Nobel Prize in Physics 2006

Cosmic Background Radiation and Precision Cosmology

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The discovery of the cosmic microwave background radiation in 1965 was a defining moment in the history of cosmology – the science that deals with the universe as a whole, its origin, evolution and future. This discovery was recognized with Nobel Prizes to Penzias and Wilson in 1978. The Nobel Prize in Physics for 2006 further acknowledged the importance of the study of this background radiation. The precise measurement of the spectrum of this radiation and its variation across the sky have helped our understanding of the evolution of structures in the universe. This article explains these discoveries and their importance.

1. Introduction

Nobel Prizes in physics are usually given to individuals for achievements of high intellectual calibre. But every once in a while, these prizes are also given to team leaders who spearhead a large collaboration which produces a significant breakthrough. The Prize in 2006 belongs to this category and has gone to John Mather and George Smoot who led a team of about one thousand scientists, engineers and administrators who were collectively responsible for the COBE satellite mission. This mission detected in 1992, for the first time, tiny wiggles in the temperature of cosmic microwave background radiation, thereby heralding the age of precision cosmology.

The historical background for this discovery probably should begin in 1965, when two American scientists, Arno Penzias and Robert Wilson at the Bell Laborato-

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ries stumbled on a discovery which proved to be of crucial importance. (They shared the 1978 Nobel Prize in physics for the discovery). A radio receiver they were developing detected radiation at the wavelength of 7.35 cm which did not originate from any of the known sources in the sky. Further studies showed that this radiation was filling the entire universe and was reaching us, so to speak, from the depths of space. It was uniform all over the sky and had a characteristic temperature of about 3 Kelvin (270 degrees centigrade below zero!); it was as though the entire universe was enclosed in a box kept at this temperature.

Such a radiation field was expected to exist in the expanding, evolving, model of the universe (called the 'big-bang model'). In the late 40's, three scientists – Alpher, Gamow and Herman – had predicted that there should be a relic radiation field permeating the universe in the big bang model. They reasoned that if the big bang model of the universe is correct, then the universe must have been considerably hotter in the past. A thermal radiation covering the universe would be a tell-tale relic of an earlier hotter phase. But observers and experimentalists did not take this seriously. In 1964, two Russian scientists Doroshkevich and Novikov published an article in which they envisaged a search for such a radiation focusing on its blackbody characteristics. Interestingly enough, some measurements of energy level transitions in interstellar molecules as early as 1940 had shown indirect evidence for such a radiation – but was again overlooked. Though not known to Penzias and Wilson at that time, there was a team of cosmologists Bob Dicke, Jim Peebles and Dave Wilkinson at Princeton University who expected such a radiation to exist on theoretical grounds and, of course, realized its importance immediately.

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If this radiation is a relic of the big bang, then it was essentially emitted when the universe was about thousand times smaller and contains valuable information about the state of the universe at that time. When the universe was a thousand times smaller, it would not have contained the structures like galaxies, stars, etc. which we see today but would have been a featureless plasma. Nevertheless the seeds of the cosmic structures we see today must have existed even then, producing small 'ripples' or fluctuations in the radiation field. If our ideas about the formation of the visible universe are correct, then the radiation field must share these ripples. The information contained in these ripples is crucial to our understanding of cosmological models.

If our ideas about the formation of the visible universe are correct, then the radiation field must have ripples.

So important was this idea that NASA put into orbit a satellite called 'Cosmic Background Explorer' ('COBE' for short) looking specifically for these small fluctuations (*Figure* 1). The analysis of the data collected by the satellite dramatically confirmed in 1992 our theoretical ideas about the origin of structures in the universe. The temperature of the radiation does vary from direction to direction by an incredibly small amount. The fractional change is about one part in hundred thousand but the radio eye of COBE did not miss it!

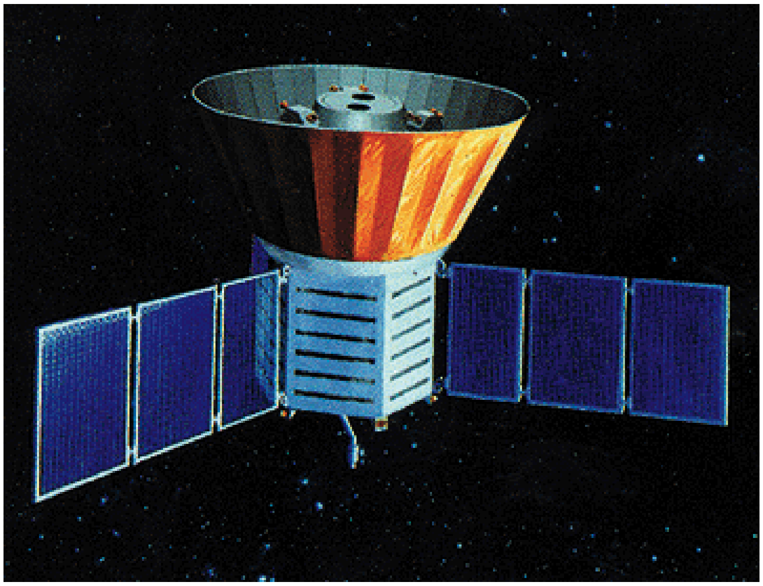

Figure 1. The COBE satellite was launched in 1989 by NASA.

(Courtesy: NASA)

To understand all the implications in a broader context one needs to take a closer look at our universe and models describing it – a task we shall now turn to.

2. The Big Bang Model of the Universe

Looking at the night sky, one may think that the vast expanse of space is filled with stars. Nothing could be farther from the truth! The stars are only the smallest units which emit light. They appear clustered together in the form of galaxies. The stars which we see in the sky are all part of our own galaxy – called the 'Milky Way'. A typical galaxy like the Milky Way contains about a hundred billion stars. Powerful telescopes have shown that our observed universe contains more than a billion such galaxies.

The distance scales involved in the study of these objects are so vast that one needs special units to measure them. One most popular unit is a 'light-year' which represents the distance travelled by light – which buzzes about at 300,000 kilometers per second – in one year. This distance is about ten thousand billion kilometers. Even with such a gigantic unit at our disposal, astronomical distances can be mind-boggling. For example, our galaxy is about seventy thousand light years in radius; and the nearest galaxy to us – called Andromeda – is three million light years away. In other words, the light we receive from Andromeda today left that galaxy three million years ago! The most distant galaxies we see can be three thousand times farther than Andromeda.

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The most fascinating aspect of galaxies, however, is not their sizes or distances but their motion. Distant galaxies are flying away from us (and from each other) with speeds increasing with distance. This is equivalent to saying that 'the whole universe is expanding' with distances between galaxies increasing all the time.

All these facts might seem bizarre and esoteric. How-

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ever, the most important point to remember about our universe is that it is fairly well understood in terms of precise mathematical models. A model for the universe worked out by the Russian scientist Friedmann in 1922 – based on Einstein's theory of relativity did predict mathematically that the universe must be expanding the way it does. Popular articles often put an aura of mystery around the universe. It should be stressed that to a cosmologist equipped with the laws of physics, the universe is fascinating and exciting – but not mysterious.

The fact that we really understand the behaviour of the universe in terms of the basic laws of physics offers a major advantage: It allows the cosmologist to reconstruct the past universe from the present. If the universe is expanding today, it follows that it would have been smaller, denser and – consequently – hotter in the past. During such a hot phase, the matter in the universe would have been in a form very different from what we see today. Ordinary matter in the form of solid, liquid or gaseous state can exist only at temperatures below 10,000 degrees or so. At higher temperatures, matter exists in a form called 'plasma'. In this fourth state, matter exists essentially as a gas of charged particles – electrons, protons and positively charged ions. The intense temperature also produces tremendous amount of radiation which may be thought of as a gas of 'photons' – the quanta of light.

That is what the early universe would have looked like: a hot soup of photons, electrons and positive ions. How can we test such a prediction of the cosmologist? It turns out that the radiation discovered by Penzias and Wilson is the key.

To see how this comes about, let us study the evolution of the universe, starting from a time when it was, say, ten thousand times smaller and had a temperature of about 30,000 degrees. The radiation (in the form of photons) and matter (in the form of ions and electrons) were strongly coupled to each other and the photons would have been constantly scattered by the electrons. As the universe expanded, it cooled and the temperature dropped. When the universe was about thousand times smaller (compared to today) its temperature would have been about 3,000 degrees. At this temperature, matter could make a transition from the plasma state to the ordinary gaseous state. (This is similar to steam condensing as water at 100 degrees centigrade). The electrons and ions came together to form normal atoms of Hydrogen and Helium at this time.

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But what happened to the photons? Once the atomic systems formed, the photons stopped interacting strongly with matter. They were no longer scattered and hence flowed freely through space. As the universe expanded, their energy (and temperature) dropped. We said that the temperature was 3,000 degrees when the universe was thousand times smaller; when it expanded by a factor of thousand, the temperature should have dropped to 3 degrees or so. Hence we should see all around us a radiation field with a temperature of around 3 degrees. And this conclusion was triumphantly verified by the discovery of Penzias and Wilson in 1965.

Can we do better? Given that the radiation field (usually called the 'Cosmic Microwave Background Radiation' or CMBR) is a relic from the past, can we use it to probe the conditions that existed then? It is precisely such questions which led to the discovery of 'ripples'.

3. Ripples in Radiation

The universe we see today is littered with galaxies and is fairly nonuniform at small scales. One could ask whether these inhomogeneities have always existed or whether they are of recent origin. Most cosmological models suggest that structures like galaxies formed rather re-

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cently – when the universe was less than about ten times smaller in size. Nevertheless, the 'seeds' of these structures must have existed even in the earlier phases of the universe. These seeds, so to speak, would have manifested as small deviations from uniformity in the matter distribution when the universe was, say, a thousand times smaller. As the universe expanded, the deviations would have grown and, eventually, formed structures like galaxies. If we could detect these deviations then we would have really understood the origin of galaxies.

Any non-uniformity in matter distribution would have left an imprint on the radiation field. This means that the cosmic radiation reaching us from different directions will have slightly different temperatures.

Unfortunately, these deviations are too faint to be seen directly. But remember that, in the early universe, matter and radiation were strongly coupled to each other. Any non-uniformity in matter distribution would have left an imprint on the radiation field. This means that the cosmic radiation reaching us from different directions will have slightly different temperatures. Calculations show that this temperature difference is also extremely tiny – about one part in hundred thousand! But it is vital to look for these temperature fluctuations to verify the theoretical models.

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In the late seventies and eighties, some experiments attempted to measure these temperature variations. These experiments are very difficult to carry out from the ground because of the interference due to water vapour in the atmosphere. Water vapour absorbs and emits radiation in the microwave region of the spectrum in which one is trying to make measurements. To have a fighting chance, one has to carry out experiments at exceptionally high or dry locations. Even then, these experiments could only reach a sensitivity of three parts in hundred thousand and did not see any deviation. The microwave radiation looked quite uniform.

The real breakthrough came when NASA put into orbit the COBE satellite, specifically designed to look for temperature deviations in the microwave radiation.

4. The COBE Satellite Experiment

In 1974, NASA made an announcement of opportunity for 'small scale' experiments in astronomy. It took another 15 years for the COBE project to be developed and launched into orbit, on 18 November 1989, thanks to the dedication and competence of more than 1,000 scientists, engineers and administrators who were involved in the mission. COBE carried on board three instruments covering the wavelength range 1 m to 1 cm called DMR (Differential Microwave Radiometer), FIRAS (Far InfraRed Absolute Spectrophotometer) and DIRBE (Diffuse InfraRed Background Experiment). John Mather was the COBE Principal Investigator and was also primarily responsible for the FIRAS instrument. George Smoot was the DMR principal investigator. (The third instrument, DIRBE was to study the diffuse infrared radiation background with a principal investigator Mike Hauser; while this led to a result which is important in its own way, the CMBR observations stole the limelight!).

The idea was to measure the CMBR over the entire sky, which was possible with the chosen satellite orbit. This was expected to lead to significant improvement over previous measurements from ground which were done with limited sky coverage. The DMR searched for anisotropies at three wavelengths, 3 mm, 6 mm, and 10 mm in the CMB with an angular resolution of about 7 degrees. Temperature anisotropies at these scales were expected to come from the gravitational potentials of the largest scale structures in the universe. Roughly speaking, the photons which come from deeper gravitational potential wells will lose more energy compared to those coming from shallower potentials, which will lead to a temperature anisotropy that is roughly the same at all large angular scales. (This is called Sachs–Wolfe effect after the two scientists who first worked it out in 1967.) The FIRAS was designed to measure the spectral distribution of the CMBR in the range 0.1 to

10 mm to verify that it has the precise blackbody form expected in the big bang model. This was important for the following reason: Before COBE, several independent measurements of the radiation were made by Wilkinson and others, using mostly balloon and rocket-borne instruments as well as from ground. The intensity of the radiation peaks at a wavelength of about 1 mm where the absorption in the atmosphere is strong and measurements were difficult. Although most results gave support to the blackbody form, few measurements were available on the high frequency side of the peak; some measurements even gave results that showed significant deviations from the blackbody form. Since the blackbody form was a firm prediction from big bang model, it was important to lay all doubts to rest.

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The COBE mission was a success on all counts with the instruments working very well. The temperature fluctuations of the order of 10^{-5} were found and the background radiation with a temperature of 2.725 K followed very precisely a blackbody spectrum. Cosmology became an exact science (*Figures* 2 and 3).

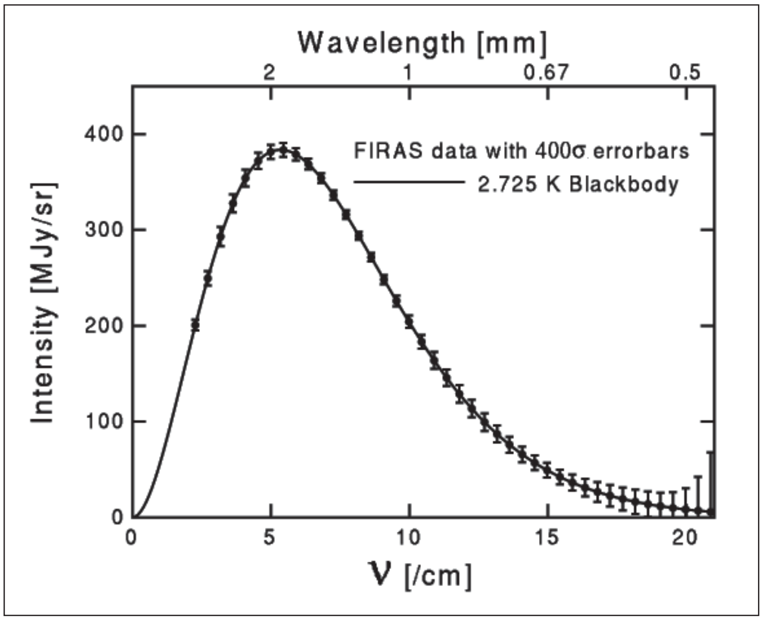

Figure 2. The spectrum of the cosmic microwave background as measured by COBE. Error bars have been multiplied by 400 times to make them visible. The theoretical curve for a Planckian spectrum fits the data extremely well.

(Courtesy: NASA)

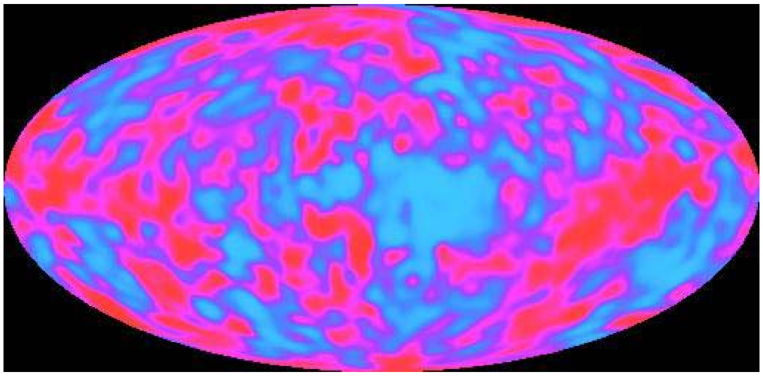

Figure 3. The minute difference in the temperature of the microwave background radiation in different parts of the sky as measured by COBE.

(Courtesy: NASA)

5. The Aftermath of COBE

What are the implications of this discovery for cosmology? To begin with, it shows that the theoretical models about the formation of the structures in the universe are basically sound. The universe was indeed smoother in the past but not completely so. The small departures from uniformity are what have grown into galaxies we see today.

Second, the discovery may throw some light on another key issue in astrophysics: the nature of 'dark matter'. This, among other things, holds the key to the question: What will happen to the universe in the future? Will it go on expanding for ever? Or will it reach a maximum size and start contracting afterwards? This situation is analogous to the behaviour of a stone thrown vertically up from the earth. Usually, the stone will rise up to a maximum height and fall back on earth. If we increase the initial velocity of the stone, it will reach a higher altitude before falling back. This, however, is true only if the initial velocity is below a critical value called the 'escape velocity'. If the stone is thrown with a velocity larger than the escape velocity, it will escape from the gravity of the earth and will never fall back. In other words, if the gravity is strong enough, it can reverse the velocity of the stone and bring it back; but if the gravity is not strong enough, the stone will keep moving farther

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and farther away from earth. We can compare the expanding universe to a stone which is thrown from the earth. If the gravitational force of the matter in the universe is large enough, the expansion can be reversed and the universe will eventually start contracting. Since the gravitational force increases with the amount of matter, the fate of the universe depends on the amount of matter present in the universe today. If the matter density is higher than a critical value, this gravitational attraction will eventually win over the present expansion and the universe will start contracting. The critical value of density which is needed for this recontraction to take place can be estimated if we know the speed with which the universe is expanding. It turns out that for our universe to contract back eventually, it should have a matter density of about 5×10^{-30} gm cm^{-3} or more. This density is called 'critical density'.

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We can make a fairly good estimate of the density contributed by matter which exists in the galaxies, clusters, etc. as long as the matter is emitting electromagnetic radiation of some form: visible light, X-rays or even radio waves. This density of visible matter turns out to be less than about five percent of the critical density needed to make the universe recontract. So if all matter in the universe is visible, then the universe will expand forever. Interestingly, this is not the whole story. It turns out that all the matter which exists in the universe is *not* visible! In fact, it could very well be that up to ninety-five percent of the matter in the universe is 'dark' and does not emit any form of electromagnetic radiation. If this were the case then it is important to identify and estimate the amount of dark matter which is present in the universe since it is the dark matter which is governing the dynamics of our universe.

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How do we determine the amount of dark matter present in the universe? Astronomers use different techniques for different objects but the basic principle is to look for gravitational effects which are *unaccounted* for by the visible matter. By studying the dynamics of galaxies and clusters of galaxies, astronomers have found that these systems contain a lot of matter which does not emit light. Obviously, one would very much like to know whether the dark matter is made of the same building blocks as visible matter (made of neutrons and protons which contribute most of the mass of atoms; usually called baryonic matter) or whether they are made of any other kind of elementary particle. Again COBE results have something to say about this: The amount of temperature variations detected in the microwave radiation lends support to the idea that dark matter is non-baryonic. Calculations suggest that the temperature fluctuations would be nearly a hundred times larger than what was detected, if the dark matter was made of the same material as ordinary matter. So the dark matter is made of particles which are different from normal matter.

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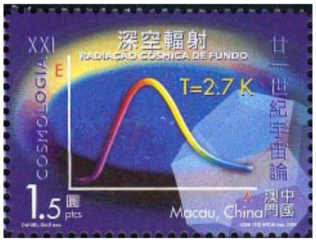
The story is actually more fascinating than that. Even before the COBE results came, cosmologists believed – based on other evidence – that most of the matter in the universe was dark and was made of some weakly interacting, massive, elementary particles and the most popular model at that time was something called cold dark matter (CDM) model. This model is based on a universe with critical density with most of the density contributed by dark matter particles. COBE results added an intriguing twist to this tale when combined with other observations. The theoretical analysis of COBE data by two independent groups – Padmanabhan and Narasimha at TIFR, India and Efsthathiou, Bond and White from UK and Canada – suggested that the dark side of the universe was actually made of two components. One was the standard dark matter but the other one was distributed very smoothly over large scales; that is, even the dark sector of the universe should contain at least two components. COBE could not throw more light on the dark side but subsequent cosmological observations have now led to an intriguing composition for the universe: two-thirds of the dark sector is made of an exotic component with negative pressure – now called ‘dark energy’ and one third is made of cold dark matter. COBE already contained the hints of this mystery, which still defies our theoretical understanding.



The stamp (issued by Macau in 2004) shows the spectrum (as in Figure 2).

Finally, there is another bit of information which one can obtain from the CMBR temperature fluctuations. We can use it to determine the motion of our galaxy. Remember that the COBE satellite is not at rest with respect to the radiation field: COBE is orbiting earth; earth is orbiting the sun; the sun is moving in our Milky Way galaxy and the galaxy itself is moving in space. All these motions, combined together, make the COBE move in some specific direction with respect to the cosmic radiation. The motion will produce a tell-tale variation in the temperature over and above any intrinsic variation we are looking for. It is quite easy to isolate this effect and – working backwards – determine how exactly our galaxy is moving. COBE has determined this motion with great precision. Cosmologists now know for sure where they are heading to, thanks to COBE!

Suggested Reading

[1] The best popular introduction to cosmology is in: W Weinberg, *The First Three Minutes*, 2nd edition, Basic Books, 1988&1993.

[2] These books present a more recent view:
J C Mather and J Boslough, *The Very First Light*, Basic Books, 1996.
G Smoot and K Davidson, *Wrinkles in Time,* Little, Brown and Company, London, 1993.

[3] The following URL has the details of COBE project at the NASA web site: http://lambda.gsfc.nasa.gov/product/cobe/

[4] A technical review of several aspects of cosmology is available in the special edition of Current Science and further references are available in the review articles in that volume: *Current Science*, Vol. 88, 2005.

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