Dark energy

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Abstract
Our ideas about the mass and energy make-up of our universe and the way in which it will evolve in the future have undergone a marked change in the last few years. A wide diversity of experiments have now shown that the universe is dominated by a mysterious 'dark energy', and that the normal matter which makes up the stars, planets and ourselves accounts for only some 4% of its total mass and energy content.

Einstein's blunder?

Modern cosmology arose from Einstein's General Theory of Relativity—essentially a theory of gravity. As gravity was the only force of infinite range that could act on neutral matter, Einstein realized that the universe as a whole must obey its laws. He was led to believe that the universe was 'static', or unchanging with time, and this caused him a real problem because gravity, being an attractive force, would naturally cause a number of stationary objects in space to collapse down to one point. To overcome this he had to give a non-zero value to what he called the Cosmological Constant, Λ (Lambda). This represents a form of antigravity and has the interesting property that its effects become greater with distance. So, with one force decreasing and the second increasing with distance it was possible to produce a static solution. He later realized that this was an unstable situation and that a static universe was not possible. He called this 'the greatest blunder of my life'. He could have predicted that the universe must be expanding or contracting. However, as we shall see, perhaps he wasn't quite as wrong as he thought.

Big Bang models of the universe

A Russian meteorologist, A A Friedmann, was the first to solve Einstein's equations to produce a set
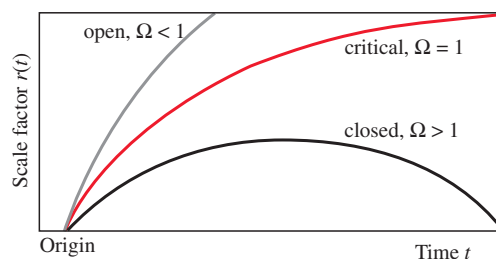

Figure 1. The Friedmann Big Bang models of the expansion of the universe.

of models in which the universe expanded from a point, or singularity (figure 1). These were given the name 'Big Bang' models by Fred Hoyle—this was meant to be a disparaging term, Hoyle did not like them! In all of these models an initial fast rate of expansion is slowed by the attractive gravitational force of the matter of the universe. If the density of matter within the universe exceeded a critical amount, it would be sufficient to cause the expansion to cease and then the universe would collapse down to a 'Big Crunch' (these are called closed universes). If the actual density is less than the critical density, the universe would expand for ever (called open universes). In the critical case that is the boundary between the open and closed universes, the rate of expansion would fall to zero after infinite time (called the 'flat', or 'critical' universe).

The models are distinguished by a constant, Ω, which is defined as the ratio of the actual density to the critical density. In closed universes space has positive curvature: Ω is greater than 1, the angles within an enormous triangle drawn between cluster of glaxies add up to more than $180°$ and two initially parallel light rays would converge. In open universes space has negative curvature; Ω is less than 1, the angles within a huge triangle add up to less than $180°$ and two initially parallel light rays would diverge. In the critical case, space is said to be 'flat'; Ω is equal to 1, the angles within a triangle add up to $180°$ and two initially parallel light rays will remain parallel. Whilst this is true on the extremely large scale, in the region of a massive object, such as a star or galaxy, the space becomes positively curved, giving rise to what we call 'gravity').

The expansion of the universe

In the late 1920s Edwin Hubble, using the $100''$ Hooker Telescope on Mount Wilson, measured the distances of galaxies in which he could observe bright stars of variable intensity of a type called Cepheid variables. Cepheid variables were known to have an extremely regular pattern of intensity variation. Many in the Small Magellanic Cloud had been studied by Henrietta Leavitt and she had discovered that their absolute brightness was related to their period. Thus, if one could observe a Cepheid variable in a distant galaxy and measure its period, its absolute brightness could be found. Knowing both the star's apparent brightness from Earth and its absolute brightness allowed its distance to be calculated.

Hubble also studied the spectra from these Cepheid variables and found that all but the closest stars had red-shifted spectra: as if the galaxies were travelling away from Earth. Using the simple Doppler formula for light, he calculated the apparent speed of recession for the stars and combined these measurements with the distances he had found from the stars' brightness to produce a graph of 'recession speed' (in km s^{-1}) against distance (in Mpc)[1]. His graph showed clearly that the greater the distance, the greater the apparent speed of recession.

The graph led directly to 'Hubble's Law', in which the speed of recession and the distance were directly proportional and related by 'Hubble's Constant' or H_0. The value that he derived for H_0 was 500 $\text{km s}^{-1} \text{Mpc}^{-1}$ [2].

We can explain Hubble's observations if we assume that we are observing an expanding universe in which the space itself is expanding. If one makes the simple assumption that the universe has expanded at a uniform rate throughout its existence, then it is possible to backtrack in time until the universe would have had no size—its origin—and hence estimate the age, known as the Hubble Age, of the universe. This is very simply given by $1/H_0$ and, using Hubble's original value of H_0, 500 $\text{km s}^{-1} \text{Mpc}^{-1}$, one derives an age of about 2 billion (i.e. 2×10^9) years. In fact, in all the Friedmann models, the real age must be less than this because the universe would have been expanding faster in the past. In the case of the 'flat' universe the actual age would be 2/3 that of the Hubble Age or $\sim$1.3 billion years old.

A problem with age

This result obviously became a problem when the age of the solar system was determined ($\sim$4.5 billion years): how could the solar system be older than the universe? Calculations relating to the evolution of stars made by Hoyle and others indicated that some stars must be much older still, $\sim$10 to 12 billion years!

During the blackouts of the World War II, Walter Baade used the $100''$ telescope to study the stars in the Andromeda Galaxy and discovered that there were, in fact, two types of Cepheid variable stars. Those observed by Hubble were four times brighter than those that had been used for the distance calibration. The galaxies were found to be twice as far away as had first been thought. As a result, Hubble's constant reduced to 250 $\text{km s}^{-1} \text{Mpc}^{-1}$. There were still many problems in estimating distances, but gradually the observations have been refined and, as a result, the estimate of Hubble's constant has reduced in value to about 70 $\text{km s}^{-1} \text{Mpc}^{-1}$. But this still gives a Hubble age of $\sim$14 billion years, corresponding to the age of a 'flat' universe of only $\sim$10 billion years. We suspect that the universe is somewhat older than this so, if we believe the current value of Hubble's constant, then there could still be an age problem with the standard Big Bang models.

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[1] 1 Mpc is a distance of 1 million parsecs or 3.26 million light-years.

[2] The correct unit for the Hubble constant is s^{-1}, but $\text{km s}^{-1} \text{Mpc}^{-1}$ is invariably quoted by cosomologists.
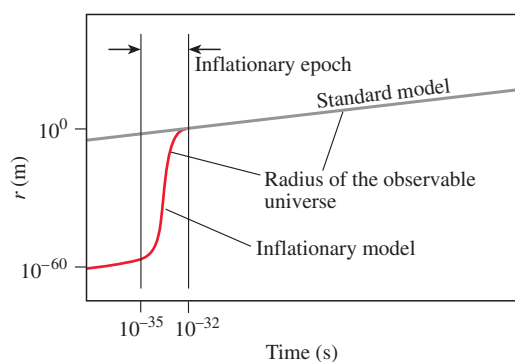
Figure 2. The inflationary phase in the expansion of the universe.

Inflation

Other problems with the standard Big Bang models arose which were addressed with the idea of 'inflation', first proposed by Alan Guth and refined by others. In this scenario the whole of the visible universe would have initially been contained in a volume of roughly the size of a proton. Some 10^{-35} s after the origin, this volume of space began to expand exponentially and increased in size by a factor of at least 10^{60}—to the size of a sphere a metre or more in size (figure 2). This huge expansion of space would force the geometry of space to become 'flat', just as the surface of a balloon appears to become flatter and flatter as it expands. (Hence one would naturally get a 'flat' universe.) Inflation would also ensure that the whole of the visible universe would have uniform properties.

The Big Bang

Half of the gravitational potential energy that arose from this inflationary period was converted into kinetic energy, from which arose an almost identical number of particles and antiparticles, but with a very small excess of matter particles (about one part in several billion). All the antiparticles annihilated with their respective particles, leaving a relatively small number of particles in a bath of radiation. The bulk of the 'baryonic matter' was in the form of quarks which, at about a time of one second after the origin, grouped into threes to form protons and neutrons. An almost equal number of protons and neutrons were produced, but as free neutrons are unstable, the only ones to remain were those that were incorporated into helium nuclei, comprising two protons and two neutrons. So, after a few minutes, the matter in the universe was very largely composed of hydrogen nuclei (protons), helium nuclei (alpha particles) and electrons—with one electron for each proton.

The cosmic microwave background

It was the American physicist, George Gamow, who first realized that the radiation (released in the annihilation of antimatter particles) associated with a hot Big Bang should still pervade the universe. This radiation is now called the cosmic microwave background (CMB).

Initially in the form of very high energy gamma rays, the radiation became less energetic as the universe expanded, so that by a time some 300 000 to 400 000 years after the origin of the universe the peak of the radiation was in the optical part of the spectrum. Up to that time the typical photon energy was sufficiently high to prevent the formation of hydrogen and helium atoms and thus the universe was composed of hydrogen and helium nuclei and free electrons, so forming a plasma. The electrons would have scattered photons and thus the universe would have been opaque—rather as water droplets scatter light in a fog.

This close interaction between the matter and radiation in the universe gave rise to two critical consequences: firstly, the radiation would have a blackbody spectrum corresponding to the then temperature of the universe of $\sim$3000 K, and secondly, the distribution of the nuclei and electrons (normal matter) would have a uniform density except on the very largest scales. We will return to the second consequence later, but now will continue with the first.

At this time, $\sim$300 000 years after the origin, the typical photon energy became low enough to allow atoms to form. There were then no free electrons left to scatter radiation so the universe became transparent. We say that matter and radiation became 'decoupled'. This is thus as far back in time as we are able to 'see'. Since that time, the universe has expanded by a factor of about 1000. The wavelengths of the photons that made up the CMB will also have expanded by 1000 times and so will now be in the far infrared and radio part of the spectrum—but would still have a blackbody spectrum. The effective blackbody temperature of this radiation will have fallen by just the same factor and would thus now be $\sim$3 K.

The discovery of the CMB

Radio astronomers Arno Penzias and Robert Wilson serendipitously discovered this background radiation in 1963, but incontrovertible proof as to its origin had to wait until 1992 when the Cosmic Background Explorer (COBE) satellite was able to show that the background radiation had the precise blackbody spectrum that would have been expected. The average temperature was 2.725 K but COBE's measurements were also able to show statistically that the background showed small variations in temperature. Since then, observations from balloons and high mountain tops have been able to make maps of these so-called 'ripples' in the CMB—temperature fluctuations in the observed temperature of typically 60 μK.

What causes the 'ripples' in the CMB

Why are these small variations present? To answer this we need to understand a little about 'dark matter'. Though not yet directly detected, its presence has been inferred from a wide variety of observations. (To give just one example: if a galaxy were made up of only normal matter, the rotation speed of stars around its core would decrease towards its periphery, but in fact it stays relatively constant across the outer parts of the galaxy. This can only be explained if the galaxy is embedded in a halo of dark, invisible matter whose mass is several times that of the normal matter in the galaxy.)

If only normal matter had been present at the time matter decoupled from radiation, the process by which it gravitationally collapsed to form stars and galaxies could only have begun then. Simulations have shown that if that had been the case, galaxies would only be coming into existence about now—not many billions of years ago. If there was several times more mass than normal matter in the form of dark matter which *did not* interact with the photons this dark matter would have begun to clump earlier, forming mass concentrations that would then have been able to gravitationally attract the normal matter into pre-existing gravitational wells. This greatly reduced the time required for galaxies to form.

How dark matter affects the CMB

The concentrations of dark matter that existed at the time the CMB originated have an observable effect: radiation travelling away from a clump of matter has to 'climb out of a gravitational potential well' and in doing so it will be red-shifted (gravitational red-shift). So the photons of the CMB that left regions where the dark matter had clumped have longer wavelengths than those that left regions with less dark matter. With longer wavelengths corresponding to cooler bodies, the effective blackbody temperature of photons coming from denser regions of dark matter is less than that of photons from sparser regions. We can observe these temperature fluctuations. Such observations can tell us directly about the universe as it was just 300 000 or so years after its origin: it is not surprising that they are so valuable to cosmologists! Not only that: the photons that make up the CMB have travelled across space for billions of years and will have been affected by the curvature of space. It is possible to simulate the expected pattern of fluctuations if space were negatively curved, positively curved or flat. This is why astronomers were so keen to map these fluctuations accurately. This is no easy matter.

The CMB needs to be observed at millimetre radio wavelengths. For receivers on the Earth's surface such signals are masked by emission from water vapour in the Earth's atmosphere. Experiments have been flown in balloons (Boomerang and Maxima) or located at high dry sites on Earth such as the Atacama Desert in Chile at a height of 16 000 ft (4900 m) or on the flanks of Mount Teide in Tenerife (the CBI and VSA experiments respectively). Another very good site, where the DASI experiment is located, is at the South Pole, where it is so cold that the water vapour is largely frozen out of the atmosphere! The results of these observations of the small temperature fluctuations in the CMB confirm, without exception, that space is flat: $\Omega = 1$ (figure 3).

Dark energy

The fact that the space in our universe is flat immediately gives us a value for the total mass (and energy) content of our universe. From observations of galaxy rotation and studies of galaxy clusters it has been possible to estimate the total mass of both the normal and dark matter. Taken together, normal and dark matter cannot explain why the universe is flat; they can only make up about 30% of that required for Ω to be 1.
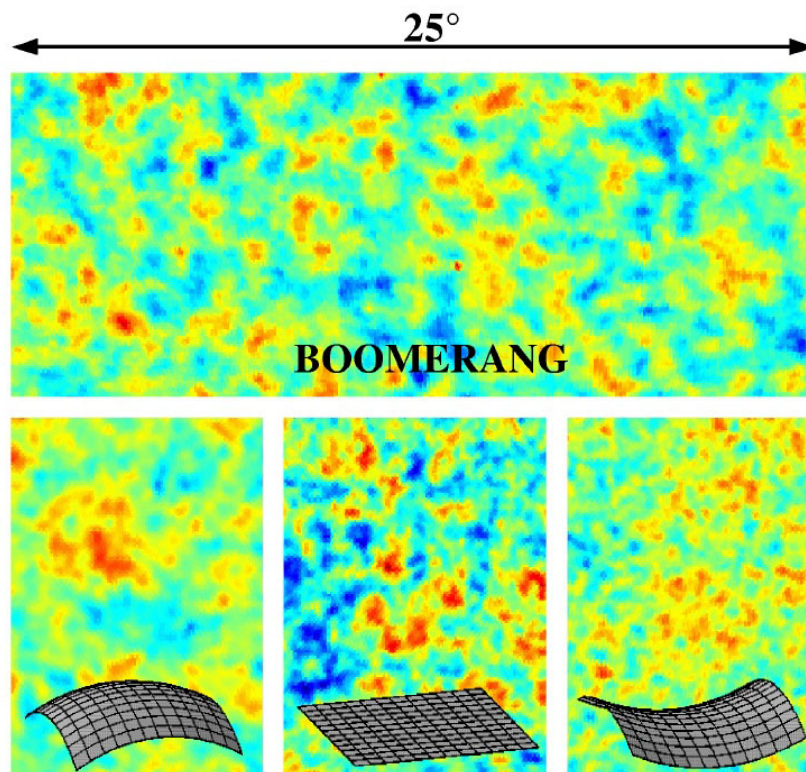
Figure 3. At top, the Boomerang balloon flight observations of the temperature fluctuations of CMB. The structure revealed is consistent with a flat universe as shown by the results of simulations shown in the lower panel.

What can the remaining 70% be? We believe that it is in the form of 'dark energy'—an energy derived from the vacuum of space which is related to the cosmological constant, Λ, in Einstein's equations. One effect it has is to make space expand and hence carry the galaxies apart. It appears that initially, when the amount of space was not too great, gravity was able to slow the expansion of the universe just as in the Friedmann Big Bang models, but as the universe expanded and the volume of space grew, its repulsive force has overcome gravity and is now causing the universe to expand at an ever faster rate.

The accelerating universe

We have real evidence for this accelerating expansion from observations that have enabled the Hubble plot to be extended out to far greater distances. It has recently become possible to measure the distances of galaxies too distant for Cepheid variables to be observed. Almost the brightest individual objects that can be seen are type Ia supernovae—so bright that they can be seen far across the universe. They have, we believe, a well-defined brightness, so that they can be used as 'standard candles'. (Given the same brightness and ignoring any dust extinction, if one appeared 1/100th as bright as another it would be ten times more distant due to the inverse square law.) As the supernova measurements came in it became obvious that the results were not consistent with a universe in which the expansion was slowing down as happens in all of the standard Big Bang models. The results could only be explained by a universe in which the expansion is now accelerating—the effect, we believe, of the 'dark energy'.

A model of the universe

We now have sufficient evidence to construct a model of the universe:

(1) A reasonably accurate value for Hubble's Constant at just over 70 km s^{-1} Mpc^{-1}.
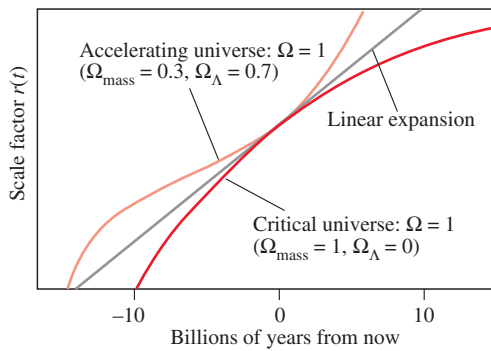(2) The type Ia supernova observations showing the accelerating expansion of space.

Figure 4. A plot showing the scale size of the universe with time.

(3) Cross sections of the universe showing the 'clumpiness' of the galaxy distribution in the universe, such as the 2dF Galaxy Redshift Survey published in May 2002 comprising data from over 220 000 galaxies.

(4) The pattern of fluctuations in the CMB telling us about the very early universe and the curvature of space through which this radiation has travelled.

(5) Observations of the number of gravitational lenses where a foreground galaxy has 'imaged' a distant quasar due to the gravitational lens formed by the distortion of space in its vicinity. The percentage of distant quasars that will be gravitationally lensed is dependent on the geometry of space.

All now give a consistent model in which normal matter accounts for just ∼4%, dark matter ∼26%, with the remaining ∼70% of the total mass energy content of the universe being in the form of dark energy. Over the next few years as the CMB observations are refined we will have pretty accurate values for these percentages. Figure 4 shows how we believe that the scale size of the universe has changed with time in the past and how it will expand ever faster in the future. You will see that the actual age of the universe is similar to the Hubble Age with a value of about 13–14 billion years.

The future of the universe

The accelerating expansion of the universe that is now accepted has a very interesting consequence. It used to be thought that with a slowing expansion, as the universe became older (and hence the distance we could see becomes greater), we would see an increasing number of galaxies. In a universe whose expansion is accelerating the exact opposite will be true—yes, we will be able to see farther out into space, but there will be increasingly less and less for us to see as the expansion carries galaxies beyond our horizon. Perhaps it a good thing that we are living now!

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