Primordial radiation of the Universe

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October 4, 2006

1 Nobel Prize for COBE

The Physics Nobel Prize for the year 2006 has been awarded for precision measurement of the Cosmic Microwave Background Radiation (CMBR) performed using COsmic Background Explorer (COBE) satellite launched in 1989. Please refer to NASA link `http://lambda.gsfc.nasa.gov/product/cobe/` for details. These results were first announced in 1992. Its chief findings were (1) an accurate determination of the temperature of the relic radiation and (2) confirmation of expected inhomogeneities in this radiation, to the tune of ten parts per million. Here we trace some of the history and the significance of the results to our understanding of the Universe, in turn some secrets of our existence.

While we celebrate this Nobel Prize the sequel experiments have moved far ahead. As of 2003 the WMAP experiment has not only confirmed COBE but gone far beyond it. This is discussed in the concluding section.

2 Radiation from stars and on earth

The origins of this discovery can be traced to the invention of that humble paraphernalia of the modern undergraduate laboratory, the Bunsen burner. In 1850's Gustav Kirchhoff and Robert Bunsen at the University of Heidelberg wanted to compare spectra of the light from stars with spectra one can produce on earth. They needed to heat metals to high temperatures to achieve this comparison. The blue flame of the Bunsen burner did the job.

These studies led Kirchhoff, more known to us for his circuit laws, to propose a classic challenge to theorists. His conjecture was that the spectrum of the radiation depended only on the temperature of the metal (and hence that of the radiation gas) and on nothing else.

Figure 1: Robert Bunsen (left) and Gustav Kirchhoff

3 Desperate measures

For decades theorists struggled to prove this using Maxwell's theory of electromagnetic radiation, but in vain.

In the year 1900 Max Planck was a young theorist at Berlin. The experiments with radiation were continuing, the far infrared part of the spectrum being the most difficult to measure, being heat waves. Based on a hint a he got from the experimentalists at Berlin, Planck made the leap of faith which gave us the mathematical expression of Planck spectrum.

Many years later Planck recalled that he was desperate to get the answer, and he did so by bending the rules of Thermodynamics in a way no one understood. The mysterious counting based on the hypothesis of discretization or "quantization" of energy, reproduced the observed spectrum perfectly.

4 The photon hypothesis

In 1905 Einstein explained the origin of Planck spectrum by demanding that the quantization of energy actually belonged to radiation itself, not merely an artifact of how energy is distributed. He also insisted that this was a universal feature, common to all emission and absorption of radiation. He predicted the photoelectric law now known after him. In 1905 it was not a properly measured effect.

The hypothesis that radiation was universally emitted and absorbed in lumps was so radical and so contradictory to Maxwell theory that it was taken to be complete humbug. For several decades, even after the photoelectric effect was established in great detail there was pressure on Einstein to withdraw his "spurious" photon hypothesis.

The Nobel Prize in 1922 was given to him, not for correct physical explanation of the photoelectric effect but only for predicting the formula describing the phenomenon.

5 Quantum indistinguishability

While no one in the western world believed Einstein's photons and Einstein did not believe the counting methods developed by Boltzmann and Planck, (this divergence was the motivation for Einstein's photoelectric effect paper), a young professor in Dhaka university believed both the statistical methods of Boltzmann and Planck as well Einstein's hypothesis.

In 1924 Satyendra Nath Bose succeeded in proving in a paper three pages long that Planck's spectrum can be systematically derived from Einstein's hypothesis using standard methods of Statistical Mechanics.

The unusual counting used by Planck was formally introduced by Bose as an intrinsic property of photons. It required a property we now know as Quantum indistinguishability as against classical indistinguishability used in proving classical Maxwell-Boltzmann distribution.

In some sense, Bose and de Brogli were the real pioneers of the Quantum. Till date the "wave nature" of electrons is over-emphasized while teaching Quantum Mechanics, however ones understanding of quantum principles is only partial if the unusual statistics pioneered by Bose and Einstein for photons and by Fermi and Dirac for electrons is not emphasized.

6 Relic radiation in the expanding Universe

In 1915 large telescopes began to be built in the US which for the first time permitted looking at galaxies beyond our own. By 1929 Edwin Hubble's proposal that the Universe was expanding was established. This implied that the Universe must have been much smaller and much hotter in the remote past, since nothing else is known to intervene in gravitational expansion.

Figure 2: Satyendra Nath Bose

In the late 1940's, a Russian emigree to England, George Gamow and his student Herman Alpher applied some terrestial physics seriously to the expanding Universe. They studied the epoch when the Universe must have cooled for the first time to a temperature where neutral Hydrogen can be stable. Before this the Universe was fully ionized and photons could not move freely. But once the neutral Hydrogen formed the radiation would be free. Thus these were the oldest photons that could reach us today. If there was thermal equilibrium at this "surface of last scattering", then the radiation should just be lingering around, as a Planck spectrum. Alpher and Gamow's estimate of the temperature was 5 to 7 K. This proposal was not taken seriously for two decades since the means to make serious measurements of the microwave sky did not exist.

7 A noisy microwave link

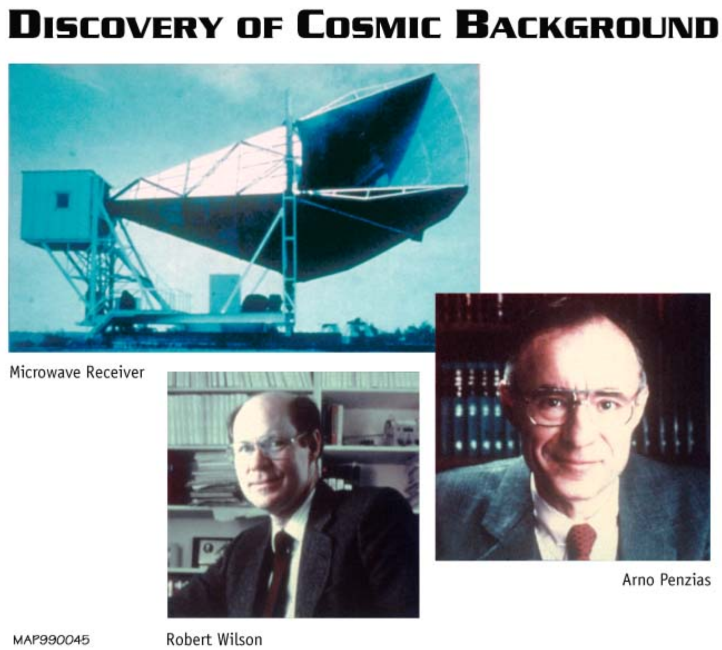
In 1964 Physicists at Princeton University started planning an antenna to detect this radiation. But before they could do it, two engineers Arno Penzias and Robert Wilson working at nearby Bell Laboratories found an annoying and persistent noise in their microwave communication link. The rest as they say was history. Man had finally discovered the flames of the oldest burning fire, lingering since some 14 billion years ago. The peak of the spectrum suggested a temperature of 3 K. As conjectured long ago by Kirchhoff, the value of the temperature alone should determine the complete spectral distribution of the radiation. Panzias and Wilson received the Nobel Prize for their completely accidental but totally momentous discovery.

8 COBE detects imperfection within perfection

There remained the important verification that the spectrum was indeed that of free radiation. But there was a more important question.

If the radiation is fully homogeneous, so would be the charged medium in contact with it. Thus the neutral Hydrogen formed would remain a perfectly homogeneous free gas. The problem with that is that no stars or galaxies could form, no sun could exist, no earth, no author, nor you dear reader could exist.

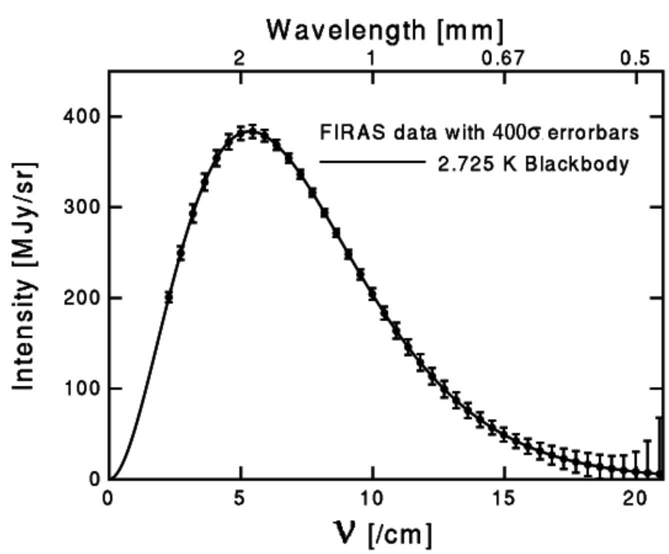
Our picture of the Universe today based on extensive observations confirms two aspects. The existence of galaxies shows there was inhomogeneity in the original plasma. But the distribution of galactic clusters is homogeneous. In other words, inhomogeneities must exist at large scales. But the distribution of the inhomogeneities must be uniform, since they are only small departures from an overall homogeneous situation.



Classical analysis showed that the formation of galaxies can be explained correctly if the extent of inhomogeneities was about 1 in 10^5 or ten parts per million. If extrapolated from the last scattering epoch till the present epoch, this magnitude of seed inhomogeneities was just right to form the observed galactic distribution.

The COBE satellite experiment was fitted with three instruments. Two of them are relevant to our discussion. One called FIRAS measured the entire spectrum as accurately as possible. Another experiment focused on measuring the departure from perfect homogeneity. Both experiments performed with flying colors.

9 The original Planck spectrum



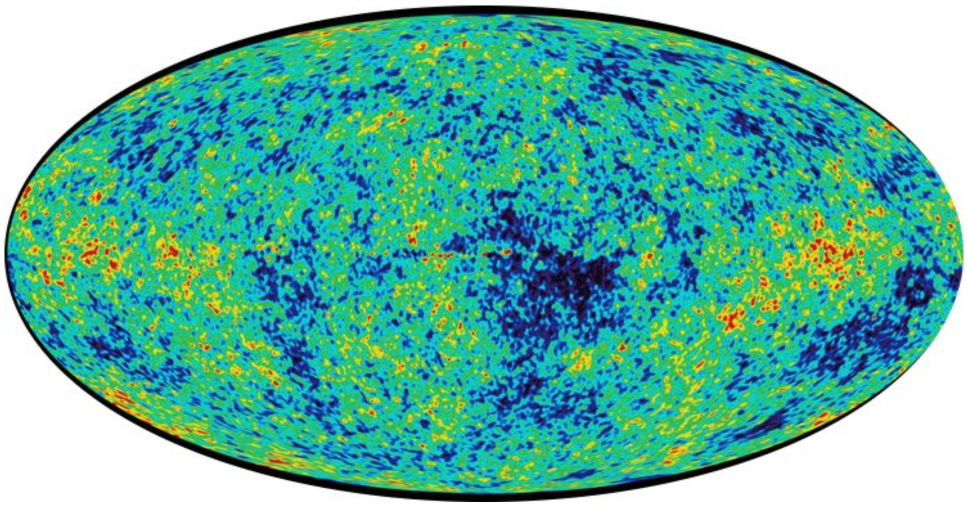


Figure 3: WMAP's microwave picture of the sky with fluctuations color coded

FIRAS produced this perfect picture of the spectrum. The experimental points are shown with their error bars and the solid curve is the theoretical curve at the temperature $T = 2.725\mathrm{K}$. We all live within a cold photon gas.

The 2006 Physics Nobel has been awarded to the leaders of the COBE project.

10 Perturbations and the Quantum Universe

COBE also discovered the required inhomogeneities almost embarrassingly on the nose, ten parts per million. During the decade since, a number of ingenious experiments have confirmed this basic feature. A comprehensive experiment WMAP more or less fingerprinted the whole sky when it measured the CMB temperature in any direction of viewing to within a micro-Kelvin. Largest visible fluctuations are in milli-Kelvin.

These measurements provide the detailed spectrum of the inhomogeneities, which must have pre-existed the formation of neutral Hydrogen. Now armed with the knowledge of the fundamental forces we can extend our theoretical study of the Universe much farther back. But in nothing that we know is there a mechanism for producing these inhomogeneities exactly of this extent. A theory called Inflationary Universe proposes that these inhomogeneities originated from the quantum fluctuations of some fields populating the early Universe. This would require us to build a Grand Unified Theory to correctly predict the fluctuations.

An alternative is that the inhomogeneities arose with the birth of the Universe itself, governed by that unknown realm of Physics called Quantum Gravity. The only theory where Quantum Gravity seems amenable to any calculation is Superstring Theory. In this theory what appears to be a violent and singular event (the Big Bang) has alternative mathematical description where it would be tame and calculable.

A number of cosmology experiments, some operational, some in planning, will pin down the detailed structure of the fluctuations within the coming decade. They are aimed at allowing us to distinguish the origin of the fluctuations, whether from the Quantum Gravity era or a little later from the era of Grand Unification. They will then provide further insight into the nature of the unified forces.