Modelling the Universe

OCR Physics A Module 5
for 2016 exam

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5.5.1 Structure of the universe

The Universe

The universe consists of approximately 100 billion **galaxies**, each containing approximately 100 billion stars. It also contains **energy** in the form of **electromagnetic radiation**.

The Solar System

The solar system consists of the Sun, planets, planetary satellites and comets.
The Sun is an average star, approximately 5 billion years old and is approximately half way through its life.
The planets and the comets orbit the Sun.
The planets have near-circular orbits, but the comets generally follow elliptical orbits.
Planetary satellites (aka moons) orbit planets, rather than the Sun.
The Sun is much more massive than all the rest of the solar system put together.

Formation of a star

All stars are formed from **interstellar dust and gas**.
A large lump of interstellar dust and gas contracts under its own **gravity**.
As the PE of the system decreases, its KE and therefore **temperature** increases.
If the lump of gas and dust is large enough, then the temperature and the pressure at the centre rises to such a high value that it "**ignites**" and a process of **nuclear fusion** starts.
From this point on, the new-born star spends a very long time, an average of about 10 billion years, **fusing hydrogen into helium** and producing tremendous amounts of **energy** that causes it to **shine**.

A star in this state is called a **main sequence** star. Most stars in the sky are in this state.
A star spends most of its life, more than 90%, in this state and then dies rather quickly.
Important: The only source of a main-sequence star's energy is nuclear fusion in its core (hydrogen fuses to helium releasing large amounts of energy).

Death of a star

Throughout the life of a star there is a battle between **gravity** and **pressure**. Gravity wins in the end, **core collapse** occurs, and the star dies.
Gravity pulls towards the centre, aka **core**, of the star.
Nuclear fusion is taking place at the core creating **thermal pressure** and radiation pressure, both of which push outward and balance the gravitational force. During the lifetime of the star these opposing forces are in equilibrium.
As hydrogen which is star's nuclear fuel runs out, the outward force produced by pressure reduces, gravity begins to win and the star starts to collapse. What happens next depends entirely on the **mass** of the star.
If the star is about the size of the Sun or less, (we say 1 **solar mass** or less) then the star ends up as a **white dwarf**.
A **bigger** star will end up as a **neutron star**.
If the star is **bigger still**, it will end up as a **black hole**.

Final stages of a star

For stars of one solar mass or less:

Towards the end of its life, the Sun swells up to become a **red giant**, cooler and much larger than at present, engulfing Earth's orbit.
Then it will throw off its outer layer of gas, and the core will contract to form a white dwarf.
Finally, as there is no source of energy, it cools and fades away to a **dark remnant**.
All stars of one solar mass or less will end up in this way.

For stars of more than one solar mass:

Towards the end of its life, the star swells up greatly to become a **super red giant**.
Then it will throw off its outer layer of gas, and due to greater gravitational force, the core will contract much further, and then explode as a **supernova**.
The extremely dense collapsed core becomes a **neutron star**.

For stars of still greater mass:

Same as above, but the extremely dense collapsed core becomes a **black hole**.

Astronomical units of distance

Astronomers and cosmologists do not always use SI units (m) to measure distances. This is due to historical reasons and unfortunate, but we have to live with it and get used to it. For your A2 exam you need to be familiar with three units of distance: **Parsec (pc)**; **Light-year (ly)**; and

Astronomical Unit (AU). You need to learn the definitions as given below, and the approximate value in metre.

Astronomical Units (AU)

Is defined as the average distance between the Earth and the Sun; ~1.5×10^{11} m

Parsec (pc)

Is defined as the distance of an object whose parallax is 2 seconds of arc; ~3×10^{16} m
FYI: Parsec stands for PARallax SECond.

Light-year (ly)

Is defined as the distance travelled by light in one year; ~9×10^{15} m

Olbers' "paradox"

The "paradox" itself

Suppose the Universe is:

Infinite and

Static (meaning stars and galaxies are stationary, the Universe is not expanding, or changing in any way, as time increases.) and

Uniform (*This* part of the Universe is practically the same as *that* part).

Now, divide the Universe into shells, like an onion, with the Earth at the centre.

As we go from the Earth out into space, the volume of the shell at distance *r,* and therefore the number of stars in that shell, **increases** as r^2. So, the amount of light available from the shell increases as r^2.

But the quantity of light reaching the Earth from each star **falls** as r^2.

Therefore, here on Earth, we receive a **constant** quantity of light from **every** shell (layer of the "onion"). So, if the assumptions are true, then there are an infinite number of shells and the night sky should be **infinitely bright!**

The interpretation of the "paradox"

We know that the night sky is not infinitely bright, therefore our assumptions must be incorrect. In particular, the Universe cannot be infinite as suggested by Isaac Newton.

The Cosmological Principle

States that the Universe is generally **uniform** in all respects. Regions close to us are similar to regions far away from us.

If this assumption is not true, then we can say nothing about regions of space that are far away from us. We can only know what is happening in the vicinity of the Earth.

Hubble's redshift observations

Edwin Hubble studied the line spectra from galaxies and stars. He found that the **pattern** of the spectra were **exactly** the **same** as the **emission spectra** we obtain from gases on Earth, most commonly hydrogen, but **shifted** towards **longer** wavelengths (hence the term **red** shift, as red has high wavelength). He suggested that **all** galaxies and stars in the Universe were receding (going away) from us and the red shift is due to the Doppler effect that this creates.

Using the equation $\Delta\lambda/\lambda = v/c$

The following formula applies to red shift:

$\Delta\lambda/\lambda = v/c$

where λ is the wavelength, v is the speed at which the galaxy or star is receding, and c is the speed of light in vacuum.

[Let them do a question using this equation. Star emits green 550 nm, recedes at .024*c*. Calc observed wavelength. Answer: 563 nm.]

Hubble's law

[KL to explain "Standard candle" and the Cepheid variables aurally.]

States that speed of recession is proportional to distance.

Mathematically

$v \propto x$ or $v = H_o x$

Where v = speed of recession, H_o Hubble's constant, and x = distance to galaxy or star

Note 1: Red shift is easy to measure, distance is difficult. Hubble used Cepheid variables to measure the distance to the galaxy.

For a Cepheid variable, the pulsation period (easy to observe) allows luminosity to be calculated and luminosity allows distance to be calculated. This is what Hubble used.

Note 2: Hubble concluded that the Universe is **expanding** — everything is moving away from everything else, not just from the Earth.

Note 3: Hubble's conclusion that the Universe is expanding breaks one of Olbers' assumptions—that the Universe is static. Distant stars are receding from the Sun very fast and the resulting red shift is sufficient to increase the wavelength of their light to infrared which is invisible. This is one of the reasons why the sky is dark at night.

The age of the Universe

Comparing $v = H_o x$ with $v = (1/t)x$, it is reasonable (and can be shown to be valid) to suppose that $H_o = (1/t)$, where t is the **age of the Universe**. We have:

age of the Universe = $1/ H_o$ approximately

Current best estimate for H_o is 71 km s^{-1} Mpc^{-1}
giving the age of the Universe as approximately 13 billion years.

Converting the Hubble constant to s^{-1}

The Hubble constant H_o is usually given in its conventional units of km s^{-1} Mpc^{-1}. You need to be able to convert this to SI units of s^{-1}.

Example Given that H_o = 71 km s^{-1} Mpc^{-1}, find a value for H_o in SI units.
Solution We have: 1 pc = 3×10^{16} m, therefore, 1 Mpc = 3×10^{22} m. Also, 71 km = 71 000 m.
We get: 71 km s^{-1} Mpc^{-1} = (71 000 m s^{-1})/(3×10^{22} m) = 2.4×10^{18} s^{-1}

The significance of the 3K microwave background radiation

Introduction We believe that the Universe started from a **single point** mainly for three reasons: **Hubble's work** (the Universe is expanding, so extrapolating *back* in time, it must have started from a single point), the **microwave background radiation** (aka the Cosmic Microwave Background, the CMB), and the **chemical composition** of the Universe.

The CMB When we look at the sky from the Earth, regardless of the direction in which we look, we see a microwave "light" in the sky. Of course, microwave radiation cannot be seen with the naked eye—we "see" it with microwave telescopes. Where does this microwave radiation come from? When we look, or point a telescope, at a star we receive some radiation. That is understandable—the star produces the radiation. But the CMB is there, *any* direction we look, including *in between* the stars and galaxies. What "produces" the CMB? To investigate further, we sent up two satellites dedicated to looking at the CMB. The first was **COBE** (the COsmic Background Explorer) by NASA, and the second was **Planck Spacecraft** by the ESA (European Space Agency). These satellite telescopes have produced a complete and detailed map of the CMB.

The significance of the 3K CMB Is that it provides strong evidence in favour of the **big bang theory** and against the **steady-state theory**.

Reason Calculations based on the big bang theory predict the **existence** of the CMB and at the **observed temperature** (of 2.7 K). The fact that observation fits theoretical predictions so well is strong evidence in favour of the big bang theory. The steady-state theory does not predict the existence of the CMB.

Reason in more depth As time has passed since the big bang and the universe has expanded, the gamma ray radiation of the time of big bang has increased in wavelength and reached the microwave region of the em spectrum that we observe today.

Summary of big bang theory

Big bang theory: The universe began 13–14 billion years ago from a single point and was very hot and very dense.

Observations that support the big bang theory:

1. All galaxies are observed to to be moving away from each other (this was first observed by Edwin Hubble). Extrapolating back in time, they should have all started from a single point some time in the past.
2. The existence of Microwave Background Radiation at the predicted temperature of 2.7 K.
3. The chemical composition of the universe, in particular the existence of hydrogen, helium, lithium and other light elements in quantities predicted by the big bang theory.

FYI The first people who predicted that the 'remains' of the very short wavelength radiation present at the time of the big bang 13.7 billion years ago should still be observable and calculated the wavelength that we should expect to observe today were George Gamow, Ralph Alpher, and Robert Herman, 1948.

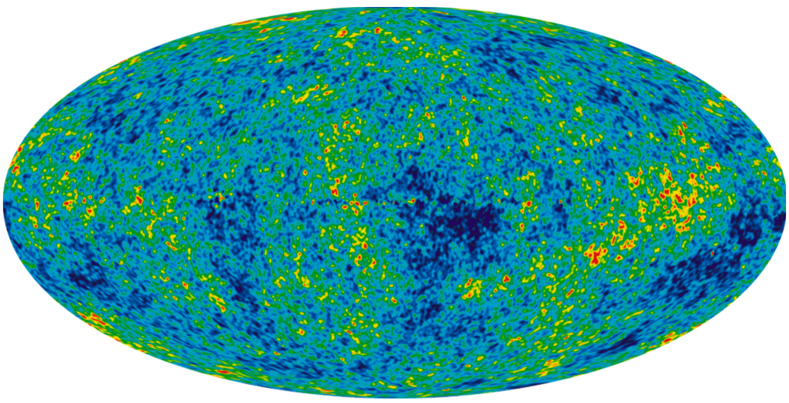

Figure 1. The CMB map, a crown jewel of Human achievement. Google "CMB map" for this very famous green computer-generated image based on date collected from 2001 to 2010.

FYI How do we measure the temperature of the CMB? It makes sense to measure the temperature of a *body*, but in what sense can we measure the temperature of some *radiation*? The answer is we look at the *distribution of the wavelengths* present and compare this with the distribution of black body radiation. Look at these graphs, from Georgia State University, and ask KL to explain if you still have any doubts.

[Show them a pyrometer]

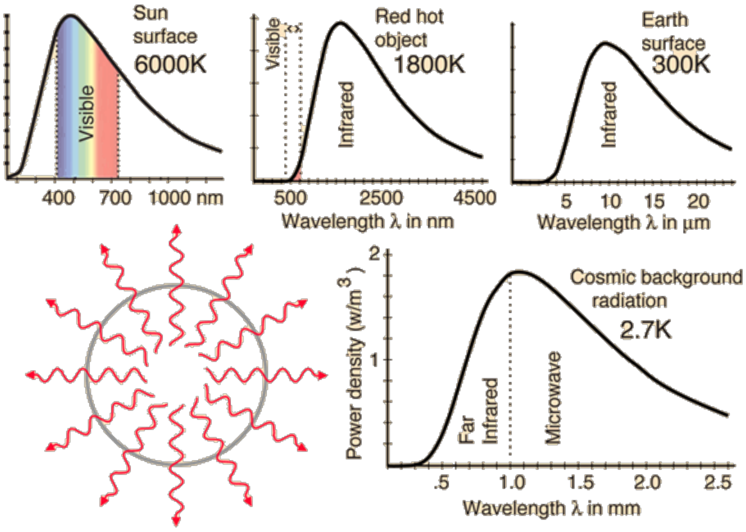

Figure 2. The distribution of wavelengths can be used to calculate the temperature of an object. By analogy, we can assign a temperature to the CMB as its distribution fits that of an object at a temperature of 2.7 K. This method of determining temperature is called pyrometry

FYI Next graph, from Georgia State University, shows how well the big bang theory prediction fits observed data.

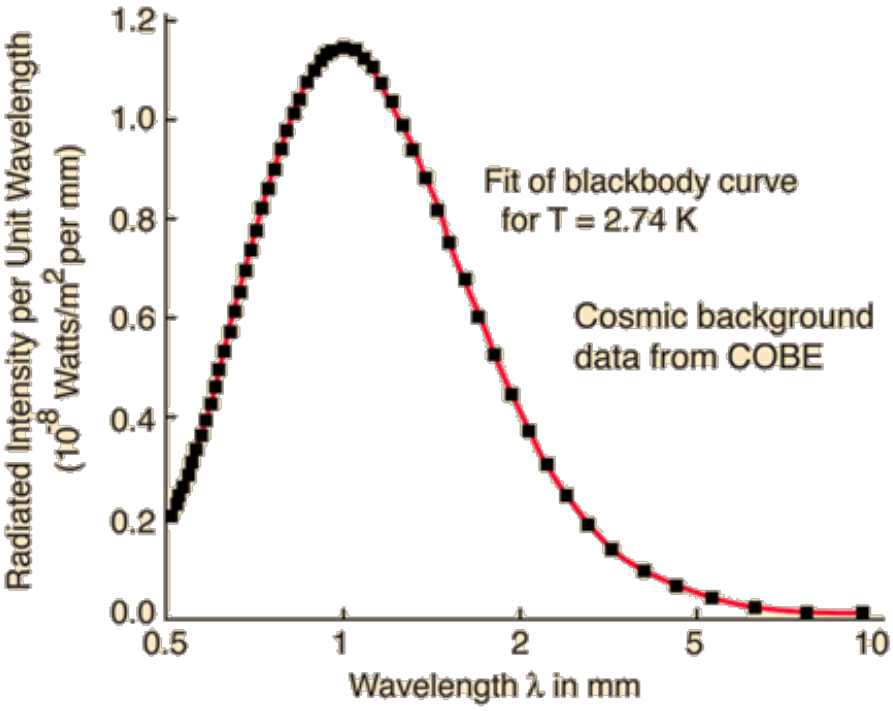

Figure 3. The curve is theoretical prediction and the squares are the observed data. The curve passes through the centre of most data points.

Notes 1. In case you would like to copy-paste from this document to add to your own summaries, an electronic version is available at http://layegh.com/sj

2. What are cepheid variables and how do they determine luminosity? If you are curious see NASA web site: http://map.gsfc.nasa.gov/universe/uni_expansion.html and Australia Telescope National Facility site: http://www.atnf.csiro.au/outreach/education/senior/astrophysics/variable_cepheids.html

[End of FYI — back to your syllabus.]

5.5.2 The evolution of the universe

The standard (hot big bang) model of the universe implies a finite age for the universe

All galaxies are observed to to be moving away from each other. Extrapolating back in time, they should have all started from a single point some time in the past. This implies that the Universe has existed for only a finite length of time, namely since the big bang.

Notes: 1. The **big bang model** is in contrast to the **steady-state theory** which asserts that the Universe is **static** (does not change) and has existed **forever** (has an age of infinity). FYI: Isaac Newton believed in the steady-state model.

2. FYI our current estimate of H_o is 67.80 ± 0.77 km s^{-1} Mpc^{-1} released by ESA in March 2013.

Exercise: Show that according to the 2013 ESA estimate of Hubble's Constant, the age of the Universe is 14.02 billion years.

The evolution of universe 10^{-43} s after the big bang to the present

Before 10^{-43} s: We know nothing.

After **10^{-43} s**: **Temperature (T) 10^{27} K**. All forces of Nature—gravitational, electromagnetic, weak nuclear, and strong nuclear forces were unified. The Universe expanded very rapidly.

Time 10^{-34} s: T 10^{22} K. The gravitational force separated from the other three forces. Too hot for quarks to coalesce to form fundamental particle. The "primordial lurk soup plus photons" stage.

Time 10^{-16} s: T 10^{16} K. Strong force separated from the weak force and the electromagnetic force. Leptons formed from photons. There was more matter than antimatter.

Time 10^{-3} s: T 10^{10} K. The week and the electromagnetic forces separated. Protons and neutrons formed from quarks. The ratio of protons to neutrons was about 4:1, the same as now. Almost all antimatter was annihilated by combining with matter.

Time 100 s: T 10^{7} K. The nucleus of lighter elements, helium and lithium were formed. (Note that hydrogen is just proton and was formed in the previous stage. So by this time we had H, He and Li.) All matter was in **plasma** form. (Note that plasma is a fourth state of matter: solid, liquid, gas, plasma. Plasma state occurs at *very* high temperatures at which all electrons are stripped from the nuclei. No electrons are bound to any nuclei.)

Time 10^{5} years: T 10^{4} K. Atoms were formed. (Note that atom means nucleus plus *bound* electrons.) The Universe was transparent. CMB was formed.

Time 10^6 years: T 6000 K. Density fluctuations resulted in the first structure of the universe. [KL to explain structure via analogy with fog (has almost no structure) versus cloud (has structure)]

Time 10^9 years: T 17 K. Most structures were formed including stars and galaxies. Heavy elements were formed as a result of the gravitational collapse of strs.

Time 13 billion years: T 2.7 K. The present time. Life on earth has formed. The ratio of protons to neutrons in the Universe is 4:1.