ASTROCHALLENGE 2015 DATA RESPONSE QUESTIONS

JUNIOR ROUND

INSTRUCTIONS

- This paper consists of 15 printed pages, excluding this cover page.
- Do **NOT** turn over this page until instructed to do so.
- You have 2 hours to finish all questions in this paper.
- At the end of the paper, **submit this booklet together with your answer script**.
- Your answer script should clearly indicate your school, as well as the individuals in said team.
- It is your team's responsibility to ensure that all pages of your answer script have been submitted.

School/Team: ___________________________________

1. Goldilocks in Space: The Habitable Zone [20 marks]

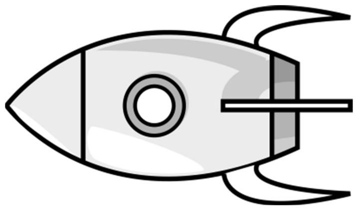


Figure 007: Your spaceship. Do **NOT** decorate unless you are absolutely confident of completing this assignment and every other on time in this paper. Strictly no marks will be awarded for having a better design.

Suppose a hypothetical scenario whereby you and your crew aboard the spaceship, Goldilocks-007, visits an extrasolar planet system located in the Ursa Major constellation. Your crew chanced upon a stellar neighbourhood and found a suitable system with Earth-like planets surrounding Star X. The spectrophotometer on board Goldilocks-007 reveals the peak wavelength of Star X to be 411 nm.

a) Deduce the effective surface temperature of X. **[0.5 marks]**

Table 1: Spectral class of stars corresponding to effective surface temperature

Spectral Class	Apparent Color	Effective surface temperature (K)
O	Blue	30,000 – 50,000
B	Deep Blue-white	10,000 – 30,000
A	Light Blue-White	7,500 – 10,000
F	White	6,000 – 7,500
G	Yellow White	5,000 – 6,000
K	Yellow Orange	3,500 – 6,000
M	Light Orange Red	2,500 – 3,500

b) Using information from the table, and given that Star X is a main sequence star, deduce its spectral class based on your calculations, and show whether it will be more, equally or less massive compared to our sun. **[1 mark]**

Despite your theoretical calculations, authorities from Wizard-01, a nearby local space station, insists the star to be a yellow white star with a surface temperature of 7000 K. Use this value for all your subsequent calculations.
Thankfully, the radius of Star X was determined by them to be exactly 1.17 times that of our Sun.

c) With this new information, calculate its Luminosity and provide the appropriate units. How many times, then, would Star X be brighter than our Sun? **[2 marks]**

Wizard-01 requests for assistance in verification of the following claim submitted by a **lazy scientist** on board:

Suppose you have a planet of a distance D from any star of luminosity L.
Assuming the star radiates isotropically, and the planet is of sufficient distance from the star, the power absorbed by the planet can be given by treating the planet as a disc of radius R (in metres), which intercepts some of the power spread over the surface of a sphere of radius D (the distance of the planet from the star, also in metres). At the same time, the planet reflects some of the incoming radiation; this is accounted for with an albedo parameter. An albedo of 1 means all radiation will be reflected, while an albedo of 0 means all of it is absorbed. The expression for absorbed power is thus:

$$E_{absorbed} = \frac{L \times R^2 \times (1-\alpha)}{4D^2}$$

Suppose then that the entire planet is at the same temperature T, and that the planet radiates as a blackbody. The Stefan-Boltzmann law gives an expression for the power radiated by the planet:

$$E_{emitted} = \sigma T^4 \times 4\pi R^2$$

Blah blah blah, and somehow you can magically get this equation:

$$T = \sqrt[4]{\frac{L \times (1-\alpha)}{16\sigma D^2}}$$

d) Prove that the lazy scientist is right i.e. the temperature of an object (in Kelvin) of a distance D away from the star can indeed be determined by the above equation, and state the additional key assumption required **[2 marks]**

Next, Wizard-01 mailed you some data regarding the three planets orbiting star X, which your crew designated as Papa, Moma and Cub based on their relative size and distance. Unfortunately, due to unknown interference, some data has been lost.

Table 2: Data for celestial objects orbiting Star X

Observed object	Planet A (Papa)	Planet B (Moma)	Planet C (Cub)
Semi-major axis (AU)	0.402	1.487	1.780
Radius of orbit at periapsis (AU)	0.393	1.467	
Radius of orbit at apoapsis (AU)	0.411	1.507	
Eccentricity	0.0224		0.0815
Mass (M⊕)	18.2	5.1	2.8
Density (g/cm^3)	1.09	4.43	3.22
Primary composition of Atmosphere	Hydrogen, Helium, Methane, Ammonia	Methane, Water, Nitrogen	Hydrogen, Methane, Water, Nitrogen
Average Albedo	0.46	0.31	0.22
Mean surface temperature (°C)	913	20	-19

e) Using the given data, re-calculate the missing information **[1.5 marks]**

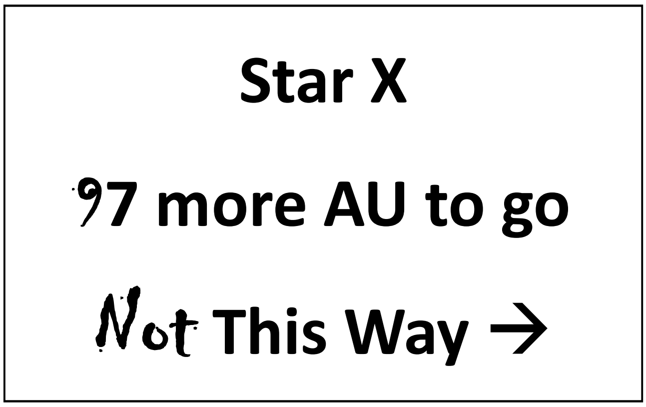
f) When a planet is of a distance away from its parent star equal to its semi-major axis of orbit, it is possible to deduce its average effective temperature. Calculate the average effective surface temperature of Planets A, B and C, and compare the values you obtained with those given in Table 2. Which planet has the largest disparity in theoretical and actual temperature? Assume absolute zero to equal -273.15 K. **[4 marks]**

g) Give two short explanations to account for the disparity between your theoretical temperature, and the actual measured effective surface temperature on the planets in general. **[2 marks]**

Suppose for this star system, the lower bound for the habitable zone is defined to be 1.28 AU away. It is then estimated that if Planet C is at a distance with an effective temperature of -20°C or less, ice formation would exceed its equilibrium rate.

h) Using this temperature and planet C as a reference, calculate the upper bound of the habitable zone. Would Planet C's orbit cause it to exit the habitable zone at any point in time? **[2 marks]**

i) Write a short explanation on the eventual fate of Planet C and its ability to sustain life. You may also instead propose a mechanism, showing clearly parameters involved. Next, propose to explorers from Wizard-01 the best planet to investigate for life in this extrasolar planet system **[2.5 marks]**



Unknown Figure: Vandalised direction signs in your local stellar neighbourhood are a bummer for astronauts trying to find their way.

j) The explorers aboard Wizard-01 are worried they might be lost. <u>Draw a simple top-down map or diagram to show the relative position of Star X, each planet and their orbits, as well as the habitable zone.</u> It need not necessarily be drawn to scale, but do indicate relative sizes of each object and the upper/lower limits of the habitable zone with respect to the planet's orbits clearly. [2.5 marks]

Congratulations, brave scouts from Goldilocks-007 for completing this ordeal. Your efforts will be well-remembered, and the habitable zone shall be named the Goldilock's zone in your honor.

(Actually, it already is. :P)

2. History in Astronomy: Jupiter's moons [21 marks]

Figure 1: The hall of fame goes to Galileo Galilei (left) and Ole Rømer/ Roemer (right) whose discoveries are still in use for astronomy and this question in particular today.

The four large Galilean moons of Jupiter have captured mankind's attention ever since their initial observation by Galileo Galilei in 1610. Subsequently, he observed the precise orbits and eclipse timing of Jupiter's moons as a method to tell time. This is subsequently investigated by Ole Roemer, who initially tracked eclipses of Jupiter's moons as a mean to determine longitude to help seafarers discern their location (not to mention in his times, it would be a fast track to getting rich and famous). But by accident, he worked out the first estimate of an important constant: The speed of light!

a) Because any more historical information will be extremely boring, it is now your group's turn to write a short, interesting paragraph about any one of the four Galilean moons to ensure your grader won't fall asleep. Include any key features, landmarks, and interesting trivia you deem to be of interest to the reader. **[4 marks+]**

(p.s. if your grader falls asleep anyway because your article is too long or boring, a penalty will be imposed. As a rule of thumb, having 4 distinctive traits or 2 really interesting features with elaboration would be enough to score full marks for this column. If your article is on par with a short column in a science newsletter we **might** consider giving up to 1 bonus mark.)

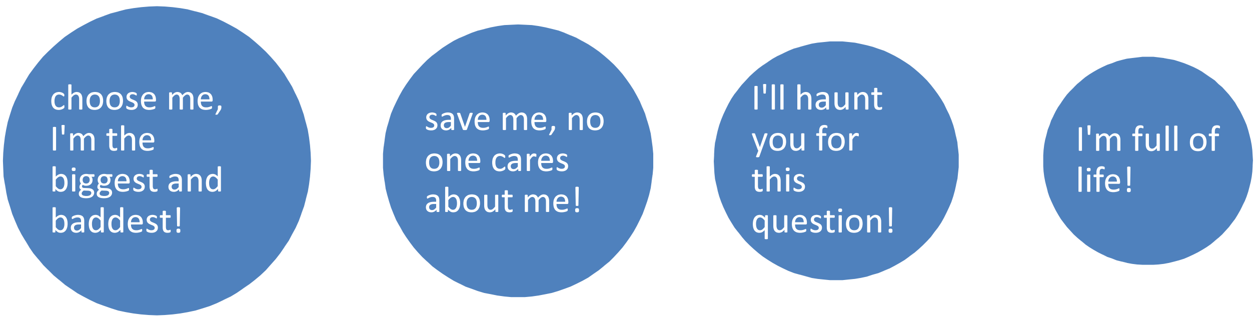


Figure X: jokes that you'll only understand if you know all 4 moons well enough

Before we can attempt Ole Roemer's experiment using various objects in space, we need to first consider the distance traveled in space by Earth and Jupiter.

Using information in the data booklet, calculate:

b) The distance travelled by Earth within one complete orbit, in AU. **[1 mark]**

c) Jupiter is known to be 5.2 AU away from the Sun. Thus, calculate the distance travelled by Jupiter in the same time taken for Earth to complete one orbit, in AU. **[2 marks]**

Ready? Now, yet another history lesson begins.

For the sake of simplicity and more possible observations, Io was chosen by Ole Roemer for observation due to its short period. He initially started by predicting the time taken for Io to eclipse (move behind Jupiter's shadow), based on known data of Io's synodic period (the time taken for it to complete one orbit).

He observed the eclipse of Io at two different times, once when Earth and Jupiter are really close and once when they are further away from each other. And then something unexpected happened: **There existed a difference in the time taken, about several minutes, between his estimated transit timing and its actual occurrence!**

Baffled, he hypothesized that if the observation of said transit does not occur on schedule when given a different Earth-Jupiter distance… is because the speed of light is not instantaneous! (i.e. the information contained by light that Io has eclipsed behind Jupiter's shadow will take a longer time to travel to an observer who is further apart on Earth). Thus, said speed of light can be calculated using the difference in Earth-Jupiter distance divided by the difference in transit time, as given by the following equation:

$$\text{Speed of light} = c = \frac{\Delta D}{\Delta T}$$

d) … In case you're feeling sleepy, here's a pop quiz. Draw and label a diagram showing the relative position of the Sun, Earth and Jupiter at 4 different timings:
(A) During a superior conjunction
(B) 3 months after a conjunction
(C) 1 month before an opposition
(D) During opposition

You may draw 4 separate sub-diagrams or one large diagram. Be sure to label the position of all celestial objects, especially Earth clearly. Use the information calculated from the above section (i and ii) to make a more informed decision on relative position of the planets. The diagram need not be drawn to scale, but make it as neat as possible for reference purposes in the subsequent section. **[4 marks]**
Ole Roemer observed transits only 3 months following a conjunction (B) and 1 month before an opposition (C), but not during the conjunction itself (A). In theory, the Earth-Jupiter distance should be the greatest during superior conjunction.

e) <u>So why didn't – or couldn't – he observe an eclipse at this time? Explain this in one sentence. (Hint: take a close look at your diagram)</u> **[1 mark]**

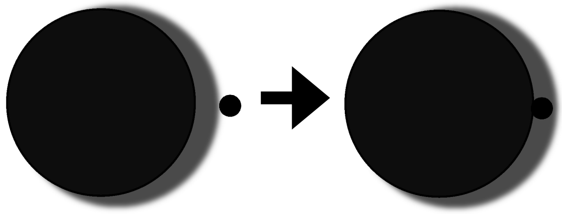
The following is a dataset corresponding to real-life dates with the theoretical positions of Earth and Jupiter, from A-D.

Phenomena	Date	Time
(Superior) Conjunction (A)	24th July, 2014	20:43:58 UT (JD: 2456863.363862)
Opposition (D)	6th Feb, 2015	18:19:51 UT (JD: 2457060.263782)

Phenomena	Date	Start of Io Transit	Exact Earth-Jupiter Distance
3 months after a conjunction (B)	25th Oct, 2014	01:11:23 UT (JD: 2456955.549572)	5.52113 AU (8.25949×10^8 km)
1 month before an opposition (C)	5th Jan, 2015	14:36:26 UT (JD: 2457028.108634)	4.49916 AU (6.73065×10^8 km)

Table 2: Real-life observation data obtained. Two transits were observed during Earth-Jupiter positions at (B) and (C). JD refers to Julian Days, which is the number of days elapsed since a reference point, the Julian period.

Now, all the ingredients are in place and you can work out Ole Roemer's famously cryptic working (don't worry, this will be guided) to calculate the speed of light! For the purpose of accuracy, treat the synodic period of Io to be 1.769861 days for calculation purposes.



"Hey, why did Io disappear before it is supposed to today?!"

Figure 2: Ole Roemer's experiment in a nutshell

f) <u>First, calculate how many orbits Io *seemed* to have made on the 5th of Jan, 2015 since 25th Oct, 2014</u>. **[1 mark]**

Hint: use the difference in Julian days to make life a lot easier. Do NOT round up as precision is key in this step!

But wait… Io's synodic period should be a **precise constant** – so the only reason why you would not observe an exact whole number is because of the **time difference for information to travel in the form of light to us**! That is why the number of orbits fell short of expectation by a tiny margin.

g) *Now*, calculate the predicted time whereby the eclipse will occur, using the nearest whole number of orbits for predicted time. Then find the Time Difference (ΔT) between the times of the observed eclipse and the predicted eclipse. **[1 mark]**

h) Next, find the difference in Distance (ΔD) between Earth and Jupiter on both relevant dates in Astronomical Units (AU). **[1 mark]**

i) Using the formula, Speed of light = c = ΔD / ΔT, and letting 1 AU be 149,597,870,700 meters, calculate the speed of light and determine by how many percent is it greater or less than the theoretical value. **[1 mark]**

j) Give an explanation why the speed of light is different from the presently accepted value. **[2 marks]**

k) If you have had enough of Io for today, how about wishing that it is going to disappear? At present, Io is 421,700 km away from Jupiter's center and 350,000 km from Jupiter's cloudtop. It has a density of 3.53 g/cm^3. Calculate the distance due to the Roche limit for it to be reduced to fragments. Would you expect it to end up in pieces around Jupiter anytime soon? (Assume Jupiter to be a perfect sphere of volume 4/3 π R^3, where R refers to its radius.) **[3 marks]**

3. Surface Brightness and Observation Plans [20 marks]

We know that the apparent magnitude of a star is simply how bright it looks. But how exactly do we quantify it? It turns out that the apparent magnitude of an object can be described by the following formula

$$m = -26.74 - 2.5\log\frac{B}{B_{Sun}}$$

Where $\frac{B}{B_{Sun}}$ indicates the apparent brightness of the object, relative to that of the Sun. For instance, if $\frac{B}{B_{Sun}} = 2$, the object appears to be as twice as bright as the Sun

However, most deep-sky objects are not point sources. In particular, galaxies and nebulae are diffuse objects: their light is spread out over a certain area. Because their light is spread out, large objects can be extremely dim and hard to see, even if their apparent magnitude appears to be relatively bright.

This is where surface brightness comes in. Surface brightness is the average apparent magnitude of a one square arcminute patch of the object. Intuitively, we are taking the apparent brightness of the object and spreading it out evenly across its area. By measuring the apparent magnitude of a unit area of this object, we have a measure of how easily visible these objects are.

This implies that surface brightness (S) can be defined by the following formula:

$$S = -26.74 - 2.5\log\frac{B_1}{B_{Sun}}$$

Where $\frac{B_1}{B_{Sun}}$ is the apparent brightness of an average square arcminute of the object, relative to the Sun. The next few questions will show that not only is surface brightness easily determined, it has a particularly nice property.

a) Suppose a nebula has an apparent area of A square arcminutes and magnitude m_{nebula}. Prove that the surface brightness (S) is given by the following expression **[3 marks]**

$$S = m_{nebula} + 2.5\log \mathrm{A}$$

Now, suppose that the distance to the nebula is increased by k times. By definition, the absolute magnitude of the nebula (M_{nebula}) remains unchanged, but the apparent area of the nebula now shrinks to Ak^{-2} (You do not need to prove this)

b) What is the new apparent magnitude (m'_{nebula})? Express your answer in terms of k and m_{nebula} only **[3 marks]**

c) Hence, determine the new surface brightness of the nebula, S'. Express S' in terms of S. What do you notice? **[2 marks]**

I hope you can see that surface brightness is far more useful than apparent magnitude!

Observation Plans

What is an observation plan? Essentially, it is a list of objects that you wish to observe, along with other important information that would help you during your observation session. With that in mind, you are given a list of the following planetary nebulae for an upcoming observation session on the Equator

Object	RA	Dec	Apparent Magnitude, m	Area (square arcminutes)
M27 (Dumbbell Nebula)	19h 59m	+22° 43′	7.5	44.8
M57 (Ring Nebula)	18h 53m	+33° 01′	8.8	14.7
M76 (Little Dumbbell Nebula)	01h 42m	+51° 34′	10.1	4.9
M97 (Owl Nebula)	11h 14m	+55° 01′	9.9	11.2
C39 (Eskimo Nebula)	07h 29m	+20° 54′	10.1	0.6
C63 (Helix Nebula)	22h 29m	−20° 50′	7.6	180

d) What are planetary nebulae? Briefly describe how they are formed. **[3 marks]**

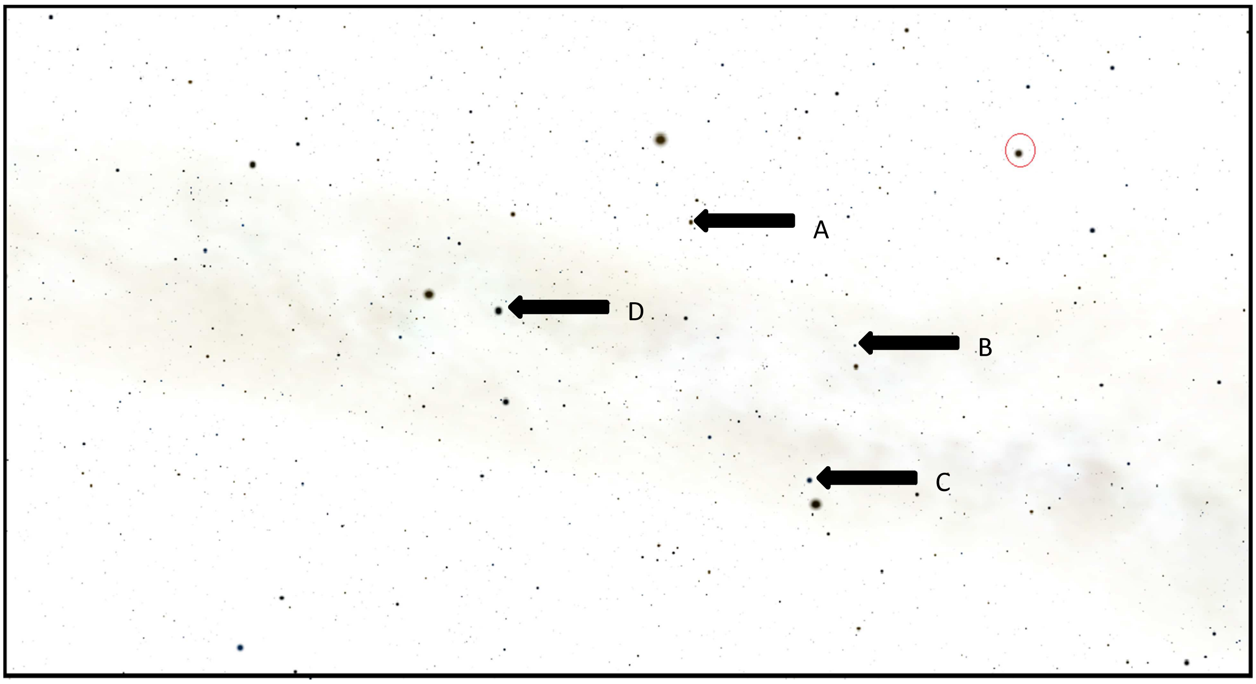
e) A proper observation plan should be sorted by the time objects rise. Sort the objects by the order in which they rise, with the earliest object first. **[3 marks]**

f) Calculate the average surface brightness of these objects, then rank these objects accordingly (highest surface brightness object first). **[4 marks]**

g) Suppose that during one night, you notice that the Owl Nebula is setting. Other than the Owl Nebula, what object(s) are above the horizon right now? **[1 mark]**

h) On another night, you notice that Object X in your list is currently near the zenith (i.e. it is crossing the meridian). As it does so, you also notice that the Little Dumbbell Nebula is setting in the West. What is Object X? **[1 mark]**

4. Occultation of Jupiter [17 marks]



On a certain night in June, Clarence and Qi En held observation sessions in 2 different places along the Equator. Clarence in Pontianak (0° S, 109.3° E) is looking at a patch of night sky as shown above.

Clarence managed to find the following 4 stars and matched them to Qi En's catalog (arrows). He also knows that the star Rasalhague (the brightest star in Ophiuchus) is the circled star above. The coordinates of the following stars are shown below.

Star	RA	Dec
Rasalhague	17h 34m	+15° 04'
A	18h 58m	+32° 41'
B	18h 59m	+15° 04'
C	19h 46m	+10° 36'
D	20h 22m	+40° 15'

a) Can we determine which direction is approximately celestial north? Explain why/why not. If yes, mark this direction clearly with an arrow on the diagram. **[2 marks]**

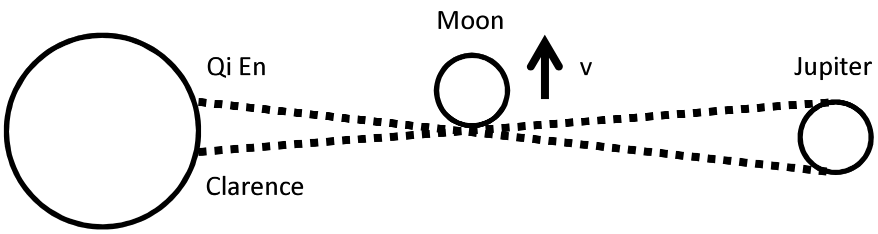
b) Clarence notices that right now (0052 hours), Rasalhague is on its upper culmination. When will star C set? **[1 mark]**

After gazing at this patch of sky for a while, Clarence gets bored and now intends to find some deep sky objects nearby.

c) Mark at least 1 deep sky object on the image and give its name. Clearly state what should Clarence expect to see when he has found the object. In order to help Clarence find your object, please attach a set of finding instructions/draw a finding chart. **[3 marks]**

While Clarence was waiting for you to finish, he read some astronomy news and found out that there would be an Occultation of Jupiter on that night. He informs Qi En, and they decide to observe the Jupiter Occultation simultaneously from their locations. When Clarence sees the end of the occultation, Jupiter has completely exited the edge of the Moon (surfaces tangent/barely touching each other).

However, from Qi En's location, the occultation is still ongoing. Just when Clarence spots that Jupiter completely exited the edge of the Moon, Qi En simultaneously notes that Jupiter starts to appear from behind the Moon. A simple sketch is given below (not to scale).



For the rest of this question, assume that:

- all observers and objects are on the same plane (i.e. the celestial equator).
- all objects have circular orbits
- both Clarence and Qi En are equidistant from the line connecting the center of Earth, the edge of the Moon and the center of Jupiter

d) You know that when the occultation ended, the Moon is exactly at Last Quarter. What is the distance between Jupiter and Earth, as well as Jupiter and the Moon? Hint: use more than 3 significant figures.**[4 marks]**

e) Hence or otherwise, what the distance between Clarence and Qi En? Remember to account for the curvature of the Earth. **[6 marks]**

f) Clarence observed that sunrise occurred at 0640 hours. Hence, approximately when did the occultation end for Clarence? Justify your answer **[1 mark]**

5. Astronomy in another land [22 marks]

Elliot, a budding astronomer from country X, has recently purchased a telescope. Its specifications and accessories are stated below. However, he does not know what his equipment can do.

Aperture	6 inches [150 mm]
F-ratio	?
Focal length	750mm
Optical Design	Newtonian Reflector
Eyepieces and Accessories	9 x 50 Finder scope 32 mm eyepiece 25 mm eyepiece 10 mm eypiece 6 mm eyepiece 2x Barlow lens 5x Barlow lens LP Filter

Setting up [9 marks]

a) What is the F-ratio of the telescope? **[1 mark]**

b) The manufacturer claims that this set can obtain a magnification power exceeding 600x. Given the telescope accessories provided, what is the highest magnification that can be obtained? Hence, is the manufacturer's claim true? **[2 marks]**

c) Should Elliot try to observe objects through this telescope at 600x? Explain. **[2 marks]**

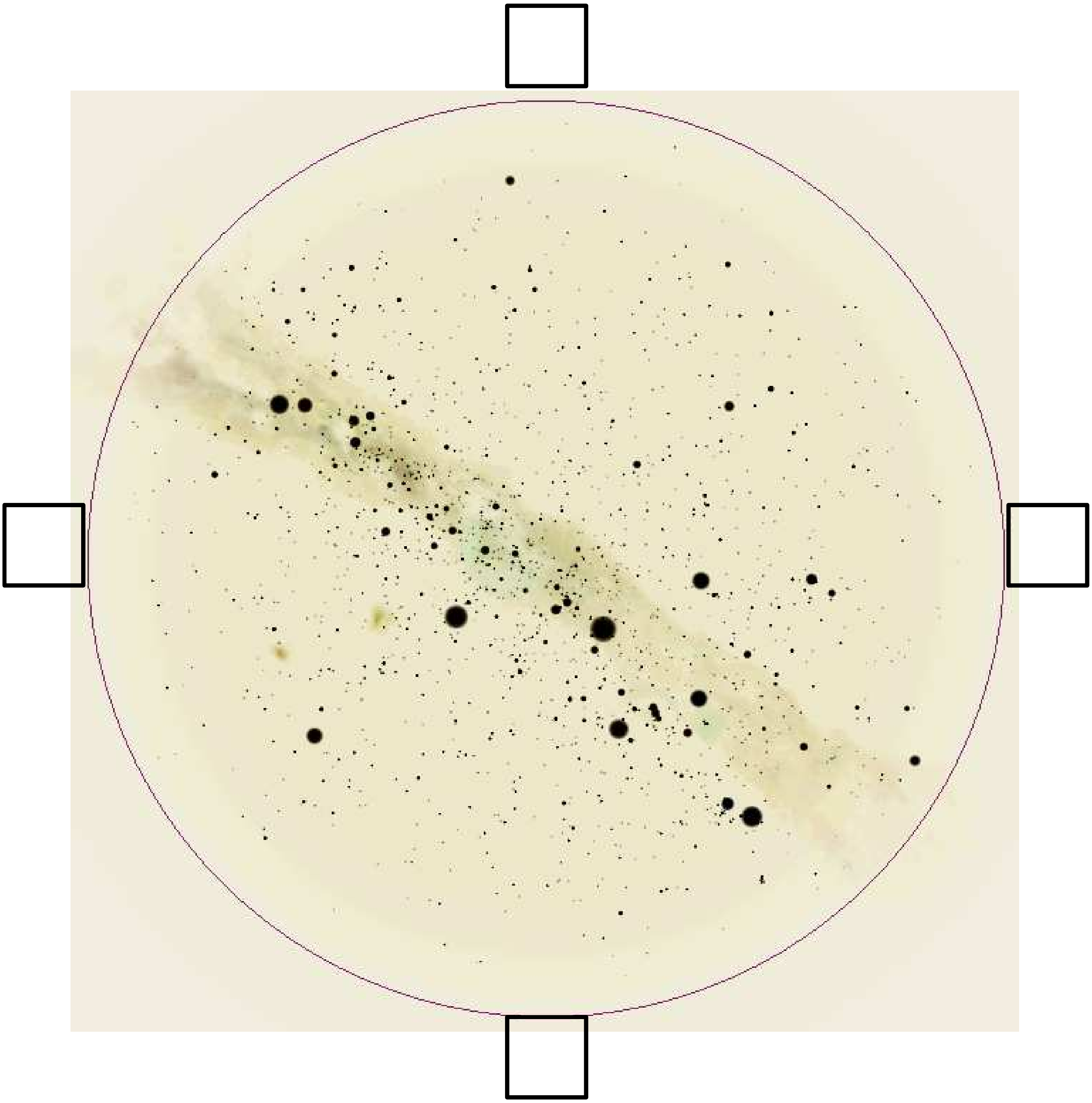
d) List an advantage and disadvantage of a Newtonian compared to a refracting telescope. **[2 marks]**

e) Determine the resolution of the telescope if an astronomer is observing at a wavelength of 500 nm. **[2 marks]**

The Observation Session [13 marks]

Thanks to you, Elliot's telescope is finally ready for first light. There's a catch however: When Elliot went out to a dark site, he was lost amidst the stars…

f) In order to guide him, please fill in the cardinal points (North, South etc.) on the diagram **[2 marks]**



g) Is Elliot in the Southern or Northern Hemisphere? Briefly justify your answer **[2 marks]**

h) Can any naked eye planet(s) be observed right now? If yes, please **circle** and **label** the planet(s) accordingly. **[2 marks]**

i) Name a double/multiple star system (not a cluster) that's currently up in the sky AND can be visually separated with the given telescope. **[1 mark]**

j) Name a galaxy that's currently up in the sky AND can be seen in the given telescope. **[1 mark]**

k) Name a nebula that's currently up in the sky AND can be seen in the given telescope. **[1 mark]**

l) Name a star cluster that's currently up in the sky AND can be seen in the given telescope. **[1 mark]**

m) Identify 3 other deep sky objects that are currently up in the sky AND can be seen in the given telescope. To obtain full credit, **name** the constellations they are in. **[3 marks]**