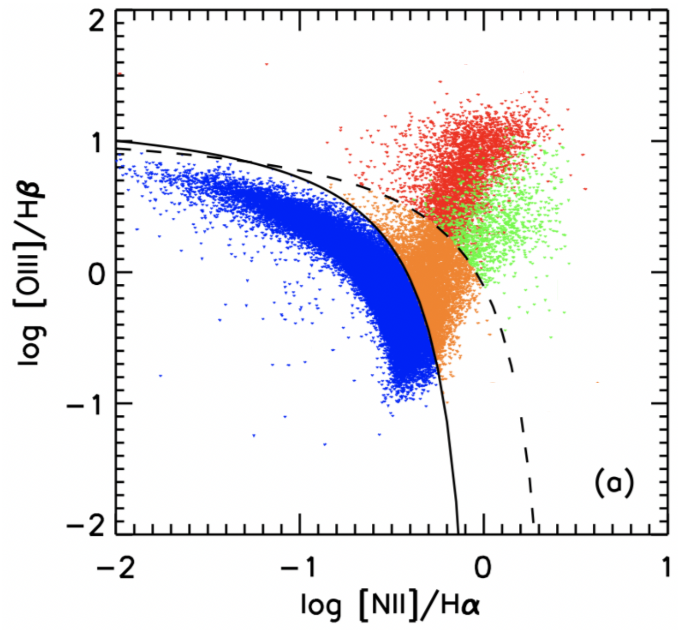


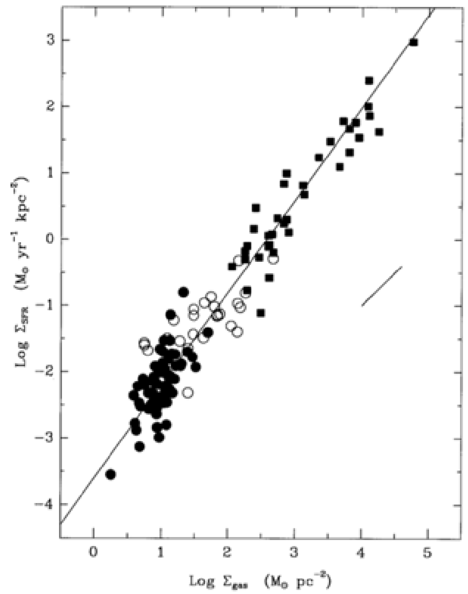


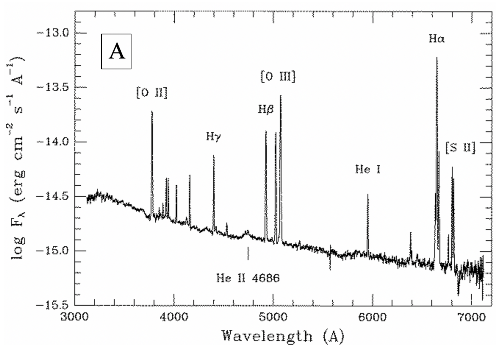


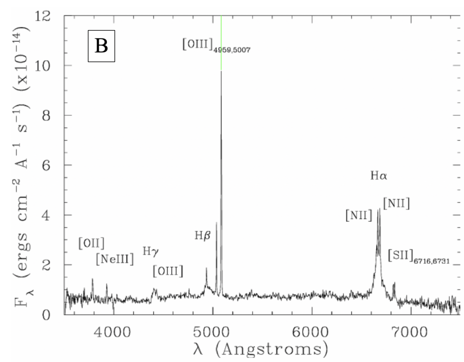
7. Identify:
   (a) The nuclear process that creates the black line in the top image.
   (b) The name for the relation shown in the second image from the top.
   (c) The type of black hole related to the third image from the top.
   (d) (6 points) At least one letter (or NA if there are none) in the fourth image from the top where one would expect to find:
      i. The Sun
      ii. Horizontal branch stars
      iii. Main sequence stars fusing hydrogen via the CNO cycle
      iv. Blue stragglers in a globular cluster
      v. A black hole
      vi. The progenitor of a neutron star merger
   (e) (4 points) The term that describes:
      i. The interaction when two galaxies collide and "eat" each other.
      ii. The motion of objects solely due to the expansion of the universe.
      iii. Objects where neutron stars exist completely within a red supergiant.
      iv. The study of pulsation modes of stars in order to investigate their internal structures, chemical composition, rotation, and magnetic fields.
   (f) (2 points) Consider a theoretical 200 $M_\odot$, Population III, main sequence star. Predict:
      i. The eventual type of supernova.
      ii. The eventual remnant.

Question 7: Diagnostic Diagrams









8. Baldwin-Phillips-Terlevich (BPT) diagrams are useful for distinguishing between different ionization mechanisms of nebular gas. One is shown on the top left. It is known that starburst regions produce *weaker* high-excitation lines as compared to other ionization mechanisms (AGNs, LINERs, etc.).

   (a) What does the bracket notation around NII signify? Briefly explain the cause.

   (b) (6 points) What is the color of the region on the BPT diagram where one would expect to find:

      i. The source that created spectrum A (bottom left).

      ii. The source that created spectrum B (bottom right).

      iii. A "Green Pea" galaxy.

   (c) What is the name of the relation shown in the image in the top right?

   (d) Where would one expect to find source A on the diagram in the top right - as a filled circle, open circle, or filled square?

   (e) Use spectrum B to calculate the redshift z of its source.

   (f) Calculate source B's recessional velocity, in km/s.

   (g) A recent paper determines via supernova photometry that the source that created spectrum A is 110.4 Mpc away. Use this to calculate Hubble's constant, H_0.

   (h) Use this Hubble constant to calculate the Hubble time of the universe, in Gyr.

Problem 8 (Tidal Forces). Suppose we are living in a two-dimensional world where there exists a $1/r$ gravitational force instead of our $1/r^2$ force in three dimensions. Let this gravitational force be given by

$$\vec{F}_g = -G_2 m_1 m_2 \frac{\vec{r}_1 - \vec{r}_2}{|\vec{r}_1 - \vec{r}_2|^2}.$$

The **tidal force** $\vec{F}_t$ on a 2particle mass m from a 2star mass M is given by the difference between this gravitational force $\vec{F}_g$ and the **fictitious translational force** $\vec{F}_s$

$$\vec{F}_t = \vec{F}_g - \vec{F}_s = G_2 Mm \frac{\vec{p} - \vec{r}}{|\vec{p} - \vec{r}|^2} - G_2 Mm \frac{\vec{p}^2}{|\vec{p}|^2}$$

where $\vec{p}$ is the vector from the 2particle to the 2star and $\vec{r}$ is the vector that describes the radius of our 2particle.

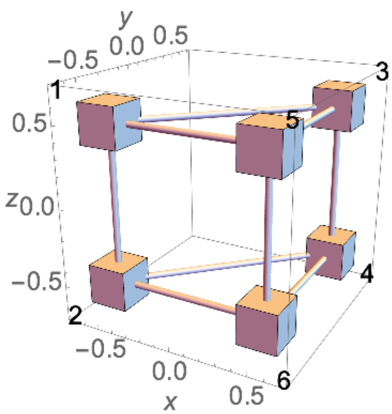
Problem 1.a. Find the tidal force on a 2particle of mass m on the surface of a circular 2planet with radius r orbiting a 2star with mass M at a distance $a \gg r$ as a function of the angle θ shown below. Take the center of the 2planet to be the origin of your coordinate system and assume that the 2star is at $(a, 0)$. Then θ is the angle from the x-axis.

Hint. Manipulate the given equation and Taylor expand around a reasonable variable in calculations.

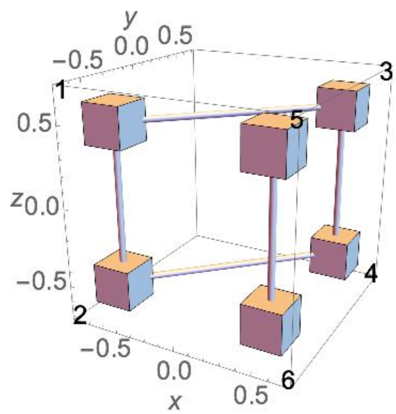
Problem 9 (Disintegrating Rods). Consider the following six-mass system connected by massless rods. The mass' positions are given by:

$$\vec{r}_1 = \left(-\tfrac{l}{2}, -\tfrac{l}{2}, \tfrac{l}{2}\right) \qquad \vec{r}_2 = \left(-\tfrac{l}{2}, -\tfrac{l}{2}, -\tfrac{l}{2}\right) \qquad \vec{r}_3 = \left(\tfrac{l}{2}, \tfrac{l}{2}, \tfrac{l}{2}\right)$$
$$\vec{r}_4 = \left(\tfrac{l}{2}, \tfrac{l}{2}, -\tfrac{l}{2}\right) \qquad \vec{r}_5 = \left(\tfrac{l}{2}, -\tfrac{l}{2}, \tfrac{l}{2}\right) \qquad \vec{r}_6 = \left(\tfrac{l}{2}, -\tfrac{l}{2}, -\tfrac{l}{2}\right)$$

where $l = 1$ and each block has mass m with moment of inertia I with respect to all **principal axes**. A principal axis is an axis that arises from symmetry (ie. any axes perpendicular to a plane of symmetry, any axis parallel to a rotational axis of symmetry). Objects rotating about a principal axis require no additional torques to keep it rotating.



(a) System before disintegration



(b) System after disintegration

Consider the system at (a) rotating with angular velocity

$$\vec{\omega} = \omega_0(\hat{x} + \hat{y})$$

and the system (b) at time $t = 0$ immediately after some of the rods spontaneously disintegrate.

Problem 2.a. Find the forces and torques of each of the masses immediately after the rods disintegrate.

Hint. A small change in momentum $d\vec{p}$ of any one of the blocks can be described with the ***cross product*** *$d\theta \times \vec{p}$*

$$d\vec{p} = d\theta \times \vec{p}.$$

This is because the magnitude of the momentum never changes, only its direction — an infinitesimal change in the momentum is simply an infinitesimal change in the angle of the initial momentum vector. Use this fact, combined with the ***no-slip condition***

$$\vec{v} = \vec{\omega} \times \vec{r}$$

to determine the forces.

Problem 2.b. Determine the equations of motion of the "1234-frame" and the "56-dumbbell" as a function of time after disintegration.

Hint. You may want to consider rotation matrices in three-dimensions.

Problem 10 (Special Relativity). Special relativity is the generally accepted physical theory regarding the relationship between space and time — spacetime. According to Einstein's original formulation, it is based on two postulates

- The laws of physics are invariant with respect to all inertial reference frames (non-accelerating frames of reference)
- The speed of light c in a vacuum is the same for all observers, regardless of the motion or light source of the observer

Events with coordinates with respect to two reference frames S and S' are related by **Lorentz transformations**. These transformations relate the positions, times, and lengths from one reference frame S to another S' moving at a speed v relative to S with the **Lorenz factor** γ given by

$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}.$$

The Lorentz transformations give us the following relationships/phenomena:

1. Time Dilation: a time difference $\Delta t'$ measured by a clock in S' is *longer* than a time difference Δt measured by a clock in S.
$$\Delta t' = \gamma \Delta t$$
2. Length Contraction: a length $\Delta l'$ measured in a moving frame S' is *shorter* than the length Δl measured in the rest frame S.
$$\Delta l' = \Delta l/\gamma$$
3. Velocity addition: if an object is moving at a velocity $\vec{u}\,'$ in the moving frame S', then its velocity $\vec{u}$ in the rest frame S is given by
$$\vec{u} = \frac{v + u'}{1 + vu'/c^2}$$

In relativistic units, we can set $c = 1$ and add in factors of c at the end of calculations appropriately for units.

Problem 3.a. Consider a relativistic rocket length L that is traveling from Earth to Mars at a speed v_1. A relativistic astronaut walks from the rear to the front of the rocket with a speed v_2 with respect to the rocket.

How long does the astronaut's walk take according to a clock at the rear of the ship?

Problem 3.b. How long does the walk take according to the astronaut's clock?

Answer Sheet A: Questions 1-4

1. (a) ______
   (b) ______
   (c) ______
   (d) ______
   (e) ______
   (f) ______
   (g) ______
   (h) ______
   (i) ______
   (j) ______
2. (a) ______
   (b) ______
   (c) ______
   (d) ______
   (e) ______
   (f) ______
   (g) ______
   (h) ______
   (i) ______
   (j) ______
3. (a) ______
   (b) ______
   (c) ______
   (d) ______
   (e) ______
   (f) ______
   (g) ______
   (h) ______
   (i) ______
   (j) ______
   (k) ______
4. (a) ______
   (b) ______
   (c) ______

(d) ____________________

(e) ____________________

(f) ____________________

(g) ____________________

(h) ____________________

Answer Sheet B: Questions 5-7

5. (a) ____________________
   (b) ____________________
   ____
   ____
   (c) ____________________
   (d) ____________________
   (e) ____________________
   (f) ____________________
   (g) ____________________
   (h) ____________________
   (i) ____________________
   (j) ____________________
   (k) ____________________
6. (a) ____________________
   (b) ____________________
   (c) ____________________
   (d) (i) ____________ (ii) ____________
   (iii) ____________ (iv) ____________
   (v) ____________ (vi) ____________
   (e) (i) ____________ (ii) ____________
   (iii) ____________ (iv) ____________
   (f) (i) ____________ (ii) ____________
7. (a) ____________________
   ____
   (b) (i) ________ (ii) ________ (iii) ________
   (c) ____________________
   (d) ____________________
   (e) ____________________
   (f) ____________________
   (g) ____________________
   (h) ____________________

Answer Sheet C: Questions 8-10

8. (a)

9. (a)

   (b)

10. (a)

   (b)