2.5 Cosmic Microwave Background Radiation (CMBR)

The **Cosmic Microwave Background Radiation (CMBR)** is one of the most important pieces of evidence for the Big Bang model of the universe. It is the afterglow of the hot, dense state of the early universe, providing a snapshot of the universe when it was just about **380,000 years old**. The CMBR is a form of **electromagnetic radiation** that fills the universe and is observable in all directions. It offers a wealth of information about the universe's early conditions, its age, composition, and the physics governing its expansion.

Overview and Discovery of the CMBR

The CMBR was first detected in **1965** by **Arno Penzias** and **Robert Wilson** at the Bell Telephone Laboratories, unintentionally while working on a radio receiver intended for satellite communications. They discovered a persistent background noise coming from all directions in the sky, which turned out to be the **CMBR**. This discovery confirmed theoretical predictions made by **George Gamow**, **Ralph Alpher**, and **Robert Herman** in the 1940s, who suggested that the Big Bang would leave behind an observable radiation signal.

Since its discovery, the CMBR has become a cornerstone of cosmological research, providing critical insights into the early universe, its composition, and the physical processes that shaped its development.

Nature and Characteristics of CMBR

Thermal Radiation: The CMBR is a **blackbody radiation** that corresponds to the heat left over from the Big Bang. It has a **characteristic temperature** of about **2.725 K** (Kelvin), which is just above absolute zero. The spectrum of the CMBR is almost a perfect fit to that of a blackbody, meaning that it is emitted uniformly and has the same temperature in all directions.

1. **Uniformity and Isotropy**: One of the most remarkable features of the CMBR is that it is **uniform** and **isotropic**, meaning it is almost the same temperature in every direction we look. This suggests that the early universe was in a state of thermal equilibrium, where all regions were in contact with each other and had the same temperature. However, small fluctuations in temperature at the level of **1 part in 100,000** are also observed, providing valuable information about the structure and evolution of the universe.
2. **Wavelength and Frequency**: The CMBR falls within the **microwave region** of the electromagnetic spectrum, with wavelengths ranging from **1 mm to 1 cm**. This corresponds to a frequency range of approximately **30 GHz to 300 GHz**, with the peak frequency occurring around **160 GHz** (a wavelength of about 1.9 mm). The radiation from the CMBR corresponds to a **blackbody spectrum**, meaning that the intensity of radiation at any given wavelength follows a well-defined curve that peaks at a wavelength corresponding to the temperature of the radiation.
3. **Redshift and Cooling**: The CMBR has been redshifted as the universe expanded. When the radiation was first emitted, the universe was much hotter, with temperatures exceeding **3000 K**. Over time, as the universe expanded, the wavelength of the radiation was stretched, cooling it to its present temperature

of **2.725 K**. This redshifting is a key observation that supports the expanding universe model.

Origins of the CMBR

The CMBR originated about **380,000 years** after the Big Bang during a period called **recombination** or the **decoupling era**. To understand the CMBR's origins, it is important to break down the key phases leading up to its creation:

1. **Big Bang Nucleosynthesis (BBN)**: About three minutes after the Big Bang, the universe had cooled enough for the formation of **light nuclei** such as hydrogen, helium, and trace amounts of lithium. This process is known as **Big Bang nucleosynthesis**, but no neutral atoms were formed yet. The universe was still a hot, dense plasma of free protons, neutrons, electrons, and photons.
2. **Photon-Electron Interaction**: During the early universe, photons (light particles) were in **thermal equilibrium** with free electrons and nuclei. The universe was so hot that electrons were constantly scattering off photons in a process called **Thomson scattering**. As a result, the universe was opaque to radiation, and light could not travel freely.
3. **Recombination (Decoupling)**: Around **380,000 years after the Big Bang**, the universe had cooled enough for electrons and protons to combine and form neutral hydrogen atoms in a process called **recombination**. This drastically reduced the number of free electrons available for scattering, allowing photons to travel freely through space. This moment, known as **decoupling**, marks the moment when the CMBR was released.
4. **The "Surface of Last Scattering"**: The release of the CMBR corresponds to the point in time when the universe transitioned from being opaque to transparent. This epoch is called the **surface of last scattering**, and it provides a snapshot of the universe at that time. The radiation from this event is what we now observe as the CMBR.

Key Features and Information Encoded in the CMBR

1. **Temperature Fluctuations (Anisotropies)**: Although the CMBR is remarkably uniform, tiny temperature fluctuations on the order of **1 part in 100,000** are present. These fluctuations provide crucial information about the **density** and **structure** of the universe at the time of decoupling. These temperature variations are linked to **density perturbations** in the early universe, which later evolved into the galaxies and large-scale structures that we see today. The pattern of these fluctuations can be mapped in a **power spectrum** that gives insights into the age, composition, and geometry of the universe.

2.The Sachs-Wolfe Effect: The **Sachs-Wolfe effect** describes the relationship between the temperature fluctuations in the CMBR and the gravitational potential of regions in the universe. Areas of higher gravitational potential (due to more mass) cause photons to lose energy as they climb out of these wells, leading to a slight **redshift**.