Studying the Universe's past with the COBE satellite

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The Big Bang theory provides the general and by now the only scientifically acceptable framework for the global evolution of the Universe. According to it the Universe started its expansion about 10-20 billion years ago from a state of extremely high density and temperature. During the first approximately 10^5 years it was a mixture of matter and the radiation left over from the Big Bang itself. Since the temperature was very hot, the matter was ionized and tightly coupled to the (relic) radiation. Because of this it was opaque to the photons and since they could not reach observers this epoch is impossible for us to observe. As the Universe expanded it cooled down until at the age of about 100,000 years it became sufficiently cool for protons and electrons to recombine to form neutral hydrogen atoms. At that time the relic radiation decoupled from matter and began to propagate freely to the observer. Thus this epoch represents the earliest time the Universe can be observed. According to the standard picture no stars or galaxies existed in the Universe at that time, only the very small density fluctuations that were destined to form later the structures we live in today. The epoch of recombination is the earliest stage in the history of the Universe that can be observed and studied through observations with photons. This offers an important tool for studying the early Universe, but also shows the limitations of how far into its infant stage it can be seen. Hence the importance (the earliest age to observe) and the difficulty (only the tiniest structures existed) of observing the Universe at that stage. In November 1989 NASA launched its first cosmology satellite - COBE (Cosmic Background Explorer) - with the explicit task of attempting to observe that stage in the evolution of the Universe.

Even though the law of expansion of galaxies was discovered by Edwin Hubble in the thirties, the Big Bang theory was really placed beyond reasonable doubt only after the discovery of the microwave background radiation by Penzias and Wilson in 1964. This is the relic radiation left over from the Big Bang itself and it was predicted to exist as a consequence of the Big Bang theory as early as 1948. Since this radiation is a relic from the very early stage in the evolution of the Universe it was predicted to have various properties. An important property of any radiation is its spectrum, i.e. how much energy is carried by the photons of various frequencies. Since the Universe once went through a very hot and very dense phase, this radiation, via its interactions with the hot, dense and opaque plasma, should have thermalized to have the so-called black-body (or Planckian) spectrum. Such a spectrum is produced by all objects that are opaque so that the radiation photons interact efficiently with the matter and have time to achieve thermal equilibrium with the matter or to *thermalize* to that spectral distribution. E.g. since the Sun is opaque (we do not see its center) it has black-body spectrum centered at the visible (roughly green-yellow) part. Its spectrum is shown in Figure 1: it is approximately black-body, but because (among other things) the outer parts of the Sun are transparent there are small deviations from the black-body curve. The relic radiation was very hot during early phases, by now it has cooled so much that its peak has (red)shifted into the microwave/radio region of the spectrum. At the same time it must have remained strictly of the black-body form. Hence it is generally called *the microwave background radiation* and ever since its discovery it has been considered most important to prove that the microwave background radiation has a black-body spectrum to a very high accuracy.

The second prediction relates to the spatial structure of the microwave background. It is widely accepted that the structures we observe in the Universe today (e.g. galaxies) formed out of small density fluctuations that have existed (or been produced) in the very early Universe. The matter within these fluctuations feels a larger gravitational field than the rest of the Universe and therefore fluctuations *grow* with time. It was also generally accepted that these small density fluctuations must have already existed at the time of recombination. In a seminal paper in 1965, shortly after the discovery of the microwave background, two theoreticians Sachs and Wolfe showed that the slightly inhomogeneous gravitational field generated by density fluctuations, if already present then, should lead to very small temperature fluctuations in the microwave background. Their amplitude should be very tiny - about one part in ten to a hundred thousand in the relative temperature differences on scales separated by several degrees (or more) on the sky. Hence, the searches for these anisotropies, which George Smoot of Berkeley called poetically "the wrinkles of time", began very soon after the microwave background was discovered. However, it is very difficult to observe these tiny structures through the Earth's atmosphere and despite persistent searches for these anisotropies from the ground and by balloon-borne experiments since 1964 nothing has been found.

Thus the COBE satellite was launched with the explicit task of measuring the microwave background sky from above the atmosphere. The COBE had three instruments: the FIRAS (Far InfraRed Absolute Spectrograph) to measure the energy spectrum of the microwave background very accurately, DMR (Differential Microwave Radiometers) to measure the anisotropies and DIRBE (Diffuse InfraRed Background Experiment) to find and measure the infrared background left over by the first galaxies. The tasks from the first two are now by and large completed; the data from the third experiment is still being analysed.

The first COBE results came from the FIRAS measurements of the microwave background radiation. Although it took only 9 minutes to measure the necessary data above the atmosphere it took the COBE team almost a year to analyse it and when it was released by John Mather at the American Astronomical Society meeting in 1991 the data (and the team, of course) received a standing ovation from the gathered astronomers. Fig.2 shows the spectrum measured by the COBE FIRAS. The blue line shows the theoretically predicted black-body spectrum produced by radiation of just 2.73 degrees Kelvin (or -270.42^{o}C) and the yellow bars show the measurements with the errors amplified 20 times. The spectrum is black-body to an unprecedentedly high accuracy and few labs would be able to produce such accurate black-body radiation. (Compare to the Solar spectrum on Fig.1). These results mean that indeed the microwave background radiation has originated in a very hot and dense phase of the Universe as predicted by the Big Bang theory. But they also mean there was very little hot gas in the Universe between the epoch of recombination and recent times, for otherwise it would have left measurable features in the spectrum. This is another important result of these measurements and tells us much about the efficiency of structure formation and stellar activity in the post-recombination Universe.

While it may be easier to measure the microwave background anisotropies from above the atmosphere, it is by no means a trivial task and it was planned that the COBE DMR should operate for four years in orbit before arriving at final results. The energy spectrum of the radiation peaks at a frequency of about 5cm^{-1} or $\sim$ 150 GHz. Since one observes it through the "smog" of our Galaxy, in order to find the tiny fluctuations one has to eliminate the contributions from the Galaxy to a very high degree of accuracy. It turns out that at frequencies less than about 20 GHz Galactic synchrotron and other emission make it impossible to measure any such anisotropies. At frequencies in excess of 150 GHz emission from the dust in our Galaxy would also prevent us from reliably measuring such small anisotropies (although we could still see the microwave background itself). Thus the COBE DMR were chosen to have 3 frequency bands: 31, 53 and 90 GHz.

Still even with this optimal choice of bands the task of finding the *primeval* anisotropies would be formidable. The reason is the so-called dipole of the microwave background which was discovered by George Smoot of Berkeley and his collaborators in the early 70's. The dipole is produced by the Doppler effect which results from motion with respect to any emitted waves and is familiar in daily life from the change in the pitch of an ambulance (emitting sound waves) as it moves past a stationary spectator. Similarly if we were moving with respect to the microwave background we would measure a slightly hotter radiation coming from the direction of motion and a slightly colder one in the opposite direction. This way it was determined that our Galaxy is moving at a speed of 630 km/sec with respect to the microwave background; this motion was confirmed almost two decades later by direct galaxy surveys. Since the dipole by far dominates any primeval anisotropies it has to be very accurately eliminated before the latter can be found. All this requires very accurate measurements and modelling in order to detect the spatial structure in the microwave background.

Because of this complexity the COBE DMR experiment was supposed to last for the total of four years. Such a long time is needed to reduce the intrinsic instrument noise of the COBE DMR. However, the results were analysed after each year of observations. Thus the noise after the final four years of data should be approximately half of its value after the first year; after two years it is decreased by approximately 40% compared to the first year. It took almost two years to analyse the first year of data and in April 1992 at the American Physical Society meeting in Washington, DC the COBE team announced the discovery of anisotropies at a level of about one part in a hundred thousand on a scale of a few degrees over the sky. This was met with great excitement by the physics community and Stephen Hawking of Cambridge called it "the discovery of the century, perhaps all time".

Fig.3 shows the microwave background sky as seen by the COBE DMR after the first year of observations. The top picture shows the dipole that is generated due to the local motion of our Galaxy and needs to be removed in order to get through to the underlying primeval structure. The middle picture shows the second step in the analysis: the dipole has been removed and one can see now the dominant contribution due to our Galaxy (central bright red band). Finally, after the Galaxy contribution is removed the final goal appears: the map of the primordial anisotropies in the microwave background radiation itself, the "time wrinkles", is shown on the bottom picture. What was measured and is shown there is nothing less than the *entire* observable Universe when it was only approximately 10^5 years old. The map was produced with an angular resolution of about 10 degrees of arc and the size of each island (or continent) is about several hundred million light years (for comparison the distance to our nearest galaxy Andromeda is about 1.5 million light years). The second year maps have by now also been analysed and released and the noise in them is decreased by further 40%. These maps are shown for each of the three COBE DMR frequencies in Figure 4. One can see that the features generally look clearer, but also one can see how Galaxy contaminates the maps at the various frequencies (which testifies to the difficulty of its accurate removal). The amazing nature of this measurement is illustrated by the fact that the difference in temperature between the hottest and the coldest continents on this map is only a couple of hundred microkelvin or $\sim 0.002^o$K. These seeds have later produced galaxies such as our own. Within the observational uncertainties the angular structure of the anisotropies is consistent with a number of currently fashionable theories for the evolution of structure in the Universe, but the hope is that after the analysis of the four years of data, when the instrumental noise is reduced further, it should be possible to accurately pinpoint the roots of the structure in the modern Universe. These data should be released to the scientific community later this year.

The last, but certainly not the least experiment on board COBE is devoted to studying the diffuse infrared background radiation as its name, DIRBE, suggests. Such radiation is predicted to have been produced by the early generations of galaxies. These galaxies, because they are located very far away, cannot be studied or even seen with normal telescopes but the hope is that they can be detected via the total radiation they produced. This radiation should have been produced when the Universe was less than about 1 billion years old and this fills in the gap between the very early Universe (about 100,000 old) observed with the COBE DMR and the present-day Universe seen in normal telescopic studies (about 10 billion years). Through it one can study the actual processes that led to early generations of stars, formation of galaxies themselves and the evolution of chemical elements in the Universe. Although there are some theoretical models the energy spectrum for this background is not known for sure (unlike the black-body spectrum of the microwave background) this experiment has ten frequency bands. It is also very difficult to analyse: it had to be designed so that its frequency bands lie at frequencies where the microwave background radiation is no longer dominant (otherwise the diffuse background due to galaxies may be too negligible to measure). This by default puts it in the region where the emission due to light scattered from the Solar system and the emission due to stars in our Galaxy are dominant. The results have not been released yet, but should be released within this year and are awaited by the scientific community with great interest. When did galaxies form? How efficiently? How bright did they shine and at what wavelenghts? These are just some of the questions the DIRBE results will shed light on.