IAAC
2020

International Astronomy and Astrophysics Competition
Pre-Final Round 2020

Answer Sheet

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Pre-Final Round 2020

Important: Read all the information on this page carefully!

General Information

- We recommend to print out this problem sheet. Use another paper to draft the solutions to the problems and write your final solution (with steps) on the provided space below the problems.
- You may use extra paper if necessary, however, the space under the problems is usually enough.
- Typing the solution on a computer is allowed but not recommended (no extra points).
- The 10 problems are separated into three categories: 4x basic problems (A; four points), 4x advanced problems (B; six points), 2x research problems (C; ten points). The research problems require you to read a short scientific article each to answer the questions. There is a link to the PDF article.
- You receive points for the correct solution **and** for the performed steps. Example: You will not get all points for a correct value if the calculations are missing.
- Make sure to **clearly** mark your final solution values (e.g. underlining, red color, box).
- You can reach up to 60 points in total. You qualify for the final round if you reach at least 25 points (junior, under 18 years) or 35 points (youth, over 18 years).
- It is not allowed to work in groups on the problems. Help from teachers, friends, family, or the internet is prohibited. Cheating will result in disqualification! (Textbooks and calculators are allowed.)

Uploading Your Solution

- Please upload a file/pictures of (this sheet with) your written solutions: https://iaac.space/login
- Only upload **one single PDF file!** If you have multiple pictures, please compress them into one single file. Do not upload your pictures in a different format (e.g, no Word and Zip files).
- The deadline for uploading your solution is **Sunday 21. June 2020, 23:59 UTC+0**.
- The results of the pre-final round will be announced on Monday 29. June 2020.

Good luck!

Problem A.1: Interstellar Mission (4 Points)

You are on an interstellar mission from the Earth to the 8.7 light-years distant star Sirius. Your spaceship can travel with 70% the speed of light and has a cylindrical shape with a diameter of 6 m at the front surface and a length of 25 m. You have to cross the interstellar medium with an approximated density of 1 hydrogen atom/m^3.

(a) Calculate the time it takes your spaceship to reach Sirius.

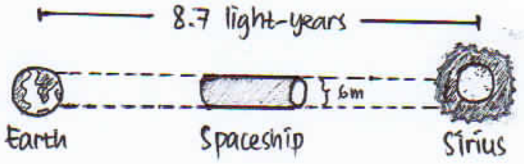
(b) Determine the mass of interstellar gas that collides with your spaceship during the mission.

Note: Use 1.673×10^{-27} kg as proton mass.

(a) Using the concept of uniform liniear motion

$$\Delta t = \frac{\Delta s}{v} = \frac{8.7 \text{ light-year}}{70\,\% \text{ speed of light}} = \frac{c \times 8.7 \text{ years}}{0.7c} = 12.42857 \text{ years} \;//$$

(b) By assuming the spaceship moves in a straight line, than the volume of trajectory it travels is :



$$V = \pi r^2 s$$
$$= \pi \times (3\text{m})^2 \times 8.7 \text{ ly} \times 9.46073 \times 10^{15} \frac{\text{m}}{\text{ly}}$$
$$= 2.32721 \times 10^{18} \text{ m}^3$$

So, the mass of interstellar gas that collides with the spaceship during the mission is :

$$M = \rho V$$
$$= 1 \text{ hydrogen atom} / \text{m}^3 \times 2.32721 \times 10^{18} \text{ m}^3$$

(assuming the mass of hydrogen $\approx$ the mass of proton)

$$= 1.673 \times 10^{-27} \text{ kg}/\text{m}^3 \times 2.32721 \times 10^{18} \text{ m}^3$$
$$= 3.893 \times 10^{-9} \text{ kg} \;//$$

Problem A.2: Time Dilation (4 Points)

Because you are moving with an enormous speed, your mission from the previous problem A.1 will be influenced by the effects of time dilation described by special relativity: Your spaceship launches in June 2020 and returns back to Earth directly after arriving at Sirius.

(a) How many years will have passed from your perspective?

(b) At which Earth date (year and month) will you arrive back to Earth?

(a) By using the concept of theory of special relativity, then the time dilation will be occur for moving observer with speeds near the speed of light.

$$\Delta t' = \frac{\Delta t}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{12.42857 \text{ years}}{\sqrt{1-\frac{(0{,}7c)^2}{c^2}}} = \frac{12.42857 \text{ years}}{\sqrt{1-\frac{0{,}49\cancel{c^2}}{\cancel{c^2}}}} = 17.40348 \text{ years}$$

(b) The total time taken by spaceship from launch to return back for observer on the Earth is:

$$\Delta t = 2 \times 12.42857 \text{ years} = 24.85714 \text{ years} = 24 \text{ years } 10.3 \text{ months}$$

So, the spaceship will arrive back to the Earth at date:

$$\begin{aligned} t &= t_0 + \Delta t \\ &= \text{June } 2020 + 24 \text{ years } 10.3 \text{ months} \\ &= \text{April } 2045 \end{aligned}$$

Problem A.3: Magnitude of Stars (4 Points)

The star Sirius has an apparent magnitude of -1.46 and appears 95-times brighter compared to the more distant star Tau Ceti, which has an absolute magnitude of 5.69.

(a) Explain the terms *apparent magnitude*, *absolute magnitude* and *bolometric magnitude*.
(b) Calculate the apparent magnitude of the star Tau Ceti.
(c) Find the distance between the Earth and Tau Ceti.

(a)
- Apparent magnitude is the apparent brightness of a star (a measure of the light received at Earth) measured by the stellar magnitude system. Because stars are at different distances from us and the interstellar medium has a variable absorption, apparent magnitude is not a reliable key to a star's real (intrinsic) luminosity.
- Absolute magnitude is the visual magnitude that a star would have a standard distance of 10 parsecs.
- Bolometric magnitude is the measure of the total of all wavelengths emitted by or received from a star expressed on the stellar magnitude scale.

(b) Using the Pogson's equation relating the magnitude of two objects, m_1 and m_2, to their brightness, I_1 and I_2

$$m_1 - m_2 = -2{,}5 \log\left(\frac{I_1}{I_2}\right)$$

$$m_{Tau\ Ceti} - m_{Sirius} = -2{,}5 \log\left(\frac{I_{Tau\ Ceti}}{I_{Sirius}}\right)$$

$$m_{Tau\ Ceti} = m_{Sirius} - 2{,}5 \log\left(\frac{I_{Tau\ Ceti}}{I_{Sirius}}\right)$$

$$m_{Tau\ Ceti} = -1{,}46 - 2{,}5 \log\left(\frac{I_{Tau\ Ceti}}{95\, I_{Tau\ Ceti}}\right)$$

$$= -1{,}46 - 2{,}5 \log\left(\frac{1}{95}\right)$$

$$= 3{,}4843 \,//$$

(c) Because the apparent magnitude and absolute magnitude of Tau Ceti star are known, we can use the concept of distance modulus. (Assuming the absorption of interstellar medium is ignored.)

$$\underbrace{m}_{\text{apparent magnitude}} - \underbrace{M}_{\text{absolute magnitude}} = -5 + 5 \log \underbrace{d}_{\text{distance in parsecs}}$$

$$d = 10^\wedge\left(\frac{m - M + 5}{5}\right)$$

$$d_{Tau\ Ceti} = 10^\wedge\left(\frac{3{,}4843 - 5{,}69 + 5}{5}\right)$$

$$= 3{,}6213 \text{ parsecs} \,//$$

Problem A.4: Emergency Landing (4 Points)

Because your spaceship has an engine failure, you crash-land with an emergency capsule at the equator of a nearby planet. The planet is very small and the surface is a desert with some stones and small rocks laying around. You need water to survive. However, water is only available at the poles of the planet. You find the following items in your emergency capsule:

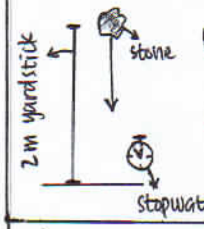
- Stopwatch
- Electronic scale
- 2m yardstick
- 1 Litre oil
- Measuring cup

Describe an experiment to determine your distance to the poles by using the available items.

Hint: *As the planet is very small, you can assume the same density everywhere.*

The following is the flow of the experiment that I will do with the available items to determine the distance from the equator to the poles of the planet :

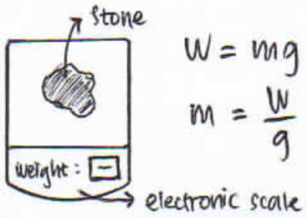
1) I will drop a stone from a height 2 m and measure how long it will fall to get the value of gravitational accelerating



$$t = \sqrt{\frac{2h}{g}}$$

$$g = \frac{2h}{t^2}$$

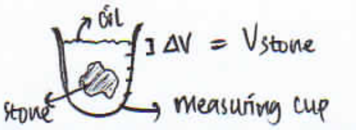
2) I will measure the weight of the stone using the electronic scale , then estimate its mass



$$W = mg$$

$$m = \frac{W}{g}$$

3) I will put the oil in the maguring cup , then dip the stone into it and see the change in volume to find out the volume of the stone .



4) After I know the mass of the volume of the stone , I can calculate its density . And this can be assumed to be density of the planet because the planet is very small and have the same density everywhere

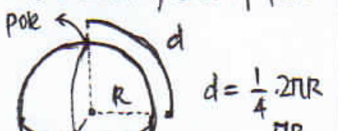
$$\frac{m_{stone}}{V_{stone}} = \rho_{stone} \approx \rho_{planet}$$

5) After I know the planet's density , I can estimate the radius of the planet by using the relationship with its gravitational acceleration .

$$g = \frac{GM}{R^2} = \frac{G\frac{4}{3}\pi R^3 \rho}{R^2}$$

$$g = \frac{4}{3}\pi G\rho R \rightarrow R = \frac{3g}{4\pi G\rho}$$

6) Finally , I can determine the distance from the equator to the poles which is a quarter of the circumfrence of planet .



$$d = \frac{1}{4} \cdot 2\pi R = \frac{\pi R}{2}$$

Problem B.1: Temperature of Earth (6 Points)

Our Sun shines bright with a luminosity of 3.828 x 10^{26} Watt. Her energy is responsible for many processes and the habitable temperatures on the Earth that make our life possible.

(a) Calculate the amount of energy arriving on the Earth in a single day.
(b) To how many litres of heating oil (energy density: 37.3 x 10^6 J/litre) is this equivalent?
(c) The Earth reflects 30% of this energy: Determine the temperature on Earth's surface.
(d) What other factors should be considered to get an even more precise temperature estimate?

Note: The Earth's radius is 6370 km; the Sun's radius is 696 x 10^3 km; 1 AU is 1.495 x 10^8 km.

(a) The flux energy received by the Earth from the Sun is :

$$F = \frac{L_\odot}{4\pi d^2} = \frac{3.828 \times 10^{26}\ J/s}{4\pi \times (1.496 \times 10^{11}\ m)^2} = 1361.1277\ J/s/m^2$$

So, the amount of energy arriving on the Earth in a single day is :

$$1361.1277\ J/s/m^2 \times 60\ \frac{s}{m} \times 60\ \frac{m}{h} \times 24\ \frac{h}{d} = 1.176 \times 10^8\ J/day/m^2 \ //$$

(b) The amount of heated oil using the energy flux received by the Earth in a day is :

$$n = \frac{F}{\rho_E} = \frac{1.176 \times 10^8\ J/day/m^2}{37.3 \times 10^6\ J/litre} = 3.15\ \text{litres}/day/m^2 \ //$$

(c) By assume the Earth as a black body, then :

$$L_\oplus = F \cdot \tfrac{1}{2} A_\oplus \cdot (1 - 30\%)$$

Earth luminosity

↳ Earth surface Area (only half the part overlooking the Sun)

$$\cancel{A_\oplus} \sigma T_\oplus^4 = F \cdot \tfrac{1}{2} \cancel{A_\oplus} \cdot (1 - 30\%)$$

$$T_\oplus = \sqrt[4]{\frac{F(1-30\%)}{2\sigma}}$$

$$= \sqrt[4]{\frac{1361.1277(1-0.3)}{2 \times 5.67 \times 10^{-8}}}$$

$$= 302.75\ K = 29{,}6^\circ C \ //$$

(d) There are other factors should be considered to get an even more precise temperature estimate, that is greenhouse effect (the presence of atmosphere) and internal energy of the planet.

Problem B.2: Distance of the Planets (6 Points)

The table below lists the average distance R to the Sun and orbital period T of the first planets:

	Distance	Orbital Period
Mercury	0.39 AU	88 days
Venus	0.72 AU	225 days
Earth	1.00 AU	365 days
Mars	1.52 AU	687 days

(a) Calculate the average distance of Mercury, Venus and Mars to the Earth.
Which one of these planets is the closest to Earth on average?

(b) Calculate the average distance of Mercury, Venus and Earth to Mars.
Which one of these planets is the closest to Mars on average?

(c) What do you expect for the other planets?

Hint: *Assume circular orbits and use symmetries to make the distance calculation easier. You can approximate the average distance by using four well-chosen points on the planet's orbit.*

(a) • Average distance of Mercury to the Earth is :

$R_{Mercury-Earth} = R_{Earth} - R_{Mercury} = 1.00\ AU - 0.39\ AU = 0.61\ AU$ //

• Average distance of Venus to the Earth is :

$R_{Venus-Earth} = R_{Earth} - R_{Venus} = 1.00\ AU - 0.72\ AU = 0.28\ AU$ //

• Average distance of Mars to the Earth is :

$R_{Mars-Earth} = R_{Mars} - R_{Earth} = 1.52\ AU - 1.00\ AU = 0.52\ AU$ //

The closest planet to the Earth on average is Venus //

(b) • Average distance of Mercury to Mars is :

$R_{Mercury-Mars} = R_{Mars} - R_{Mercury} = 1.52\ AU - 0.39\ AU = 1.13\ AU$ //

• Average distance of Venus to Mars is :

$R_{Venus-Mars} = R_{Mars} - R_{Venus} = 1.52\ AU - 0.72\ AU = 0.80\ AU$ //

• Average distance of Earth to Mars is :

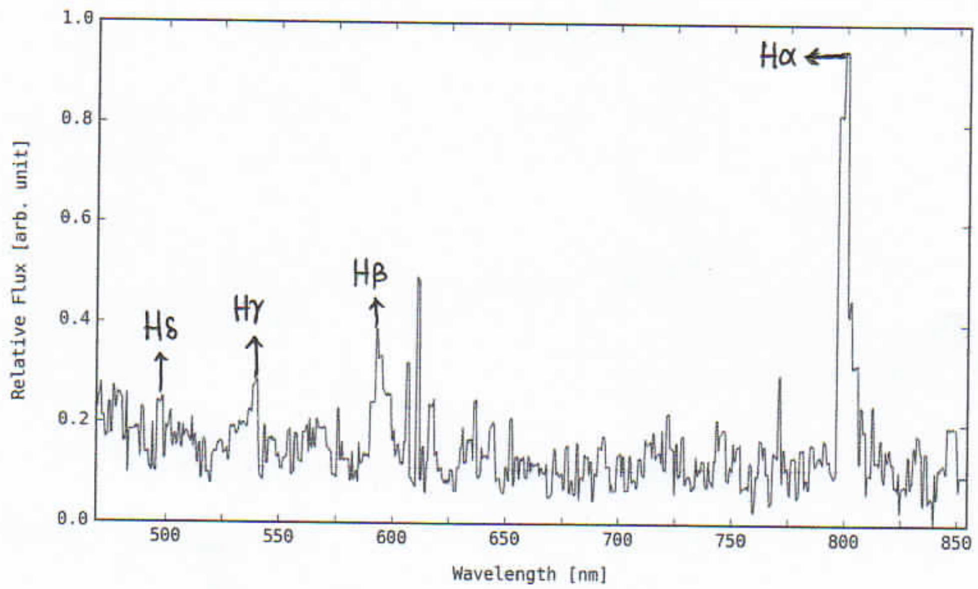
$R_{Earth-Mars} = R_{Mars} - R_{Earth} = 1.52\ AU - 1.00\ AU = 0.52\ AU$ //

The closest planet to Mars on average is Earth //

(c) The other planets, i.e., Jupiter, Saturnus, Uranus, and Neptunus, has greater average distance R to the Sun and longer orbital period T than the four planets above.

Problem B.3: Mysterious Object (6 Points)

Your research team analysis the light of a mysterious object in space. By using a spectrometer, you can observe the following spectrum of the object. The Hα line peak is clearly visible:



(a) Mark the first four spectral lines of hydrogen (Hα, Hβ, Hγ, Hδ) in the spectrum.
(b) Determine the radial velocity and the direction of the object's movement.
(c) Calculate the distance to the observed object.
(d) What possible type of object is your team observing?

(b) Position of the Hα line at rest is at :

$$\frac{1}{\lambda_0} = 1.09678 \times 10^7 \left(\frac{1}{2^2} - \frac{1}{3^2} \right) \Longleftrightarrow \lambda_0 = 6.56467 \times 10^{-7} m = 656.467 \text{ nm}$$

So, the redshif is :

$$z = \frac{\Delta\lambda}{\lambda_0} = \frac{\lambda_{obs} - \lambda_0}{\lambda_0} = \frac{800 \text{ nm} - 656.467 \text{ nm}}{656.467 \text{ nm}} = 0.21864$$

Then, its radial velocity is :

$$v = \frac{(z+1)^2 - 1}{(z+1)^2 + 1} \times c = \frac{(0.21864+1)^2 - 1}{(0.21864+1)^2 + 1} \times 2.99792458 \times 10^5 \text{ km/s} = 5.852 \times 10^4 \text{ km/s}$$

(c) Use the Hubble Law

$v = H_0 d$, with H_0 is the Hubble constant (~ 70 km/s/Mpc)

$$d = \frac{v}{H_0} = \frac{5.852 \times 10^4 \text{ km/s}}{70 \text{ km/s/MPc}} \approx 836 \text{ MPc}$$

(d) The object is a galaxy, because it has a spectrum profile which a lot of emission lines.

Problem B.4: Distribution of Dark Matter (6 Points)

The most mass of our Milky Way is contained in an inner region close to the core with radius R_0. Because the mass outside this inner region is almost constant, the density distribution can be written as following (assume a flat Milky Way with height z_0):

$$\rho(r) = \begin{cases} \rho_0, & r \leq R_0 \\ 0, & r > R_0 \end{cases}$$

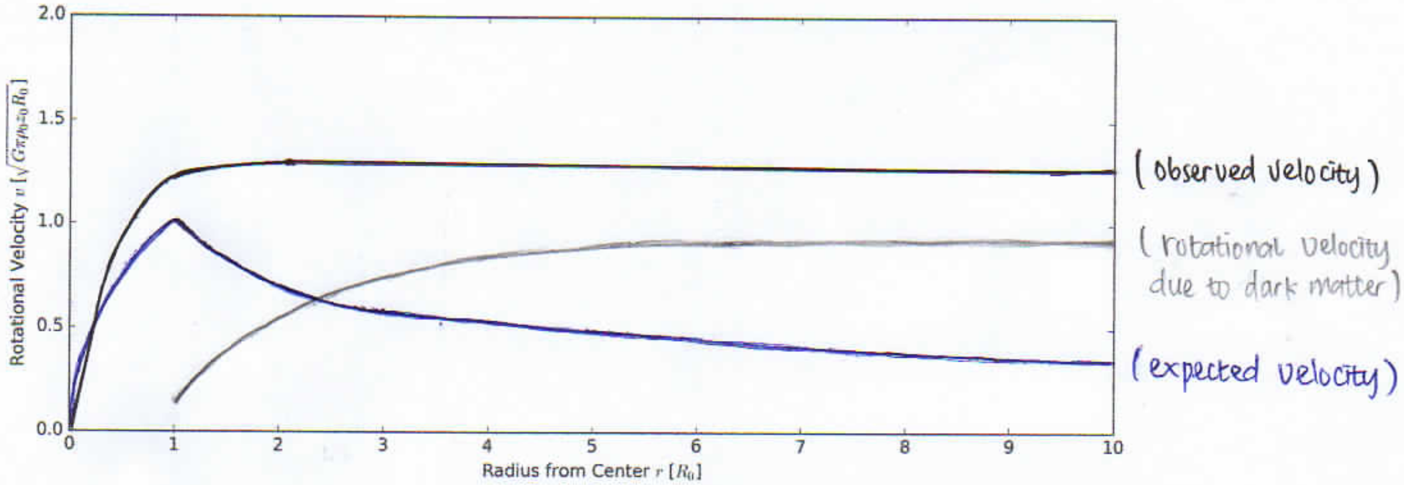
(a) Derive an expression for the mass $M(r)$ enclosed within the radius r.

(b) Derive the expected rotational velocity of the Milky Way $v(r)$ at a radius r.

(c) Astronomical observations indicate that the rotational velocity follows a different behaviour:

$$v_{obs}(r) = \sqrt{G\pi\rho_0 z_0 R_0}\left(\frac{5/2}{1+e^{-4r/R_0}} - \frac{5}{4}\right)$$

Draw the expected and observed rotational velocity into the plot below:

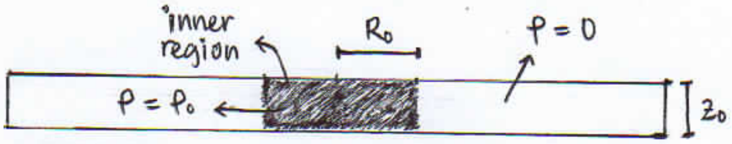


(d) Scientists believe the reasons for the difference to be *dark matter*: Determine the rotational velocity due to dark matter $v_{DM}(r)$ from R_0 and draw it into the plot above.

(e) Derive the dark matter mass $M_{DM}(r)$ enclosed in r and explain its distributed.

(f) Explain briefly three theories that provide explanations for *dark matter*.

(extra page for problem B.4: Distribution of Dark Matter)



(The appearance of the galaxy from the edge)

(a)

$$M(r) = \begin{cases} M(r) = \rho(r)V(r) = \rho_0 \pi r^2 z_0 , & r < R_0 \\ M_{\text{inner region}} = \rho_0 V_0 = \rho_0 \pi R_0^2 z_0 , & r \geq R_0 \end{cases}$$

(b)

$$v(r) = \sqrt{\frac{GM(r)}{r}} = \begin{cases} \sqrt{\frac{G\rho_0 \pi r^2 z_0}{r}} = \sqrt{G\rho_0 \pi r z_0} , & r < R_0 \\ \sqrt{\frac{G\rho_0 \pi R_0^2 z_0}{r}} , & r \geq R_0 \end{cases}$$

(c)

- $v_{obs}(r)\,[\sqrt{G\pi\rho_0 z_0 R_0}] = \left(\frac{5/2}{1+e^{-4r[R_0]}} - \frac{5}{4}\right)$ → observed velocity (using black ink on the plot)
- $v(r)\,[\sqrt{G\pi\rho_0 z_0 R_0}] = \begin{cases} \sqrt{r[R_0]} , & r < R_0 \\ \sqrt{\frac{1}{r[R_0]}} , & r \geq R_0 \end{cases}$ → expected velocity (using blue ink on the plot)

(d)

$$v_{DM}(r, r \geq R_0) = v_{obs}(r, r \geq R_0) - v(r, r \geq R_0)$$

$[\sqrt{G\pi\rho_0 z_0 R_0}]$

$$= \left(\frac{5/2}{1+e^{-4r[R_0]}} - \frac{5}{4}\right) - \sqrt{\frac{1}{r[R_0]}}$$

→ rotational velocity due to dark matter (using grey ink on the plot)

(e) dark matter mass

$$\frac{M_{DM}(r)}{M(r)} = \frac{\frac{(v_{DM}(r))^2 \cancel{r}}{\cancel{G}}}{\frac{(v(r))^2 \cancel{r}}{\cancel{G}}} = \frac{(v_{obs}(r) - v(r))^2}{(v(r))^2} = \begin{cases} \frac{\left(\left(\frac{5/2}{1+e^{-4r[R_0]}} - \frac{5}{4}\right) - \sqrt{r[R_0]}\right)^2}{\left(\sqrt{r[R_0]}\right)^2} & \boxed{r < R_0} \\ \frac{\left(\left(\frac{5/2}{1+e^{-4r[R_0]}} - \frac{5}{4}\right) - \sqrt{\frac{1}{r[R_0]}}\right)^2}{\left(\sqrt{\frac{1}{r[R_0]}}\right)^2} & \boxed{r \geq R_0} \end{cases}$$

visible matter mass

(f)
- Dark Matter Halo ; it seems to be roughly spherically distributed on halo galaxy and accounts for about 90 % of the entire mass of the galaxy. This causes the addition of the object speed surround the galaxy center (ex : MACHOs).
- Luminous Arc in Galaxy Clusters ; a striking example of gravitational lensing is the formation of arcs by light passing through a cluster of galaxies. One such arc in the cluster Abell 370 which has a mas about 5×10^{14} M⊙ and luminosity of a few $\times 10^{11}$ L⊙. This implies mass-to-light ratio at least 1000 M⊙ / L⊙, indicating the presence of large amount of dark-matter.
- Dark matter candidates are usually divide into Hot Dark Matter which consist of particles moving with relativistic velocities (ex : neutrino) and Cold Dark Matter which particle that moves slowly (ex : WIMPs).

Problem C.1 : Detection of Gravitational Waves (10 Points)

This problem requires you to read the following recently published scientific article:

Observation of Gravitational Waves from a Binary Black Hole Merger.

B. P. Abbott et al., LIGO Scientific Collaboration and Virgo Collaboration

arXiv:1602.03837, (2016). Link: https://arxiv.org/pdf/1602.03837.pdf

Answer following questions related to this article:

(a) How was the existence of gravitational waves first shown?

On September 14, 2015 at 09 : 50 : 45 UTC the two detectors of Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational wave signal. The signal sweep upwards in frequency of 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}.

(b) Which detectors exist around the world? Why did only LIGO detect GW150914?

Only the LIGO detectors were observing at the time of GW150914. The Virgo detector was being upgrade, and GEO 600, though not sufficienly sensitive to detect this event, was operating but not in observasional mode.

(c) Explain the components of the LIGO detectors.

- Each arm contains a resonant optical cavity, form by its two test mirrors.
- A partially transmissive power-recycling mirror at the input provides additional resonant buildup.
- A partially transmissive signal-recycling mirror at the output optimites the gravitational-wave signal extraction by broadening the bandwith of the arm cavities.

(d) Describe the different sources of noise. How was their impact reduced?

Thermal noise is minimalized by using low-mechanical-loss material in the test masses and their suspensions. To minimize additional noise source are mounted on vibration isolation stages in ultrahigh vacuum. To reduce optical phase fluctuations caused by Rayleigh scattering, the pressure in the 1.2 m diameter tubes containing the arm cavity beams is maintained below 1 μPa.

(e) What indicates that the gravitational wave originated from the merger of a black hole?

The detected waveform matches the prediction of general relativity for the inspiral and merger of a pair of blackholes and the ringdown of the resulting single black hole. The observation unique access to the properties of space-times in the strong field, high-velocity regime and confirm predictions of general relativity for the nonlinear dynamics of highly disturbed black holes.

(f) Which are the methods used to search for gravitational wave signals in the detector data?

GW150914 is confidently detected by two different types of searches. One aims to recover signals from the coalescence of compact objects, using optimal matched filtering with waveforms predicted by general relativity. The other search target a broad range of generic transient signals, with minimal assumptions about waveforms. These searches use independent methods.

(g) How were the source parameters (mass, distance, etc.) determined from the data?

The matched-filter search is optimized for detecting signal, but it provides only approximate estimates of the source parameters. To refine them scientists use general relativity-based, some of which include spin precession, and for each model perform a coherent Bayesians analysis to derive posterior distributions of the source parameters. The parameter uncertainties include statistical errors from averaging the results of different waveform models. Using the fits to numerical simulations of binary black hole merger, scientists provide estimate of the mass and spin of the final black hole.

Problem C.2 : First Image of a Black Hole (10 Points)

This problem requires you to read the following recently published scientific article:

First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole.
The Event Horizon Telescope Collaboration, arXiv:1906.11238, (2019). Link: https://arxiv.org/pdf/1906.11238.pdf

Answer following questions related to this article:

(a) Calculate the photon capture radius and the Schwarzschild radius of M87* (in AU).

- $M = (6.5 \pm 0.7) \times 10^9 M_\odot$
- $r_g = \frac{GM}{c^2} = (9.599 \pm 1.034) \times 10^{12}$ m $= (64.165 \pm 6.91)$ AU
- Photon capture radius $\rightarrow R_c = \sqrt{27}\, r_g$

  $R_c = \sqrt{27}(64.165 \pm 6.91)\,AU = (333.41 \pm 35.9)\,AU$
- Swarzschild radius $\rightarrow R_S = 2 r_g$

  $R_S = 2(64.165 \pm 6.91)\,AU = (128.33 \pm 13.82)\,AU$

(b) Why was it not possible for previous telescopes to take such a picture of the black hole?

Because the previous telescope did not have theoretical difraction - limit resolution with enough ability to resolve the central compact radio as an bright emission ring with diameter of 42 ± 3 μas due to limited baseline coverage.

(c) Describe the components and functionality of the event horizon telescope.

The Event Horizon Telescope is a Very Long Baseline Interferometry that directly measures visibilities of the radio brightness distribution on the sky. For the observation at a wavelenght of 1.3 mm, the EHT collaboration fielded a global VLBI array of eight stations over six geograpical locations. Baseline lenghts range from 160 m to 10,700 km, resulting theoretical difraction-limit resolution of 25 μas.

(d) Explain the two algorithms used to reconstruct the image from the telescope data.

- Traditional CLEAN approach used in radio; CLEAN is an inverse - modeling approach that deconvolves the interferometer point-spread function from the Fourier-transformed visibilities.
- Regularized maximum likelihood; RML is a forward - modeling approaches that searches for an image that is not only consistent with the observed data but also favors specified image properties.

(e) What parameters were required for the GRMHD simulations to generate an image?

A typical GRMHD simulation in the library is characterized by two parameters : the dimensionless spin $a_* \equiv Jc/GM^2$, where J and M are respectively, the spin angular momentum and mass of the blackhole, and the net dimensionless magnetic flux over the event horizon $\phi = \Phi/(\dot{M} R_g^2)^{1/2}$, where Φ and $\dot{M}$ are the magnetic flux and mass flux (or accretion rate) accross the horizon; respectively.

(f) Explain the physical origins of the features in Figure 3 (central dark region, ring, shadow).

When surrounded by a transparent emission region, black holes are reveal a dark shadow in the central region cause by gravitational light bending and photon capture at the event horizon. The assymmetry in brightness in the emission ring can be explained in terms of relavistic beaming of the emission from a plasma rotating close to the speed of light around a black hole.

(g) How can the image resolution be increased in future observations?

Future observations and further analysis will test the stability, shape, and depth of the shadow more accurately. One of its key features is that it should remain largely constant with time as the mass of M87* is not expected to change measurebly on human timescales. Higher resolution image can be achieved by going to a shorter wavelength, i.e, 0.8 mm (345 GHz), by adding more telescopes and, in more distant future, with space-based interferometry.