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The Big Bang: status and prospects

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The 20th century saw the establishment of the first quantitative theory seeking to describe the behaviour of the Universe as a whole – the Big Bang. This sets up a framework within which there has been great success in interpreting a wide range of observations, including the abundances of light chemical elements, the existence and spectrum of the cosmic microwave radiation, and the formation and evolution of galaxies. At the end of the 20th century, the surprising conclusion of the Big Bang theory is that 95% of the Universe is made of two different unknown types of material whose nature remains unclear: dark matter and dark energy. Needless to say, this is a major challenge for science. At the beginning of the 21st century, cosmology appears poised to enter a high-precision era, where the key quantities of cosmology will be determined to two or more significant figures. If cosmologists are on the right track, this will confirm the existence of dark matter and dark energy; if not, it will force us to revise our current picture of the Universe. Either way, the prospect is for exciting years ahead in cosmology.

The Big Bang

Overview

Although cosmology as a science was almost non-existent at the beginning of the 20th century, it developed rapidly during its early decades, thanks to the foundations laid by Albert Einstein, Georges Lemaitre, Willem de Sitter, Alexander Friedmann and others. By the end of the 20th century, a framework was in place that appears to be an excellent basis for understanding the ever-increasing array of observations probing the nature of our Universe.

After the initial discovery by Edwin Hubble in 1929 that the more distant galaxies are receding faster than the nearby ones, the expansion of the Universe has been established beyond any reasonable doubt. The general Big Bang paradigm holds that the Universe has been expanding and cooling from a hot dense

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initial phase, leading eventually to the formation of the galaxies and stars we see around us (although whether there was an actual explosion to set this off this chain of events remains controversial).

There are two major features of the paradigm that are particularly impressive and about which there is remarkable consensus. The first is the cosmic microwave background radiation that continuously and uniformly bathes our planet, for whose discovery Arno Penzias and Robert Wilson were awarded a Nobel Prize in 1975. In the Big Bang theory, it is successfully interpreted as the relic radiation left over from the cosmic fireball – the hot, dense phase of the Big Bang.

The second successful feature of Big Bang theory is the way that it accounts for the formation of the lighter elements, including helium and deuterium. The idea, again associated with a Nobel prize, this time to William Fowler in 1983, is that the more primitive matter of the Big Bang produced these nuclei in the first few minutes of the life of the Universe. The lighter elements build up one by one, in sequence from the lightest element, hydrogen. Intricate calculations show that the Big Bang theory predicts the light element abundances in the right quantities. The combined success of the microwave background and the light element abundances place the Big Bang as by far the leading framework for interpreting observations of our Universe.

However, within the general framework of Big Bang theory, there is a wide range of possibilities for cosmologists to construct different models, because the basic idea leaves many more detailed questions unanswered. For example, the Big Bang paradigm specifies neither the amount of material present in the Universe, nor the form it takes. As the density and properties of this material determine the forces acting upon the Universe, such as the strength of gravity, which slows the expansion, they determine the answers to such basic questions as 'what will be the eventual fate of the Universe?' A rarefied Universe will expand forever, whereas a sufficiently dense one is doomed, eventually, to re-collapse.

A second example of the scope for discussion within the Big Bang paradigm is the question of how the galaxies were formed. When did they form? Why are they the size that they are? Why are galaxies clustered together rather than distributed randomly in the Universe? To make progress on these topics, we need to know not only the properties of the materials from which the galaxies are made, but we also need to know something of conditions early in the Universe which gave the seeds from which the present-day galaxies grew.

The various quantities we are aiming to determine, such as the densities of different types of material, are known as parameters. In effect a cosmological model is a complete list of relevant parameters and their values. Although the general principles of cosmology may be laid down on the basis of scientific theory as an input, in applying those principles to produce a description of the evolving

Universe there is no choice but to attempt to determine the values of the parameters from observation. Theory describes the collection of possible universes that we might, in principle, inhabit, amongst which observation identifies the one Universe we do inhabit.

The requirement of observations to complete the specification of a theory, as well as to test its viability, is a situation common in physics. In general, scientists are best pleased when theories are 'elegant', with as few arbitrary quantities as possible. General Relativity is regarded as highly elegant, with only two free parameters to be measured – the speed of light and the strength of gravity. Our present description of the behaviour of fundamental particles, the so-called Standard Model of Particle Physics, is far messier. It describes 17 particles, and about 20 parameters have to be measured to specify their masses and the way they interact, making the theory look rather contrived.

Current discussions of cosmological theory suggest that it lies in a middle ground between these other examples, with perhaps around ten cosmological parameters to be determined empirically. One such quantity is the Hubble constant, the rate of expansion of the Universe at the present epoch. A strong feature of the case made to NASA to construct and launch the Hubble Space Telescope (HST) was that it would determine this quantity to an accuracy of 10% or, perhaps eventually, better. It has succeeded in this aim. From the Hubble constant, it is possible to estimate (under some assumptions) the age of the Universe to be 12 to 15 thousand million years. At one time, astronomers were worried about whether the age of the Universe is enough to accommodate all the objects within it, such as the oldest stars. This would have been a fatal inconsistency, but such worries have been largely assuaged in recent years.

To help determine the parameters that define our Universe, cosmologists have a tool that should be the envy of historians. They are lucky enough to benefit from a kind of 'time machine'. Because the speed of light is finite, as one looks at more and more distant objects one is seeing into the past of the Universe. Observations of objects at different distances can therefore probe different stages of the Universe's evolution. When we study nearby galaxies we are examining the state of the Universe as it was relatively recently, almost as it is now. By contrast, the cosmic microwave background carries an image of the conditions in the Universe when the cosmic fireball radiation was finally released to our gaze. Before then, when the Universe was dense, its material repeatedly intercepted and diverted the radiation of the cosmic fireball, and scrambled any images that it may have carried, just as water droplets in fog scramble the optical images from beyond the range of visibility. At a certain epoch, the density of the Universe became reduced and the nature of its matter changed, so that the Universe became transparent, making the image of the fireball visible. This was the time when the radiation of the cosmic fireball ceased interacting with matter, a few hundred thousand years after the Big Bang.

The images of the Universe carried by the cosmic microwave background from its early epoch are very smooth, with the intensity of radiation that is coming from different directions being nearly identical. This lends strong justification to the original cosmological models, which treated the idealization of a perfectly smooth Universe containing no structures at all (by cosmic structures I refer to any phenomenon that represents a departure from smoothness, for example galaxies and clusters of galaxies). However, by contrast, the images of the nearby Universe show a web of sheets and threads of galaxies stretching over hundreds of millions of light years, intersecting in dense clusters of galaxies, with virtually empty holes between. A smooth, structureless Universe is evidently not the Universe we now live in now.

Presumably the cosmic structures were seeded in the hot material of the Big Bang. A good cosmological theory should be able to say how the smooth early Universe turned into the lumpy Universe of today. To link those different epochs, a theory for the evolution of structure is required, which incorporates a range of physical processes. The most important of these is the tendency of gravity to gather up material. If there are any lumps at all in the distribution of material, initially over-dense regions, gravity draws in surrounding material and amplifies them.

The evolution of cosmic structures is proving of ever-increasing importance to cosmologists. It is not only a key question in its own right. The details of the 'gravitational instability' process depend on most of the quantities that we need to be able to identify our Universe amongst those theoretically possible. Hence, if we study how structure is formed, we can measure more about what kind of Universe ours is. For example, the details of how gravitational instability acts will certainly depend on how rapidly the Universe is expanding, and so would independently check the value of the Hubble constant measured by the HST. They also depend on the properties of the material within the Universe, and hence are an ideal probe of its material composition.

Proof and disproof in cosmology

By necessity, cosmology, in common with the majority of astrophysics, is developed by a rather different process to the rest of science. In the first place, astronomers are observers rather than experimenters. They lack the ability to manipulate their apparatus in order fully to understand the uncertainties associated with measurements. Further, by definition, there is only one Universe (only one observable Universe, anyway), requiring care in the use of statistical inference. Accordingly, cosmology has often been the subject of controversy. Fortunately, the subject is evolving from a past where observations were sparse and speculation relatively unconstrained, into one where the room for theoretical manoeuvre is becoming quite limited. The Big Bang picture has stood up extremely well to this much improved situation, with only some tinkering needed to keep it in line with observations.

As always in science, as expounded by Karl Popper, the focus in cosmology should be placed firmly on the side of attempted disproof, not proof. We have a general idea – the Big Bang cosmology – that encompasses a whole range of possible predictions on the choice of cosmological parameters. Our goal is to test the continuing viability of the paradigm by finding models within this set that are capable of fitting all reliable observational data.

To test the Big Bang paradigm itself, rather than specific versions of it, one can look for grand overarching predictions. The key predictions, such as the expansion of the Universe and the existence of the cosmic microwave background, are now established beyond reasonable doubt and cannot be expected to lead to a disproof. Instead, the best approach currently appears to be to aim to constrain the range of valid Big Bang models using as many different and independent types of observations as possible, in order to check for consistencies between the interpretations of different data sets. This is a meaningful pursuit, provided the sum total of observations contains significantly more information content than the variety of models being probed. Up until now this has at best been marginally true, but the indications are that the situation is changing.

The Standard Cosmological Model

A fundamental ingredient of the Standard Cosmology Model is the density of the Universe. According to Einstein's General Relativity, this density determines the 'geometry of the Universe'. General Relativity tells us that space-time is curved, and indeed that this curvature is the origin of the gravitational force. Surprisingly, General Relativity leaves open the question of whether space alone might have a flat geometry, i.e. that the curvature might entirely be in the time dimension! The answer depends on the total density of material; if it takes on a special value, known as the 'critical density', then space is flat, whereas otherwise space as well as space-time is curved. This is the cosmological version of the long debate as to whether the surface of the Earth was curved or flat. For want of empirical evidence, cosmologists have historically adopted this critical value for the density, and hence the flat Universe, for reasons of simplicity and aesthetics. Only recently has this value begun to receive strong support from observation.

The best current understanding indicates that the Universe's present constituents are roughly in the proportions shown in Table1.

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Table 1. The constituents of the Universe

Baryons (protons and neutrons)	5%
Radiation (photons and neutrinos)	0.01%
Dark matter	30%
Dark energy	65%

This quite alarming list starts innocently. We ourselves, and the stars and galaxies that comprise the visible Universe, are made from baryons, protons and neutrons, i.e. ordinary matter. Ordinary matter amounts to only 5% of the total material in the Universe. Radiation is a readily identifiable form of energy which, according to Einstein's principle of mass–energy equivalence, contributes to the density of the Universe. However, while once it may have dominated during the hot, dense, early stages, its contribution is now minor.

The last two entries in the table are startling evidence of how far cosmology still has to go. There are fundamental scientific questions still unanswered. The list says that by far the majority of the density of the Universe is in a dark form whose existence we can infer indirectly but cannot see, and whose fundamental nature remains a mystery. Not only that, but it also says that there are two different types of dark density, with different but largely unknown physical properties, one being a kind of matter and the other some kind of energy. A further worrying feature of the list of Table 1 is that these two dark components are present in the Universe in quite similar amounts; this looks incredible.

This apparently unnatural state of affairs induces considerable misgivings in many cosmologists, including myself; it seems far removed from the simple aesthetics upon which we might like to believe the Universe is based. However, cosmologists now almost universally accept this inventory as our leading description of the constituents of the Universe. That this description has supplanted simpler alternatives, particularly those without dark energy, serves as an indication of just how powerful the accumulated evidence for the entries in Table1 has become. Let me examine in a little more detail the impressive observational support for each of the constituents listed.

The photons, which are observed directly in the form of the cosmic microwave background, dominate the total energy of the Universe across the whole electromagnetic spectrum. The high temperature of the cosmic fireball (several thousand degrees when the radiation was first released) has been cooled by the expansion of the Universe and the temperature of its radiation now is $T = 2.725 \pm 0.001$ Kelvin.[1] This is by far the most accurately known quantity in cosmology. There is no known means of directly detecting the neutrinos (a type of light particle created in the early Universe) but, according to theory, their density is correlated with that of the photons and so can be estimated.

The other components (baryons, dark matter and dark energy) are detected indirectly by a variety of complementary techniques and I list some of the best here. Notice that none of the elements of this picture is hanging by a single observational thread, rather they tie together into a coherent unified explanation of a diverse range of observations. The baryon density can be determined by measuring the mix of light elements formed in the cauldron of the Big Bang. In the first few minutes of the life of the Universe, the elements were built up in sequence from baryons by fusion. However, the mix in the cauldron freezes out rapidly because, at a certain time, the Universe becomes too rarefied for fusion to continue and the sequence terminates. In particular, the abundances of deuterium and helium relative to hydrogen are very sensitive to the initial numbers of protons and neutrons in the Universe. At present, the deuterium abundance is the most useful and gives an accurate value for the density of the baryons that made its production possible. It is also possible to study the baryons directly in the largest structures to have formed so far in the Universe, great clusters of galaxies, some of which are so hot that they emit X-ray radiation. Astronomers can see this directly by X-ray telescopes and calculate it, finding an answer in good agreement with that predicted from the deuterium abundance.

The dark matter density is also determined by looking at the large-scale structures in the Universe, a technique pioneered by Fritz Zwicky. After counting all the matter that they see in the galaxies (the baryons), astronomers watch how fast it is moving. If what they can see were all there is, the clusters would long since have dispersed as their gravity would be too weak to hold them together. When they calculate the gravitational pull needed to hold galaxies and galaxy clusters together, there is a difference between what is necessary and what is visible. Astronomers have attributed this difference to dark matter.

It is worth spending more time on dark energy, whose apparent necessity has been the big surprise of recent years in cosmology. For several decades cosmologists had had to reconcile two issues. The total density of matter (both dark and shining) adds up only to perhaps one-third of the critical density. At the same time, there were aesthetic reasons to want to have the Universe at that critical density. Cosmologists sought reconciliation in a parameter known as the ‘cosmological constant’ to explain the shortfall. The cosmological constant had been introduced by Einstein on very general mathematical principles. He later rejected it, thinking it inconsistent with observations, and called it his ‘greatest blunder’. Its re-introduction to make the Universe the right density was ad hoc tinkering. There was no observational evidence supporting the assumption that the Universe was at its critical density, only theoretical prejudice.

The cosmological constant describes, loosely speaking, the energy of empty space, hence the name ‘dark energy’. There is an analogy in quantum mechanics,

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called the zero-point energy. The density associated with dark energy must resist gravitational collapse, otherwise it would simply be another form of dark matter. This is intuitively possible if the material has a negative pressure that supports or even overcomes the gravitational self-attraction of the material, and General Relativity confirms that the cosmological constant has this property. Indeed, many cosmologists had developed a broad view of dark energy, considering it to be any new form of matter with negative pressure, not necessarily corresponding strictly to the energy of empty space.

The acceptance of the dark energy as a major part of the standard cosmology came less than 5 years ago. The key measurements, from a technological and logistical tour de force, were the use of the largest ground-based telescopes in the best mountain-top observing sites, and the Hubble Space Telescope, to view exploding stars called supernovae in very distant galaxies. These measurements enabled two independent teams of astronomers to determine the expansion rate of the Universe at that great distance, which, because of the time travel effect I described earlier, is the expansion rate of the Universe as it was a long time ago. Effectively, they determined the expansion history of the Universe (i.e. its size as a function of time).

The surprise punchline was that the expansion of the Universe is accelerating.[2,3,4] The cosmological constant, which is able to explain this, gained strong independent support and moved into mainstream cosmology. The density of dark energy as given in Table 1 was determined from what is required to drive the observed acceleration.

The discovery of accelerated expansion overturned the belief that the dynamics of the Universe would be dominated by the gravitational attraction of the material within it, which would necessarily lead to a deceleration of the expansion. The cosmological constant alters this conclusion, because it gives rise to a gravitational force that is effectively repulsive. Such a phenomenon would not be possible within Newton's theory of gravity, where all material attracts, but General Relativity permits such a possibility provided the pressure is negative. If the density of the cosmological constant is high enough, as compared with that of the ordinary matter plus dark matter, this repulsive force dominates and leads to acceleration. Having this independent and fairly direct evidence in favour of the cosmological constant proved sufficient to convince the majority of the astronomical community that the theoretical arguments favouring a critical density for the Universe should be taken seriously (see Figure 1).

Entering precision cosmology

The values of some of the ten parameters that Standard Cosmology identifies as required to describe our Universe are already known to an accuracy of around

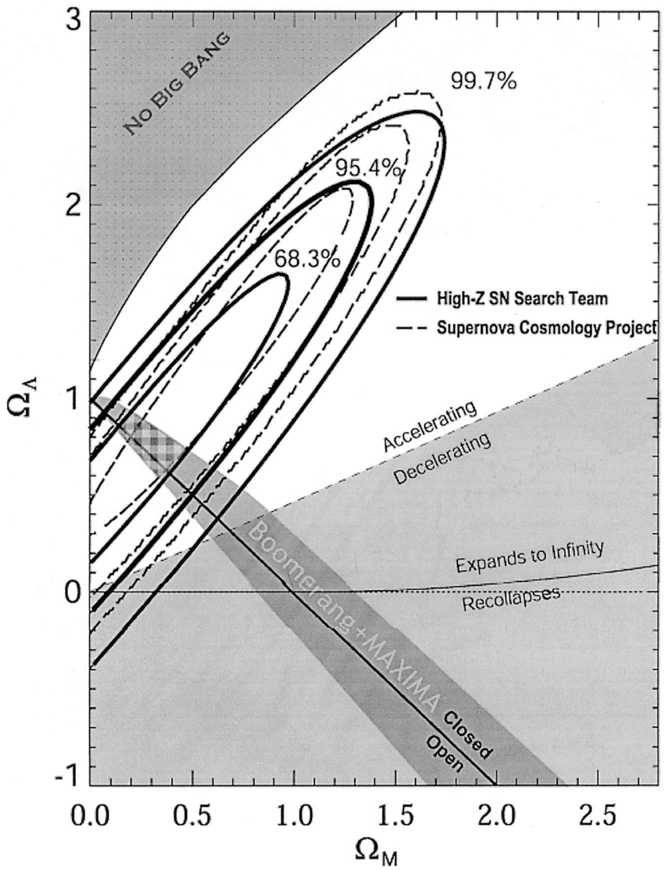

Figure 1. Some of the evidence for the Standard Cosmological Model. The horizontal axis is the density of baryons in the Universe plus dark matter, as a fraction of the critical density, while the vertical axis is the density of the dark energy. The contour lines show the favoured region from two separate studies of supernovae that determine the history of the expansion rate of the Universe. The shaded diagonal band shows the region allowed by the Boomerang and Maxima measurements of the anisotropies of the cosmic microwave background. The diagram is divided into zones where various cosmological models lie. For extreme values of the cosmological constant in the top left, the repulsive force would be so strong that there could not be a Big Bang explosion, although this area does not agree with observation. In the lower quarter of the diagram, the Universe would re-collapse. Only the small chequered area where the measurements are consistent is allowed by all sets of data and this is the region where the Standard Cosmological Model lies. The value of the vertical axis in the middle of this region is about 2/3 (the Universe is 65% dark energy). The value of the horizontal axis shows the Universe is about 1/3 matter (nearly all of it dark matter, in fact). The Universe that this represents has a Big Bang, is presently accelerating in size and will expand forever. (Figure courtesy Brian Schmidt.)

10%, the baryon density being one of these. Others, such as parameters describing the initial density perturbations, are only vaguely known. And, at the margins, there are some parameters for which there is no agreement as to whether they are necessary or not, let alone what their values might be – for example, whether neutrinos have a mass large enough to impact on cosmology.

Over the next decade, a key goal in cosmology must be both to firm up the list of important parameters, and to supply the first precision determinations of those quantities. Ideally, in many cases, this means specifying them at the 1% level. A variety of new observations will contribute to this enterprise and address many important questions:

(1) What does the Universe contain, and how is the matter distributed? The largest ever mapping of galaxies in our local Universe, by the Anglo-Australian 2dF Galaxy Redshift Survey[5] and by the American-led Sloan Digital Sky Survey,[6] is providing unprecedented knowledge of how material is distributed in the Universe.
(2) What is the expansion history of the Universe? The supernova observations indicate the answer, but new generations of high-redshift supernova studies, perhaps including a dedicated satellite project SNAP[7] (currently under consideration for funding by NASA), will map the expansion history of the Universe in more detail, more reliably and out to further distances and thus further back in time.
(3) How did galaxies develop? To see as far back as possible into the past we must look at as great distances as possible, and that means looking at fainter and fainter galaxies. Surveys for extremely distant galaxies and galaxy clusters, using larger and larger telescopes operating in wavelengths from the X-ray through to radio waves, will penetrate to the galaxy formation epochs.
(4) How did structure form in the first place? This is especially important because the patterns of irregularities in the cosmic microwave background enable the dark matter density and the dark energy density together to be estimated.

While the best constraints will inevitably come from the combination of all these types of data, I will focus on a single technique, which in itself promises to provide powerful constraints. The focus of interest is the study of anisotropies in the cosmic microwave background. These measurements are difficult because the anisotropies are minute. However, this is not the pursuit of extreme accuracy for its own sake, since this technique has already provided some crucial evidence that boosts confidence in the deductions about the density of the Universe. The word *anisotropies* refers to the fact that the cosmic microwave radiation that we receive exhibits some small variations in its brightness as we look in different directions.

These variations reveal the state of widely separated regions of the young Universe and tell us that the conditions in these different regions were different. In particular, some regions had a higher density of material than others. Those are the overdense regions of the Universe that, long after the radiation had left, attracted neighbouring material to build up galaxies and clusters of galaxies in that region.

The microwave anisotropies were first detected in 1992 by NASA's COBE satellite, which confirmed a growing expectation that the anisotropies are very small indeed. Some of the final COBE results, published in 1996, are shown in Figure 2.[8] The cosmic microwave background is much more uniform in brightness than the finest piece of blank white paper, with variations of only one part in a hundred thousand (0.001%). At the epoch that the cosmic microwave background was released, the Universe was indeed very smooth. The contrast has been turned up a million-fold in Figure 2 to show the anisotropies. The cosmic microwave background is evidently probing the beginnings of the gravitational instability process. This is lucky for us, because there are considerable advantages in studying the process at that early time. The physical conditions in the Universe were much simpler before the galaxy and stars actually formed. It is relatively easy to make what are thought to be highly accurate predictions for the patterns of

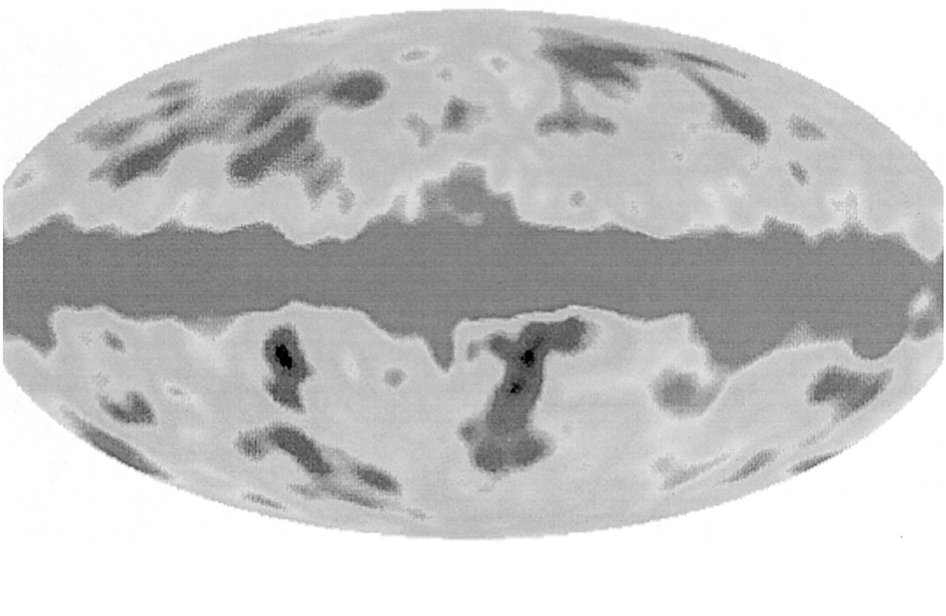

Figure 2. One of the definitive COBE maps of the cosmic microwave background, showing the anisotropies. To make this figure, the sky has been flattened into a disk, so this image shows the entire sky. The horizontal band is emission from our own Galaxy, but the rest is essentially cosmic microwave background (courtesy NASA).

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anisotropy at that epoch from different cosmological models. These patterns act as a kind of 'fingerprint' enabling cosmologists to decide which, if any, of their cosmological models are consistent with observations.

The COBE satellite's ground-breaking observations in 1992 probed the pattern of anisotropies only on large angular scales, from a few degrees upwards, which by modern requirements is a rather coarse scale. The main ability to discriminate between cosmological models lies on angular scales from a few degrees down to a few arc-minutes.

Pioneering studies at high resolution have been made by the Boomerang[9] and Maxima[10] experiments. These consisted of microwave detectors mounted on high-altitude balloons. Boomerang flew at 40 km altitude for ten days in 2000, above the cold Antarctic region to minimize interference. The experiments were able to map small areas of the sky at an angular resolution of around ten arc-minutes and found prominent anisotropies on that scale. The characteristics of these anisotropies gave direct observational support to the standard assumption that the Universe is at or near critical density, consistent with the theoretical expectation (or prejudice), and with the supernova observations. Figure 1 summarizes some of the data leading to this conclusion. The experiments also provide further evidence that the density of ordinary matter is about 5% of the critical density. All the data are converging to support the makeup of the Universe outlined in Table 1. The future of microwave background observations lies in combining high-sensitivity detectors with the capability of mapping large areas of the sky at high angular resolution in order to obtain the best possible statistical sample. To achieve these goals, it is necessary to return to space. NASA has recently launched a mission called MAP,[11] which will survey the sky during 2002. The European Space Agency will launch an ambitious mission called Planck in 2007[12] (Figure 3), which seeks to be a definitive project whose measurements extend to the various natural limitations. Furthermore, Planck should be capable not only of seeing variations in brightness, but also in the polarization of the microwave background light. This should give it an unprecedented ability both to test our current cosmological models, and, if the models prove successful, to pin down many of their parameters at the 1% level. If we are indeed on the verge of establishing the first precision cosmological model, these experiments are likely to be in the forefront.

Towards the bang?

Particularly amongst the public, the exciting questions tend to be 'What caused the bang?' or 'What came before the bang?' Sadly, these remain questions for

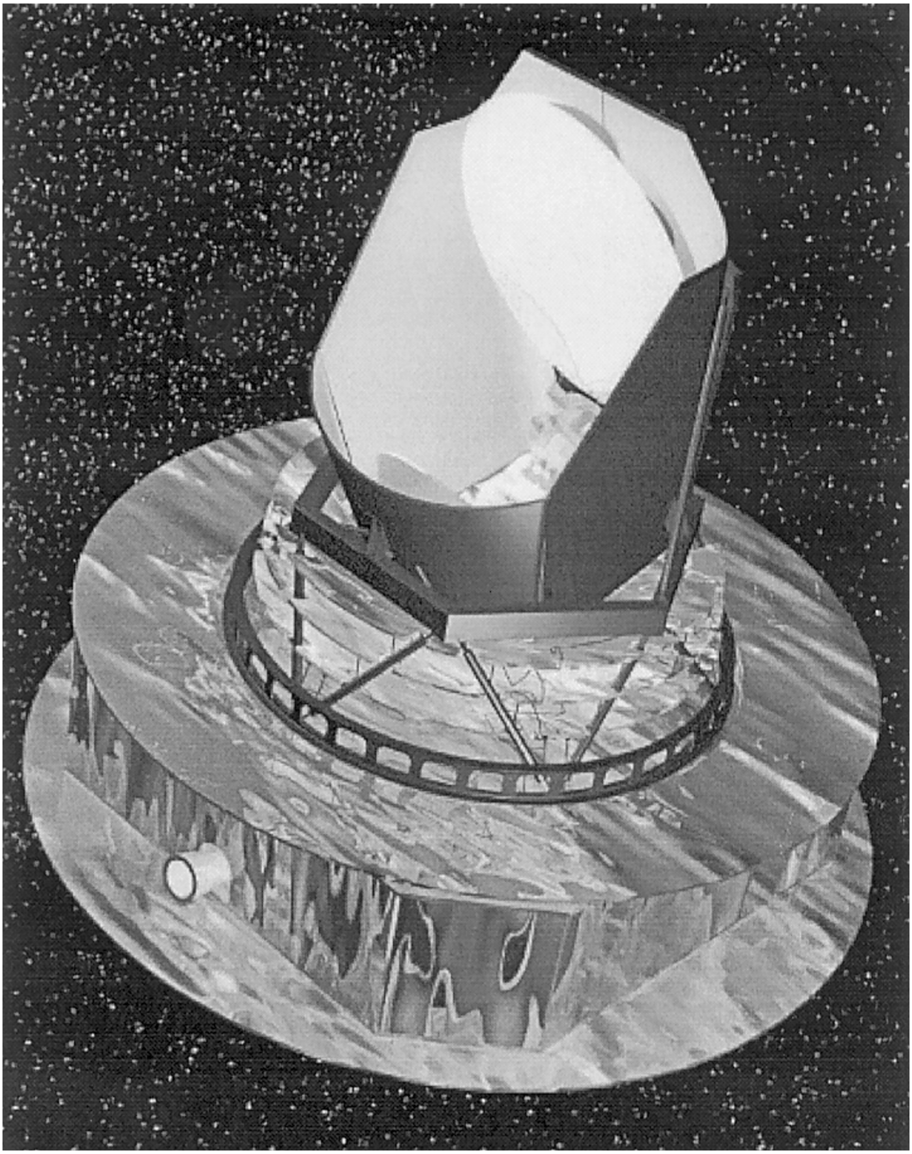

Figure 3. Computer-generated impression of the Planck satellite (courtesy ESA).

which we have no answers, or indeed much prospect of obtaining answers. Hitherto, cosmologists have not talked much about the Big Bang itself, but instead of its aftermath, asking 'What came from the Big Bang?'. Galaxies are even now expanding from one another and have been doing so for about 12 billion years.

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The cosmic microwave background looks like the remains of the cosmic fireball of the Big Bang, released when the Universe was aged about 300 000 years. The light elements – hydrogen, deuterium and helium – are the aftermath of the fusion processes of the first few minutes. What we see does very much have the appearance of being the result of a dramatic explosion. However, at present we have neither the observational nor the theoretical tools to study the instant of the explosion itself.

Nevertheless, we may be able to find some evidence of what happened during earlier stages of the Universe than have been studied up until now; like archaeologists, we can always hope to come across relics of earlier eras by digging deeper. Asking what kind of physical processes took place during the very hot early stages is not an easy question. If we go to times earlier than around 10^{-10} s after the Big Bang, the temperature would have been hotter than any temperature ever created on Earth, leaving us uncertain even as to which laws of science might apply. Still, extrapolating from known laws of physics allows us to consider the types of processes that might have occurred, with the hope of addressing such questions as:

(1) What is dark matter?
(2) Where did it come from?
(3) What determined how much of it there is?
(4) Likewise, what of dark energy?
(5) What created the variations in density in the Universe, which ultimately led to the formation of all structures?

There are plenty of good theoretical ideas concerning the dark matter. Mostly these are based around the suggestion that it is comprised of elementary particles that interact only weakly with normal matter and so are effectively invisible apart from their gravitational pull. These particles are sometimes called Weakly Interactive Massive Particles, giving rise to the acronym WIMPs. However, unless and until such particles are detected directly in a laboratory, their detailed properties will remain unknown.

As concerns the initial irregularities in the Universe, in the Standard Cosmology Model these are presumed to have their origin in a period of accelerated expansion, known as inflation, in the very early Universe. This theory leads to a particularly simple form for the perturbations. One of the successes in cosmology, in fact, is that while there used to be two good ideas about the origin of the irregularities, inflation is now the only one. Its historical rival, the theory of cosmic strings,[13] has fallen by the wayside, disproved and abandoned. Behind the concept of inflation, implemented during the extremely early stages of the Universe, perhaps as little as 10^{-30} s after the Big Bang, the laws of physics are ones that we can only guess about. Nevertheless, the theory of inflation gives an excellent fit to the

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data about the variations of the cosmic microwave background and is currently the leading candidate to explain the origin of structure.[14] This is a striking achievement, and demonstrates that there is much more to the cosmology of the early Universe than unconstrained speculation. Inflation has become an established part of the Standard Cosmological Model of the Big Bang.

Outlook

To understand the power of a theory, one should understand its weaknesses as well as its strengths. In that regard the Big Bang cosmology is now in a rather powerful position, as it has yet to have serious difficulties in confronting the ever higher precision experimental data that are coming in and there are few significant chinks in its armour that expose the current theory to danger.

By far the most alarming aspect of current cosmology is that its inventory contains dark energy. While particle physicists can generate endless ideas about the nature of dark matter (various kinds of WIMPs), dark energy is currently anathema to them. Not only is there no fundamental understanding of what the dark energy might be, but there are currently no useful ideas even as to how to address the problem.

Another significant issue is why we should live at an epoch of the Universe's evolution where dark energy and dark matter have such similar densities. Their densities evolve in completely distinct ways, so this state of affairs will last only briefly, so why now? In effect, the similarity of the densities of dark matter and dark energy partly turns on the Copernican view that we live at a special time in the history of the Universe. This question makes the inventory of the Universe (Table 1) philosophically deeply unsatisfying. That the dark energy has cropped up so convincingly in observational studies has created a situation that may lead to a major rethink of either particle physics or cosmology, and who is to say which it will be?

Setting aside, however, more fundamental worries, there seems little room for doubt that Big Bang cosmology is healthier now that it has ever been. The improvement in quality of astronomical equipment in the last 20 years has been staggering, yet the observations made have time and again found the best interpretation within the Big Bang cosmology. Whether this remains true as the equipment makes further improvement in the next 20 years remains to be seen. If the Big Bang concept remains viable we will, by then, be in possession of something that can truly be called a precision description of our Universe. If not, cosmology will be all the more exciting!

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References

1. J. C. Mather, D. J. Fixsen, R. A. Shafer, C. Mosier and D. T. Wilkinson (1999) Calibrator design for the COBE far infrared absolute spectrophotometer (FIRAS). *Astrophys. J.*, **512**, 511–520.
2. S. Perlmutter *et al.* (1998) Discovery of a supernova explosion at half the age of the Universe. *Nature*, **391**, 51–54
3. A. G. Riess *et al.* (1998) Observational evidence from supernovae for an accelerating universe and a cosmological constant. *Astronom. J.*, **116**, 1009–1038.
4. S. Perlmutter *et al.* (1999) Measurements of omega and lambda from 42 high-redshift super novae. *Astrophys. J.*, **517**, 565–586.
5. 2dF Galaxy Redshift Survey home page at http://msowww.anu.edu.au/2dFGRS/
6. Sloan Digital Sky Survey home page at http://www.sdss.org/
7. SNAP satellite home page at +http://snap.lbl.gov/
8. C. L. Bennett *et al.* (1996) Four-year COBE DMR cosmic microwave background observations: Maps and basic results. *Astrophys. J.*, **464**, L1–L4.
9. P. De Bernardis *et al.* (2000) A flat universe from high-resolution maps of the cosmic microwave background radiation. *Nature*, **404**, 955–959.
10. S. Hanany *et al.* (2000) MAXIMA-1: a measurement of the cosmic microwave background anisotropy on angular scales of 10′-5 degrees. *Astrophys. J.*, **545**, L5–L9.
11. MAP home page at http://gsfc.nasa.gov/
12. Planck home page at http://astro.estec.esa.nl/Planck/
13. A. Vilenkin and E. P. S. Shellard (1994) *Cosmic Strings and other Topological Defects* (Cambridge University Press).
14. A. R. Liddle and D. H. Lyth (2000) *Cosmological Inflation and Large-scale Structure* (Cambridge University Press).

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