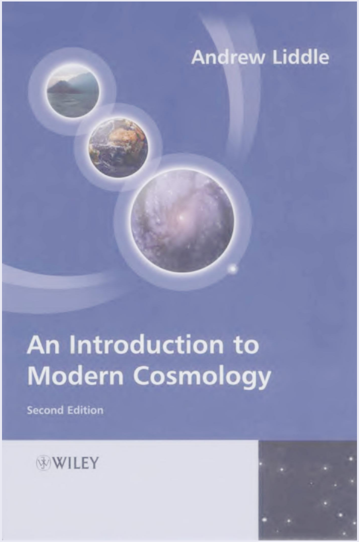
Short Introduction to Modern Cosmology

Michal Šumbera

February 26, 2018

Literature

Our discussion is based on the book



- A Brief History of Cosmological Ideas
- Observational Overview
  - In visible light
  - In other wavebands
  - Homogeneity and isotropy
  - The expansion of the Universe

A Brief History of Cosmological Ideas

- **The ancient Greeks**, in a model further developed by the Alexandrian Ptolemy – the Earth is at the centre of the cosmos. It is circled by the Moon, the Sun and the planets, and then the 'fixed' stars are further away.
  $\Rightarrow$ Rather complex combination of circular motions, **Ptolemy's Epicycles**, was devised in order to explain the motions of the planets, especially the phenomenon of retrograde motion where planets appear to temporarily reverse their direction of motion.
- In the early 1500s **Copernicus** stated the view, initiated nearly two thousand years before by Aristarchus – the Earth and the other planets are circling around the Sun. By ensuring that the planets moved at different speeds, retrograde motion could easily be explained by this theory.
  Although Copernicus is credited with removing the anthropocentric view of the Universe, which placed the Earth at its centre, he in fact believed that the Sun was at the centre.

A Brief History of Cosmological Ideas

- **Newton's theory of gravity** put Kepler's discovery that the planets moved on elliptical orbits on a solid footing. Newton believed that the stars were also suns pretty much like our own, distributed evenly through- out infinite space, in a static configuration. However it seems that Newton was aware that such a static configuration is unstable.
- Later it became increasingly understood that the nearby stars are not evenly distributed, but rather are located in a disk-shaped assembly which we now know as the Milky Way galaxy. The **Herschels** were able to identify the disk structure in the late 1700s, but their observations were not perfect and they wrongly concluded that the solar system lay at its centre.
- In the early 1900s **Shapley** realised that we are some two-thirds of the radius away from the centre of the galaxy. Even then, he apparently still believed our galaxy to be at the centre of the Universe.

A Brief History of Cosmological Ideas

- In 1952 was it finally demonstrated, by **Baade**, that the Milky Way is a fairly typical galaxy $\Rightarrow$
- **Cosmological principle**: belief that the place which we occupy in the Universe is in no way special, i.e. that the Universe looks the same whoever and wherever you are. It is the cornerstone of modern cosmology.
- This contradicts to previous views held almost for as long as the mankind exists that we occupy a very special location, usually the centre of something...
- **The cosmological principle is an approximation** which we believe holds better and better the larger the length scales we consider. Even on the scale of individual galaxies it is not very good, but once we take very large regions (though still much smaller than the Universe itself), containing say a **million galaxies**, we expect every such region to look more or less like every other one.

A Brief History of Cosmological Ideas

- The cosmological principle is therefore a property of the global Universe, breaking down if one looks at local phenomena.
- The cosmological principle is the basis of **the Big Bang Cosmology**. The Big Bang – picture of our Universe as an evolving entity, which was very different in the past as compared to the present.
- The Big Bang was originally forced to compete with a rival idea, **the Steady State Universe** – the Universe does not evolve but rather has looked the same forever, with new material being created to fill the gaps as the Universe expands. However, the observations now support the Big Bang so strongly that the Steady State theory is almost never considered.

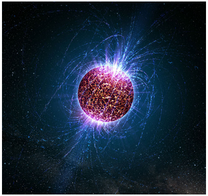
Observational Overview

- In visible light
- In other wavebands
- Homogeneity and isotropy
- The expansion of the Universe

In visible light – Stars

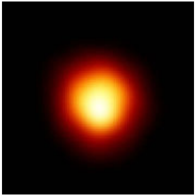
- **Stars** – main source of visible light in the Universe (nuclear fusion). Typical star – the Sun, $M_\odot = 2 \times 10^{30}$ kg.
- Stars range in size from neutron stars ($r = 10 - 20$km) to supergiants like Betelgeuse in the Orion constellation, ($r = 5 \cdot 10^8 km = 650 \cdot r_\odot$). However, Betelgeuse has a much lower density than the Sun.
- The nearest stars to us are a few light years away. Light year = distance that light can travel in a year ($\simeq 10^{16}$m). For historical reasons, an alternative unit, the parsec (1pc=3.261 light years), is more commonly used in cosmology.

Pleiades



neutron star

Sirius with white dwarf



Betelgeuse

In visible light – Galaxies

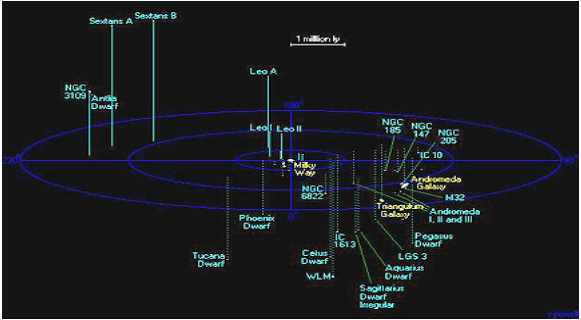
- **Galaxy** – smallest unit considered in cosmology.
- Our solar system lies in the **Milky Way** galaxy: $\simeq 10^{11}$ stars $(0.1 M_\odot \lesssim m_\star \lesssim 10 M_\odot)$. MW consists of central bulge plus a disk of radius 12.5 kpc and a thickness 0.3 kpc. We are located in the disk about 8 kpc from the centre.
- The disk rotates slowly (and also differentially, with the outer edges moving more slowly, just as more distant planets in the solar system orbit more slowly). At our radius, the galaxy rotates with a period of 200 million years. Because we are within it, we can't get an image of our own galaxy. It probably looks like M101 galaxy.




In visible light – The local group

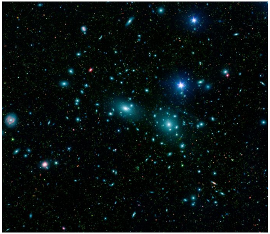
- Our galaxy resides within a small concentrated group of galaxies known as the local group.
- The nearest galaxy – the **Large Magellanic Cloud** is 50 kpc away.
- The nearest galaxy of similar size to our own is the **Andromeda Galaxy**, at a distance of 770 kpc.
- The Milky Way is one of the largest galaxies in the local group. A typical galaxy group occupies a volume of a few cubic Mpc.

$1Mpc = 3.086 \times 10^{22} m$ is the cosmologist's favourite unit for measuring distances, because it is roughly the separation between neighbouring galaxies.

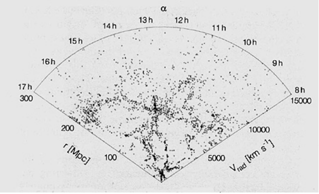


In visible light – Clusters of galaxies, superclusters, voids

- At scale of 100 Mpc, one sees a variety of large-scale structures.
- In some places galaxies are clearly grouped into clusters of galaxies; a famous example is the Coma cluster of ($\simeq 10^4$)galaxies which is about 100 Mpc away from our own galaxy
- However, most galaxies, sometimes called field galaxies, are not part of a cluster.
- Galaxy clusters are the largest gravitationally–collapsed objects in the Universe. They themselves are grouped into **superclusters**, perhaps joined by **filaments** and **walls** of galaxies. In between this 'foamlike' structure lie large **voids**, some as large as 50 Mpc across.



Coma cluster of galaxies.
Each point is a distinct galaxy.



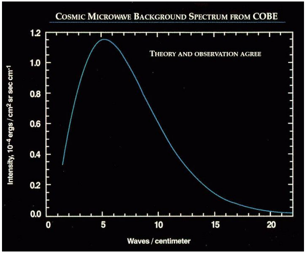
A map of galaxy positions in a narrow slice of the Universe.

In visible light – Large-scale smoothness

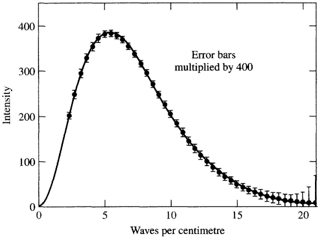
- At larger scales $\gtrsim 100 Mpc$ the Universe begins to appear smooth. Extremely large galaxy surveys, the 2dF galaxy redshift survey and the Sloan Digital Sky Survey have surveyed volumes containing hundreds of thousands of galaxies.
- Such surveys do not find any huge structures beyond the galaxy superclusters and voids which are thus likely to be the biggest structures in the present Universe.
- The belief that the Universe does indeed become smooth on the largest scales, the cosmological principle, is the underpinning of modern cosmology.
- It is interesting that while the smoothness of the matter distribution on large scales has been a key assumption of cosmology for decades now, it is only fairly recently that it has been possible to provide a convincing observational demonstration.

In other wavebands – Microwaves

- The most important waveband for cosmology.
- 1965: Penzias & Wilson accidentally discovered the microwave radiation, with a black-body spectrum at a temperature of around 3 K $\Rightarrow$ the most powerful pieces of information in support of the Big Bang theory, around which cosmology is now based.
- Observations by the **FIRAS** (Far InfraRed Absolute Spectrometer) experiment on board the **COBE** (COsmic Background Explorer) satellite confirmed that the radiation is extremely close to the black-body form at a temperature 2.725 ± 0.001 K.
- Furthermore, the temperature coming from different parts of the sky is astonishingly uniform, and this presents the best evidence for the cosmological principle.

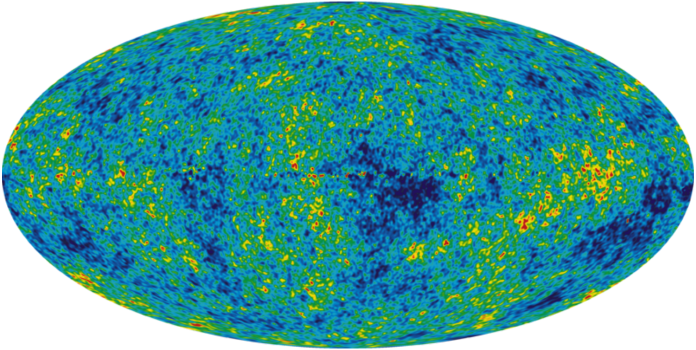


CMB spectrum from FIRAS. The data points and error bars are obscured by the th. curve.



In other wavebands – Microwaves: CMB fluctuations

- In fact, it has recently been possible to identify tiny variations (at the level of $\Delta T/T \approx 10^{-5}$) between the intensities of the microwaves coming from different directions. It is believed that these are intimately related to the origin of structure in the Universe.

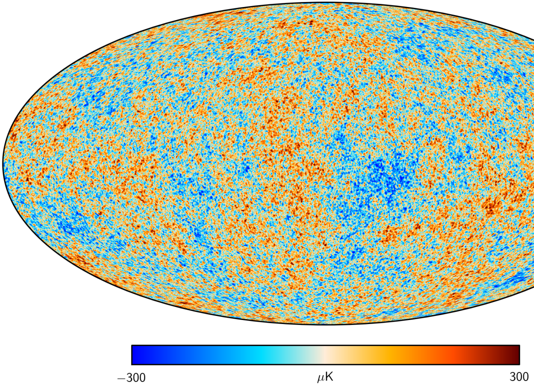


WMAP image of the CMB temperature anisotropy.

http://map.gsfc.nasa.gov/media

In other wavebands – Microwaves: CMB fluctuations

- In fact, it has recently been possible to identify tiny variations (at the level of $\Delta T/T \approx 10^{-5}$) between the intensities of the microwaves coming from different directions. It is believed that these are intimately related to the origin of structure in the Universe.



Map of CMB temperature from Planck satellite (2015).

http://www.cosmos.esa.int/web/planck/picture-gallery

In other wavebands

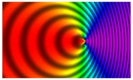
- **Radio waves**: A powerful way of gaining high–resolution maps of very distant galaxies. Many of the furthest galaxies known were detected in this way.
- **Infrared**: excellent way of spotting young galaxies, in which star formation is at an early stage e.g. IRAS (InfraRed Astxonomical Satellite) in the 1980s. is an Infrared is particularly good for looking through the dust in our own galaxy to see distant objects, as it is absorbed and scattered much less strongly than visible radiation. Accordingly, it is best for studying the region close to our galactic plane where obscuration by dust is strongest.
- **X-rays**: vital probe of clusters of galaxies. In between the galaxies lies gas so hot that it emits in the X-ray part of the spectrum, corresponding to a temperature of $\sim 10^7$K. This gas is thought to be remnant material from the formation of the galaxies, which failed to collapse to form stars.

Homogeneity and isotropy

- Smoothness of the Universe on large scales $\Rightarrow$ belief that large–scale Universe is homogenous and isotropic.
- **Homogeneity**: the Universe looks the same at each point
- **Isotropy**: the Universe looks the same in all directions.
- These do not automatically imply one another.
  - Universe with a uniform magnetic field is homogeneous, as all points are the same, but it falls to be isotropic because directions along the field lines can be distinguished from those perpendicular to them.
  - Spherically–symmetric distribution, viewed from its central point, is isotropic but not necessarily homogeneous.
  - However, if we require that a distribution is isotropic about every point, then that does enforce homogeneity as well.
- The cosmological principle is not exact $\Rightarrow$ Universe does not respect exact homogeneity and isotropy. Indeed, the study of departures from homogeneity is currently the most prominent research topic in cosmology.

The expansion of the Universe

- Everything in the Universe moves away from us, and the further away something is, the more rapid its recession appears to be.



  - Velocities from redshift, i.e. the **Doppler effect** applied to light waves.
  - Absorption and emission lines of the galaxies have well known characteristic frequencies. However, if a galaxy is moving towards us, the light waves get crowded together raising the frequency (blueshift). If the galaxy is receding, the characteristic lines move towards the red end of the spectrum (redshift).
  - First used to measure a galaxy's velocity by Vesto Slipher $\sim$ 1912, and applied systematically Edwin Hubble, in the following decades.

- **Redshift**

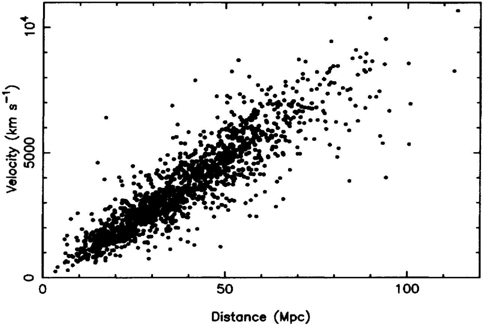
$$z \equiv \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}} = \sqrt{\frac{1 + v/c}{1 - v/c}} - 1 \approx \frac{v}{c} \qquad (1)$$

where λ_{em} and λ_{obs} are the wavelengths of light at the points of emission (the galaxy) and observation (us). v is the speed of receding object. The last approximation is true for non-relativic velocities.

Hubble's law

- Hubble realised that his observations, which were of course much less extensive than those available to us now, showed that the velocity of recession was proportional to the distance of an object from us:

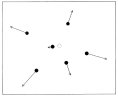
$$\vec{v} = H_0 \cdot \vec{r} \qquad (2)$$



Velocity vs. estimated distance for 1355 galaxies. A straight-line relation implies Hubble's law.
The considerable scatter is due to observational uncertainties and random galaxy motions, but the best-fit line accurately gives Hubble's law.

(The z-axis scale assumes a particular value of H_0.)

Hubble's flow



- Everything moves away from us ⇒ we are at the centre of the Universe ⇒ the cosmological principle is violated!?
- No, every observer sees all objects rushing away from him with velocity proportional to distance.
  - Analogy: baking a cake with raisins in it, or blowing up a balloon with dots on its surface. As the cake rises (or the balloon is inflated), the raisin (or dots) move apart. From each one, it seems that all the others are receding, and the further away they are the faster that recession is.
  - N.B. Works only for the linear relationship between velocity and distance; any other law and it wouldn't work!
- Everything is flying away from everything else ⇒ in the distant past everything in the Universe was much closer together. The initial explosion is known as the **Big Bang**, and a model of the evolution of the Universe from such a beginning is known as the **Big Bang Cosmology**.