Echoes of the Big Bang
Transcript

Date: Wednesday, 5 March 2014 - 1:00PM

Location: Museum of London
Today’s lecture is about the radiation that fills the sky in every direction – it pervades the space between the stars and the galaxies, and is far more smoothly distributed. The glow is not visible to our eyes, as it is only apparent to telescopes and detectors operating at microwave/millimetre wavelengths. It is known as the cosmic microwave background radiation, and it is a ghost from the early Universe, at a time when it was far denser and hotter than it is now. The discovery of the cosmic microwave background established the pre-eminence of the Big Bang theory for the origin of the Universe, and the determination of its detailed properties plays a very important role in modern cosmology. They reveal much about the matter-energy composition of the cosmos, how the Universe expanded and cooled as it aged to evolve into the structure we see around us today – and along the way the story ties into the problem of understanding the origin of the chemical elements. There will necessarily be some overlap with, and referral to, some of the subject matter covered in my earlier lecture concerning The age of the Universe.

By the early part of the 20th century the American astronomer Edwin Hubble had demonstrated that the universe is expanding, from the way that all galaxies are receding away from us; space is growing in size and pushing the galaxies farther apart. One of the observable consequences of this expansion of space is the cosmological redshift. As a photon of light travels through a stretching volume of space, its wavelength also becomes stretched; the further a photon has to travel through space, the more its wavelength will be lengthened so that the light redness. By the time it reaches us, we describe the light as having been redshifted. Astronomers determine the redshift of a distance cosmic object by comparing the observed wavelength of spectral features (such as emission or absorption lines) in its light to the wavelength such a feature would have been emitted at.

Another, perhaps more philosophical, consequence is that an expanding Universe must evolve and change. Tracing the expansion backwards through time leads to a logical conclusion that there must have been a start to the Universe - the average distance between galaxies gets smaller and smaller until at some point it is non-existent. At this moment we obtain a ‘singularity’, a region of infinitely large density which was first espoused by Georges Lemaître in 1931 as the ‘primeval atom’. He deduced this using Einstein’s equations of General Relativity (without the need for Einstein’s cosmological constant), which enable us to mathematically link space and time together in a single geometry. The inference is that there was a beginning to everything, when some event initiated the Universe and set it on its outward motion - an event that we now commonly refer to as the Big Bang, a phrase coined by the British astronomer Fred Hoyle in the 1950’s.

Finally, as everything moves apart from everything else uniformly, the expanding Universe implies that nowhere is special, and so that any part of the present Universe is pretty much like any other. This leads to the important cosmological principle that the Universe looks the same in every direction and there is no preferred place. Indeed, if you ignore the small-scale clumpiness of structure of galaxies and stars, the Universe appears the more or less same in all directions from our location. When averaged on a scale of around 100 million light-years, the Universe is close to uniform.

Despite the clear inference for the expansion of the Universe from the observed recession of the galaxies, the Big Bang interpretation was left vulnerable by a clear mismatch between the implied age of the Universe and the known age of objects within it. Unfortunate errors in the estimated distances to the galaxies (which we now know to have been out by about a factor of 10) led to an overestimate of the expansion rate, suggesting that the age of the Universe was a mere 1.8 billion years. This was in rather obvious conflict with the data on the radioactive decay of the oldest rocks on Earth and in meteorites, which had established their age as at least 3-4 billion years old. The major errors in the galaxy distance scale and a true reconciliation in age estimates was not achieved until 1960, which means that the acceptance and confirmation of the Big Bang idea remained a major problem for the first half of the 20th century. Mathematically it required quite contrived solutions (eg the use of a cosmological constant) in order to stretch out the age of the Universe sufficiently. And observationally, as Hubble had been using the best telescope in the world at the time, it was difficult for other astronomers to reproduce or substantially improve on his observations. Some scientists were also uncomfortable with the philosophical issues raised about generating the original Big Bang in a frame where there was no space or time.

One of the alternative interpretations that sought to account for the recession of the galaxies without the requirement of a Big Bang was the ‘Steady State’ theory of cosmology, formulated by Herman Bondi, Thomas Gold and Fred Hoyle in 1948. This theory proposed that new matter is continually and spontaneously created, and over time collects and condenses to form fresh galaxies. In this way new galaxies appear to fill the voids opened up by older galaxies moving away from each other in the universal expansion. The cosmological principle is retained as the density of the Universe is kept in balance, and nature of the Universe is grossly uniform on the largest scales. The principle is also extended to suggest that as well as no preferred place in the Universe, there is also no preferred time; with no need for a Big Bang, the Universe would be eternal and unchanging. Although
the idea of the steady state cosmology captured the public’s imagination, it was not taken very seriously by cosmologists. It did, however, make definite predictions that stimulated important observational tests in the 1950’s and 1960’s.

One of the predictions of the steady state theory is that a uniformity in space and in time demands that distant regions of the Universe should closely resemble the nearby Universe. The fact that light can travel only at a finite speed means that over astronomical distances, the light we receive from a distant galaxy will have left it many billions of years ago; we thus see more distant galaxies as they appear in the past. In the Big Bang theory, distant galaxies are intrinsically younger and so could look very different from galaxies today. In the steady state theory both the far and near Universe should contain a similar mix of both young and old galaxies.

A chance to test these ideas arose in the late 1950’s/early 1960’s when all-sky surveys of extra-galactic radio sources showed that some large galaxies are very powerful sources of radio emission. Even without a deep understanding for the origin of this radio emission, the distribution of the population of radio sources could provide a useful discriminant between the theories. As the radio emission was so powerful, it could be seen from galaxies at a great distance from Earth. The test was to observe a large sample of radio sources, measuring how bright each is; then create a plot of how many sources there are at different levels of brightness. The steady state theory predicts that the distant population is similar to the nearby one, and so there should be the same population, just diluted in brightness because they are further away and thus one would expect the numbers to drop off in a predictable manner. In an evolving universe, distant sources are inherently different to local ones – maybe their brightness will change with time. This means that the relationship between source counts and brightness is less predictable, as sources could be weaker not just because they are further away, but also because they might not be the same intrinsic brightness when younger. When this test was carried out by the radio astronomy group led by Martin Ryle in the Cavendish Laboratory in Cambridge using the 3C and 4C radio surveys, they found an excess of many weak sources over the no-evolution situation predicted for the steady state theory. This indicated an evolution in the radio source population with time; many more of the younger galaxies were strong sources of radio emission, and that the distant universe was indeed different to that around us. This finding was compounded with the discovery of powerful radio-emitting quasars, which showed an even clearer case of cosmic evolution – although they are very abundant in the past, there are none in the local Universe. By the mid-1960’s, the steady state view of cosmology was effectively dead.

Another major problem under consideration in the middle of the 20th century that was also linked to cosmology was the origin of the chemical elements. Hydrogen is the most common element, helium the next common (25% by mass), and there is only about 2% contained in heavier elements. By the 1940’s astronomers knew that the abundance of chemicals was relatively uniform in all stars, implying a common origin; they had also that stars like our Sun were powered by the conversion of hydrogen to helium at their core, but it was less clear how more massive stars created their energy, or how the heavier elements were forged.

Not knowing how to make elements in the stars at that time, astronomers looked to the cosmology of the expanding Universe to see if it offered a solution. Maybe in its earliest stages, the Universe could be so dense and hot that nuclear fusion reactions would occur to produce the right relative mix of all the elements. If all the elements were created in the extreme conditions of the primordial Universe, their relative abundances would be fixed by the temperature and density at the time, and ‘frozen in’ at fixed values as the Universe expanded and cooled. There was some progress with this idea, but in practice a solution could not be found whereby all the elements could be synthesized at a single temperature and density. The conditions necessary for the rapid nuclear reactions existed for too short a time, and the universe would have expanded and cooled too quickly. There were also major discrepancies between theory and observations, such as the fact that light elements (such as lithium, beryllium and boron) were vastly over-produced, while much heavier elements (iron and beyond) were under-produced. This approach could only succeed with major medication, and was abandoned for a while.

We know now, of course, that the heavy elements are created in the main sequence burning of the more massive stars. However, it wasn’t until 1957 that Hoyle and his collaborators Fowler, Burbidge and Burbidge finally cracked the sequence of nuclear fusion reactions required to progress beyond the formation of Helium nuclei onto carbon and successively heavier elements in the cores of massive stars, in the cool envelopes of red giants, and in the storm of a supernova explosion.

A side consequence of the early work on primordial nucleosynthesis, however, was the first prediction of a diffuse background radiation. Estimates of the properties of the early phases of the Universe suggested that the contents could be at temperatures of billions of degrees. Any hot object emits thermal radiation - and the higher the temperature, the more energetic the light. The very early Universe was hot enough to have given off light as gamma-rays and the idea of this thermal ‘background’ radiation was predicted by Alpher and Gamov in 1948. After billions of years this radiation would still be around, but would have cooled to resemble the light from a source of temperature around only 5K above absolute zero. The prediction could not be verified at the time, as the radiation would be observable in the cm and mm wavebands, an area of the electromagnetic spectrum that was not observable at the time, as radio astronomy still in its infancy.

Another fundamental problem was that even with an understanding of how helium was created by main
sequence stars, there was still too much helium in the Universe. Helium is difficult to observe (it has a high excitation potential which means it can only be observed in very hot stars), but its universal abundance was eventually established as about 25% by mass. Even though it powers the light of 90% of all stars in all galaxies, main sequence burning doesn’t operate rapidly enough – and even at the end of its main sequence life, a star will only have converted 10% of its original mass to helium. Thus during the lifetime of a galaxy (so far) there’ll have been time for about only 1% of its stellar mass to have been converted into helium.

In the 1960’s Fred Hoyle (along with Roger Taylor, John Faulkner and Willy Fowler) took on the problem of helium by revisiting the idea that it could have been preferentially formed in an early phase of a hot dense Universe, but now reworking the earlier calculations in the light of intervening developments in particle physics. They showed that the cosmic abundance of helium – along with the other light elements – could be made in the first few minutes after the Big Bang, and then frozen out the observed values as the universe expanded and cooled.

Unlike the other elements, the cosmic helium abundance is primarily determined by the thermodynamics of the early universe, and not by microphysics involved in the nuclear reactions.

Twenty-five seconds after the Big Bang, the Universe had a temperature of around 2 billion degrees, and consisted mainly of neutrinos and photons, along with a smattering of protons, neutrons and electron-positron pairs. The protons could not simply link up with electrons to form hydrogen atoms (or with neutrons to form deuterium) as they would be immediately broken apart by energetic radiation. Later, when the Universe reaches an age of about a minute, it will have cooled enough for deuterium nuclei to hold together, and a chain of nuclear reactions is triggered that converts almost all of the deuterium into helium along with tiny quantities of some other light elements. All the free neutrons have been used, so no more deuterium (and hence helium) can be produced – thus there is a limit to how much of the primordial material can be converted into helium, and it is constrained by how rapidly the Universe expands in its early stages, and on the ratio of neutrons to protons at that time. It’s only after about a few hundred thousand years that the Universe cools sufficiently (although still at a temperature of thousands of degrees!) for the helium nuclei to join with electrons to form atoms. Hoyle et al confirmed that they could also successfully produce the correct abundances of light elements in this way. Along with the evolution of the radio source counts, the success of this primordial nucleosynthesis consolidated the support for the Big Bang cosmology.

But the strongest piece of evidence for a Big Bang was the serendipitous detection of the cooled thermal radiation that had been predicted by Alpher and Gamov’s earlier work. It was an accidental discovery made by Arno Penzias and Robert Wilson in 1964 at the Bell Laboratories in New Jersey, and for which they were awarded the Nobel Prize in physics in 1978. The two men were calibrating a horn-shaped microwave antenna; radio waves entered through the wide aperture to be directed onto a detector at the narrow end of the horn (the shape suppresses radiation from directions other than that in which the horn is pointing, and is meant to particularly block signals from the ground, a strong source of microwave radiation). The antenna had been in use for receiving signals from telecommunications satellites (such as Telstar) but it could also be used to detect astronomical signals.

There was a problem in that the antenna was also picking up extra radiation as ‘noise’ and Penzias and Wilson were trying to isolate the cause of this persistent signal, checking it did not originate from any component in the receiver or horn system. The noise remained constant wherever the horn pointed in the sky. This simple fact ruled an origin as radiation from cosmic objects in either the Galaxy and in the Solar system, as these would have been concentrated only in certain known directions in the sky. The noise didn’t show any directional preference to cities, change with time, or correlate with known extragalactic radio sources either. They spent a year carefully ruling out possible causes, including the removal of some pigeons roosting in the antenna, along with the ‘white dielectric material’ they had left behind. The noise persisted, and they began to realise that they could perhaps be detecting a real signal - it was only through conversations with a group of researchers in Princeton, led by Robert Dicke, that they realised they had serendipitously discovered the cosmic microwave background radiation.

The detector was tuned to work at a single wavelength of 7.35 cm, so they could not confirm the spectrum of the detected signal, but their observation provided the first point on the graph of the cosmic microwave background spectrum, ie the measurement of the intensity of radiation with wavelength. Within a few months the Princeton group had also detected the emission at a wavelength of 3.2cm; and other detections at other wavelengths soon followed, adding more data points to the spectrum.

The shape of the spectrum is significant as it follows what is known as a black body curve, characteristic of thermal radiation. The wavelength at the peak of this curve depends precisely on the temperature of the matter giving off the radiation, and the spectrum of the cosmic microwave background radiation implied it was due to thermal radiation at a temperature of 2.7 K above absolute zero (-273°C), only 2.3 K lower than the original 1948 prediction.

The observations established the presence of a background of microwave radiation that filled the sky in every direction, a remnant from a time when our Universe was much denser and hotter than it is now. But the radiation would originally have been emitted from a much higher temperature, meaning that the peak of the
spectrum used to be at a shorter wavelength. Thus the wavelengths of the background photons would originally have been much smaller, and then systematically redshifted during the subsequent expansion of the Universe. One interesting consequence of the blackbody shape is that it is preserved as the Universe expands - if all the photons that make up the spectrum are redshifted by the same amount the shape is unchanged. Only the temperature of the radiation changes as the universe expands, dropping in inverse proportion to the scale of the Universe. There has always been cosmic background radiation throughout cosmic history - it’s just now that it’s observed as a microwave background.

Many follow-up measurements of the background by various techniques confirmed the shallow slope of the black body spectrum at wavelengths longer than 1cm, and by 1970 observations had traced the curve up to 3mm. Observations to confirm of the exact shape of the peak of the curve were more difficult, as the light near these wavelengths is heavily absorbed by the atmosphere. Establishing the steep drop of intensity at shorter wavelengths is important to determine the exact nature of the background light, and measurements in this part of the electromagnetic spectrum can only be made from high altitude, as the atmosphere is itself a strong source of radiation at these wavelengths. Detections were attempted from instruments carried aloft on balloons, aircraft, rockets and satellites – although the results were broadly consistent with the black body spectrum the difficulty of the observations means that there were large systematic errors which left room for deviations from the curve that if proven right, would challenge our understanding about the nature of the early Universe.

Definitive measurements had to await observations from space, which were only achieved with the launch of the COBE (COsmic Background Explorer) satellite in 1989. Its data confirmed the background to follow a beautifully perfect blackbody spectrum for a temperature of 2.73 K. The satellite carried three experiments: FIRAS (far-infrared absolute spectrometer) which was designed to measure the black-body spectrum of the radiation; DMR (differential microwave radiometers) to look for any variation of the background temperature across the sky; and DIRBE (diffuse infrared background experiment) to measure the extragalactic background at 140 and 240 microns. Following the tremendous success of COBE, the leaders of the science teams for the FIRAS and DMR experiments, John Mather and George Smoot, shared the Nobel prize for physics in 2006. COBE also produced the first map of the anisotropies in the cosmic microwave background, even though it could not resolve structures on scales smaller than 7° on the sky (a resolution equivalent to the width of 14 full Moons…).

Maps of the microwave sky do not initially reveal a uniform glow, but there are structures inherent within it. The most obvious variation is one of hot and cold to either side of the sky at the level of about 1%, which is caused by the motion of the Earth through the radiation. This dipole anisotropy is easily removed, and is not an intrinsic feature of the background. After correction from the motion of the Earth, there remains strong signal aligned with the plane of the Galaxy, which is due to emission by cold, dusty clouds in the flat disc the Milky Way. Far away from the plane of the Galaxy, the light takes on a mottled appearance, revealing subtle variations in the temperature of the background radiation.

Once the effect of the Earth’s motion and the foreground Galactic emission are removed, the microwave background is amazingly uniform, at nearly equal temperature across the sky. Maps of the cosmic microwave background radiation don’t make it look uniform, however, as they are usually manipulated to emphasise where there are departures from the average temperature. These are false colour images as well, where the colours represent the temperatures of the radiation. The maps reveal a mottling all across the sky with a variety of sizes, and these fluctuations from the mean are at a level of a few parts in 100,000: to give a sense of this, this is equivalent to a variation of height of about 100m on the scale of the width of the Earth.

Even though the temperature variations are very subtle, they are vitally important for cosmology, as they trace slight density enhancements in the matter distribution at the time: regions that were slightly denser than average were also slightly warmer than average, and less dense regions were slightly cooler than average. Thus the slightly warmer regions will become the focus for the growth of mass concentrations under gravity that will eventually evolve to become the structures we see today, such as galaxies and clusters of galaxies. We shall return to the topic of these anisotropies shortly, but first let’s review where the background radiation actually comes from.

The Universe starts with a Big Bang, which should be considered as an infinitely dense and infinitely hot point. The temperature immediately begins to fall as the Universe spreads out, so the expansion of the Universe is inextricably connected to both its cooling down and its evolution. We currently have no consistent description of physics that can be applied simultaneously to both gravity and quantum physics; so the theories break down and cannot describe the event of the Big Bang.

Currently we can only realistically attempt an explanation for what happens once the Universe ceases to be a ‘quantum’ object. At this point the Universe is approximately 10-43 seconds old – this is known as the Planck time and it represents an absolute limit of our understanding with our current knowledge of physics. At this point the Universe will already be 10-35 m across and have a temperature of 1032 K.

The Big Bang suggests a steady outwards expansion but there seems to be a short period of dramatic change once the Universe is about 10-36 s old, as we infer that the Universe does not simply, but inflates in size incredibly rapidly. The idea of inflation was first mooted by Alan Guth in 1982, to account for a couple of known
problems. The first is the horizon problem: the Universe (and particularly the cosmic background radiation, for example) is uniform in all directions; there are regions of the Universe that are separated by such vast distances that they cannot be in communication with each other (as information transfer such as energy or heat can only be transmitted at the speed of light), yet they're all at an identical temperature. Inflation allows for these regions to be once all closely connected, and in a state of thermal equilibrium with each other, only then to be pushed far apart so rapidly that they could no longer be in contact with each other. A period of rapid inflation can also explain the flatness problem: the curvature of space is flat – every tiny wrinkle in the shape of space can be smoothed out if it blown up quickly to much larger scales.

We thus invoke a very brief period of exponential expansion form when the Universe was less than 10-32 s old, whereupon it doubled in size every 10-34 s at least a hundred times over, taking it away from the quantum regime to something the size of a grapefruit. Inflation is an separate theory from the Big Bang model of cosmology – it is an expedient working model, and explains rather than predicts anything that can be tested experimentally. After this short period of inflation the universe continues to expand, but at a more leisurely rate.

Skipping forward to when the Universe reaches about 1 second in age, it is now about a km in diameter, and baryons such as protons and neutrons have begun to form from the quarks. For reasons that are deeply unclear, matter has come to dominate over anti-matter. By the time it is three minutes old, the Universe is full not just of baryons, but electrons and neutrinos have been realised.

At three minutes the Universe-cools sufficiently for protons and neutrons to unite under the strong nuclear force to create the first atomic nuclei in the Universe, but this period of primordial nucleosynthesis lasts for only 17 minutes before the temperature drops too low for the processes to continue. Most of the nuclei formed are single protons (ie nuclei of hydrogen), along with alpha particles (ie helium nuclei) consisting of two protons and two neutrons. There are about three times as many hydrogen nuclei forming as helium nuclei, along with tiny amounts of other light nuclei, such as deuterium (an isotope of hydrogen consisting of a single proton and neutron) or lithium (three protons and three neutrons bound together).

The tiny temperature anisotropies of the cosmic microwave background radiation trace inhomogeneity in the mass density of the Universe; these perturbations in density are crucial to providing all the structure inherent in our present day universe on the scales of galaxies and clusters of galaxies. A tiny enhancement in density in one region over the average background density will grow under gravity (once the universe is matter-dominated) as it will gravitationally attract matter from nearby places. Thus a small departure from the average can grow by gravitational instability to eventually form much larger gravitationally bound concentrations.

We can calculate the size of the matter density fluctuations required at the time of recombination in order to grow the current large-scale structure in the universe, and infer the size of the perturbations in the temperature of the background radiation that these would cause. Before recombination, the way that photons are scattered by the free electrons inherently connects radiation and matter, in that the plasma and the radiation are 'coupled' together to move like a fluid. The radiation gives the fluid an outwards pressure, opposing the inward pull of gravity. Given an over-dense region of the primordial plasma, the over density will gravitationally attract matter towards it, but the heat of photon-matter interactions creates a large amount of outward pressure. These counteracting forces of gravity and pressure create oscillations that move through the plasma, analogous to sound waves. Whether the pressure or the gravity dominates depends on the length scale of the density perturbation: on large scales gravity dominates and fluctuations can grow; on small scales pressure wins and produces an oscillation in the baryon-radiation fluid of the early Universe rather than growing more clumpy.

At recombination the matter is now in the form of atoms, and suddenly no longer coupled to the radiation: the atoms can collect under gravity and the decoupled photons can stream away to form the background radiation.
But because their distribution had been tied together until that moment, the oscillations of the baryon-radiation fluid are imprinted on the distribution of the light escaping as the cosmic background radiation. The size of the anisotropies in the radiation background tells us which sound waves were crossing the Universe at the moment of recombination, and thus reveals the size of the condensations that form the seeds for the development of structure.

It’s not that we can track individual structures in the background radiation to the formation of particular clusters of galaxies. We can only make a statistical comparison to theoretical models, which mathematically characterises the amount of clumpiness in the cosmic microwave background. It’s not just how clumpy the structure is, but how clumpy it is on different scales – it’s quite possible for something to be smooth on large length scales, but clumpy on small scales.

The amount of clumpiness is plotted as a function of length scale (expressed as an angular separation between clumps on the sky; and remember that the diameter of the full Moon in our sky measures about half a degree) in an important graph known as the power spectrum of the oscillations. The angular separations are on the horizontal axis, with the amount of variation present on each angular scale plotted on the vertical axis, ie the extent to which the temperature measured at one point will, be (on average) be correlated with the temperature at some other point at that angular distance away.

We can compute a power spectrum of oscillations as a function of length scale from theoretical models by backtracking from the observed large-scale distribution of clusters of galaxies seen today, and this comparison was an important early test of the cosmological models. But early predictions of the acoustic oscillations required to produce today’s structures predicted a much larger anisotropy than was observed - they needed to be large then to have grown into the clusters of galaxies observed today, but the anisotropies in the cosmic microwave background radiation were smaller than expected. This discrepancy can be accounted for by the presence of dark matter, non-baryonic matter that does not interact with electromagnetic radiation in any way. The fact that it does not interact with photons of light means that dark matter is not coupled into the baryon-radiation fluid of the Universe before recombination. There is then nothing to prevent it gathering earlier under gravity, permitting a clumpy distribution of matter to develop without disturbing the radiation. The dark matter is then key to providing large enough regions of increased mass density to provide a focus for gravity, but without disturbing the light of the background radiation too much.

Determining the angular scale of the anisotropies, however, is far from trivial. Early (pre-COBE) attempts only produced upper limits for the anisotropies on small scales, and observations of the large angular scales were made difficult by the need to observe a large part of the sky, as the Earth blocks much of the sky from either balloon-borne or ground-based observations. There were many notable attempts and experiments to pin down the anisotropies on smaller scales, for example with the BOOMERanG experiment (Balloon Observations Of Millimetric Extragalactic Radiation and Geophysics). International collaboration flew detectors at heights of around 40 km suspended high-altitude balloons in the late 1990’s, obtaining 10 and a half days of observation in the dry skies above Antarctica. While the technique was much cheaper than a satellite, it could only map only a limited region of sky, albeit at a much better sensitivity, and at an angular resolution of less than a degree across.

By the late 1990’s the first prominent peak in the power spectrum had been clearly established. The next big advance came with the launch of the WMAP (Wilkinson Microwave Anisotropy Probe) satellite in 2001. Like its predecessor COBE, WMAP produced an all-sky map of the anisotropies, but now down to an angular resolution of 0.1°. The resulting detailed map of the background radiation enabled a measurement of the anisotropies on large angular scales to be confidently confirmed, although the smaller scale measurements were still limited by its angular resolution. The power spectrum showed the scales at which the temperature variations in the background radiation are the strongest; there is a pronounced peak corresponding to an angle of slightly less than 1° , with a succession of lesser peaks at smaller separations.

Comparing the calculated size of the fluctuations (which we can predict as we know the length scales of sound waves in the pre-recombination plasma) to the angular size observed provides a crucial measurement of the curvature of the intervening space (see my Age of the Universe talk for more information!). The shape of space depends on the mass-energy content filling it – and is a measure of how much ordinary and dark matter, and dark energy is required.

Interpretation of the power spectrum requires an assumption of a cosmological model, and so for this reason its shape – the relative heights of the peaks, and where they occur – can be used as a powerful discriminant between different cosmologies. Comparison of predictions to the real power spectrum is an efficient way of deducing the values of all the cosmological parameters (for example, the relative abundances of dark matter/dark energy/baryonic matter) simultaneously.

The results from WMAP confirmed that we live in a spatially flat Universe that is dominated by dark energy; and they constrain the composition to be 4.6% ordinary (baryonic) matter, 24% dark matter and 71.4% dark energy. The resulting age of the Universe is calculated to be 13.772±0.059 billion years. All these conclusions are in impressive agreement with determinations from other methods of observations – from distant supernovae, from clusters of galaxies. WMAP thus ushered in an era of precision cosmology: it marked a successful vindication of
the standard model of cosmology whereby the contents of the Universe are no longer a matter a debate

The most recent and most sophisticated observations of the cosmic microwave background radiation have been taken with the NASA/ESA satellite Planck, which observed the whole sky at nine different wavelengths. This multi-wavelength approach enabled the thorough removal of foreground and background sources of contamination from interstellar material and radiation in our Galaxy and extragalactic radio sources (all of which show a different spectrum to the cosmic background). Planck was able pinpoint the clumpiness of the microwave background radiation on scales of 0.5° and 0.05° with far greater precision than previous experiments. The results again confirmed the standard model of cosmology at an unprecedented accuracy, albeit with a slight review of the mass-energy composition of the Universe to 4.9% baryonic matter, 26.8% dark matter (nearly a fifth more than the previous estimate), and slightly weaker dark energy at around 69%. The Planck data also set a slightly slower value for the rate at which the Universe is expanding today, implying that the Universe is also a little older than previously thought, at 13.8 billion years.

Having established the concordance cosmology, there is still work to be done. Part of the background radiation is polarised as it is generated by a scattering process, and clear detection of the polarised component of light can provide independent confirmation of the cosmological parameters. An even greater challenge would to one day use the density fluctuations to test the assumption about the process of inflation.

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