Searching for the fingerprints of the Big Bang

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According to modern cosmology the Universe was created 13.72 billion years ago from the massive expansion of an extremely dense ‘energy point’. Astronomers obtained confirmation of this with the discovery of cosmic background radiation (CBR), the radiation which pervades the entire Universe and which is regarded as the fossil of the Big Bang. Why are we still seeing the background radiation today if it was emitted 3.7 billion years ago? And why does it have a temperature of 2.7 Kelvin today if the Universe was 3000 Kelvin back then? Does radiation always cool down if it is travelling for a longer period of time? The Planck satellite will make it possible to measure very small temperature fluctuations in background radiation. Why are they so important, and what do they reveal to us about the primordial Universe? It is questions such as these that we want to look into in a way that we can visualise.

Overview of references		
Astronomy	Cosmos	Cosmic background radiation (CBR), the Big Bang, the meaning of fluctuations in temperature of the CBR
Physics	Oscillations and waves, thermodynamics	Light as a wave, the electromagnetic spectrum, thermal light sources
Related disciplines	Astrophysics	Light from the past

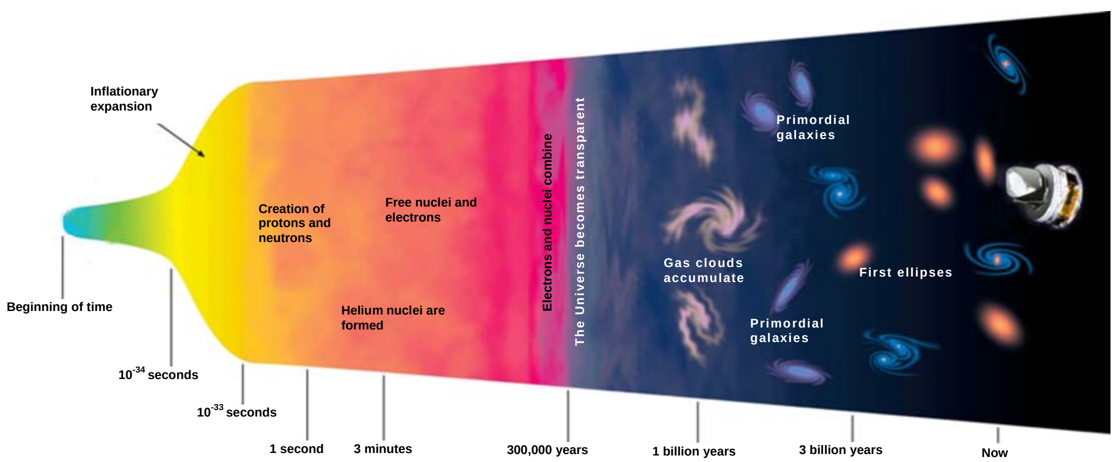


Figure 1: Diagram of the development of the Universe with the Planck satellite (right)

General information

Because this article is aimed at the intermediate level, we have not included a formal description of light as an electromagnetic wave and as particles. Instead we will draw parallels with acoustic waves and talk about ‘light rays’.

1. Introduction: A glimpse into the past

On a clear night we are able to see hundreds of stars in the sky. Perhaps what we are not immediately aware of is that we are only seeing the past from these sources of light. This is because light also needs a certain period of time to traverse distances in space.

So when we see the solar sphere in the sky during the day we are actually seeing how it was 8 minutes ago. This is because its light needs 8 minutes to travel the 150 million km to Earth (Fig. 2a). If the Sun were to disappear, we would only be aware of it 8 minutes afterwards! The light from Alpha Centauri, the closest neighbouring star to the Sun, needs 4.5 years to reach us. So we never see Alpha Centauri as it is now in the sky, we only see what it looked like 4.5 years ago (Fig. 2b). Even older is the light that we receive from the Andromeda galaxy, our closest neighbouring galaxy (Fig. 2c). It took 2.5 million years for it to reach the Earth. In principle astronomers are not doing anything different to what archaeologists do. They reconstruct the cosmic past by peering more deeply into space using large telescopes, similar to archaeologists who dig deeper into the earth in order to uncover increasingly older layers of lost cities.

Figure 2:
(a) Picture of the Sun: 8 min old light
(b) Picture of Alpha Centauri (left star): 4.6 year old light
(c) Picture of Andromeda: 2.5 million year old light

Light from the beginning of the world

Light that has already been travelling for 13.7 billion years reaches us from the depths of space, light that was created virtually at the beginning of the world. This so-called ‘cosmic background radiation’ pervades all of space and can be found in every direction. Its existence represents the final confirmation of the Big Bang theory. In order to understand where background radiation comes from and why it bears the fingerprints of the Big Bang, we must first study the nature of light.

2. What is light?

In the 17th century the physicist *Sir Isaac Newton* discovered that sunlight can be refracted into different colours. We are certainly all aware of this phenomenon in the form of a rainbow or from an experiment using a prism. The colour distribution is called the *'spectrum of light'*.

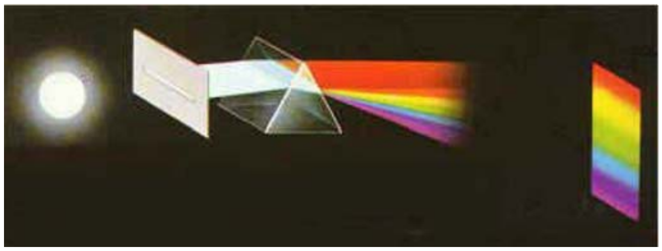


Figure 3: The colour spectrum of light

As early as 1690 the Dutch physicist Christiaan Huygens described light - with reference to sound waves - as having a wave-like quality. In the case of light we speak of *electromagnetic waves.* We already know about the sound waves that are created when a vibrating object compresses the air particles. Just as for sound waves, the wavelength λ - the distance between two wave crests or wave troughs - is an important characteristic of electromagnetic waves. Another characteristic is the frequency f which tells us how many wave crests or wave troughs reach us per second. The shorter the wavelength the more waves can be counted per second and the higher the corresponding frequency (see also Fig. 5). Conversely, the frequency decreases if the wavelength increases. Because all electromagnetic waves (in a vacuum) move at a speed of c = 300,000 km per second, the frequency can be calculated from the wavelength λ using the relationship $f = c/\lambda$.

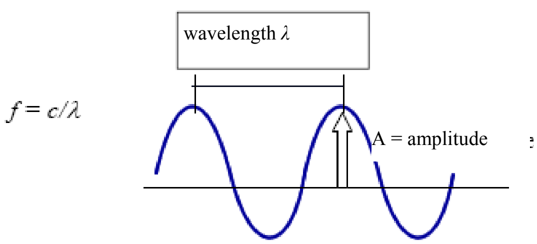


Figure 4:
Characteristic parameters of a wave

The colour spectrum of the light is generated by electromagnetic waves that have different frequencies (see Fig. 5). The waves in the blue range (indicated by 4 wave crests per second) have a higher frequency than that of the yellow range (in our example: 3 wave crests per second) and certainly than that of the red range (2 wave crests per second).

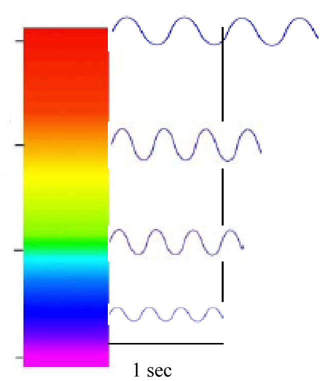


Figure 5: Different waves in the colour spectrum of light

Electromagnetic waves transport energy. The radiation energy of a wave depends on the frequency and on the amplitude of the wave. The higher the frequency, the more energy can be transported by a ray: E ~ f (5 hammer blows per second on an anvil transfer more energy than only 3 hammer blows). The greater the amplitude of the wave, the more energy is transported (a sledgehammer transfers more energy than a goldsmith hammer).

2.1 Invisible light

The colour spectrum of light that is visible to us represents only a very small section of the total electromagnetic spectrum. The electromagnetic spectrum extends each side of the red and the violet range to cover smaller (ultraviolet, X and gamma radiation) and larger (infrared, microwave and radio radiation) wavelengths. We cannot see these electromagnetic waves with our eyes because the ‘detectors’ in our eyes (the photoreceptors in the retina of the eye) are not sensitive to it. Gamma radiation (very high frequency, Fig. 6 left) has the most energy, and radio radiation (very low frequency, Fig. 6 right) has the least energy.

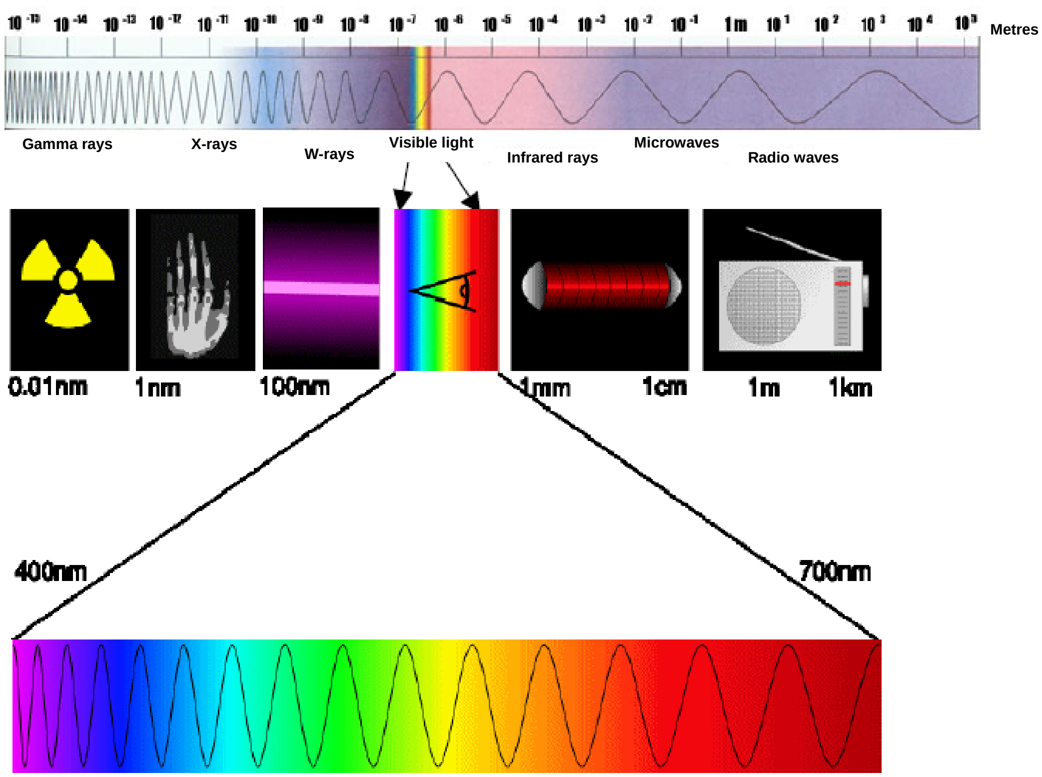


Figure 6: Diagram of the entire electromagnetic spectrum

If the wavelength of the electromagnetic radiation is between 400 and 800 nanometres (1 nanometre = 1 millionth of a millimetre), the light in question is visible..

Thermal sources of electromagnetic radiation

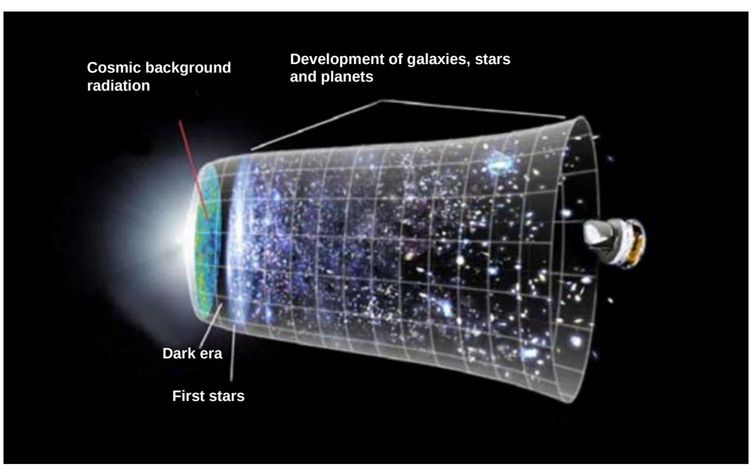
Thermal energy is converted into light in thermal sources of radiation. Examples are a light bulb, burning wood and the stars. *As the temperature of the source increases, however, the radiation maximum (the frequency at which the greatest amount of radiation is emitted) adjusts and the colour of the light changes.* For example, if we heat an iron rod it starts to glow after a while. At a temperature of 50 °C the radiation maximum is in the infrared range (not visible to us), at 1100 °C the light is dark orange and at a temperature of 1300 °C it is white. *The hotter a thermal radiation source, the shorter the frequencies of the electromagnetic waves generated:*

Temperature		Annealing colour
+ 700 °C		dark red
+ 900°C		cherry red
+ 1000°C		light cherry red
+ 1100 °C		dark orange
+ 1200 °C		yellow
+ 1300°C		white

However we must remember that with thermal radiation sources we are always seeing a combination of frequencies. If we see red light we must be aware that there is always also a small blue portion in this light. White light is the impression we obtain from a mixture of frequencies that contains a somewhat equal amount of red and blue light. There is a considerable connection between the colour of the light and the frequency or the wavelength in order to understand how the CBR has changed over time.

3. The Big Bang theory and background radiation

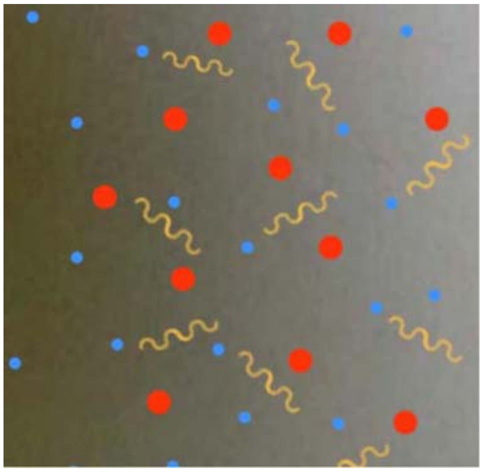
According to modern astronomy the entire Universe came into being 13.72 billion years ago as a result of the massive expansion of a tiny but extremely dense point out of which matter, space and time emerged.



There is no exact cause for the Big Bang. Because space and time were created at the time of the Big Bang it makes little sense to ask what exists outside of the Universe and what there was before the Big Bang.

Figure 7: Diagram of the development of the Universe with the Planck satellite (right)

At the beginning the Universe was tiny and had the inconceivable density of 5.4 10 g/cm^3 (so-called Planck density) and a temperature of around 10^{32} K. As a consequence of the high temperature, particles and energy continuously converted into each other in the form of radiation in accordance with Einstein’s equation $E = m\text{-}c^2$. After the first few minutes the Universe comprised a soup of free protons, electrons, neutrons and light. At this time the light rays were trapped as if in a thick fog because they were scattered in every possible direction by the charged particles (see Fig. 8*)*. This is why the early cosmos was opaque.



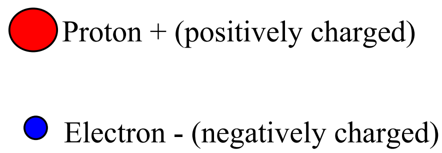
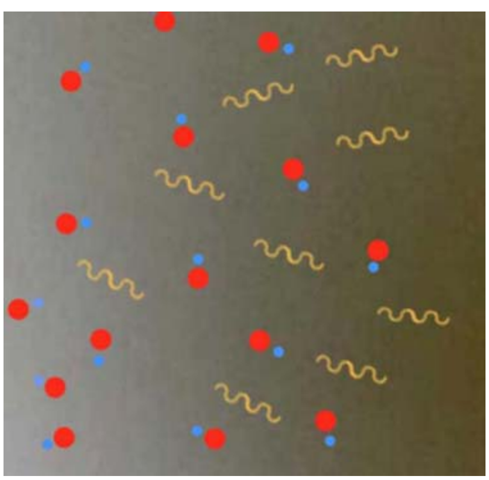


Figure 8: Permanent scattering of light rays by free electrons in the early Universe

370,000 years after the Big Bang the Universe had expanded so much and also cooled down so much that the temperature had decreased to 3000 K. This caused the electrons to move more slowly, allowing them to be caught by the protons. The first neutral hydrogen atoms and helium atoms were formed (the so-called *recombination era).* The rays of light were then able to move unhindered through space and the Universe became transparent and light (Fig. 9).



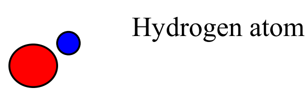


Figure 9: The rays of light detached from the matter as the first atoms were formed.

It is this age-old initial radiation that still fills the Universe today and that is called background radiation (CBR). Because the Universe was 3000 K at the time the CBR was released, it first had wavelengths the same as visible light (between 400 and 800 nm) with a maximum of 650 nm. This means that the CBR would have been visible to the human eye when it was formed!

3.1 The discovery of background radiation

Cosmic background radiation (CBR) was predicted as early as 1948 by the physicists George Gamow, Ralph A. Alpher and Robert C. Herman to be the result of the Big Bang, the cosmic expansion and the corresponding cooling down of the Universe. But what does cooling down actually mean relative to the cosmos as a whole? Even after the recombination our cosmos continued to expand (and is continuing to do so). We need to imagine the light rays of the CBR in connection with space. The wavelengths of the CBR increased to the same degree as space increased, such that nowadays they are in the microwave range (see Fig. 6 and 10). Radiation of this type is emitted by a thermal source of radiation that would have to have a temperature of around 3 K. This is why we often speak of 3K radiation.

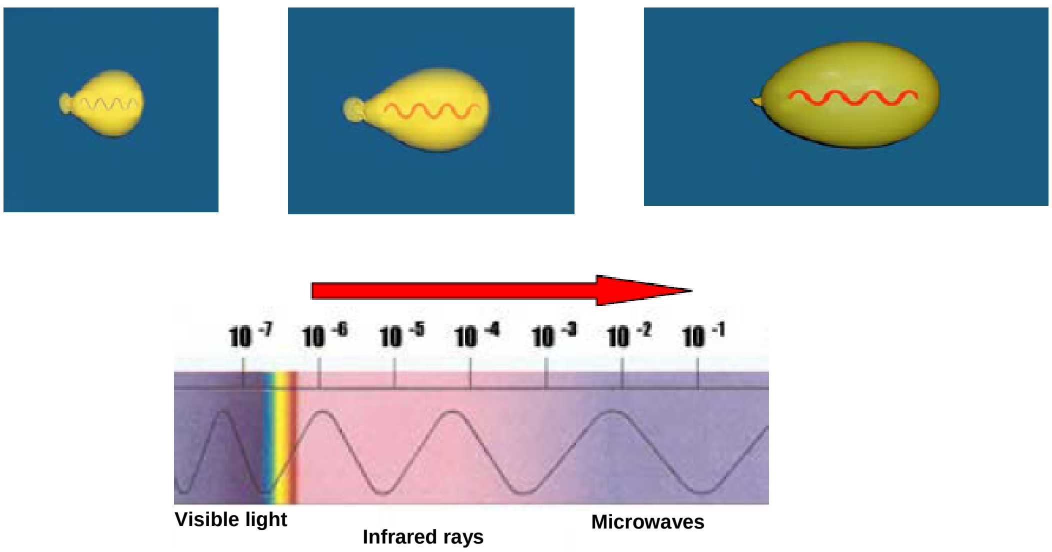


Figure 10: Lengthening of the wavelength of background radiation during the expansion..

Figure 11: Penzias and Wilson and their radio antenna.

In fact, background radiation was discovered in the early 1960's, albeit by accident! The engineers Penzias and Wilson noticed a strange disturbance in their radio receiver (see Fig. 11) for which there was no normal explanation. This 'disturbance' was immediately identified as cosmic background radiation by cosmologist Robert Dicke who was already looking for it. The two engineers received the Nobel prize for Physics in 1978 for their discovery.

3.2 What does background radiation look like today?

In 1989 NASA sent the satellite COBE (Cosmic Background Explorer) into orbit around the Earth at a height of 900 km in order to measure the background radiation. COBE was able to measure an average temperature of 2.7 K for the CBR and created a map of the CBR that is shown in Fig. 12. However on the map one could see that the temperature of the CBR is not homogeneous, and that there are areas with slightly lower and slightly higher temperatures (red ranges on the map). The meaning of this fluctuation in temperature is explained below.

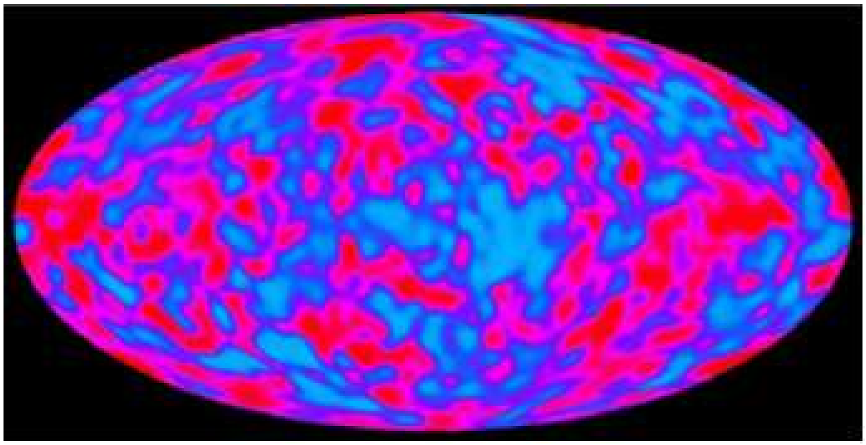
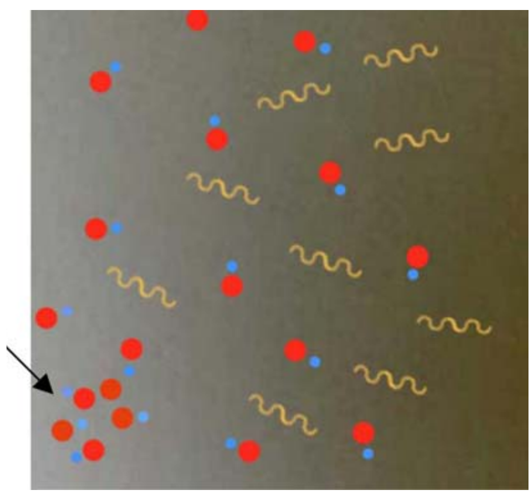


Figure 12: COBE picture of the background radiation (source: NASA).

3.3 What background radiation tells us about the early Universe

Background radiation not only confirms the Big Bang theory: its temperature fluctuations also supply important information about the distribution of matter at the time of the recombination. These fluctuations suggest that prior to the recombination the matter (comprising free protons, neutrons and electrons) was not distributed perfectly homogeneously in space and that there were locations at which the particles were packed more densely together (see below, left in Fig. 13).

Figure 13:
Area in which the particles of matter were more densely packed together



Now the matter from which stars and planets and even we are made amounts to only around 4 % of the entire energy in the Universe. An additional 22 % consists of particles that are invisible and only recognisable by their gravitational effect. It is still mystery what this 'dark matter' is made of. What we do know is that in the early Universe the dark matter first condensed in centres around which the visible matter could subsequently concentrate. These compressions formed the grains of small protogalaxies that gradually merged with each other and formed the galaxies that exist today. *It is one of the tasks of cosmology to determine how large these fluctuations in density were previously and how they have grown over time.*

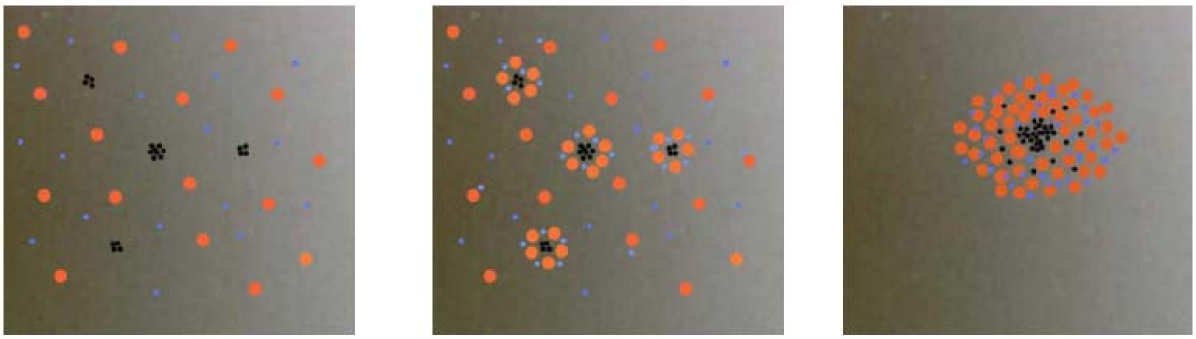


Fig. 14: (a) initial compressions of the dark matter, (b) compression of the visible matter around the dark matter; (c) Formation of the first protogalaxies

Two effects played a part in forming the fluctuations in temperature that are observed in the CBR today:

a) Due to the more frequent collisions between particles in denser areas and the correspondingly higher kinetic energy of the particles there the recombination was somewhat delayed in these regions. The rays of light were therefore released somewhat later than average. Their lengthening following the cosmic expansion therefore also commenced somewhat later such that the rays underwent less of a red shift than average. This now means that the light rays from the hotter areas reach us with shorter wavelengths (and are bluer).

b) When leaving these dense areas the rays lose energy because a higher attractive force is exerted on them. As a result their wavelengths become longer. This effect is called *gravitational red shift* and is one aspect of Einstein's general theory of relativity. As a result this section of CBR is cooler (and therefore redder) than the average (has a longer wavelength, see Fig. 15).

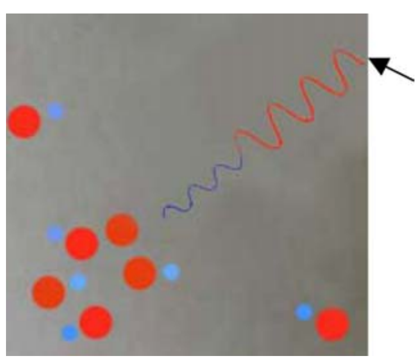


Figure 15:
gravitational redshift of the wavelength. This increases when the light rays leave denser areas.

These two effects thus function in opposing ways thereby partially cancelling each other out. Finally, however, the gravitational red shift wins because the first effect (a) amounts to only 2/3 of the second (b). The areas with lower temperature in the COBE picture (Fig. 12, red regions) were therefore ultimately caused by the gravitational red shift in the denser areas.

3.4 Why can we still see the background radiation?

The CBR was released 370,000 years after the Big Bang and has already been travelling for 13.7 billion years before reaching us. Why can we still see it when it was a type of 'flash' in the early Universe? Why doesn't it simply 'fade away'? We can explain this with the aid of a light bulb model (Fig. 16).

A single light that is switched on and left on for a certain period of time is seen only temporarily. But let's imagine a very broad plane full of lights which are all switched on and then off again at the same time and are observed from a fixed point in the distance. We see the ones closest to us immediately and the ones a little further away a little later, and so on, but until we still cannot see the lights at the edge of the plane we will see a continuous glow even when the first lamps have long since gone off.

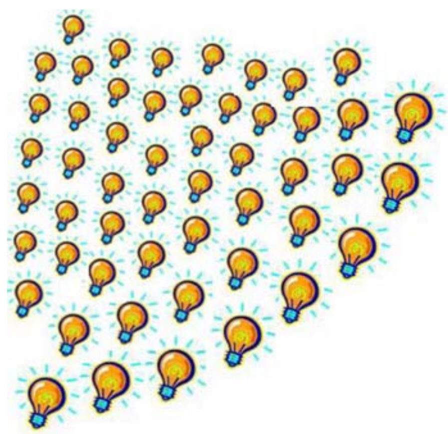


Figure 16: Plane full of lights that are switched on at the same time but located at different distances from an observer.

It is exactly the same with the CBR. Because it was released everywhere at the same time we see it as a continuous light source although its release took only 40,000 years (!). Since this time the light rays of the CBR have been moving freely through space. The ones we are now seeing flow past us have taken 13 billion years to reach us. The other point is that the wavelength of the background radiation grows together with space. The CBR is therefore bound to space and cannot escape from space. It must therefore remain visible everywhere.

4. What the Planck satellite will explore

Planck, a new satellite from ESA, will continue to explore cosmic background radiation, doing so as the successor to the COBE satellite and the WMAP satellite (Wilkinson Microwave Anisotropy Probe) that is already very sensitive. The launch of the 1800 kg Planck satellite together with the infrared satellite Herschel is planned for 2009 using an Ariane 5. Planck is expected to create a map of the entire sky with a resolution that will show differences in temperature of as little as approximately 10^{-6} K! This will allow us to measure the magnitude of the temperature fluctuations and the corresponding fluctuations in density during the recombination much more accurately than ever before. As a result cosmologists will be able to better support their theories about the early Universe.

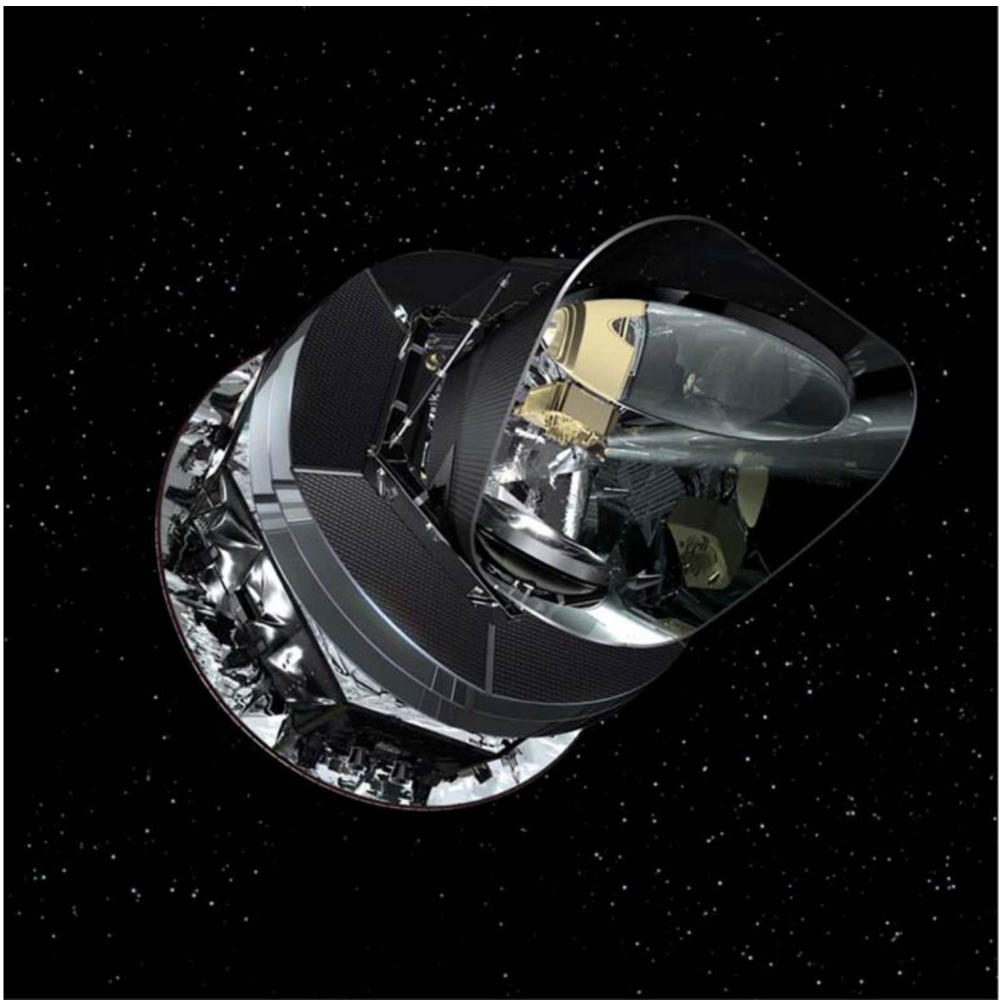


Fig. 17: Planck satellite with open mirror