PH5 Pre-release Materials[1]

Joe Rowing

24 April 2016

[1] Freely modified from various Wikipedia pages and annotated by Joe Rowing

This document adds to the pre-release materials from WJEC and hopefully illustrates some suitable questions.

The Big Bang Theory

1

The Big Bang theory is the prevailing cosmological model for the early development of the universe. The key idea is that the universe is expanding. Consequently, the universe was denser and hotter in the past [2]. Moreover, the Big Bang model suggests that at some moment all matter in the universe was contained in a single point, which is considered the beginning of the universe. Modern measurements place this moment at approximately 13.8 billion years ago, which is thus considered the age of the universe. After the initial expansion, the universe cooled sufficiently to allow the formation of subatomic particles, including protons, neutrons, and electrons. Though simple atomic nuclei formed within the first three minutes after the Big Bang, thousands of years passed before the first electrically neutral atoms formed. The majority of atoms produced by the Big Bang were hydrogen, along with helium and traces of lithium (see figure 1)

. Giant clouds of these primordial elements later coalesced through gravity to form stars and galaxies, and the heavier elements were synthesized either within stars or during supernovae.

The Big Bang theory offers a comprehensive explanation for a broad range of observed phenomena, including the abundance of light elements, the cosmic microwave background radiation (CMBR), large scale structure, and Hubble's Law. Today, the distances between galaxies is increasing hence, in the past, galaxies were closer together. The known laws of nature can be used to calculate the characteristics of the universe in detail back to a time when densities and temperatures were extreme. While large particle accelerators can replicate such conditions, resulting in confirmation and refinement of the details of the Big Bang model, these accelerators can only probe so far into high energy conditions. Consequently, the state of the universe in the earliest instants of the Big Bang expansion is poorly understood and still an area of open investigation. The Big Bang theory does not provide any explanation for the initial conditions of the universe; rather, it describes and explains the general evolution of the universe going forward from that point on[3]. Belgian Catholic priest

[2] Olbers' paradox, also called the "dark night sky paradox", is worth noting here - it's the argument that the darkness of the night sky conflicts with the assumption of an infinite and eternal static universe. The darkness of the night sky is one of the pieces of evidence for a dynamic universe such as the Big Bang model. If the universe is static, homogeneous at a large scale, and populated by an infinite number of stars, any sight line from Earth must end at the (very bright) surface of a star, so the night sky should be completely bright. This contradicts the observed darkness of the night.

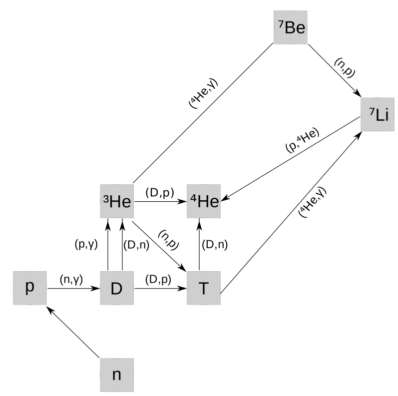

Figure 1: Big Bang Nucleosynthesis took place via twelve nuclear interactions that produced three isotopes of hydrogen, two of helium, and one isotope each of lithium and beryllium. Presumably the Be-7 that was produced is not mentioned here because it has a halflife of only 53d. Free neutrons were also produced, but their half-life is even shorter, at only 10.6min

2

[3] It is tempting to ask what came"before the Big Bang", but the Big Bang was both the creation of space and time, so this is a bit like asking what colour physics is.

3

and scientist Georges Lemaitre proposed what became the Big Bang theory [4] in 1927. Over time, scientists built on his initial idea of cosmic expansion, which, his theory went, could be traced back to the origin of the cosmos and which led to the formation of the modern universe. The framework for the Big Bang model relies on Albert Einstein's theory of general relativity and on simplifying assumptions such as homogeneity and isotropy of space. In 1929, Edwin Hubble discovered that the distances to faraway galaxies were strongly correlated with their red shifts. Hubble's observation was taken to indicate that all distant galaxies and clusters have an apparent velocity directly away from our vantage point: that is, the farther away, the higher the apparent velocity, regardless of direction. The interpretation is that all observable regions of the universe are receding from each other. While the scientific community was once divided between supporters of two different expanding universe theories - the Big Bang and the Steady State theory - observational confirmation of the Big Bang scenario came with the discovery of the CMBR in 1964, and later when its spectrum was found to match that of thermal radiation from a black body. **4**

[4] English astronomer Fred Hoyle is credited with coining the term "Big Bang" during a 1949 BBC radio broadcast. It is popularly reported that Hoyle, who favoured an alternative "steady state" cosmological model, intended this to be pejorative, but Hoyle explicitly denied this and said it was just a striking image meant to highlight the difference between the two models

The History of the Universe

Inflation

The earliest phases of the Big Bang are subject to much speculation. **5** In the most common models the universe was filled homogeneously[5] and isotropically[6] with an incredibly high energy density and huge temperatures and pressures and was very rapidly expanding and cooling. Approximately 10^{-37} seconds into the expansion, a phase transition caused a cosmic inflation, during which the universe grew exponentially. After inflation stopped, the universe consisted of a quark-gluon plasma, as well as all other elementary particles. Temperatures were so high that the random motions of particles were at relativistic speeds, and particle-antiparticle pairs of all kinds were being continuously created and destroyed in collisions. At some point baryogenesis, a reaction that we know little about, violated the conservation of baryon number, leading to a very small excess of quarks and leptons over antiquarks and antileptons - of the order of one part in 30 million. This resulted in the predominance of matter over antimatter in the present universe.

[5] Uniform in structure or composition throughout, as of a chemical mixture.

[6] To exhibit the same properties or behaviour in all directions

Protons Forming

The universe continued to decrease in density and fall in temperature, hence the typical energy of each particle was decreasing. After **6**

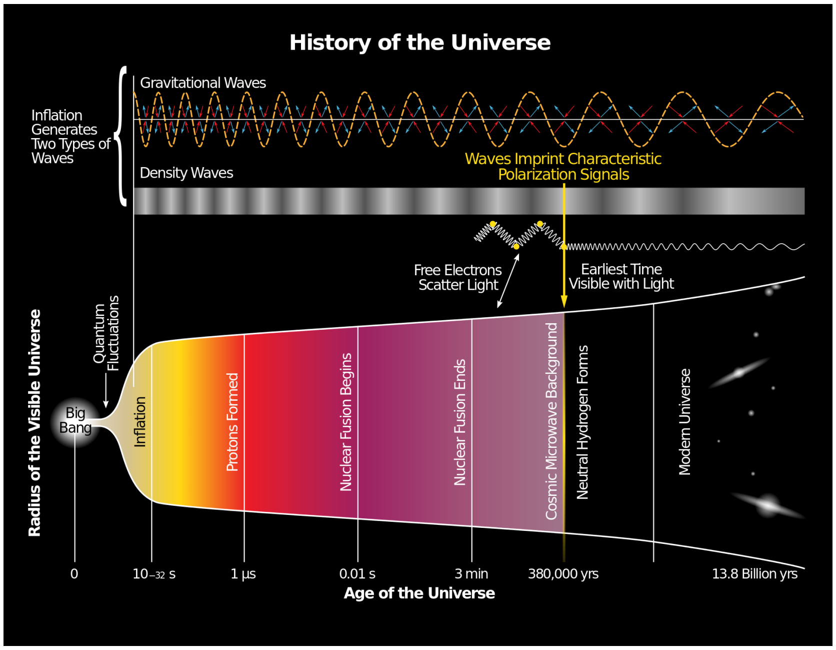

Figure 2: History of the Universe

about 10^{-11} seconds, the picture becomes less speculative, since particle energies drop to values that can be attained in particle physics experiments. At about 10^{-6} seconds, quarks and gluons combined to form baryons such as protons and neutrons. The small excess of quarks over antiquarks led to a small excess of baryons over antibaryons. The temperature was now no longer high enough to create new proton-antiproton pairs (similarly for neutrons-antineutrons), so a mass annihilation immediately followed, leaving just one in 10^{10} of the original protons and neutrons, and none of their antiparticles. A similar process happened at about 1 second for electrons and positrons. After these annihilations, the remaining protons, neutrons and electrons were no longer moving relativistically and the energy density of the universe was dominated by photons (with a minor contribution from neutrinos).

Nuclear Fusion Begins and Ends

A fraction of a second into the expansion, when the temperature 7
was about a hundred billion kelvin (100 GK), neutrons combined with protons to form the universe's deuterium and helium nuclei in a process called Big Bang nucleosynthesis. However, around 3 minutes after the Big Bang the universe had cooled further so that fusion was no longer possible. The Big Bang theory itself predicts mass abundances of about 75% of hydrogen-1, about 25% helium-

4, about 0.01% of deuterium,[7] trace amounts (in the order of 10^{-10}) of lithium and beryllium, and no other heavy elements[8]. That the observed abundances in the universe are generally consistent with these abundance numbers is considered strong evidence for the Big Bang theory.

[7] Question Expect a question on binding energy

[8] Question Descrive how the heavier elements are formed

The Universe Becomes Transparent

After about 380 000 years the universe cooled to a temperature of 8
around 3 000 K. The electrons and nuclei combined into atoms (mostly hydrogen). This meant that radiation could travel freely without forcing free charges to oscillate and continued through space largely unimpeded. This relic radiation is known as the CMBR. It is frequently stated that the CMBR that is detected today started as gamma radiation shortly after the Big Bang. This is not strictly true because these photons were scattered and absorbed a long time ago. The CMBR that we can detect now started as mainly infra-red radiation 380 000 years after the Big Bang when the universe suddenly became transparent. Although the universe previously had been hot enough to emit gamma rays (as a black body radiator), this radiation was not able to travel very far.

The Modern Universe and The Big Bang Theory

In today's universe, the earliest and most direct observational evi- 9
dence of the validity of the theory are the expansion of the universe according to Hubble's law (as indicated by the red shifts of galaxies), discovery and measurement of the CMBR and the relative abundances of light elements produced by Big Bang nucleosynthesis. More recent evidence includes observations of galaxy formation and evolution, and the distribution of large-scale cosmic structures. These are sometimes called the "four pillars" of the Big Bang theory. Ob- 10
servations of distant galaxies and quasars show that these objects are red shifted - the light emitted from them has been shifted to longer wavelengths.

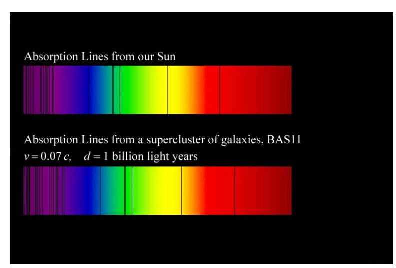

Figure 3: redshift

[9] This can be seen by taking a frequency spectrum of an object and matching the spectroscopic pattern of emission lines or absorption lines corresponding to atoms of the chemical elements interacting with the light. These red shifts are distributed evenly among the observed objects in all directions. If the red shift is interpreted as a Doppler shift, the recessional velocity of the object can be calculated. When the recessional velocities are plotted against these distances, a linear relationship known as Hubble's law is observed:

[9] Doppler's formula, $\frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}$, links the frequency shift with the velocity of the source

$$v = H_0 D \qquad \text{(Equation 1)}$$

where:

- v is the recessional velocity of the galaxy or other distant object;
- D is the distance to the object;
- H_0 is the Hubble constant [10], measured to be $2.2685 \times 10^{-18}\,\mathrm{s}^{-1}$.

If Hubble's law, $v = H_0 D$, is combined with a simple calculation for the escape velocity from a spherical universe, the so-called critical density of the universe can be calculated:

$$\frac{1}{2}mv_{esc}^2 - \frac{GMm}{R} = 0 \qquad \text{(Equation 2)}$$

where v_{esc} is the escape velocity of an arbitrary mass, m, which is a distance, R, from the 'centre' of the universe and M is the mass of the universe contained inside the sphere of radius R (upon whose surface the arbitrary mass lies). When the volume of the sphere of radius R is also included, this leads to:

$$\rho_c = \frac{3H_0^2}{8\pi G} \qquad \text{(Equation 3)}$$

The critical density, ρ_c , [11] of the universe can be calculated from this equation and corresponds to 5 hydrogen atoms per cubic metre. Not only can we calculate a mean density for the modern universe, we can also calculate a mean temperature. From the CMBR, if the universe is assumed to be a black body then a temperature of 2.725 ± 0.001K is obtained. Moreover, the microwave spectrum follows a perfect black body spectrum shape. See Figure 4

[10] H_0, the Hubble constant, is one of the least well-known of the physical constants; at various points it has been estimated to be anywhere between $50 - 90 kms^{-1}pc{-}1$. The value with the lowest error is currently that of the Planck Collaboration (see http://arxiv.org/abs/1303.5062): $(67.2 \pm 1.2) kms^{-1}pc^{-1}$

11

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[11] If the density of matter in the Universe is high (a closed Universe), self-gravity slows the expansion until it halts, and ultimately re-collapses. If the density of matter in the Universe is low (an open Universe), self-gravity is insufficient to stop the expansion, and the Universe continues to expand forever (albeit at an ever decreasing rate). Balanced on a knife edge between Universes with high and low densities of matter, there exists a critical density Universe, where the expansion is halted only after an infinite time. The density parameter is usually used to make comparisons between these models and is defined as:

$$\Omega \equiv \frac{\rho}{\rho_c} = \frac{8\pi G\rho}{3H^2}$$

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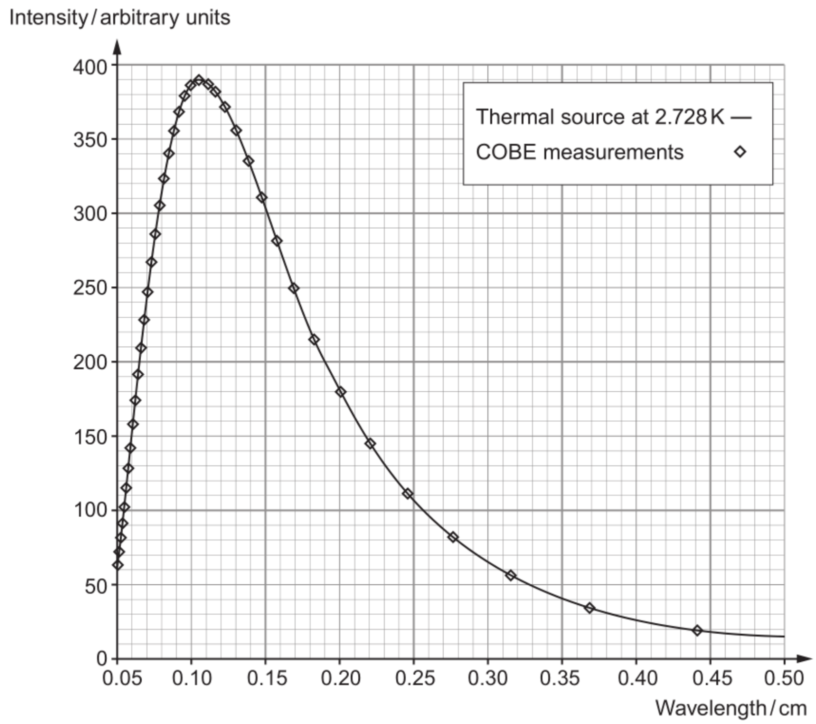

Figure 4: Comparison between the predicted spectrum of the cmbr (line) and the spectrum as measured by cobe (diamonds).

Since the early 1980s more and more evidence for larger scale order of matter in the universe has been discovered. Stars are organised into galaxies, which in turn form galaxy groups, galaxy clusters, super-clusters, sheets, walls and filaments, which are separated by immense voids, creating a vast foam-like structure sometimes called the "cosmic web". All these enormous scale structures have been simulated by computer and all seem to agree with the Big Bang theory. . . **14**

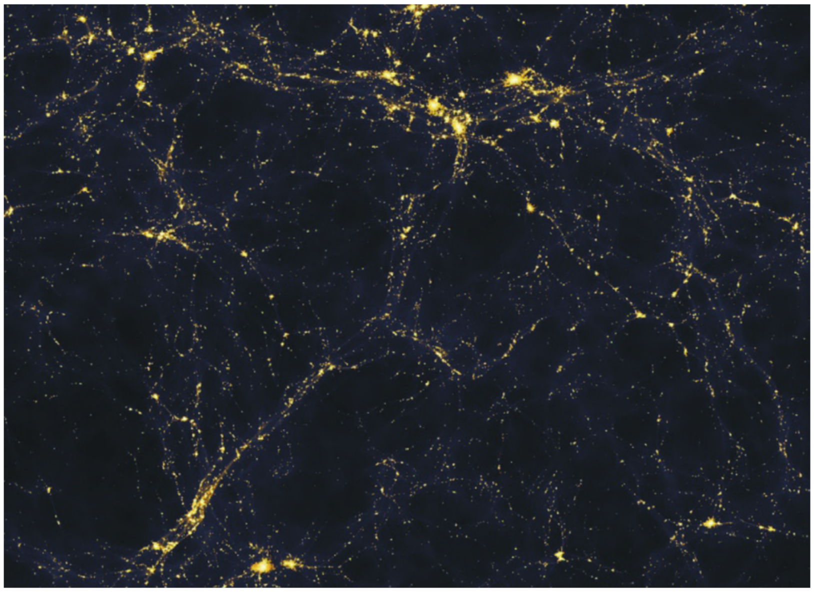

Figure 5: Cosmic Web

Practice Questions:

Where necessary, use the values for constants provided in the wjec formula booklet

1. Explain the following terms in your own words:
   (a) cosmic microwave background radiation
   (b) redshift
   (c) homogeneity (as it applies in this context)
   (d) black body
   (e) inflation
   (f) annihilation
   (g) relativistic speeds
   (h) baryogenesis
   (i) quark
   (j) lepton
   (k) gluon
   (l) quasar
   (m) Hubble constant
   (n) Doppler shift
   (o) recessional velocity
   (p) escape velocity
   (q) critical density
   (r) galactic supercluster

2. What limits our ability to simulate conditions in the earliest moments of the Big Bang?
3. What is the minimum energy is required to cause a proton-antiproton pair creation event?
4. In Big Bang nucleosynthesis there are two processes by which neutrons interact to create protons:

$$n + e^+ \leftrightarrow v_e + p$$

$$n + \bar{v}_e \leftrightarrow p + e^-$$

Show that both of these processes conserve charge, baryon number and lepton number.

5. The cmbr has a black body temperature of $(2.725 \pm 0.001)K$.
   (a) What is the peak frequency of the radiation emitted by the cosmic microwave background?
   (b) What is the uncertainty in this frequency?
   (c) What would the peak wavelength be at 380000yr after the Big Bang, and in which part of the electromagnetic spectrum would this lie?
6. Describe the structure of baryons, and give three examples.
7. Why did the Universe become transparent?
8. A bright sodium line at 589.995nm is observed from the smaller star of a binary system to be oscillating between 678.789nm and 678.200nm.
   (a) At what speed is the binary system moving away from Earth?
   (b) At what speed is the smaller star orbiting the larger star?
9. Edwin Hubble's first value for the Hubble constant was $500kms^{-1}Mpc^{-1}$.
   (a) Show that the standard unit for the Hubble constant ($kms^{-1}Mpc^{-1}$) has the same units as the unit quoted in the text (s^{-1}).
   (b) Convert Hubble's first value of the Hubble constant to s^{-1}.
10. Using the value of H_0 provided, calculate the recessional velocity (as a fraction of the speed of light) of the quasar 3C 273 which lies 2.443 gigalightyears from Earth.
11. Using your existing knowledge of gravitational fields:
    (a) Derive Equation 2.
    (b) Derive Equation 3.
12. Calculate the critical density of the Universe in kgm^{-3} and show that this is approximately "5 hydrogen atoms per cubic metre".