Evolution of the Earth 10: Big Bang and Origin of the Universe Part 1: Evidence fo an expanding universe

Introduction

Until the first decades of the 20th century, most scientists considered the universe to be a constant place, the eternal background against which the stars and planets moved their orbits.

But in 1916, when Einstein was working out the implications of his equations of general relativity, he came to a disturbing conclusion. The equations showed that the universe was dynamic, in other words, that it should either collapse or expand. Whatever it did, the universe described by Einstein's equations was not static.

Other scientists soon recognized the implications of Einstein's General Theory of Relativity in terms of an expanding universe, although the great master himself was unwilling to consider them.

So this time we deal with the origin and expansion of the universe, the so-called Big Bang.

The expanding universe

What does it mean when we say that universe is expanding? A simple way to imagine the expansion of the universe is to put little glue marks on the surface of an inflatable balloon (Fig. 1). The glue marks are the clusters of galaxies, and the balloon is the expanding universe. As we gradually inflate the balloon, the glue marks move farther and farther apart, but they themselves do not get any larger. Of course, this comparison represents reality only in a very limited way. After all, the universe is not a balloon. But to imagine the universe with the help of these comparisons helps to realize that the expansion of the universe has not necessarily something to do with galaxies moving away from each other: Indeed, it is the space between galaxies that is expanding, while the galaxies are at rest relative to space.

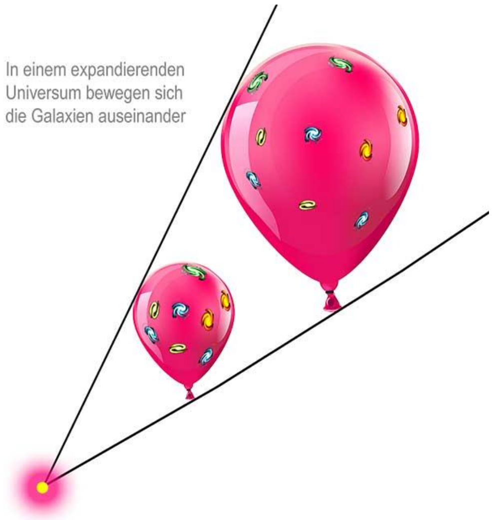

Fig. 1: Expansion of the universe using the example of a balloon.

In the early days of modern cosmology, the most influential proponent of the idea that the universe started small was Georges Lemaître (Fig. 2). Many scientists today regard Lemaître as the father of big bang cosmology because he proposed in 1927 that the universe began in the form of a space particle or uratom.

Fig. 2: Georges Lemaître

Redshift

An important step toward the realization that the universe is expanding was taken by Edwin Hubble. In 1919, he was appointed to the newly completed Mt. Wilson Observatory near Pasadena, California, and was free to use what was then the most powerful telescope in the world, a reflecting telescope with a 100-inch mirror (Fig. 3).

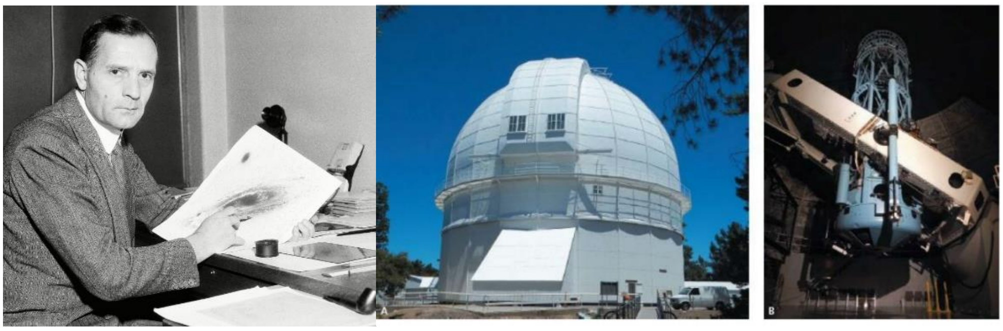

Fig. 3: Edwin Hubble and Mt. Wilson Observatorium, Pasadena

He used the telescope to systematically study as many stars, galaxies, and other large celestial objects as he could. He not only measured their distances, but also analyzed the star's light spectrum.

Visible light is a form of electromagnetic radiation that propagates in space in wave form. In addition to visible light, electromagnetic radiation is composed of radio waves, microwaves, ultraviolet radiation and X-rays (Fig. 4). The distance between two crests of radiation is called the wavelength. What distinguishes each type of radiation is its wavelength.

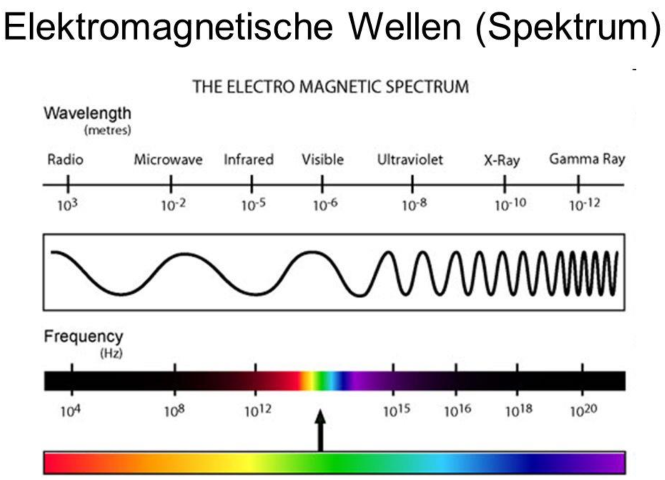

Fig. 4: electromagnetic waves

Like a prism that splits sunlight into its main colors, the light from stars can be split into a color spectrum.

An absorption spectrum is a color or electromagnetic spectrum that contains dark spectral lines. It is formed when white light passes through matter and light quanta (photons) of certain wavelengths or wavelength ranges are absorbed in the process. The absorbed photons are absent from the light passing through, which is why the spectrum is dark at the wavelengths in question (Fig. 5).

Absorption lines therefore occur because atoms or molecules absorb electromagnetic radiation of very specific wavelengths. For example, hydrogen, the most abundant element in stars, absorbs electromagnetic radiation of 410, 434, 486 and 656 nanometers (10 - 9 m). These absorption lines are like a fingerprint that can be measured for each type of atom (Fig. 5).

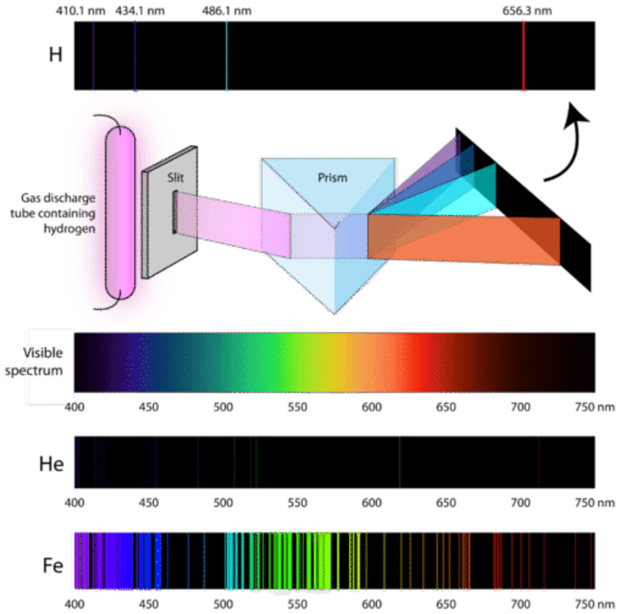

Fig. 5: Absorption spectrum of hydrogen

We can find the same bands when we analyze the spectrum of burning sodium or other metals in the lab, so each set of bands tells us which elements we are seeing.

Absorption spectra of stars also show such lines, not only lines of hydrogen, but also of other common elements such as helium, calcium, iron, sodium, and even unusual molecules such as titanium dioxide (Fig. 6).

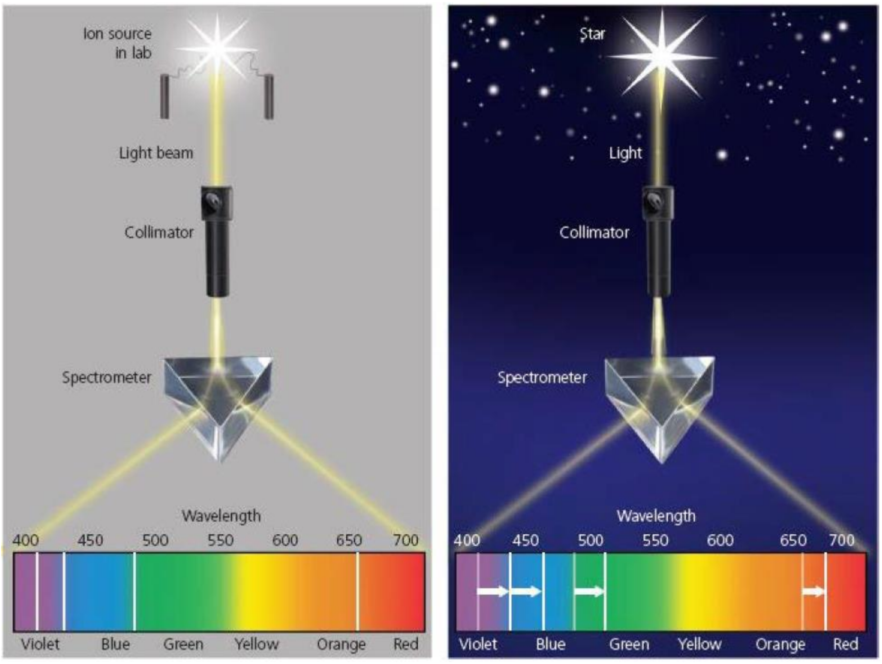

Fig. 6: When the spectrum of starlight is dissected through a prism, not only are the different colors and wavelengths visible, but there are also white absorption bands for different elements such as sodium and calcium in the spectrum at different wavelengths. Light from distant stars shows absorption bands shifted to the red end of the spectrum compared to their normal position as determined by a source in the lab.

Absorption lines help us determine the chemical composition of a star without having to take a sample. The depth or relative strength of the absorption lines can tell us what amount of that element is present in the star.

After measuring hundreds of different stars and galaxies, Hubble and his collaborator Milton Humason noticed something very strange. The nearest stars had absorption lines in their spectra that resembled the same spectrum for elements on Earth. But the farther away a star or galaxy was, the more the dark absorption bands shifted from their original position toward the red color of the spectrum (see Fig. 6).

Why do the absorption lines move toward the red end of the spectrum? This discovery was first reported and explained for some galaxies in 1912 by Vesto Slipher at Lowell Observatory in Flagstaff, Arizona. It is a so-called Doppler shift, caused by the Doppler effect. We are familiar with the Doppler effect in the propagation of sound waves. When we are standing on the street and a car comes up to us and honks, we notice that the pitch of the sound gets a little higher as it approaches. After the car passes us and moves away from us, we hear the pitch of the horn decrease again. The Doppler effect is caused by the sound waves approaching us being bundled because their source is getting closer and closer. When the waves are bundled, they increase in pitch. As the sound source moves away from us, the waves are stretched (Fig. 7).

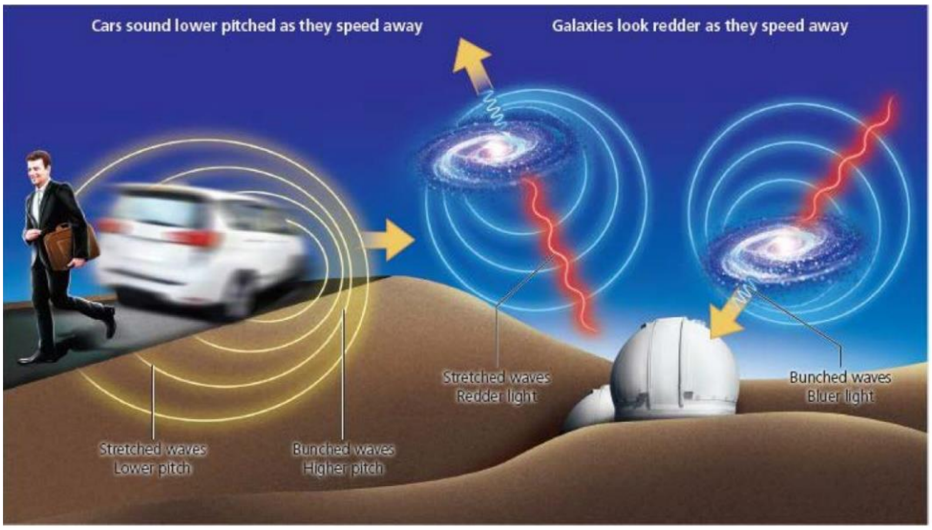

Fig. 7: The Doppler effect occurs whenever there is motion between a wave source and the observer. For example, when a moving car honks its horn, the sound waves appear to rise in pitch as they approach you and fall in pitch as they move away. This is because the sound waves are compressed as the horn approaches (the waves are focused and the wavelength is shortened, so the pitch is higher). When the sound source moves away from you, the waves are stretched and have a longer wavelength, so the pitch decreases. The same is true of light waves from distant stars. If they were to approach us, their wavelengths would bunch up and shift to the blue-violet region of the spectrum. However, all stars and galaxies are shifted toward the red end of the spectrum, showing that they are moving away from us.

The Doppler shift applies not only to sound waves, but also to light waves. If the light source is moving very fast towards us, then the light waves will be bundled and have a shorter wavelength (which corresponds to the blue and violet ends of the light spectrum). If, on the other hand, the light source is moving rapidly away from us, the waves will be stretched to a longer wavelength, corresponding to the red end of the spectrum.

The first observations by Slipher in 1912 and then Hubble and Humason's careful catalog of over 46 galaxies and many stars showed not only that galaxies were redshifted, but also that there were no blue-shifted objects that could be moving toward us. More importantly, Hubble and Humason found that the most distant objects had the largest redshift, so they must be moving away from us the fastest. Hubble realized that this meant that the universe must be expanding.

This is a startling thought that most astronomers could not accept at first. However, Hubble's and Humason's data were solid, and over time more and more objects were analyzed that turned out to be redshifted. Most astronomers did not like the idea that the universe had a beginning, but felt that it was in a "steady, constant state," with new matter constantly being created at the center. Fred Hoyle, one of these proponents of a constant state, coined the term "big bang" to mock Lemaître's model, and that name has stuck ever since.

Microwave background radiation

The Big Bang versus steady state controversy continued until the late 1950s, with no clear consensus. Then, purely by chance, a crucial discovery was made, not by astronomers, but by two engineers, Arno Penzias and Robert W. Wilson (Fig. 8). In 1964, they were employed by Bell Labs, which was responsible for developing communications technology. They worked on improving the first antennas for receiving and transmitting microwave signals, primarily to enable communications with NASA's Project Echo (the first attempts to use satellites for global communications).

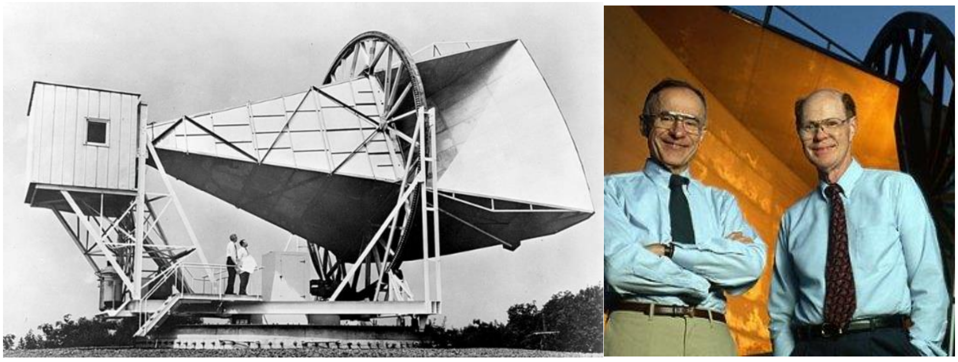

Fig. 8: Arno Penzias and Robert W. Wilson

Like light, microwaves are electromagnetic waves. Penzias and Wilson studied microwaves because they wanted to try a new type of communication; they needed to find out how much background noise was present in the microwave range. Although the two scientists carefully considered all types of background radiation, they were very concerned because their radio antenna was registering too much microwave radiation. Finally, they realized that no matter which direction in the sky they turned their antenna, the extra radiation was the same, and thus it was clear that the background noise must be coming from outside the atmosphere.

The researchers also found that the microwave background was the same strength during the day and night and throughout the year. Consequently, because the Earth rotates on its axis and also moves around the Sun, the microwaves must come in equal strength from all directions in the sky. Thus, it was clear that they must come from outside the solar system - indeed, from beyond the Milky Way.

Fortunately, just a year earlier, physicists Robert Dicke, Jim Peebles, and David Wilkinson had predicted the existence of a "background noise" left over from the Big Bang, when everything exploded in one big blast of radiation. The scientists were just beginning experiments to detect this noise when a friend told Penzias that he had seen a preprint of a paper by the scientists predicting exactly the same background noise. The two groups got in touch, and Penzias and Wilson showed them what they had found. Lo and behold, the two Bell Lab engineers had accidentally discovered proof that the Big Bang had indeed occurred. For this discovery, Penzias and Wilson were finally awarded the Nobel Prize in Physics in 1978.

As early as the 1940s, by the way, George Gamow and his collaborators Ralph Alpher and Robert Herman had predicted background radiation if the universe had begun in a hot dense state. The reason for this is that much of this radiation since that time has had no opportunity to interact with anything in the void of space and therefore should remain unchanged.

Alpher and Herman predicted that the Big Bang fossil radiation should now have a temperature of about five degrees Kelvin (K) above absolute zero (absolute zero is equivalent to -273 degrees Celsius).

The microwaves discovered by Penzias and Wilson had a temperature of 2.73 Kelvin; they are the most important observational evidence for the existence of a Big Bang. This radiation is called the cosmic microwave background, abbreviated CMB (for Cosmic Microwave Background). The CMB is the afterglow of the Big Bang, coming to Earth from a time when the universe was thousands of times smaller than it is today, long before there were planets, stars or galaxies.

Scientists have calculated that the CMB formed about 380,000 years after the Big Bang. At that time, the universe was at a temperature of 30,000 Kelvin, which is hot enough to emit radiation even in the ultraviolet region of the spectrum (Fig.9).

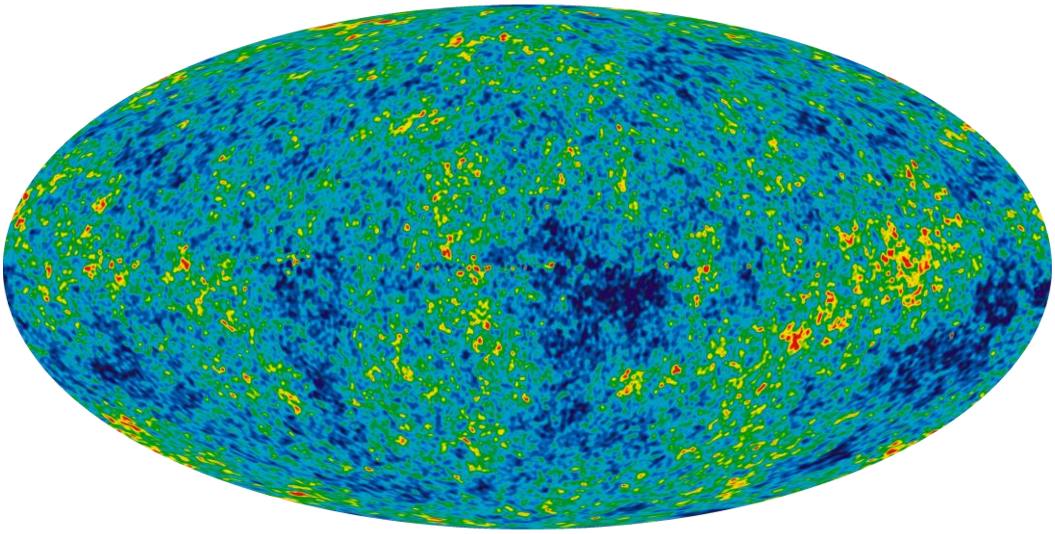

Fig. 9: Microwave background radiation

During the first 380,000 years after the Big Bang, the universe was too hot for photons, the elementary particles that are carriers of electromagnetic energy, to move freely. The universe was even too hot for atoms because the associated electrons would have simply been stripped from the nucleus by the heat. Only after the universe cooled enough for photons to continually capture electrons, forming neutral hydrogen, did the nebula dissipate and the cosmic background radiation was released.

What we see today when we observe the CMB is the fluctuation pattern that existed when matter began to dominate the universe at an age of 380,000 years. This is because most photons have not interacted with anything since then, and so continue to retain the signature of the structure of the universe at that time.

Because the detected cosmic background radiation was the same in all directions, cosmologists say that the expansion of the universe is isotropic, that is, the same in all directions.

Although the CMB is largely the same, experiments conducted with the Cosmic Background Explorer (COBE) and the Wilkinson Microwave Anisotropy Probe (WMAP) show that there are tiny fluctuations in its temperature, at a level of 1 in 100,000 Kelvin. They are the evidence of the earliest clumping of matter in the youthful life of the universe, before it had reached an age of 380,000 years.

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