ASTR 101 Midterm Test

October 2018

COMPLETE SOLUTION SET

Note: in the midterm test, everyone saw *exactly the same set of questions*. They were merely scrambled in order, in the multiple choice and "motion" sections. The correct answers for those first two sections are indicated in red print.

My answers for the short-essay questions are more thorough and carefully written than yours needed to be! I have done this so that you can understand just what we were looking for.

Please reconsider the questions you chose to answer *and ask yourself whether you were sure to answer each of the individual points addressed.* To help you, I have <u>underlined</u> the essential elements that you were asked to respond to in each question.

PART I: MULTIPLE CHOICE QUESTIONS

Instructions: there are 30 questions, each worth 1 mark. For each question, one answer is clearly best.   ***There is no penalty for a wrong answer, so if you are in doubt, guess!***

Q1: Ockham's Razor, a guideline referred to by scientists, was introduced:

A. by Copernicus, with reference to an ancient legend where someone had to make a clear distinction (a 'cut') between two possible points of view

B. by William Ockham, a 20th Century UK philosopher writing about distinguishing the perplexing world views presented by the new quantum mechanics

C. by William of Ockham, writing in the 14th century, long before the Copernican revolution

D. by Socrates, in reference to the parable of the 'sword of Damocles', with the razor about to cut the thread from which it dangles (thus resolving one's fate)

Your answer ________

Q2: Gravity dominates the mutual behaviour and motion of the Earth and Moon because:

A. the other forces that we know of do not reach out as far as gravity does

B. the magnetic fields of the Earth and Moon cancel each other out, so only the gravitational force matters

C. the Earth and Moon each contain equal numbers of positively and negatively-charged particles, so the strong electrical forces cancel out

D. they are in rapid motion: gravity is the only force that applies to such objects

Your answer ________

Q3: Just after sunset, you see the full moon rising in the East, with the bright stars of Orion nearby. Shortly before dawn, you see:

A. the stars of Orion and the Moon now in the Western sky, but the Moon now looks like a crescent

B. the stars of Orion in the Eastern sky, with the full moon in the Western sky

C. the stars of Orion and the full Moon both in the Western sky

D. the stars of Orion in the Eastern sky, with a crescent moon in the West

Your answer ________

Q4: On an equinox day, equal hours of sunlight and darkness are experienced by

A. everyone on Earth

B. people right at (or very close to) the Equator

C. people in the Northern hemisphere on March 21 and those in the Southern hemisphere on Sept 21

D. people in the Northern hemisphere on Sept 21 and those in the Southern hemisphere on March 21

Your answer: ________

Q5: The rotation of the Earth leads to it being somewhat flattened (wider through the Equator). This is most readily determined by:

A. seeing how rapidly whirlpools spin, depending on how far north or south of the equator they are

B. seeing how the position of stars overhead changes as we move north and south on the Earth

C. comparing the rate at which the 'Foucault pendulum' appears to rotate, depending on our location on the globe

D. drilling down into the Earth to see how far below our feet the 'core' is

Your answer: ________

Q6: In a solar eclipse:

A. everyone on the daylight side of the Earth will notice at least a partial eclipse

B. people in a reasonably large location will see a total eclipse; others will not see any special behaviour at all

C. people in quite a small area will experience totality; everyone else will not see any special behaviour at all

D. people in a small area will experience totality; a partial eclipse will be seen over a fairly large area; and many people will see no special behaviour at all

Your answer: ________

Q7: In a lunar eclipse, the moon does not vanish totally because:

A. the Sun is so large that the Earth is unable to block all of its light from reaching the Moon -- some still gets there

B. when the moon is in the umbra of the Earth, we can still dimly make it out because of the bit of starlight that it reflects to us

C. when the moon is in the umbra of the Earth, we can still dimly make it out because it reflects artificial illumination (city lights, etc.) from the Earth

D. even when the moon is in the umbra, some sunlight can reach it because it is scattered in various directions by the Earth's atmosphere

Your answer: ________

Q8: Proof of the non-circularity of at least some orbits in the solar system comes from the fact that:

A. solar eclipses are sometimes total, sometimes annular

B. the moon goes through phases

C. Mars displays retrograde motion

D. we do not see an eclipse every month

Your answer: ________

Q9: The stones of Stonehenge

A. were dug up in local quarries very close to Stonehenge itself

B. came from an even bigger but ruined earlier stone circle not far to the East, one about which we so far know very little

C. have a completely unknown origin, part of the mystery of Stonehenge

D. came from a couple of remote identified sites, and simple experiments have shown that they could in fact have been moved by the builders of Stonehenge

Your answer: ________

Q10: The building of the Egyptian Pyramids took place

A. quite quickly during the peak of the Egyptian dynasties, but it remains a total mystery as to how such sophisticated monuments were raised

B. during a relatively brief time following successful wars, when Egypt had thousands of captured slaves who could be forced to undertake the labour

C. with each pyramid requiring literally almost a thousand years of slow, steady construction -- a testament to the religious importance of these monuments

D. with clear developments in techniques and sophistication as the centuries passed

Your answer: ________

Q11: The Ptolemaic description of the solar system predicted a certain consequence which could be tested in principle. If Ptolemy was right:

A. then the Earth must be round, as was later shown when Columbus crossed the Atlantic

B. then we should see an effect called "stellar parallax", with nearby stars appearing to shift their positions throughout the year

C. then the planet Venus should show phases which never differ much from a thin crescent

D. then the rotation axis of the Earth should slowly precess around in space

Your answer: ________

Q12: Copernicus was fearful enough of the church's resistance to his heliocentric model of the solar system that he:

A. published his discussion in an obscure code, not deciphered for decades thereafter

B. delayed publication until he was almost literally on his deathbed

C. destroyed his results without publishing, and it is only through later reconstructions by Galileo that we can fully realize his theories

D. went into disguised self-imposed exile after publishing the results of his life's work; what became of him remains a mystery

Your answer: ________

Q13: Tycho's astronomical interests were inspired when, as a youth, he:

A. observed a bright 'new star' where one had never been before
B. was introduced to the complex calculations needed to use the Ptolemaic model, and realized he could surely do better
C. received a copy of Copernicus's book from the author himself
D. saw two very bright comets in successive years, and took that as a sign that he should become an astronomer

Your answer: ________

Q14: The hybrid model of the Solar System proposed by Tycho Brahe had one particularly appealing feature at the time, namely:

A. it fully explained the observed phases of Venus, since (in his model) Venus orbited the Sun, which in turn orbited the Earth
B. it explained why the moons of Jupiter can keep up with that planet, since it allowed for multiple centers of motion
C. it explained why there was no apparent stellar parallax, since the Earth itself did not move
D. it explained for the first time why we do not see a solar eclipse every month

Your answer: ________

Q15: The 'meridian' is

A. the point directly overhead
B. an imaginary line running exactly North-South that divides the sky above an observer into an eastern and a western half
C. an imaginary line running exactly East-West that divides the sky above an observer into a Northern and a Southern half
D. a mounted device (like a primitive telescope without lenses) that can be swung about freely to point at any star or planet in the sky

Your answer: ________

Q16: The innermost planets take less time to go around the sun than the outermost planets do. This is because:

A. their orbits are considerably shorter in length, which compensates for the fact that they travel more slowly than the outer planets
B. although they travel at the same speed as the outer planets, their orbits are shorter in length
C. they move more rapidly and their orbits are shorter in length
D. since they are small and dense, they can plow more quickly through the interplanetary gas in the solar system, while the bigger planets feel more resistance

Your answer: ________

Q17: Kepler had mystic notions about the structure of the solar system. He believed that the spacing between the planets was determined by:

A. a close similarity, or “harmonious resonance”, to the spacing observed for the moons of Jupiter as they orbited that planet

B. a repellent force which kept the planets apart in a what was described as a "mutually hostile balance"

C. an analogy to the distribution of the “prime numbers” in mathematics

D. a numerological relationship described by the way in which certain geometrical bodies (the so-called 'regular solids') could be packed together

Your answer: ________

Q18: An orbiting planet 'turns around' at both ends of its elliptical orbit although the Sun is at only one of the two foci. This is:

A. because of the Sun's gravity in both cases

B. because it is following a simple curved path and so 'falls back' even though it is well beyond the Sun's gravitational influence at the far end of its orbit

C. because of the combined gravitational attraction of all the planets acting together as a 'system'

D. because it slows down as it moves through the thin interplanetary gas

Your answer: ________

Q19: By the end of his analyses, Kepler knew:

A. the shapes of the planetary obits, their orbital periods, and their relative distances, but not the actual size of the Solar System

B. the shapes of the planetary obits, their orbital periods, and their actual distances

C. the shapes of the planetary orbits and their orbital periods but he had no ideas of their relative distances -- only their order from the Sun outward

D. the shapes and periods of the planetary orbits, but he had no ideas of their relative distances (and indeed he even had Mercury and Venus reversed)

Your answer: ________

Q20: We see only black and white at low light levels because:

A. at low light levels, there is less inflowing energy to stimulate the eye to produce the needed enzymes, with the colour sensitivity the most affected

B. the rods, which detect shades of grey but not colours, are more sensitive than the cones in the retina

C. “low light levels” simply means that objects are emitting less coloured light, so naturally look greyish

D. at low light levels, the pupil opens very wide, illuminating generally unused parts of the retina that are not very responsive to colour differences

Your answer: ________

Q21: Galileo described a falling object as seen on board a ship and from the shore, using this example to:

A. argue that falling objects seem to follow curved paths because of the 'Coriolis effect', proving that the Earth is spinning
B. argue that the vertical speed of all falling objects is the same, regardless of from where they are dropped
C. argue that the apparent path of a moving object depends on one's frame of reference (a 'relativity' principle)
D. argue that the vertical speed of all falling objects is the same, regardless of what they are over solid land or water

Your answer: ________

Q22: Galileo was the first physicist to recognize and try to compensate for:

A. the different masses of falling objects and how that affected their speeds
B. the different shapes of falling objects and how that affected their speeds
C. the fact that gravity gets weaker as we move to greater heights above the Earth's surface
D. the effects of friction and air resistance on moving and falling objects

Your answer: ________

Q23: Galileo used his observations of sunspots:

A. to demonstrate that the sun was fixed in space, unmoving
B. to argue that that the sun had structures on it, like tall mountains
C. to demonstrate that the sun rotated on its axis
D. to deduce (incorrectly) that the sun had a solid interior, glimpses of which we get through the hot outer gases

Your answer: ________

Q24: The moons of Jupiter are of special importance historically because:

A. they proved that a moon could “keep up” with a planet in orbit about the sun, thus silencing one criticism of Copernicus
B. they were confused with stars in a way which obscured our understanding of the true nature of Jupiter as a planet
C. their orbits have decayed perceptibly over the centuries, which shows that dynamical evolution is still going on in the Solar System
D. the fact that there was more than one moon suggested that Jupiter had suffered a recent catastrophic collision with another massive body

Your answer: ________

Q25: Galileo was tried by the Catholic church for heresy and:

A. was cruelly blinded by them in punishment
B. was sentenced to death
C. was put into prison for life
D. was forced to recant and put under house arrest for life

Your answer: ________

Q26: Galileo was able to estimate the approximate heights of mountains on the moon by:

A. a very simple analogy to the mountains near his home in northern Italy
B. being the first to realize that the reduced gravity on the moon would allow them to be scaled up to enormous sizes
C. noting that the peaks of mountains sticking up above the lunar surface could be illuminated by the last rays of the setting sun
D. measuring the widths of the craters out of which the material comes that goes into the mountains

Your answer: ________

Q27: Newton correctly understood one concept that Galileo got wrong:

A. Galileo's treatment of inertia was incorrect with respect to the motion of the Moon
B. Galileo had argued that more massive objects would fall faster to the ground
C. Galileo had argued that denser objects would fall faster to the ground
D. Galileo argued that the effects of gravity were much stronger on the Sun, and that this extra force explained its enormous heat

Your answer: ________

Q28: According to Newton's laws, the moon going around the Earth is:

A. always accelerating
B. never accelerating since it is in steady motion
C. weightless, so can feel no force
D. massless, because it is beyond Earth's gravity

Your answer: ________

Q29: When Newtonian introduced the notion of gravity, it was seen to be unique in that:
A. it can be described by a particularly simple mathematical expression; all other physics laws are much more complex
B. it acts only between any two objects that contained equal numbers of positively and negatively-charged particles
C. it had a limited range: objects beyond the Moon's orbit feel absolutely zero gravitational influence from the Earth
D. it acts between any two objects in the Universe, all the way from tiny atoms to entire stars and planets

Your answer: _________

Q30: Newton invented calculus so that he could:
A. work out why the moon had a "resonant" rotation period
B. develop his third law, which came many years after the first two
C. add up the total gravitational effect of a big object like the Earth
D. show theoretically how gravity could reach across empty space

Your answer: ________

Section II: Understanding motions

(This question is worth 5 marks – 1 for each correct answer.)

On the next two pages, you will find eight (8) panels showing a person standing on the ground, with the sky above. (You will have seen diagrams like this in the course PowerPoints, and in your text. If it helps, you might like to visualize someone in the middle of a park, with distant trees visible on the horizon in various directions, as shown in the top left panel. The open sky stretches overhead.)

I will now describe *five (5) different situations*, and your job is to identify which one of the panels correctly represents the behaviour you would see under the circumstances described.

1) Assume that you are on the Equator (in Ecuador, say). Consider how the sun appears to move across the sky during the day on Dec 21 (which is the winter solstice in the Northern hemisphere). Circle the letter that corresponds to the panel that shows this correctly:

A B C D E F **G** H

2) Assume that you are in a far southern location, like the tip of South America. Consider how a number of the brighter stars would appear to move across the sky during the night. Circle the letter that corresponds to the panel that shows this correctly:

A B C D **E** F G H

3) Assume that you are at a mid-Northern latitude, perhaps here in Kingston. Consider how the sun would appear to move across the sky during the day, from sunrise to sunset, *on Sept 23 (the autumnal equinox).* Circle the letter that corresponds to the panel that shows this correctly:

A B C D E F G H

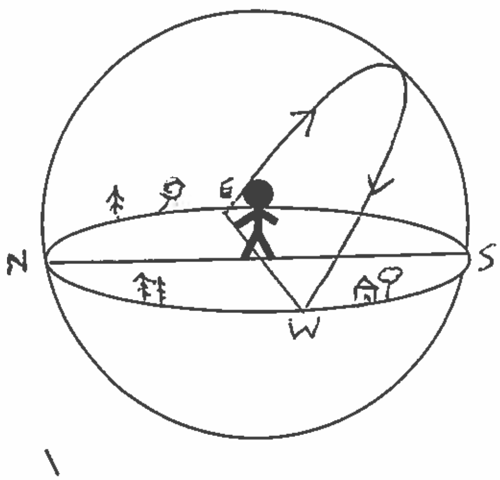
4) Assume that you are very close to the North Pole. Consider how the Sun would appear to move (if at all) during the day *on March 21st (the vernal equinox).* Circle the letter that corresponds to the panel that shows this correctly:

A B C D E **F** G H

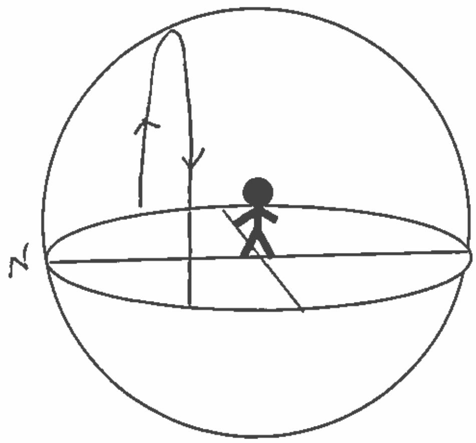
5) Assume that you very close to the equator. Consider how a number of the brighter stars would appear to move across the sky during the night. Circle the letter that corresponds to the panel that shows this correctly:

A B C **D** E F G H

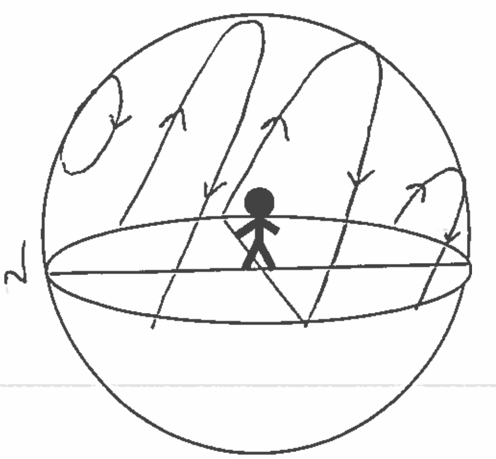
Panel A



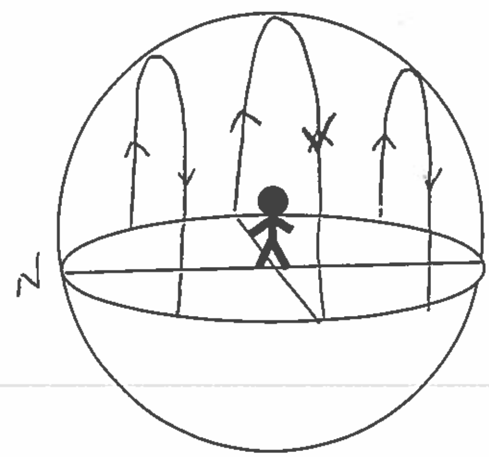
Panel B



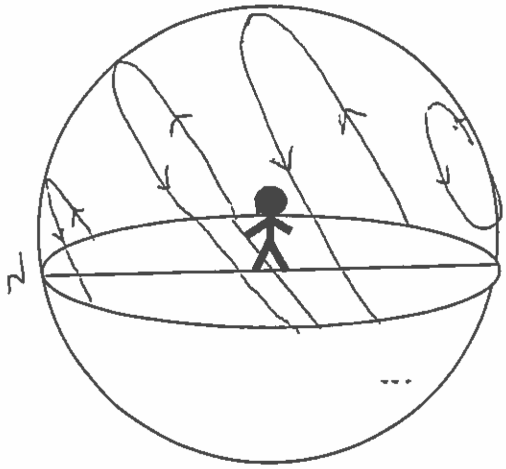
Panel C



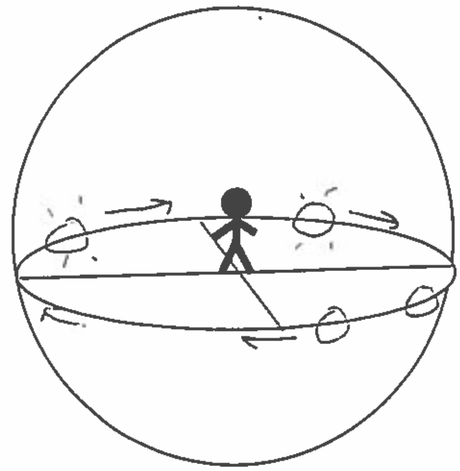
Panel D



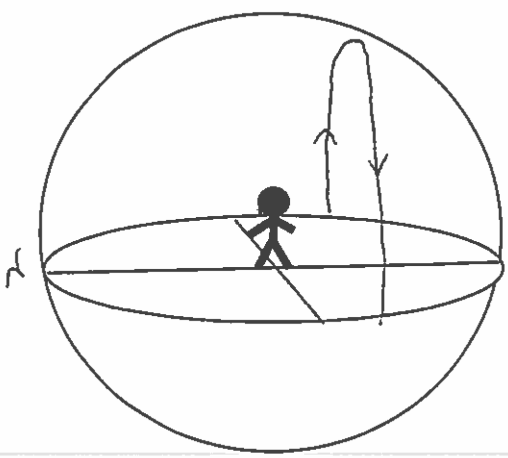
Panel E



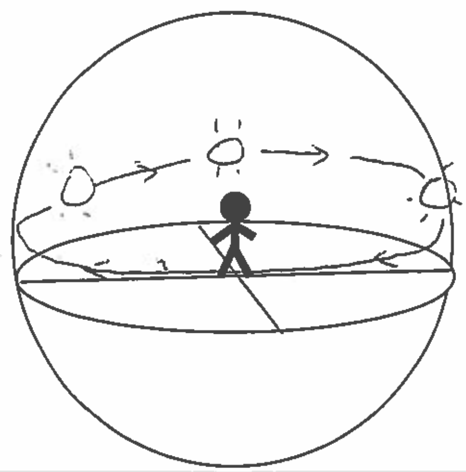
Panel F



Panel G



Panel H



III-1: Astronomy in Various Cultures and Early History

Early societies would have found it useful and important to create calendars based on regularly and repeatedly changing astronomical arrangements or appearances in the sky (rather than simply counting the passage of days). The Moon and the Sun are obvious conspicuous objects for such purposes.

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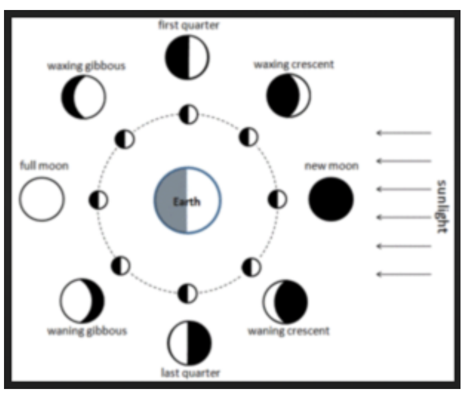
(2 marks) How would the Moon have been used in establishing a calendar? What changing behaviour would be observed, and *what is its fundamental cause*? (A diagram may help.)

The moon goes through a complete cycle of phases (ranging from invisible 'new' moon through thin crescents and all the way to full, then back down) once every 28-29 days or so. This provides a useful indicator of the passage of days on that timescale, and is the basis of the unit of time known as the 'month.'

The fundamental cause is the changing position of the moon, relative to the earth and sun, as it orbits the earth; this determines what fraction of the lit-up face of the moon we see as time passes. (See diagram below.)

The cycle of lunar behaviour had a particular significance for certain North American indigenous societies, in a way that seemed to be captured here on Earth in the form of a common animal. Describe that animal, and explain why it is significant in this respect.

The animal in question is a certain species of turtle. Its carapace (shell) has 13 large indentations, corresponding to the potential 13 full moons in a given calendar year; and it is surrounded by 28 smaller indentations around the edge, corresponding to the number of days in a complete cycle of lunar phases.



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(2 marks) What is meant by the Zodiac? How would the passage of a year be noted in terms of the Sun's 'position in the Zodiac'? How and why does that change with time?   If a friend tells you that he was born with 'the Sun in Ursa Major' (the Great Bear constellation), how and why do you explain to him that he must be mistaken?

The Zodiac is a *band of a dozen different constellations* (note: not *one constellation*) *in a belt that circles the sky*. It is through this band of constellations that the Sun appears to move steadily during the course of a year. As a result, we see different constellations at night in different months: e.g. Taurus in December, Sagittarius in July. These changes are due to the fact that *the Earth is orbiting around the Sun,* so at certain times of year some of the constellations are hidden in the brightly-lit daytime sky; at other times, they can be seen at night when we are looking 'away from the Sun.'

Ursa Major is a constellation that is *not in the ecliptic plane (the plane in which the Earth moves around the Sun)* – instead, it is 'up above,' which means that we never see the Sun in that direction. As a consequence, Ursa Major (and other constellations and stars in that part of the sky [including Polaris, which is *not* part of Ursa Major]) are visible to us every clear night.

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(2 marks) There is one star of particular significance to the Cree people of Manitoba: it is called Kiwatin, the "Going Home" star. <u>What star is this</u>, and <u>what makes it so significant</u>? Did that star have the <u>same significance for the ancient Egyptians</u>? <u>Why or why not</u>?

Kiwatin is *Polaris* (otherwise known as the *North Star* or the *Pole Star)*. Its significance stems from the fact that is lies almost directly above the North Pole of the Earth, which means that from anywhere in the northern hemisphere, it appears to maintain a fixed position in the sky even as the Earth is rotating. Its location is thus always a good indicator of the North direction (and its height above the horizon is a good indicator of our latitude on Earth -- note that Polaris cannot be seen from south of the Equator). Polaris is moderately bright and conspicuous, but it is ***not*** one of the brightest stars in the sky; its *location* is what makes it special.

This star did not have the same significance for the Egyptians, because 4000 years ago Polaris was not located directly above the Earth's North Pole, thanks to the effects of *precession* – the slow change in the orientation of the Earth's axis of rotation, thanks to the small gravitational effects of other planets and so on. (But there was a Pole Star at that time: Thuban.) Note, by the way, that Egypt is in the Northern hemisphere!

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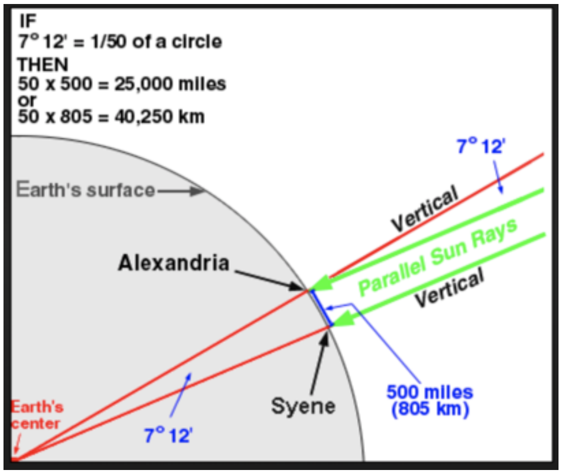
(3 marks) With what <u>evidence</u> (there were several reasons) did Aristotle argue convincingly that the Earth is <u>spherical in shape</u>? How did <u>Eratosthenes actually determine its size</u>, over 2000 years ago? (A sketch will help.) <u>Was this knowledge forgotten</u> by the time Columbus first ventured to sail westward into the Atlantic? <u>Justify</u> your yes or no answer.

Aristotle noted (a) the changing altitude of stars (like Polaris) as we travel north and south; (b) the way in which ships disappear 'hull first' as they sail away from shore, as if going 'downhill'; (c) the fact that the Earth's shadow projected on the face of the moon always shows a circular edge, and a sphere is the only object that always casts a circular shadow; and (d) the fact that at least two astronomical objects (the Sun and Moon) are clearly round.

Eratosthenes noted that a vertical stick in one location in southern Egypt casts no shadow at midday in late June, while a shadow is seen for a similar stick some hundreds of km farther north. The rays of light from the distant sun are nearly parallel, so this difference is due to the fact that the sticks are not themselves parallel: they are 'vertical' in that each of them points to the centre of the Earth (see the figure below). By measuring the angle shown, and pacing out the distance between the two locations, Eratosthenes was able to determine the full circumference (distance around) the Earth.



This knowledge was NOT forgotten – even before Columbus sailed, learned people in Europe were constructing and using spherical globes of the Earth that showed the then-known continents (Europe, Africa, and Asia – but no Australia, North America, or South America).

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(1 mark) Once they knew the size of the Earth, the ancient Greeks realized that a simple observation of a lunar eclipse allows <u>a rough estimate of the size of the Moon</u>. Explain <u>the reasoning</u>.

The assumption was made that the shadow cast by the Earth is approximately the size of the Earth itself. The appearance of the (partial) Earth shadow on the Moon suggested therefore that the Earth is (roughly) 3-4 times the size of the Moon.

III-2: Fundamental Motions and Early Cosmological Models

(3 marks) We considered several potential proofs that *the Earth is orbiting around the Sun* (rather than standing still, with the Sun moving around us once a year). Two of these were

(a) heliocentric stellar parallax; and

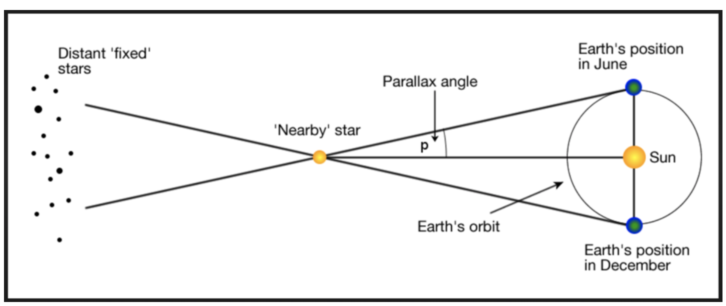
(b) stellar aberration

Which of these was the *very first* to provide absolute proof that the Earth is moving through space? Which of them has an *extra importance* because it provides essential information about the stars themselves, and what is that crucial information? Having answered those simple questions, now pick *just one* of these, (a) or (b) – your choice! – and explain (preferably with the aid of a diagram) how it works in practice.

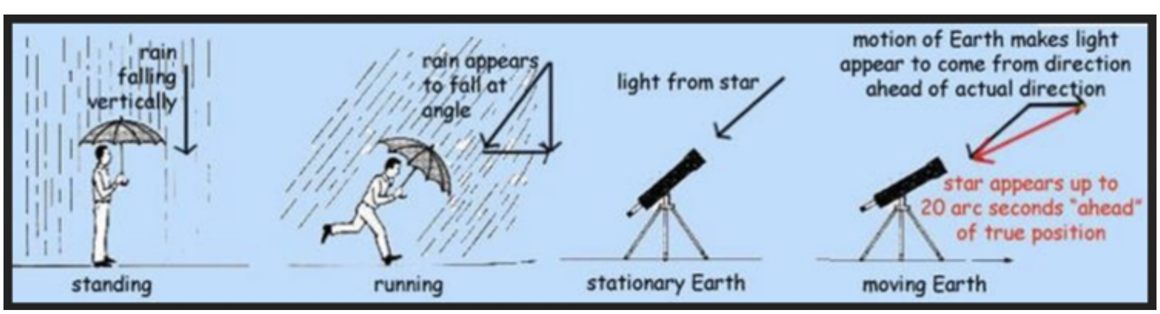
The very first proof was the discovery of *stellar aberration* (the need to 'tip' a telescope in the forward direction of the Earth's motion through space).

Heliocentric stellar parallax has extra importance because it does not just show that the Earth is in orbital motion but it also allows us to determine *the distances of at least the moderately nearby stars.*

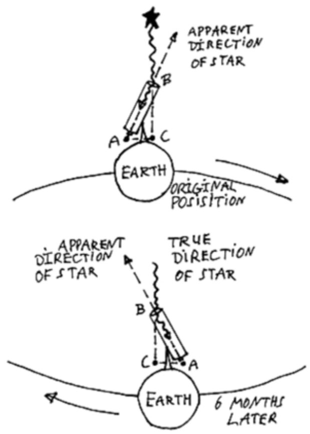
(a) Heliocentric stellar parallax: if we look in the direction of a nearby star in December (say), then in will appear in a certain position relative to the much more remote background stars. Six months later, in June, the Earth will be in a location 2 A.U. (300 million km) removed, having completed half of its annual orbit around the Sun. The same star will now seem to be somewhat displaced in position relative to the background frame. If we can determine that 'shift' (the angle through which we would need to tip our telescope to centre on the nearby star in the two different cases), we can work out the distance to the star by simple geometry because we know the length of the 'baseline' (i.e. how far the Earth has moved between December and June).



(b) Stellar aberration: As the Earth moves through space, we have to 'tip' our telescope (pointed at some star) through some small angle in the 'forward' direction to allow the light to be brought to a proper focus at the bottom of the telescope tube. This is usually explained by analogy to tipping an umbrella as we walk through rain that is falling straight down, as here:



Because light travels so fast, the angle of the 'tip' is small, but measureable. Note that the direction of the tip changes as the months pass, because we are moving in different directions at different times of year.



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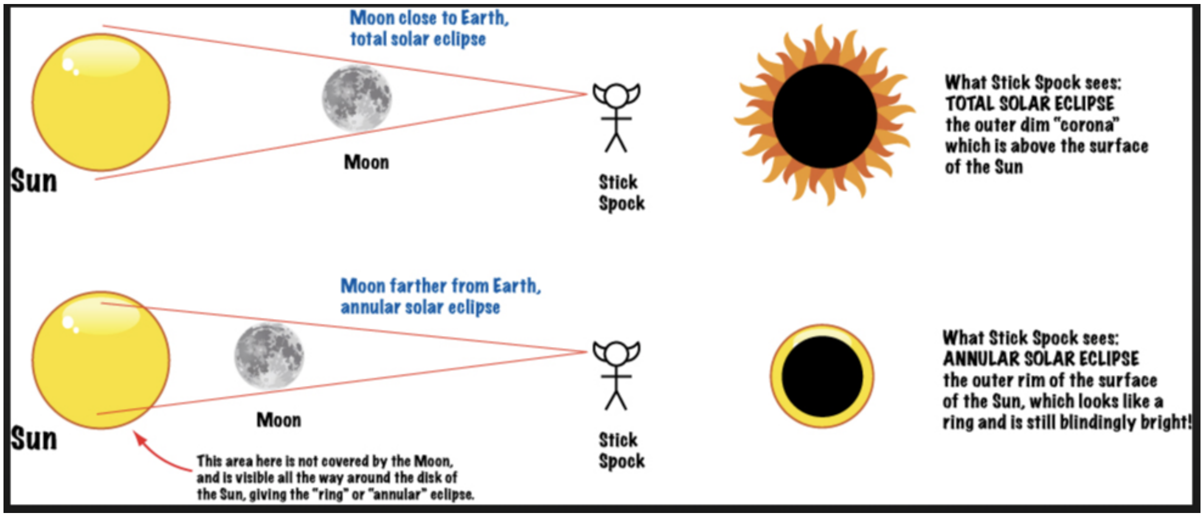
(2 marks) Your professor Dave H drove 1600 km to Nashville in 2017 to see a total eclipse of the Sun; he had earlier only ever enjoyed an 'annular' solar eclipse (but that took place conveniently here in Kingston). <u>How did these differ in appearance</u> as he watched? Explain <u>what distinguishes a total solar eclipse from an annular eclipse</u>, using sketches that <u>show the arrangement of the Sun, Moon and Earth</u> to explain why the phenomena differ.

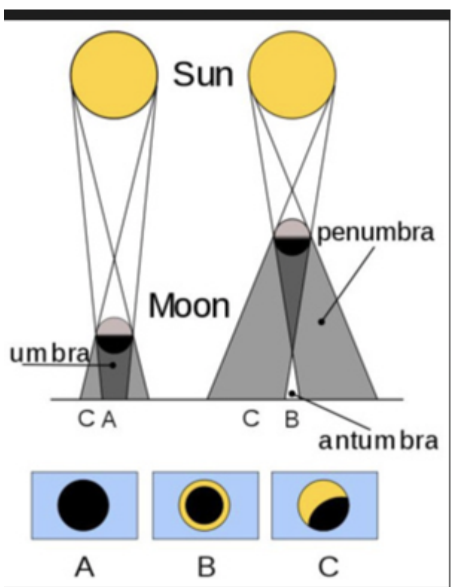
In both cases, the eclipse stars with a small 'bite' being taken out of one side of the Sun. This grows in size as the eclipse progresses, until the moon is centered directly between us and the Sun. Then, as the moon continues on its way, we see a progressively smaller and smaller 'bite' until at last the full face of the Sun is restored.

The difference is that a total eclipse (seen just above) enjoys a short period where the moon *completely* covers the bright face of the Sun (allowing us to see the fainter, distended 'corona'). In an annular eclipse, the moon is not large enough in apparent size to block off the full face of the sun, and a *ring* (an 'annulus') of light is seen, surrounding a dark central region, as here:

The *annular* eclipse occurs when the Moon is somewhat farther away from us in its orbit (which is NOT a perfect circle around the Earth). This means that it is a bit too small in 'angular size' to completely block the Sun. Here is the geometry, seen sideways on:



and here it is in terms of the shadows (umbra and penumbra) cast:



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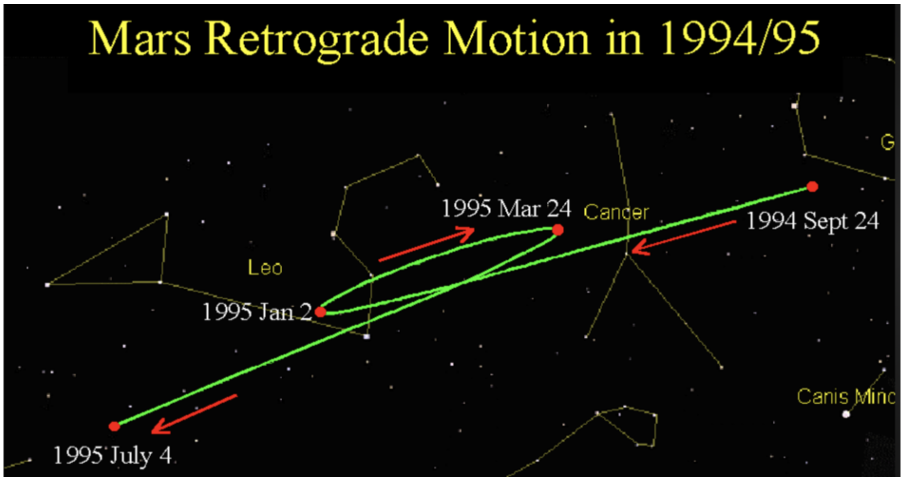
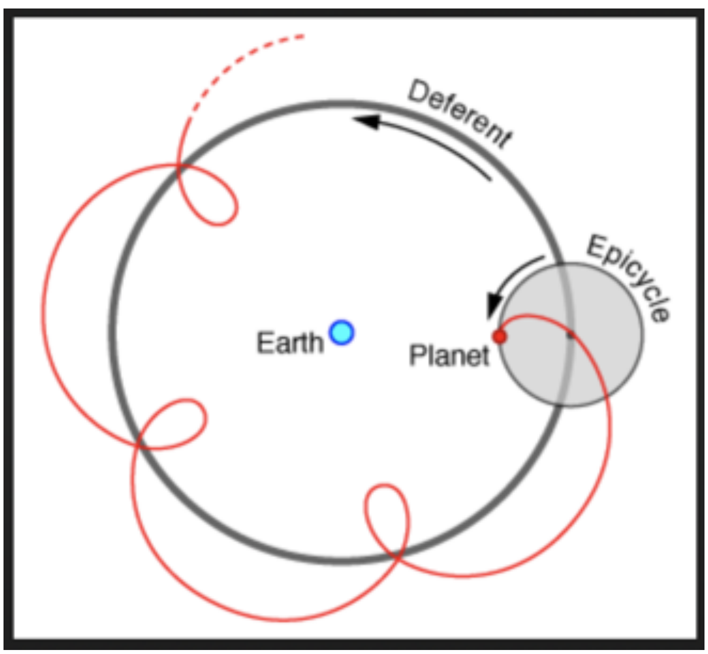
(3 marks) Explain what is meant by the *retrograde motion* of a planet such as Mars. Over what sort of timescale do we see Mars participate in this motion? What very contrived solution did Ptolemy develop in seeking to explain this behaviour? How does the heliocentric model of the Solar System explain the retrograde motion very straightforwardly?

If the Earth were sitting at rest, with Mars going steadily around it in a big near-circular orbit, you would expect to see Mars (a dot of light) moving more or less continuously in one direction (eastward) across the background frame of remote stars. It does not do that: at times it seems to slow down, come to rest, reverse tracks (hence move in 'retrograde' fashion) for a time, then slow to a halt again before once more taking up its steady eastward motion. We see this take place over a timespan of a *few months* (not mere hours or days) as shown here:



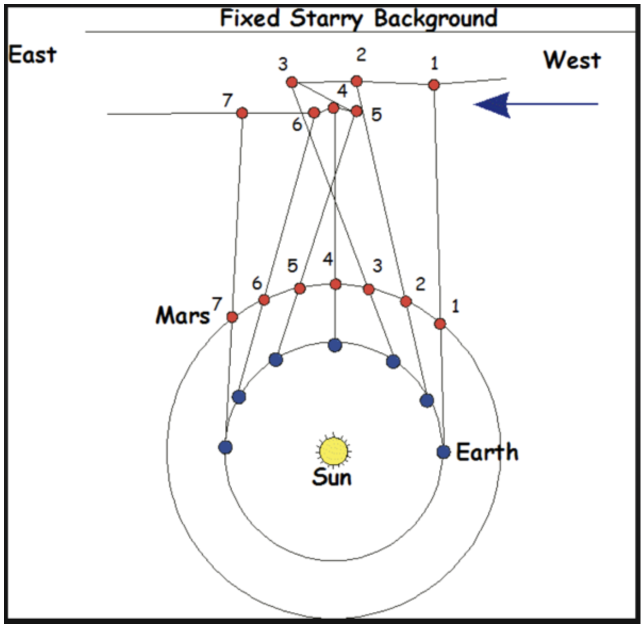
Ptolemy assumed that Mars was moving at a steady, unchanging speed on 'circles within circles' – a system of *epicycles and deferents* – giving rise to the periodic appearance of backward travel, as shown here:



The key elements in the heliocentric model are that

- the Sun is central: all the planets orbit it; and
- the inner planets move fast than the outer planets

This means that the Earth regularly overtakes Mars (and the other outer planets too) on the 'inside track,' naturally giving rise to the appearance of retrograde motion as shown here:



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(2 marks) What were the <u>basic assumptions</u> that Ptolemy adopted in his ‘cosmological model’ to explain the motions in the solar system? In defence of his model, there was one apparently compelling reason for assuming that the Earth was the <u>unique centre</u> of the universe. <u>What was that reason?</u>

Ptolemy’s basic assumptions were:

- the Earth is the unique centre of all motions (planetary + Sun and Moon)
- all motions are in perfect circles
- all motions are at uniform unchanging speed

Whether the Earth is at rest or is itself moving around Sun, it is evident that *the Moon orbits the Earth*. If you believe that there can be only one unique ‘centre of everything,’ then it must be the Earth itself.

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III-3: Basic Scientific Understanding

(6 marks) We have considered several basic physics principles, including a couple of the so-called *conservation laws,* in various astronomical contexts. These included

- the Conservation of Linear Momentum;
- the Conservation of Energy; and
- the Conservation of Angular Momentum

With reference to these laws (not necessarily in the order given!) explain:

- why it is that a star, when it forms from a distended cloud of cool gas that comes together under the influence of gravity, is *hot from birth,* even before the onset of nuclear reactions in its centre

This one depends on the *Conservation of Energy.* Stars form from an originally distended, low-density distribution of atoms occupying a huge volume, much bigger than the Solar System. By virtue of this distribution, they have a lot of *Potential Energy* (just as for a stone held above the ground, ready to fall downwards). If the conditions are right (the gas is not too hot, for instance), the atoms and molecules can start to move collectively towards each other – that is, the cloud of material will start to *contract.* The lost Potential Energy shows up in the form of *Kinetic Energy,* the energy of directed motion, as the particles fall inward and pick up speed. Since the gravitational force between them gets stronger as they get closer together, they accelerate as they go, and are soon rushing inward at very high speed.

As they near the centre, the growing density means that the particles collide with each other with great vigour, and instead of steady directed motion, they will all now be bouncing and jostling around randomly, and *very vigorously.* In other words, the particles have a lot of *Thermal Energy* – the gas cloud has become *very hot.* But the same total energy is there! (Eventually, some of the energy gradually escapes into space in the form of radiation [light] from this new hot object.)

- why Polaris (the North Star) has remained so steadily above the North Pole for recent centuries, and why the seasons (which depend on the changing path of the Sun across the sky) repeat so reliably every year

This one depends on the *Conservation of Angular Momentum*. Since the Earth is spinning rapidly, it cannot 'flop about' – the spin imparts a certain stability, and the orientation of the rotation axis remains pretty much fixed in space. It is pure coincidence that a moderately bright star (Polaris) happens to lie almost directly above the North Pole, but the steady rotation of the Earth ensures that it stays there from our point of view for protracted times (although the gravity of the other planets leads to a very slow 'precession': the Earth's axis gradually shifts in its orientation).

Similar arguments apply to the seasons. Since the Earth's spin axis is tipped relative to its orbit around the Sun, but does not change as it goes, we see the sun from different angles at different times of year – sometimes relatively high in the sky [summer], sometimes lower [winter]. The Conservation of Angular Momentum also explains why our *orbital* motion around the Sun is also steadily maintained (the reliable length of the year) – not just the Earth's *spinning* motion, which determines the duration of the *day.*

- how rockets can go from a state of rest, 'floating' in the emptiness of space, even though there is nothing for them to 'push against' when the engines are fired

This one depends on the *Conservation of Linear Momentum.* When the rocket is at rest, its total linear momentum is *zero,* and that total will be maintained (that's the conservation law!). Now consider what happens if we fling something out the back – hot exhaust gases from the rocket engine, or just bricks thrown out through a porthole. That moving material has a certain amount of linear momentum because of its velocity in one direction. To make the overall total still be *zero,* there must be some other material moving in the *opposite* direction (which you can think of as having a *negative speed,* moving in the diametrically opposed direction). In other words, *the rocket itself* will wind up moving in the direction opposite to the material it is firing out. (That material does not have to be hot gas, and there is no need for there to be something to 'push against'.)

*****

(4 marks) We have sent spacecraft to small asteroids (rocky objects in the Solar System) – indeed, one Japanese probe landed on the asteroid Ryugu in late September. A typical asteroid differs from the Earth in being irregularly-shaped, stone-cold throughout, and having no atmosphere; the Earth, by contrast, is nearly spherical in shape, has a hot interior, and possesses a moderately thick atmosphere. What are the fundamental reasons for these striking differences?

The reasons are as follows:

1. Irregular shape: sufficiently large bodies, such as the largest asteroids plus the planets (and their major moons), are big enough that their *self-gravity* overcomes the structural strength of the material of which they are made, so any irregularly-shaped object is forced to become effectively *spherical in shape.*. So the key factors are the large self-gravity and the limited strength of the materials of which they are made. This does not affect smaller objects like Ryugu.

2. Stone-cold centres: first, consider two objects of *similar shape.* The larger one has more surface area to radiate away its internal heat, but even more volume of hot interior material. So in the 'race' to shed its internal heat, the larger body has more difficulty, and will retain its inner heat longer than a small object. Changing the *shape* of the object also matters. Consider a given amount of hot material: if it is formed into (say) a long skinny object, it has lots of surface area and can readily shed its internal heat. (Equivalently, you can note that no part of the hot material inside the body is far from an exterior surface through which the heat can escape.) If, however, the object is reformed into a *sphere,* the surface area is minimized (and the hot central parts are quite far from the surface), so heat has much more trouble escaping. For both these reasons, *big spherical objects will retain their internal heat much better than small irregularly-shaped objects.*

3. No atmosphere: Any atmosphere held by a planet or asteroid will slowly dwindle away because of the random thermal motions of gas atoms and molecules: occasionally, the collisions between them will 'bump' one of the particles to a high enough velocity (greater than the 'escape velocity') that it can leave the body entirely. A large rocky planet like the Earth has more total mass (that is, more contained material) than a small asteroid made of comparable stuff, and its gravitation will thus be stronger. So although the atmosphere effectively 'boils off', the effect is *very slow* for Earth-like planets: they can retain an atmosphere for billions of years. Small asteroids very quickly lose any atmosphere they may have had originally.

III-4: Renaissance Astronomy

(2 marks) We described Tycho Brahe as, in some senses, the first really serious observational scientist. What important observations did he make of the stars and planets? (Describe the equipment and techniques that he used.) In what particular senses did his research live up to standards that would meet the approval a modern scientist?

Tycho mapped the pattern of the 'fixed stars' more precisely than anyone had ever done before. (These stars seem not to move with respect to each other as the years pass -- they are 'fixed' in place, except that the whole pattern moves across the sky each night as the Earth rotates.) He also made careful measurements of the changing positions of the planets, relative to the pattern of stars.

Tycho did not have telescopes! – to him, the stars and planets were just dots of light. He used instruments like *mural quadrants* (the name is not critical): effectively, these were long measuring sticks attached to walls but with the freedom to be swung up and down to point at various stars as they pass *through the meridian* (that is, from the Eastern half of the sky to the Western half). The *height of the stick* (the angle through which it had to be tipped) indicated how far North or South a given star was located in the overall stellar pattern; a clock indicated when that star passed through the meridian, giving an indication of how far west or east it lay relative to other stars being observed.

Tycho was like a modern scientist in that he:

- used *the very best instruments* that could be built
- made *repeated measurements* to check his results and improve the precision and reliability
- made *huge numbers of observations*, accumulating an enormous amount of high-quality data

*****

(3 marks) For a single mark apiece, explain what is entailed by each of the three famous laws developed by Kepler. (No formulas are needed; qualitative remarks will suffice.) One of these laws is explicable in terms of a modern 'conservation law.' Which of Kepler's laws is it, and what conservation law is involved?

The three laws are as follows:

- K-I: planets move in *elliptical orbits* around the Sun, and the Sun lies at *one focus of the ellipse* (the second part of this is an essential part)
- K-II: no single planet moves at constant speed as it orbits the Sun: it moves fastest when it is closer to the Sun, and slower when it is farther away. (Kepler expressed this in terms of the 'constant area' swept out by a planet in equal intervals of time)
- K-III: there is a straightforward law that relates the *period of a planet's orbit* to its *distance away from the Sun*

K-II is explicable in terms of the *Conservation of Angular Momentum.*

*****

(1 mark) In general terms, what limits our ability to see fine details on a remote object? (Consider how an image is formed on the eye.) How did Galileo's primitive telescope allow him to discern such details on astronomical objects?

Our ability to see detail is limited by

- the number and size of the cells on the retina (comparable to the 'pixels' in a digital camera); and

- the size of the image that is formed on the retina. Remote objects form only tiny images in the eye, which is why the planets and stars appear as mere dots of light.

Galileo's telescope removed these limitations by producing a *magnified (larger) image* on the retina.

*****

(2 marks) Describe Galileo's observations of
- the Moon, and what he interpreted and discovered about the nature of its surface
- the planet Saturn, and what perplexed him about its appearance

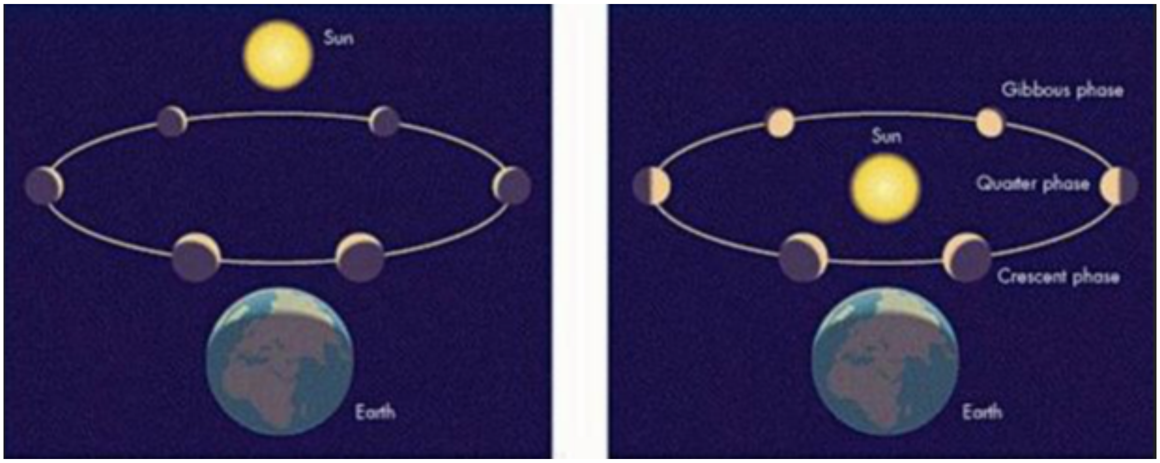
Galileo saw distinct, apparently smooth dark regions on the face of the Moon, and interpreted these as *seas* (bodies of open water comparable to those on Earth). He also noted areas of real ruggedness, as indicated by distinctly-cast shadows, and actually used the geometry of the shadows and illuminated peaks to deduce the heights of the inferred mountains (which turned out be comparable to those in Italy)

Galileo noted, early on, that Saturn was not perfectly round in appearance (as the Sun, the Moon, and Jupiter were). His images were not good enough to resolve the rings, and he speculated that he might be seeing a 'triple' system. Years later, he noted that Saturn did look round after all, and was worried about the reliability of his earlier observations (he had no photographs, merely sketches). We now know that it was because he was seeing the rings exactly edge-on, as happens from time to time thanks to the inclination of the orbit of Saturn.

*****

(2 marks) What did Galileo discover about the changing appearance of the planet Venus that led him to conclude that the Sun is the centre of the Solar System? (Use sketches if you can, and contrast the situation with what would have been seen if the Ptolemaic model had been correct.)

If Ptolemy had been right, Venus would always be somewhere between us and the Sun, and we would never see that planet fully lit up – it would show at most only crescent phases. (Consider the left-hand panel in the diagram on the next page.) But if the Sun is the centre of the Solar System, then Venus would sometimes go to the far side of the Sun from our point of view. At such times, Venus would show a fully illuminated face, and also look considerably smaller (as in the right-hand panel in that figure). This is in fact what Galileo observed.


Sun
Earth
Gibbous phase
Sun
Quarter phase
Crescent phase
Earth

III-5: Newton's Contributions

(2 marks) Newton derived his famous Three Laws of Mechanics in an effort to understand how and why things move in response to forces acting on them (in everyday life, not particularly in the realm of astronomy). He had to think carefully about three particular concepts: *inertia; unbalanced forces;* and *acceleration*. Precisely what is meant by each of these, and how are they captured in his first two laws? How does this lead to a *working definition* of the concept of the "mass" of an object?

Inertia is defined as the tendency of an object in any state of motion (including being at rest) to stay in that state of motion unless it is acted on by an *unbalanced force.* This statement is Newton's first law.

An *unbalanced force* means that there is a *net* outside force acting on a body. (If two people push on a car, one from the front and one from the back, it may not move at all because the forces cancel each other – there is no *net* or *unbalanced* force.)

Acceleration means ***any change** in the state of motion of an object* – not only a speeding up! Acceleration is also occurring if an object is *slowing down* or *changing its direction of motion.* An object will accelerate whenever it is acted on by an unbalanced force.

Newton's second law says that an unbalanced force (like a push, say) acting on an object will cause it to accelerate, but introduces the *mass of that object* by noting that there is a certain sluggishness, or *resistance to being accelerated.* That is what we mean by *mass:* more massive objects are harder to set in motion! The mass is not necessarily related to the *size* of the object, but instead depends on how much total material – atoms, etc – the object consists of. (A cannonball is harder to throw than a baseball: it is *more massive.)*

*****

(3 marks) What is meant by the word "weight"? (Contrast a physicist's understanding of that word to its everyday more conversational interpretation.) Under what circumstances does our weight vanish, and why? Your explanation should be in terms of Newton's Third Law. Why are the orbiting astronauts 'weightless' inside the International Space Station? What happens to an astronaut who is just *outside* the ISS but not connected to it?

To a physicist, *weight is a force* – the gravitational pull exerted on an object, like you or me, by some other object (usually the Earth itself). To us, however, weight is *our perception of the upward push that keeps us from falling through the floor in response to that downward pull.* (Newton's Third Law notes that gravity pulls us downward, and as a consequence our bodies are pressing down on the floor; there is an equal and opposite force from the floor acting upward on us, keeping us from falling through it.) Our perception of weight vanishes if we are *falling freely,* even though the downward pull of gravity is still at work.

The astronauts are 'weightless' because the ISS is falling freely towards the Earth (but its rapid sideways motion keeps it from reaching the ground; instead, it follows a repetitive orbital path) and *the same applies to the astronauts, so they 'float' within the ISS.* It does not matter whether they are inside the ISS or outside it, because all objects fall equivalently under the influence of gravity (as Galileo first showed). So even if the astronaut is outside, she and the ISS itself will follow parallel paths through space – she will not 'drift away' from it (unless some other force, like a push by a companion, sets her moving in some new direction).

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(3 marks) Newton considered a 'gedanken' (thought) experiment in which he visualized a cannon being fired at the top of a tall mountain. What did he conclude about the various paths that might be followed by the cannonball as it leaves the cannon? How is that related to Kepler's laws about the planets? Explain how Newton spoke *more generally* about possible paths, with particular reference to *Oumuamua,* a recently-discovered small astronomical object moving past the Sun – one that does *not* obey Kepler's laws, but would have been understood by Newton, thanks to his analysis.

Newton discovered (by applying his three laws and considering the force of gravity) that, depending on the speed with which the cannonball is fired, it would move in an orbit that was elliptical, with the center of the Earth located at one of the foci. (The point of being on the top of a very tall mountain was to eliminate air resistance and to keep the cannonball from actually running into the body of the Earth itself, allowing it to fall freely and continuously.) The ellipse could be short or long, with the Earth at the near or far focus, depending on the speed with which the cannonball was launched; moreover, there was a particular speed that would result in a perfectly circular orbit (a circle being an ellipse of a special sort). So Newton realized that Kepler's laws indicated that the planets were moving around the Sun under the influence of its gravity – nothing more.

Newton also considered objects moving so fast that they would not be 'gravitationally bound' to the Earth – that is, they would have enough energy to *move off to infinite distance,* never to return, gradually slowing down thanks to the Earth's far-reaching [but ever-weakening] gravitational pull. An object with *just enough energy/speed* (the 'escape velocity') would move off along a *parabolic* path. One that had more energy than that would follow a *hyperbolic* path. The recently-found small asteroid Oumuamua is an example of the second of these: it is an object that is not bound to the Sun, one that has fallen in from effectively infinite distance, picking up speed as it does so: it will eventually retreat to the remote depths of space, never to return.

*****

(2 marks) Humans have launched into orbit a great number of artificial satellites, including many that are said to be *geostationary (*or *synchronous).* What is the special use of such satellites, and what do we have to do to ensure that they move in a way that allows them to serve that special purpose?

If we launch a satellite into an equatorial orbit that requires precisely 24 hours to go around the Earth (moving in an Eastward direction), then it will appear to 'hover' directly above a person on the equator because the spin of the Earth keeps that person moving to the East at the same rate. This means that the satellite can serve as an always-present relay station for telecommunication signals (like long-distance phone calls) or for broadcasting uninterrupted TV signals (say) to satellite-dish receivers in people's back yards. Meanwhile, the downward-looking satellite can continuously monitor what is going on 'beneath' it – for example, watching weather systems.

To make this happen, we simply remember Kepler's third law: namely, that a satellite's orbital period depends on its distance from the central body that it is orbiting. The Earth's Moon, very far away, takes a month to orbit us; the International Space Station, just a few hundred km over our heads, takes about 90 minutes. Calculation shows that a satellite that is about 36000 km away (about 10% of the Moon's distance) will have a 24-hour period. All we have to do is launch our satellite into an orbit at that altitude, moving horizontally Eastwards with the appropriate speed.

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-- END OF TEST –