D.5 Further cosmology AHL:

Understanding ➔ The cosmological principle ➔ Rotation curves and the mass of galaxies ➔ Dark matter ➔ Fluctuations in the CMB ➔ The cosmological origin of redshift ➔ Critical density ➔ Dark energy.

Nature of science How constant is the Hubble constant? ...or when is a constant not a constant? The Hubble constant H0 is a quantity that we have used in Subtopic D.3 to estimate the age of the universe. This is a very important cosmological quantity, indicating the rate of expansion of the universe. The current value is thought to be around 70 km s 1 Mpc 1, but it has not always been this value and will not be in the future. So it is a constant in space but not in time and it would be more appropriately named the “Hubble parameter”. The zero subscript is used to indicate that we are talking about the present value of the constant – in general use we should omit the subscript. In the IB Physics course, H0 is used to indicate all values of the Hubble constant.

Applications and skills ➔ Describing the cosmological principle and its role in models of the universe ➔ Describing rotation curves as evidence for dark matter ➔ Deriving rotational velocity from Newtonian gravitation ➔ Describing and interpreting the observed anisotropies in the CMB ➔ Deriving critical density from Newtonian gravitation ➔ Sketching and interpreting graphs showing the variation of the cosmic scale factor with time ➔ Describing qualitatively the cosmic scale factor in models with and without dark energy

Equations ➔ velocity of rotating galaxies: v = √

\_\_\_\_ 4πGρ \_\_\_\_\_\_\_\_\_ 3

r

➔ critical density of universe: ρc = 3H2 \_\_\_\_\_\_\_ 8πG.

Introduction In Sub-topic D.3 we saw that the Big Bang should correspond to the simultaneous appearance of space and time (spacetime). Hubble’s law and the expansion of the universe tell us that the observable universe is certainly larger than it was in the past and that it can be traced back to something smaller than an atom, containing all the matter and energy currently in the universe. There is no special place in the universe that would be considered to be the source of the Big Bang, it expanded everywhere in an identical manner. It is not possible to use the Big Bang model to speculate about what is beyond the observable universe – it should not be thought of as expanding into some sort of vacuous void. In this sub-topic we will consider ways in which the universe might continue to expand and look at possible models for at, open, and closed universes.

Nature of science Philosophy or cosmology? Although there is substantial evidence leading us to believe in the Big Bang model nobody actually knows what instigated the Big Bang. We have explained that this was the beginning of space and time and so we cannot ask “what happened before the Big Bang?” There are a

number of theories that reect on why the Big Bang occurred – such as uctuations in gravity or quantum uctuations but these theories stimulate other questions such as “what caused this?” As of yet these theories cannot be put to the test.

The Cosmological Principle Buoyed up by the success of his general theory of relativity in 1915, Einstein sought to extend this theory to explain the dynamics of the universe or “cosmos”. In order to make headway, because he recognized that this would be a complex matter, he made two simplifying assumptions – these have subsequently been shown to be essentially true on a large scale:

● the universe is homogenous

● the universe is isotropic

The rst of these requirements simply says that the universe is the same everywhere – which, when we ignore the lumpiness of galaxies, it is. The second requirement is that the universe looks the same in all directions. Although this may not seem too different from the homogeneity idea it actually is! It really says that we are not in any special place in the universe – and ties in with the theory of relativity that says there is no special universal reference frame. Imagine that we are positioned towards the edge of a closed universe and we look outward – there would be a limited number of galaxies to send photons to us. If we look inward there would be an immense number of galaxies to send us photons. The two situations would appear very different. The isotropicity says that this isn’t the case. Jointly, these two prerequisites of Einstein’s theory are known as the “Cosmological Principle”. These assumptions underpin the Big Bang cosmology and lead to specic predictions for observable properties of the universe.

Figure 1 shows an image produced by the Automated Plate Measurement (APM) Galaxy survey of around 3 million galaxies in the Southern Hemisphere sky. The image shows short-range patterns but, in line with the cosmological principal, on a large scale the image shows no special region or place that is different from any other.

Using the cosmological principle and the general theory of relativity it can be shown that matter can only distort spacetime in one of three ways. This is conventionally shown diagrammatically by visualizing the impact of the third dimension on a at surface; however, the fourth dimension of time is also involved and this makes visualization even more complex.

● The at surface can be positively curved into a spherical shape of a nite size. This means that, by travelling around the surface of the sphere, you could return to your original position or, by travelling through the universe, you could return to your original position inspacetime.

The at surface can be negatively curved like the shape of a saddle and have an innite size. In this universe you would never return to the same point in spacetime.

● The surface could also remain at and innite as given in our everyday experiences. Again, you would never return to the same position in spacetime.

Knowledge of the amount of matter within the universe is essential when determining which model is applicable. There is a critical density (ρc) of matter that would keep the universe at and innite– this density would provide a gravitational force large enough to prevent the universe running away but just too little to pull it back to its initial state. With less than the critical density the universe would be open and innite. With greater density than the critical value the universe would be closed and nite – with gravity pulling all matter back to the initial state of spacetime. The critical density of matter appears to be no greater than ten particles per cubic metre and current research suggests that the average density is very close to this critical value.

The implications of the density of intergalactic matter As can be seen in gure 5 in Sub-topic D.3, theory suggests that, after the initial inationary period following the Big Bang, the rate of expansion of the universe has been slowing down. Instrumental to the fate of the universe is the uncertainty about how much matter is available to provide a strong enough gravitational force to reverse the expansion and cause a gravitational collapse. As discussed in Sub-topic D.3, data from Type Ia supernovae has suggested that the universe may actually be undergoing an accelerated expansion caused by mysterious “darkenergy”.

We can derive a relationship for the critical density using Newtonian mechanics:

Imagine a homogenous sphere of gas of radius r and density ρ. A galaxy of mass m at the surface of the sphere will be moving with a recessional speed v away from the centre of the sphere along a radius as shown in gure 3.

By Hubble’s law the velocity of the galaxy is given by:

v = H

0 r.

The total energy of the galaxy is the sum of its kinetic energy and its gravitational potential energy (relative to the centre of mass of the sphere of gas).

E

T = E

K

+ E

P

E

T = 1 2

mv2 - G

Mm \_ r

remembering that potential energy is always negative for objects separated by less than innity.

The mass M is that of the sphere of gas is given by

M = 4 \_ 3

πr3ρ

E

T = 1 \_ 2

m(H0r)2 - G

4 3πr3ρm \_ r.

The galaxy will continue to move providing that it has sufcient kinetic energy, thus making ET positive. In the limit ET = 0 this gives

1 \_ 2

m(H0r)2 = G

4 3πr3 ρcm \_ r

where ρc is the critical density of matter. Simplifying this equation gives

ρc = 3H02 \_ 8πG.

Note

● This equation contains nothing but constants. Any value for the critical density of the material of the universe is dependent on how precisely the Hubble constant can be determined.

● A more rigorous derivation of this equation requires the use of general relativity.

The cosmic scale factor and time The ratio of the actual density of matter in the universe (ρ) to the critical density is called the density parameter (indicated in gure 2) and is given the symbol Ω0.

Ω

0

=

ρ \_ ρc

There are three possibilities (shown in gure 4) for the fate of the universe, depending on the density parameter of the universe:

1 If Ω0 = 1 (or ρ = ρc) the density must equal the critical density and must be the value for a at universe in which there is just enough matter for the universe to continue to expand to a maximum limit. However, the rate of expansion would decrease with time. This is thought to be the least likely option.

2 If Ω0 < 1 (or ρ < ρc) the universe would be open and would continue to expand forever.

3 If Ω0 > 1 (or ρ > ρc) then the universe would be closed. It would eventually stop expanding and would then collapse and end with a “Big Crunch”.

An accelerated expansion of the universe (shown by the red line on gure 4) might be explained by the presence of dark energy. This offers an interesting and, increasingly likely, prospect.

In Sub-topic D.3 we considered the cosmic scale factor (R). This isessentially the relative size, or “radius”, of the universe. Figure4 shows how R varies with time for the different density parameters. Each of the models gives an Ω0 value that is based on the total matter in the universe. An explanation for the accelerated universe depends on the concept of the (currently) hypothetical darkenergy outweighing the gravitational effects of baryonic and dark matter.

The cosmic scale factor and temperature The wavelength of the radiation emitted by a galaxy will always be in line with the cosmic scale factor (R). So, as space expands, the wavelength will expand with it. We know from Wien’s law that the product of the maximum intensity wavelength and the temperature is a constant. Assuming that the spectrum of a black body retains its shape during the expansion this means that Wien’s law has been valid from the earliest

times following the Big Bang. Thus, the wavelength and the cosmic scale factor are both inversely proportional to the absolute temperature.

T ∝

1 \_ R (and T ∝ 1 \_ λ ).

Worked example The diagram below shows the variation of the cosmic scale factor R of the universe with timet. The diagram is based on a closed model of the universe. The point t = T is the present time.

a) Explain what is meant by a closed universe

b) On a copy of the diagram, draw the variation based on an open model of the universe.

c) Explain, by reference to your answer to b), why the predicted age of the universe depends upon the model of the universe chosen.

d) (i) What evidence suggests that the expansion of the universe is accelerating?

(ii) What is believed to be the cause of the acceleration? Solution a) A closed universe is one that will stop expanding at some future time. It will then start to contract due to gravity.

The graph should start at an early time (indicating an older universe) and touch the closed universe line at T. It should show curvature but not atten out as a at universe would do.

c) We only know the data for the present time so all curves will cross at T. By tracing the curve back to the time axis, we obtain the time for the Big Bang. This extrapolation will give a different time for the different models.

d) (i) The redshift from distant type Ia supernovae has suggested that the expansion of the universe is now accelerating.

(ii) The cause of this is thought to be dark energy – something of unknown mechanism but opposing the gravitational attraction of matter (both dark and baryonic).

Evidence for dark matter

Let us imagine a star of mass m near the centre of a spiral galaxy of total mass M. In this region the average density of matter is ρ. The star moves in a circular orbit with an orbital velocity v and radius r. By equating Newton’s law of gravitation to the centripetal force we obtain

G

Mm \_ r2

=

mv2 \_ r

Cancelling m and r

G

M \_ r = v2.

In terms of the density and taking the central hub to be spherical, this gives

G

4 3πr3ρ \_ r = v2 This means that v = √

\_\_\_\_\_ G4πρ \_ 3

r or v = constant × r

From this we can see that the velocity is directly proportional to the radius.

What if the star is in one of the less densely populated arms of the galaxy? In this case we would expect the star to behave in a similar manner to the way in which planets rotate about the Sun. The galaxy would behave as if its total mass was concentrated at its centre; the stars would be free to move with nothing to impede their orbits. This gives

G

M \_ r = v2

and so

v ∝

1 \_ √r.

When the rotational velocity is plotted against the distance from the centre of the galaxy, we would expect to see a rapidly increasing linear section that changes to a decaying line at the edge of the hub. This is shown by the broken line in gure 6. What is actually measured (by measuring the speed from the redshifts of the rotating stars) is the upper observed line. This is surprising because this “at” rotation curve shows that the speed of stars, far out into the region beyond the arms of the galaxy, are moving with essentially the same speed as those well inside the galaxy. One explanation for this effect is the presence of dark matter forming a halo around the outer rim of the galaxy (as shown in gure6). This matter is not normal “luminous” or “baryonic” matter and emits no radiation and, therefore, its presence cannot be detected.

In gure 8, the experimental curve has been modelled by assuming that the halo adds sufcient mass to that of the galactic disc. This maintains the high rotational speeds well away from the galactic centre.

Other evidence for the presence of dark matter comes from:

● the velocities of galaxies orbiting each other in clusters – these galaxies emit far less light than they ought to in relation to the amount of mass suggested by their velocities

● the gravitational lensing effect of radiation from distant objects (such as quasars) – because the radiation passes through a cluster of galaxies it becomes much more distorted than would be expected by the luminous mass of the cluster

● the X-ray images of elliptical galaxies show the presence of haloes of hot gas extending well outside the galaxy. For this gas to be bound to the galaxy, the galaxy must have a mass far greater than that observed – up to 90% of the total mass of these galaxies is likely to be dark matter.

At the moment no one knows the nature of dark matter but there are some candidates:

● MACHOs are MAssive Compact Halo Objects that include black holes, neutron stars, and small stars such as brown dwarfs. These are all high density (compact) stars at the end of their lives and might be hidden by being a long way from any luminous objects. They are detected by gravitational lensing, but it is questionable whether or not there are sufcient numbers of MACHOs to be able to provide the amount of dark matter thought to be in the universe.

● WIMPs are Weakly Interacting Massive Particles – subatomic particles that are not made up of ordinary matter (they are non-baryonic). They are weakly interacting because they pass through ordinary, baryonic, matter with very little effect. Massive does not mean “big”, it means that these particle have mass (albeit very small mass). To produce the amount of mass needed to make up the dark matter there would need to be

unimaginably large quantities of WIMPs. In 1998, neutrinos with very small mass were discovered and these are possible candidates for dark matter; other than this the theory depends on hypothetical particles called axions and neutralinos that are yet to be discovered experimentally.

Dark energy In 1998, observations by the Hubble Space Telescope (HST) of a very distant supernova showed that the universe was expanding more slowly than it is today. Although nobody has a denitive explanation of this phenomenon its explanation is called “dark energy”. ESA’s Planck mission has provided data that suggest around 68% of the universe consists of dark energy (while 27% is dark matter leaving only 5% as normal “baryonic” matter – see gure 9).

It has been suggested that dark energy is a property of space and so, with the expansion of the universe as space expands, so too does the amount of dark energy, i.e. more dark energy coming into existence along with more space. This form of energy would subsequently cause the expansion of the universe to accelerate. Nobody knows if this model is viable. It is possible that an explanation for the accelerated expansion of the universe requires a new theory of gravity or a modication of Einstein’s theory – such a theory would still need to be able to account for all the phenomena that are, at the moment, correctly predicted by the current theory.

The Dark Energy Survey (DES) With dark energy being one of the most upto-the-minute research topics in the whole of science, it is unsurprising that international collaboration is prolic. The DES is a survey with the aim of gaining the best possible data for the rate of expansion of the universe. This is being carried out by observing around 3000 distant supernovae, the most distant of which exploded when the universe was about half

its current size. Using the Victor M. Blanco Telescope at Cerro Tololo Inter-American Observatory (CTIO) in Chile, 120 collaborators from 23 institutions in 5 countries are using a specially developed camera to obtain images in the near infra-red part of the visible spectrum. The survey will take ve years to complete and will add to the sky-based research of missions such as WMAP and Planck.

Anisotropies in the CMB In Sub-topic D.3 we discussed the importance of the cosmic microwave background with regard to the Big Bang. In this model, the universe came into being almost 13.8 billion years ago when its density and temperature were both very high (this is often referred to as the hot Big Bang). Since then the universe has both expanded and cooled. The Planck satellite image in Sub-topic D.3, gure 4 showed that, although the CMB is essentially isotropic, there are minute temperature uctuations; these variations are called anisotropies. In the early 1990s, the Cosmic Background Explorer (COBE) satellite provided the rst evidence of these anisotropies but, with the launch of NASA’s WMAP in 2001 and the ESA’s Planck satellite in 2009, the resolution has been improved dramatically. Both these missions have shown signicant low-level temperature uctuations. It is thought that these uctuations appear as the result of tiny, random variations in density, implanted during cosmic ination – the period of accelerated expansion that occurred immediately after the Big Bang.

When the universe was 380 000 years old and became transparent, the radiation emitted from the Big Bang was released and it has travelled outwards through space and time, including towards the Earth. This radiation was in the red part of the electromagnetic spectrum when it was released, but its wavelength has now been stretched with the expansion of the universe so that it corresponds to microwave radiation. The pattern shown in the variation demonstrates the differences present on the release of the radiation: uctuations that would later grow into galaxies and galaxy clusters under the inuence of gravity.

The information extracted from the Planck sky map shows isotropy on a large scale but with a lack of symmetry in the average temperatures in opposite hemispheres of the sky. The Standard Model suggests that the universe should be isotropic but, given these differences, this appears not to be the case. There is also a cold spot (circled in Sub-topic D.3, gure 4) extending over a patch of sky and this is larger than WMAP had previously shown. The concepts of dark matter and dark energy have already been added to the Standard Model as additional parameters. The evidence from the CMB anisotropies may require further tweaks to the theory or even a major re-think because of this.

The Planck data also identify the Hubble constant to be 67.15 km s 1 Mpc 1 (signicantly less than the current standard value in astronomy of around 100 km s 1 Mpc 1). The data imply that the age of the universe is 13.82 billion years. Over the next few years this value may well be modied because of additional data being collected by this mission and from orbiting telescopes – including the James Webb space telescope (gure 10) and the joint NASA/ESA Euclid mission. There has, arguably, never been a more productive time in the history of cosmology.

Questions

1 (IB)

a) The star Wolf 359 has a parallax angle of 0.419 arcsecond. (i) Describe how this parallax angle is measured. (ii) Calculate the distance in light-year from Earth to Wolf 359. (iii) State why the method of parallax can only be used for stars at a distance less than a few hundred parsecond from Earth. b) The ratio apparent brightness of Wolf 359 \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ apparent brightness of the Sun is 3.7 × 10 15

Show that the ratio

luminosity of Wolf 359 \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ luminosity of the Sun is 8.9 × 10 4. (11 marks)

2 The average intensity of the Sun’s radiation at the surface of the Earth is

1.37 × 10

3 W m 2. Calculate (a) the luminosity and (b) the surface temperature of the Sun.

The mean separation of the Earth and the Sun = 1.50 × 10

11 m, radius of the Sun = 6.96 × 10

8 m, Stefan–Boltzmann constant = 5.67 × 10 8 W m 2 K 4. (4 marks)

3 (IB)

The diagram below is a ow chart that shows the stages of evolution of a main sequence star such as the Sun. (Mass of the Sun, the solar mass = M ⊙)

main sequence star mass ≈ M ⊙

red giant nebula

planetary nebula

white dwarf

a) Copy nad complete the boxes below to show the stages of evolution of a main sequence star that has a mass greater than 8 M ⊙

main sequence star mass >8 M ⊙

b) Outline why: (i)

white dwarf stars cannot have a greater mass than 1.4 M ⊙ (ii) it is possible for a main sequence star with a mass equal to 8 M ⊙ to evolve into a white dwarf. (6 marks)

4 (IB)

a) Dene luminosity

b) The sketch-graph below shows the intensity spectrum for a black body at a temperature of 6000 K.

5 (IB)

The diagram below shows the grid of a Hertzsprung Russell (HR) diagram on which the positions of the Sun and four other stars A, B, C and D are shown.

106

A

C

Sun

B

D

104

102

10 2

10 4

10 6

25 000

10 000 surface temperature (T/K) 8000 6000 5000 4000 3000

1

luminosity (L) (Sun L= 1)

a) Name the type of stars shown by A, B, C, and D. b) Explain, using information from the HR diagram and without making any calculations, how astronomers can deduce that star B is larger than star A. c) Using the following data and information from the HR diagram, show that star B is at a distance of about 700 pc from Earth. Apparent brightness of the Sun = 1.4 × 10

3 W m 2

Apparent brightness of star B = 7.0 × 10 8 W m 2

Mean distance of the Sun from Earth = 1.0 AU

1 parsec = 2.1 × 10

5 AU (11 marks)

6 (IB) a) State what is meant by cosmic microwave background radiation b) Describe how the cosmic microwave background radiation provides evidence for the expanding universe. (5 marks)

7 (IB)

a) In an observation of a distant galaxy, spectral lines are recorded. Spectral lines at these wavelengths cannot be produced in the laboratory. Explain this phenomenon. b) Describe how Hubble’s law is used to determine the distance from the Earth to distant galaxies. c) Explain why Hubble’s law is not used to measure distances to nearby stars or nearby galaxies (such as Andromeda). (6 marks)

8 (IB)

One of the most intense radio sources is the Galaxy NGC5128. Long exposure photographs show it to be a giant elliptical galaxy crossed by a band of dark dust. It lies about 1.5 × 10

7 light years away from Earth.

a) Describe any differences between this galaxy and the Milky Way. Hubble’s law predicts that NGC5128 is moving away from Earth. b) (i)

State Hubble’s law. (ii) State and explain what experimental measurements need to be taken in order to determine the Hubble constant. c) A possible value for the Hubble constant is 68 km s 1 Mpc 1. Use this value to estimate: (i)

the recession speed of NGC5128 (ii) the age of the universe. (10 marks)

9 a) Describe what is meant by a nebula b) Explain how the Jeans criterion applies to star formation. (3 marks)