AstroChallenge 2020
Junior Team Round

Saturday 5th December 2020

PLEASE READ THESE INSTRUCTIONS CAREFULLY.

1. This paper consists of **14** printed pages, including this cover page.
2. Do **NOT** turn over this page until instructed to do so.
3. You have **2 hours** to attempt all questions in this paper.
4. At the end of the paper, submit this booklet together with your answer script.
5. Your answer script should clearly indicate your name, school, and team.
6. It is your responsibility to ensure that your answer script has been submitted.
7. The marks for each question are given in brackets in the right margin, like such: [**2**].
8. The **alphabetical** parts (i) and (l) have been intentionally skipped, to avoid confusion with the Roman numeral (i).

Question 1 A long night at Pulau Ubin

The night sky is Singapore is not a particularly amazing place for stargazing enthusiasts, yet many of the brightest stars in the night sky can still be visible. You and your friends (who do not know much about astronomy, as will be evident) are out and about in Pulau Ubin, ready to immerse yourselves in the wonders of the night sky and the buzz of mosquitoes.

(a) One of your friends points up at the sky and exclaims, "That is a very bright star!" You know better, however, and you explain her mistake and point out that that particular point of light is in fact, Venus. Of course, Venus is a planet and not a star.

How do you tell apart planets from stars (without using a star chart application)? Explain how your method distinguishes between the two. **[2]**

(b) Complete the following.

(i) Having corrected her, you go on to show your friends that not all stars are white points of light. Some, like Arcturus and Betelgeuse, are very visibly red. You also show them other stars that appear blue, yellow, and orange, and explain to them that this is a result of the surface temperature. Hotter stars are bluish and cooler stars are reddish, and their colour spans the rainbow.

Someone then asks you a curious question. Why are there no green stars? Your explanation is... **[2]**

(ii) You manage to surprise your friends with the fact that the Sun is actually white in colour. It only appears yellow to us because... **[1]**

(c) Another friend, using your planet discerning method, finds that all three planets currently present in the night sky, as well as the moon, happen to lie on the same great circle. Why is this so, and what is the underlying physical reason for this?

(Note: A *great circle* is a largest circle that can be drawn on a sphere. An example is the meridian on the celestial sphere, or the equator on Earth.) **[3]**

(d) Another friend then asks if there could be a lunar eclipse tonight, because she loves it when the Moon turns red. After disappointing her (your answer was "no"), you explain why the Moon turns red during a lunar eclipse. The reason is because... **[1]**

(e) (i) This same Moon-loving friend then notes that she only ever sees one side of the Moon. Tell her the name of this phenomenon and the cause of it. **[3]**

(ii) Assuming that the Moon loses rotational momentum during the phenomenon in part (i), where or what other forms of energy has it been lost or converted to? List **three** possible avenues of energy loss or conversion. **[3]**

(f) (i) Yet another friend recognises Betelgeuse, since it was reported on the news, supposedly being close to going supernova. He worries that the Sun might do the same, as he has not fulfilled his wish of attending next year's AstroChallenge.

You comfort him by telling him that the Sun will never go supernova. He asks you why. How do you answer? **[1]**

(ii) You then show the group the star Alpha Centauri (Rigil Kent), one of the closest stars to the Sun. Yet *another* friend then asks you how astronomers know these distances. Give **two** methods astronomers use to measure distances to visible stars in the night sky. **[2]**

(g) Finally, after a long day stargazing, it's time to head back home. Your friends note that in the time you have spent there, the positions of the stars have shifted, except for Polaris, which still seems to be at the same position. You explain to them that this is because Polaris is a pole star. However, you also tell them that in two to three thousand years' time, Polaris will no longer be the pole star. What is the name of this phenomenon that causes this and why does it result in the pole star changing? **[2]**

Question 2 How to land on the moon

Our obsession with visiting the Moon is timeless. It stretches as far back as ancient China, where the goddess Chang'e was supposedly to have drank an elixir of immortality and 'flown up to the Moon'.

In reality, one does not simply 'fly up to the Moon'. Complex calculations are needed to achieve such a feat. In fact, it was not until the middle part of the 20^{th} century that it was attempted. As recently as 7^{th} September 2019, India attempted a landing on the Moon. However, the attempt was unsuccessful for multiple reasons.

Part I Lift-off

Today, we shall attempt to land a probe of mass 1000 kg on the far side of the Moon. To achieve that, we first need to achieve lift-off.

(a) Calculate the minimum velocity the probe would need to obtain in order to escape from Earth's gravitational field. **[1]**

Many rocket launchpads are constructed near Earth's equator, such as the one built in the French colony of French Guiana. This is usually done to conserve the amount of fuel needed to propel the rocket into orbit by taking advantage of the Earth's rotation about its own axis.

(b) Calculate the amount of energy saved by launching a rocket eastwards into a circular orbit with altitude 1000 km from the surface exactly at the Earth's equator, as compared to launching the same rocket to the same altirude from the surface from the South Pole. For this question, you may assume that the Earth is a perfect sphere.

(Note: You may assume for simplicity that the mass of the rocket does not change significantly. This however is not true in general, as fuel forms the bulk of a rocket's weight. Fuel is used to propel the rocket.[1]) **[2]**

(c) State Newton's three laws of motion, and explain how they apply to a rocket as it is launches upwards from the ground. Hence explain why, for a given magnitude of thrust, there is an upper limit on the payload that a rocket can carry. **[2]**

[1]There are typically two types of rocket fuel used, namely, solid fuel and liquid fuel. For a rocket that goes to low Earth orbits, liquid hydrogen and liquid oxygen are typically used. Liquid oxygen acts as an oxidiser, which allows the fuel to burn in the absence of surrounding air. This type of fuel is often referred to as non-hypergolic fuel, which means that they do not spontaneously combust when the components come into contact. It is thus preferred in many situations, due to it being safer to handle.

Part II Orbits

Magic happens, and our spacecraft has now achieved low Earth orbit at 1000 km. Also magically, we now live in the world of the 2030s and via a number of trans-lunar injections (TLIs)[2], the space station Lunar Orbital Platform-Gateway (LOP-G)[3] has been constructed and is now in lunar orbit. Our probe has thus magically teleported[4] to the LOP-G.

We now need to bring the spacecraft to the Moon. This is done via a transfer to the Hohmann orbit. Figure 1 shows a typical Hohmann transfer from a lower orbit (an orbit with a smaller semi-major axis) to a higher orbit (an orbit with a bigger semi-major axis). The middle transfer trajectory is known as a Hohmann transfer orbit.

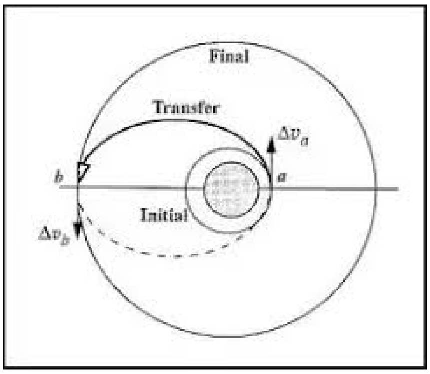

Figure 1: Illustration of a Hohmann transfer. Transfers can work in the other direction as well, from a higher orbit to a lower one.

The planned travel path for our probe to the surface of the Moon is as follows. The LOP-G will detach our probe when the LOP-G is aligned such that it is at perilune[5], on the near side of the moon opposite the intended landing site. The probe then performs a transfer to a Hohmann transfer orbit with perilune on the lunar surface, enabling the probe to land on the far side of the Moon.

Figure 2 shows this travel path. The LOP-G is[6] in an elliptical orbit with an apolune of 70000 km and a perilune of 3000 km.

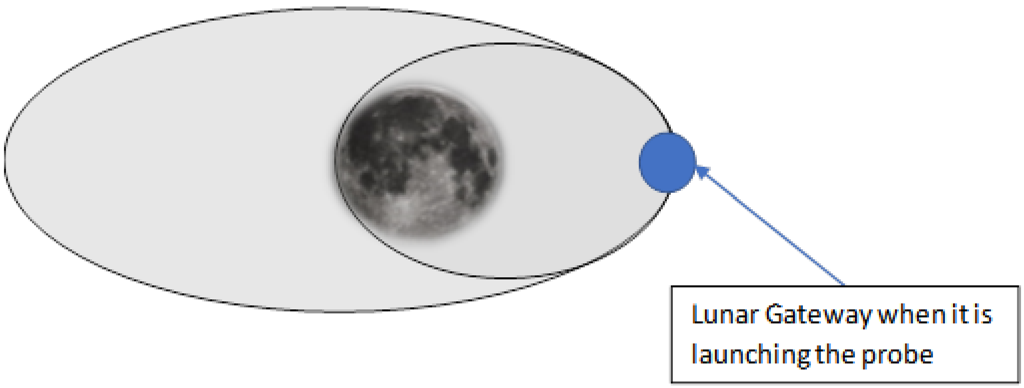

Figure 2: Illustration of the orbits of LOP-G and the probe, before and after the change in the probe's orbit.

(d) Estimate the flight time of the probe, from the time when it is with the LOP-G on the apolune of the LOP-G's orbit, to when it lands on the surface of the Moon. **[2]**

(e) By using conservation of energy, derive an expression for the speed of the probe at any distance r away from the center of the moon when it is in a lunar orbit with a semi-major axis of a. **[3]**

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[2]A TLI is a propulsive manoeuvre approximating a Hohmann transfer. A Hohmann transfer brings a spacecraft from a lower orbit to a higher orbit, and is summarised in Figure 1. The difference between a TLI and a Hohmann transfer is that a Hohmann transfer recommends at least two major changes of velocity to change the orbit parameters, while the TLI only recommends one change of velocity.

[3]This is in fact a real planned space station with a planned launch in 2024. It will orbit the Moon.

[4]Read: It performed some amazingly well-calculated orbital transfers.

[5]Perilune is the point in the orbit closest to the moon. Similarly, apolune is the point in the orbit furthest from the moon.

[6]or is planned to be

(f) Hence or otherwise, calculate the change in velocity needed to get the probe to the surface of the Moon from the LOP-G at the LOP-G's perilune via the orbit shown in Figure 2. You may assume the Moon is a perfect sphere. **[2]**

(g) Hence or otherwise, determine the landing speed of the orbiter when it reaches the landing site, assuming no further actions are taken by the probe. **[1]**

Part III Communication

LOP-G, for magical reasons, seems to encounter a communications issue and therefore will not play any further role in this question. With the given set-up, the probe will have significant difficulty trying to reach and communicate directly with ground-based mission control.

(h) Explain why this is the case, and hence explain why the landing site is also a good location to place a radio telescope. **[1]**

The typical solution to the communication problem requires another satellite to act as a relay to communicate with Earth. To maintain constant communication with both the probe and the Earth, this satellite needs to be parked at a halo orbit[7] around a Lagrangian point, hereafter referred to as Location A, to maintain communication with both the Earth and the probe. One satellite already in this particular orbit is the Chinese satellite Queqiao, launched on 20$^{\text{th}}$ May 2018.

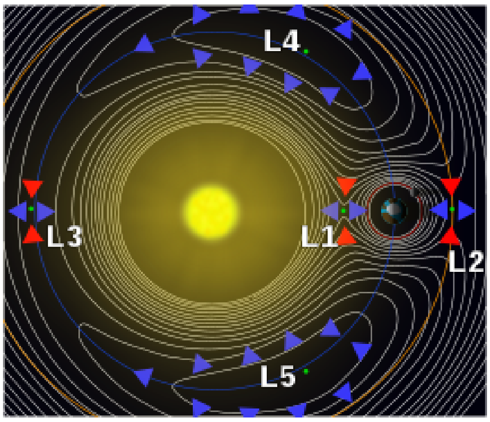

Figure 3: Illustration of all the Lagrangian points in the Sun-Earth system.

(j) Explain what is a Lagrangian point. **[1]**

(k) With the aid of a drawing of the Earth and the Moon, identify Location A. **[2]**

The relay satellite is able to maintain communication with the probe for most of the probe's duration on the Moon. However, it still encounters problem during occasions such as the Mid-Autumn Festival and during a solar flare/storm.

(m) The main issue for communication with the probe during the Mid-Autumn Festival[8] is that the probe's battery can potentially be too cold to operate. Explain why this can happen. **[1]**

(n) Solar flares and storms also pose a major issue to the inhabitants of the lunar-based probe. Suggest and explain one such issue. **[1]**

(o) Name the celestial phenomenon which you will likely see in the Northern hemisphere during a solar storm. Will you be able to see this phenomenon on the moon? **[1]**

[7] A *halo orbit* is a periodic three-dimensional orbit around one of the L1, L2, or L3 Lagrangian points. It typically has a large orbital radius. The non-periodic variants of the same are called Lissajous orbits.

[8] Held on the 15$^{\text{th}}$ day of the 8$^{\text{th}}$ month of the Chinese lunisolar calendar, when the Moon is brightest and at its full size.

Question 3 Bloom and Boom

Introduction

When it comes down to the wire, what the Universe consists of is really a cycle of things blooming, then going boom. First, the biggest boom and bloom of all, the Big Bang. Then, stars and galaxies bloomed. At the end of their life cycles, loads of stars go boom. Material is expelled, and new stars eventually bloom. Rinse and repeat.

Part I The Biggest B(l)oom

As you should know, the Big Bang is the commonly accepted model that explains the origins of our Universe today. There are four main pillars of evidence to support the Big Bang hypothesis. In no particular order, they are:

- expansion of the Universe,
- cosmic microwave background radiation,
- nucleosynthesis of light elements, and
- formation of galaxies and the large-scale structure of the Universe.

(a) Choose two of the four pillars and give a short explanation about how they support the Big Bang hypothesis. **[2]**

Part II Blooming Stars

Of the many stars that have bloomed, a certain type of star has been crucial in our astronomical studies, allowing us to determine distances. These are, of course, variable stars. The common examples are Cepheids and RR Lyrae variables, and they are often one of the first things to come to mind when the phrase 'standard candle' is mentioned.

What makes these stars immensely useful is their well-defined period-luminosity relationship. Variable stars 'bloom' at very regular intervals – their luminosities increase and decrease with a fairly constant period. This period is well-correlated with their absolute luminosity, allowing us to determine their distance from us (even though one should be aware of calibration difficulties due to effects of metallicity and/or blending).

The following table provides some data of typical Cepheids and RR Lyrae variables.

Property	**Type I Cepheids**	**Type II Cepheids**	**RR Lyrae**
Composition	Metal-rich	Metal-poor	Metal-rich
Period	Days to months	1 to 50 days	Hours
Age	Young	Old ($\approx$ 10 Gyr)	Old
Mass	Greater than $2M_\odot$ or $3M_\odot$	Low	Low ($\approx 0.5M_\odot$)

Table 1: Some characteristics of variable stars.

(b) The mechanism of 'blooming' of Cepheids and RR Lyrae variables are mostly identical. In fact, two meanings of 'blooming' can be said to take place. The star blooms in size. Then the star blooms in luminosity. Then it contracts, returning to a smaller size with lower luminosity. Then it blooms in size again.

The mediating agent, as it were, is thought to be an external shell of ionised helium. Doubly ionised helium has higher opacity to radiation as compared to singly ionised helium. Given this information, explain the mechanism of 'blooming' of Cepheids and RR Lyrae variables. You should account for both 'blooming's in your explanation. **[3]**

It is a fact that different standard candles are used for different distance measurements in the Universe. A standard candle used for nearer distances may not work for larger distances, and vice-versa. This concept is frequently called the *distance ladder*.

(c) The two Cepheid variables are used to determine distances of different objects. With reference to the given table, or otherwise, suggest objects each Cepheid variable is used to determine distances of. **[1]**

The period-luminosity relations for both Cepheid types are as follows.

Star	Relationship
Type I	$M_v = (-2.43 \pm 0.12)(\log_{10} P - 1) - (4.05 \pm 0.02)$
Type II	$M_v = -2.81(\log_{10} P - 1) - 2.66$

Table 2: Period-luminosity relations for the two main Cepheid types. Here, M_v is the mean absolute magnitude, and P is the period of pulsation in days.

The following is light curve data from a nearby quadruple system Cepheid star δ Cephei (specifically from the variable star δ Cephei A), whose observed light suffers from 0.23 magnitude extinction due to interstellar dust. Its pulsation period is 5.366249 days. It is thought to be about 4.5 solar masses and about 100 million years old.

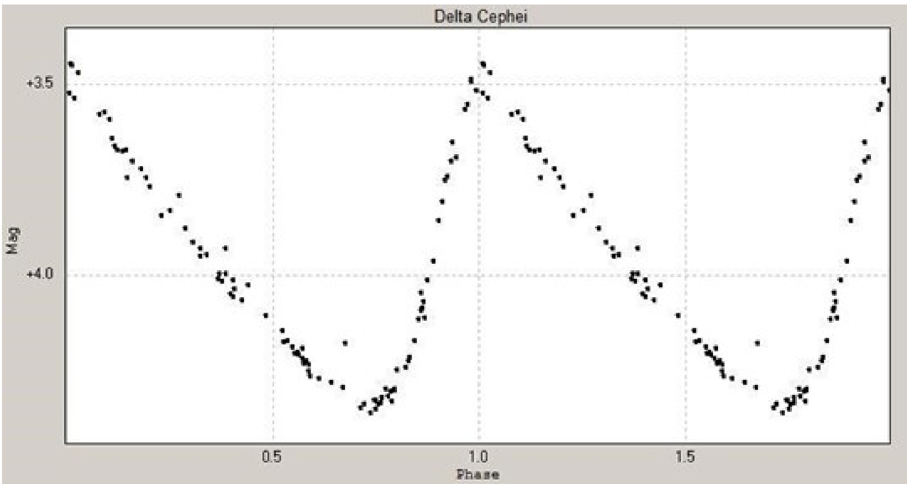

Figure 5: Observed light curve of δ Cephei.

(d) Determine the approximate distance of δ Cephei from Earth. **[3]**

Part III Booming Stars

One of the other well-known standard candles are Type Ia supernovae.

(e) Type Ia supernovae are used to provide evidence for one of the four pillars of the Big Bang hypothesis. Which one, and how? **[1½]**

As is well-known, at the end of their lives, stars have one of three main fates. They can boom into a supernova, they can b(l)oom into a planetary nebula, or they can (hypothetically) just not boom/bloom into anything, kind of like a really sad flower bud.

(f) What is the difference between a supernova and a planetary nebula, in terms of their cause/formation? **[1]**

The following are pretty pictures of planetary nebulae. Note the pretty petal-like structures, pointed out with arrows, almost like the planetary nebulae are blooming.

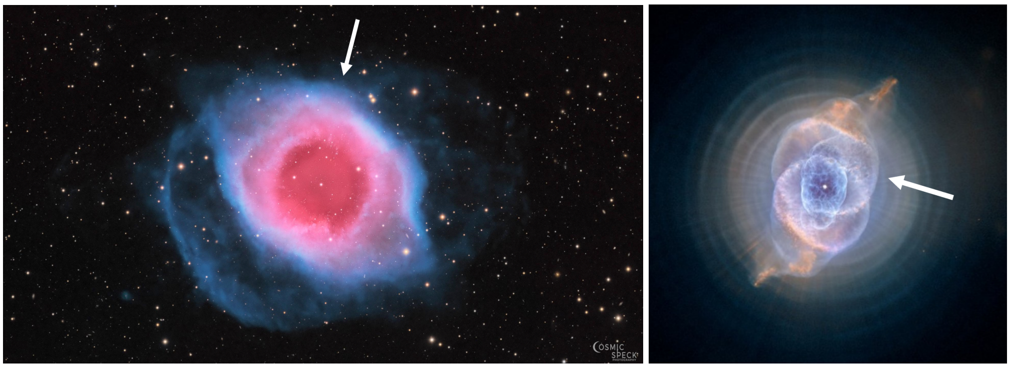

Figure 6: Two famous planetary nebulae.

(g) Explain the cause of these structures in detail. **[2]**

In general, it is difficult to determine distances of planetary nebulae from Earth. However, for short distances (approximately $< 1000\,\text{kpc}$), it is possible to directly (visually) resolve sufficiently large nebulae and perform a distance measurement by comparing measurements several years apart.

(h) Propose a method to perform this distance measurement. **[2]**

Part IV B(l)oom Into You

No question about blooming and booming is complete without discussing the most important bloom and boom: that which became you! The bloom and boom of life is a widely-discussed topic in both astrobiology and in science fiction: just look at Star Trek, or Doctor Who, or even any number of Japanese animated series.

Many portrayals of extraterrestrial life in science fiction takes place on planets where water is present. Often, this goes hand-in-hand with some mention of the 'Goldilocks zone', properly known as the *Circumstellar Habitable Zone* (CHZ). This reliance on water is not unique to science fiction, however: much of the effort made by astronomers today in finding extraterrestrial life focuses on planets and moons where water could be present.

(j) Define the term *Circumstellar Habitable Zone*. **[1]**

(k) The CHZ is a crucial concept in the search for extraterrestrial life. Explain why. **[$1\frac{1}{2}$]**

(m) Despite its well-known status, relying solely on determining the CHZ is not exactly a reliable method of finding potentially habitable worlds. Suggest and explain briefly two reasons why. **[2]**

Question 4 Hero among the constellations – Orion

Orion is perhaps one of the most famous constellations in the night sky due to its many bright stars and iconic shape. From tales of his rabbit hunt with his hunting dogs to his death upon facing a giant scorpion, Orion's legend too remains in the night sky as one of our most iconic myths.

To introduce the stars and lesser-known stories about Orion, you will have to overcome five trials and five poems about the ancient hero. Are you ready?

Common name	**Bayer designation**	**Star type (HR, MK system)**[9]	**Distance (light years)**	**Apparent magnitude**			**Machanism for Variability**
				Average	**Max**	**Min**	
Betelgeuse	α Orionis	M1-M2 Ia-ab	624	0.42	0	1.62[10]	Semi-regular Variable
Rigel	β Orionis	B8 Ia	772	0.12	0.05	0.18	α Cygni Variable
Bellatrix	γ Orionis	B2 III	245	1.62	1.59	1.64	Suspected Variability
Mintaka	δ Orionis	(O9.5 II+B1 V +B0 IV)+B3 V	916	2.26	2.23	2.29	Eclipsing Binary with Triple Star System
Alnilam	ϵ Orionis	B0 Ia	1342	1.69	1.64	1.74	α Cygni Variable
Alnitak	ζ Orionis	O9.5 Iab +B1 IV+B0 III	800	1.77	NA	NA	Triple Star System
Saiph	κ Orionis	B0.5 Ia	???	2.07	2.05	2.09	Suspected Variability

Table 3: Summarised data for several bright star in the constellation of Orion

Part I Betelgeuse

"A red beetle crawled under his arm and was crushed into beetle juice.
Immortalised in the night sky, we now call it Betelgeuse."[11]

Betelgeuse is a semiregular variable star.

(a) Calculate how many times brighter Betelgeuse is at its maximum compared to its record low earlier this year. **[1]**

(b) Suggest why stars like Betelgeuse are not a good candidate for standard candles. **[1]**

[1]As classified on the Hertzsprung-Russell diagram, under the Morgan-Keenan system.
[2]New record set in February 2020
[11]Not actually how 'Betelgeuse' is derived.

Part II Rigel

"Putting his best foot forward, Orion stands, proud and regal.
Though but the sandal of a great warrior, people name it Rigel."[12]

(c) What is an asterism? **[1]**

(d) Which famous asterism is Rigel in? Name one other star in the same asterism. **[2]**

A student new to astronomy saw Rigel's designation as a B8 Ia star. However, Rigel will end its life cycle as a Type II supernova, not a Type Ia supernova.

(e) Explain briefly why this is the case. **[2]**

Part III Bellatrix

"On his other shoulder plate is a portrait of his beloved.
The Amazoness star Bellatrix."[13]

(f) Calculate the average absolute magnitude of Bellatrix. **[2]**

Bellatrix is approximately 6 times the size of the Sun in diameter, and is approximately 9000 times more luminous than the Sun.

(g) Assuming Bellatrix is a main sequence star, calculate the surface temperature of Bellatrix using Stefan-Boltzmann law. **[2]**

(h) Comment briefly on whether your result in part **g** makes sense, given Bellatrix's classification as a B2 III giant. **[2]**

[12] Not actually how 'Rigel' is derived.
[13] Not actually how 'Bellatrix' is derived.

Part IV Belt stars

"On his belt, three bright stars to the common eye line up.
Mintaka, the belt buckle;
Alnilam, where his great scabbard and sword hangs;
Alnitak, where he keeps a flame in a lit lantern and a horsehead chess piece."[14]

Apart from the Orion Nebula (M42), the Flame Nebula (NGC 2024) and Horsehead Nebula (Barnard 33) are two other notable nebulae also found in Orion.

Figure 7: Image of Flame Nebula (left) and Horsehead Nebula(right)

The Flame Nebula appears reddish-yellow when imaged in visible light. On the other hand, it is extremely difficult to image the Horsehead Nebula, which appears as a black horsehead against a reddish backdrop.

(j) What type(s) of nebulae are the Flame Nebula and Horsehead Nebula respectively? **[1]**

(k) For each of the two nebulae, state whether they are expected to have star-forming regions. Justify. **[2]**

(m) Mintaka and Alnitak are both multi-star systems. Why does Mintaka show variability in brightness, but Alnitak does not? **[1]**

Part V Saiph

"His back foot, anchored against the ground, keeps the hunter safe.
Proud and strong Orion poses, the other sandal thus named Saiph."[15]

The absolute magnitude of Saiph is -6.1.

(n) Based on this, calculate Saiph's distance from us in light years.

(Note: You may find additional data from the table above, as well as the formula book, useful.) **[3]**

[14]Not actually how 'Mintaka', 'Alnilam', and 'Alnitak' are derived.
[15]Not actually how 'Saiph' is derived.

Question 5 ’Ike Mākou i Ke Ala

The ancient Polynesians were known to be remarkable navigators. Their canoes sailed on thousands of kilometres of open ocean to bring settlement to islands across the Pacific, from Hawaii, to Rapanui (Easter Island), to Aotearoa (New Zealand). Western navigational instruments such as compasses, clocks, and sextants were not available to the ancient Polynesians; they instead relied on nature-based navigational indicators like currents, clouds, bird movements, and at night when these things were nearly impossible to see stars. Imaginary lines were traced to connect stars in the night sky to help Polynesian voyagers memorise where and when different stars rise and set as well as the paths these stars would take throughout the night.

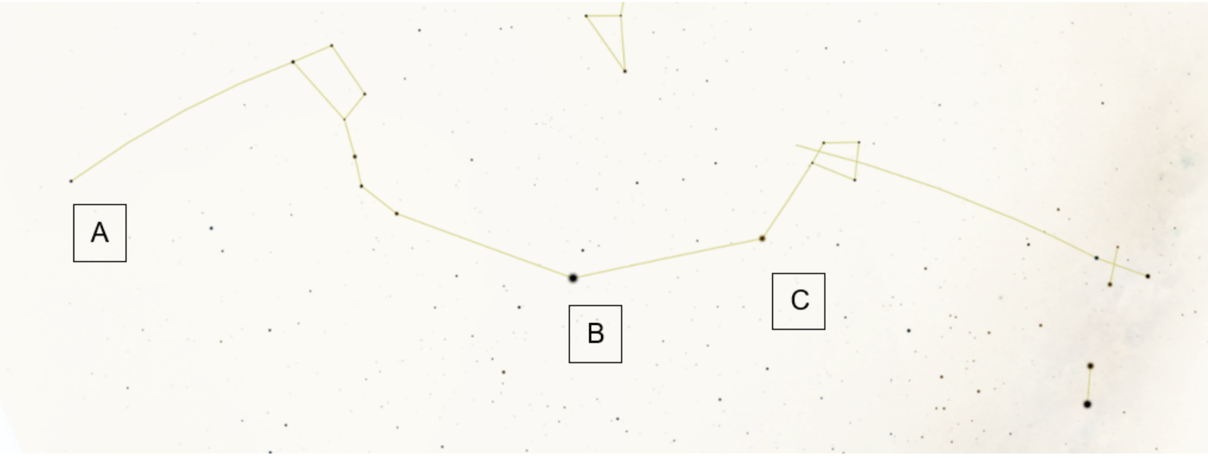

Figure 8

(a) One of these constellations is depicted below in Figure 8. State the modern name for each labelled star in parts i to iii.

(i) Star A. **[1]**

(ii) Star B. **[1]**

(iii) Star C. **[1]**

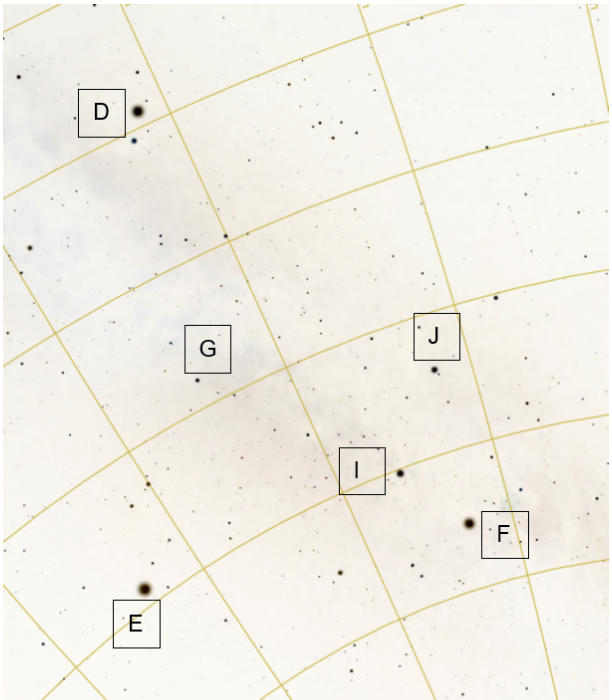

Figure 9

(b) Figure 9 shows the Navigator's Triangle on an equatorial grid. They are visible for most of the night; hence they are frequently used as markers for navigation.

(i) Three stars form the vertices of the Navigator's Triangle (Stars D/E/F in Figure 9). Name the modern IAU constellations that contain these three stars. **[1½]**

(ii) Demonstrate how the ancient Polynesian explorers possibly used the Navigator's Triangle to determine the direction of North. Two of the stars in the region of the Navigator's Triangle were particularly useful for them. You should use Figure 9 to aid in your explanation. **[1½]**

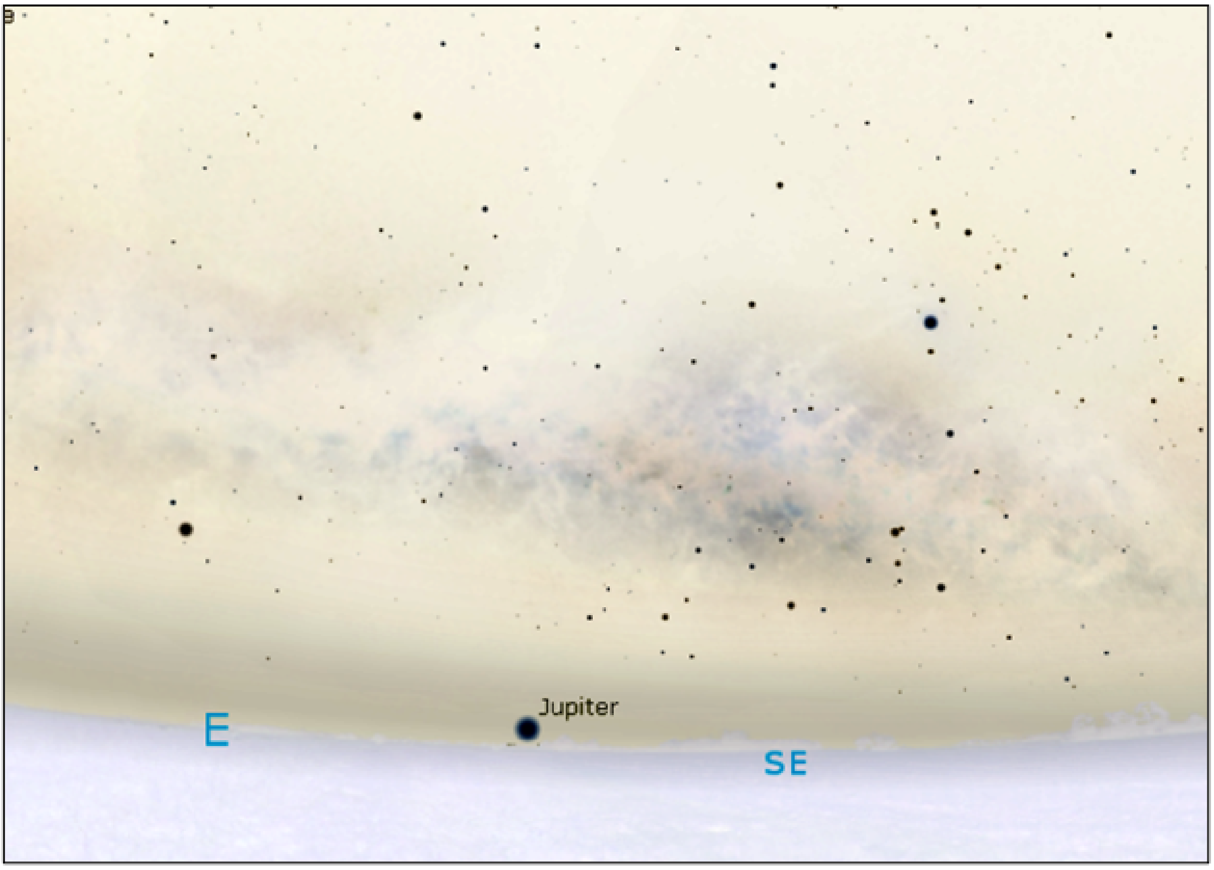

Figure 10

(c) The Chief's Fishing Hook is shaped like a fishhook lodged into a dark area of the Milky Way, poetically termed as the great celestial fish. Figure 10 is a picture of the fishhook and great celestial fish as they rise from the Eastern horizon.

(i) On Figure 10, trace the constellation of the Chief's Fishing Hook. **[1]**

(ii) The Chief's Fishing Hook coincidentally shares the same stars as a major IAU constellation. What constellation is this and what is the modern name of its brightest star? **[2]**

(iii) In the Hawaiian language there is a poetic phrase to describe the movement of the great celestial fish across the night sky: 'Ua huli ka I'a', meaning 'the fish has turned'. What astronomical phenomenon of the Milky Way could this phrase describe? Explain your answer. It may be helpful to consider how the fish hook and fish look like when they set into the Western horizon. **[2]**

Figure 11

What might be poorly translated into English as a "Scoop" is visible throughout most of the night during winter and is frequently used as a marker by the ancient Polynesians. Many deep sky objects (DSOs) that are visible even in Singapore can be seen in or around the Scoop. Figure 11 is a field of view of the night sky containing the Scoop. The constellation has already been drawn out.

(d) Name and mark at least **four** DSOs in Figure 11. **[2]**

(e) The Scoop can be seen over Singapore in the winter months. Thus, it is home to many winter constellations and two well-known winter asterisms from the modern star catalogue.

(i) Also within Figure 11, name and trace at least **three** modern constellations that appear in the field of view given of the Scoop. **[3]**

(ii) Name and trace the **two** modern winter asterisms in Figure 11. **[2]**

(f) Refer to Figure 11 to answer the following parts **i** and**ii**. State the modern names of the celestial objects given.

(i) Star K **[1]**

(ii) Star L **[1]**