1 The dark Universise

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'Space and Time are the modes by which we think, not the conditions in which we live' – *Albert Einstein*

'The only reason for time is so that everything doesn't happen at once' – *Albert Einstein*

'Time is an illusion. Lunchtime doubly so' – *Douglas Adams*

1.1 SPACE AND TIME IN COSMOLOGY

The question about the nature of space and time is intimately linked with the question of cosmology: Did space and time have a beginning? Do they go on forever? Space and time form the framework for our picture of cosmology, while our large-scale view of the Universe puts the limits on what space and time are.

The nature of space and time underwent a radical change from Newton to Einstein. As Newton set out in his Principia Mathematica, space and time was an unchanging Aristotelian background to the unfolding play of particles and waves. But even this seemingly innocuous assumption caused Newton problems. Gravity acted instantaneously everywhere (action at a distance); a radical idea for the 1770s used to the idea that every effect had a direct cause. If the Universe was infinite in extent, the forces acting on any given point would depend instantaneously on the influence of all of the matter throughout the Universe. But because the volume of space increases rapidly with distance these forces would accumulate and increase without limit in an infinite Universe. These problems were mainly swept under the carpet as Newtonian gravity clearly gave an excellent local approximation

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to the motion of the moon and planets. But these divergences made it clear that Newtonian gravity and Aristotelian space and time could not form the basis of a consistent cosmology.

When Einstein introduced his idea that gravity was a manifestation of curved space and time, allowing gravitational effects to be transmitted causally due to gravitational waves, these problems were removed. Not only was a given point in the Universe affected only by a causal region around it, but the whole of space and time became dependent on the distribution and abundance of matter residing in it.

The appearance of dynamical and wave-like properties of space and time opened up a new problem about its small-scale nature. In the Newtonian picture space and time were convenient and unchanging coordinates, detailing the changing positions of particles and waves. To ask what space and time were 'made of' in this scenario did not make much sense. Space and time are just a way to distinguish between different points and events, and had no extra existence. Even in the Einstein picture what is being described is the relationship between events and perhaps we still have no right to ask about the nature of space and time, what goes on in between the events. However, now that our coordinate system has taken on a more dynamical appearance, this does seem to suggest the space and time has much more structure to it than before and is therefore open to further investigation.

1.2 THE EXPANDING UNIVERSE

Perhaps the most impressive example of the dynamic nature of space and time in Einstein's theory of gravity is the expansion of the Universe. The discovery of the expansion of the Universe rightly rests with the American Astronomer Vesto Slipher (and not Edwin Hubble as commonly assumed) who, in a period between 1912 and 1920, noted that the light from the nebulae that he was observing seemed to be shifted to the red. He interpreted this as being due to a Doppler shift. The acoustic version of the Doppler shift is familiar to us as the change in pitch of passing cars. Cars coming towards us have a higher pitch than ones going way, since sound waves from cars travelling towards us are bunched up, or have shorter frequency. The same effect happens to light from a moving object. If a light source is moving towards us the light waves are bunched up and so bluer, and if it is moving away they are longer and so redder. Slipher suggested his observations meant that the nebulae were receding from us. Slipher even went so far as to suggest that this implied the Universe itself was expanding.

But Slipher did not know the distance to these nebulae. In fact the nature of the nebulae was still in dispute. Some thought they were clouds of gas floating around our galaxy, while others thought they may be galaxies in their own right. In the former case it could be argued that, although space may be infinite, the distribution of matter only extended as far as the galaxy and these clouds. This was the ‘Island Universe’ scenario.

But if these small nebulae were other galaxies like our own, filled with billions of stars and tens of thousands of light-years across, then they must be at huge distances away from us. And if we could see a few other galaxies, why should there not be more, an infinite number of them distributed throughout an infinite space?

Measuring the size of the Universe

It was Edwin Hubble who, in 1924, solved the problem of the nature of the nebulae and the size of space. Hubble was able to gauge the distance to the nebulae by showing that some contained variable stars, the ‘Cepheid variables’, whose variability in our own galaxy was tightly related to their brightness. Calibrating off the Cepheid variables in our galaxy, Hubble could estimate the intrinsic brightness of the Cepheid variables in one of the largest nebula, M31, and by comparing with their observed brightness estimate their distance. He found that this nebula was over a million light-years away. The Universe was suddenly a very big place.

In 1929 Hubble went further and began to compare his estimates of the distances to these galaxies to the recession velocities measured from the Doppler redshifts found by Slipher. Despite only having a few galaxies to work with and large uncertainties in the measurements, Hubble claimed that his results showed a linear relationship between the distance to a galaxy and its recession velocity. Galaxies twice as far away from us were moving twice as fast away from us. In addition he found the motion of the galaxies in different directions was the same. Subsequent observations confirmed his discovery of this distance–velocity relation, now called Hubble's Law, and the constant of proportionality between distance and velocity was later called the Hubble parameter.

In fact Hubble's leap of faith that his data showed a linear relation between velocity and distance and that the Universe was expanding was not without precedent at the time. In 1915 Albert Einstein had finally unveiled his General Theory of Relativity, which would replace the Newtonian view of gravity with a new one based on the curvature of space and time.

Einstein had quickly appreciated that his new theory of gravity could be used to tackle the question of what the Universe looked like globally, which Newtonian gravity had so dismally failed to do. To solve the complex equations, Einstein assumed a solution with rotational and translational symmetries and, in 1917, found a model of the Universe which was spatially finite with no boundary – like the surface of a sphere. But Einstein's model was unstable. Gravity, being universally attractive, wanted to collapse the model universe. Einstein found that he could also make his universe expand, but both of these options seemed to him to be unsatisfactory. Slipher's discovery was not known widely and the Universe at that time appeared to be static. To make his model stable Einstein noticed that his equations allowed for an extra term he had previously neglected. This term permitted a universal repulsion which would counterbalance the attractive nature of gravity, and his model of the Universe could be made static. This extra term has subsequently been called Einstein's 'cosmological constant'. Unfortunately for Einstein, his model was still unstable. Any slight change in either the repulsive term or the attraction of gravity, by adding more matter or increasing the cosmological constant term, would cause the model to expand or contract again.

In 1917 the Dutch mathematician Willem de Sitter found another solution to Einstein's equations of gravity which again made use of the cosmological constant. In fact de Sitter's model had no matter in it at all and so would only expand. De Sitter further showed that there would be a linear proportionality between distance and velocity in his model. This was the first prediction of Hubble's law, but only for an empty universe. However, unlike Einstein, de Sitter maintained that relativity implied that the Universe must be dynamical and not static.

In 1922 the Russian physicist Alexander Friedmann, using the same symmetries as Einstein, found the general equation governing the evolution of a relativistic Universe and showed that it must be dynamic; expanding or contracting just as de Sitter had maintained.

When Hubble's observations, and Friedmann's prediction, become more widely known Einstein was understandably dismayed that he had not appreciated that the Universe itself could be dynamic and made the first prediction himself. He disowned his cosmological constant and famously dismissed the whole thing as 'my greatest blunder'. However, he did not mean that the introduction of the cosmological constant itself was a mistake, since it is consistent with Relativity; rather that he had missed an opportunity. Indeed, having drawn attention to the possibility of the existence of a cosmological constant the issue then became where was it? Clearly Friedmann's model looked more like the real world than either Einstein's or de Sitters and so this constant was either not there or was very small. But having introduced the cosmological constant it would prove hard to ignore it again. In fact it is arguable that far from being his greatest blunder, discovering the cosmological constant may have been one of Einstein's greatest achievements.

1.3 FOUNDATIONS OF THE BIG-BANG MODEL

In the intervening eighty years since Slipher's 1920 discovery of the expansion of the Universe, Friedmann's 1922 development of a dynamic model and Hubble's 1924 measurement of the distance to the galaxies and discovery of Hubble's law, cosmology has changed radically. Hubble had only a handful of local galaxies to measure distances and recession velocities. But modern galaxy surveys contain millions of galaxies and soon will have measured the redshifts of billions. All of these observations consistently show the same thing seen by Hubble, that distances are proportional to recession velocity. However, the value of the Hubble parameter was for many years a major issue in cosmology and observational measurements of distances could easily disagree by factors of two. Cosmology was for a long time data-starved.

With the advent of advanced technology, larger telescopes and electronic imaging rather than photographic plates, cosmology has turned from data-starved to data-rich. Observational estimates of the parameters of the cosmological model are now regularly measured at levels of a few per cent, and are found from a number of independent methods. While only 15 years ago there was a vast number of diverse models of the Universe (probably hundreds under discussion) and some of the basic principles of our understanding of the Universe were open to debate, in the intervening time this has all changed. In the following sections I will try and outline the development of these changes, from the introduction and establishment of the Big-Bang model of cosmology, its extension with 'cosmological inflation', and finally its current incarnation as the Standard Model of cosmology.

The modern Standard Cosmological Model is based on the older and highly successful Big-Bang model, developed from the 1930s onward. The main difference between the two is in how the initial conditions of the observed Universe are set. I return to this interesting issue in Section 1.5. Here we shall see why the older Big-Bang model became the accepted model to understand the general features and evolution of the Universe.

The emergence of the Big-Bang model marked the acceptance of relativistic models as the right way to describe the Universe. In science we always hope for a number of competing theories which can be compared with observations to decide which is correct (or at

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least closer to the observations). In the case of relativistic theories of the Universe the Big-Bang model competed for many years from the 1940s until the 1960s with the Steady-State Theory of Herman Bondi, Thomas Gold and Fred Hoyle. The Steady-State Theory was based on the idea of extending the spatial symmetries used by Einstein to solve his gravitation equations to include time. Not only would every point in space look the same, but every point in time should look the same. To achieve this they proposed a model which looked very much like the de Sitter model, but with constant matter density rather than with a cosmological constant. However, a constant density of matter in an expanding Universe would require its spontaneous creation to fill in the expanded volume in a way which was never quite explained. The Steady-State Universe was already in trouble in the 1960s when it was shown that quasar number densities changed over time, and finally killed off with the discovery of the cosmic microwave background (CMB), a thermal remnant from the hot Big Bang. Here I outline the three main observational pillars of the Big-Bang model: the expansion of the Universe, Big-Bang nucleosynthesis and the CMB.

(i) Expansion of the Universe

Slipher and Hubble's observations of the recession of the galaxies showed that they were moving away from us in the same way in all directions; there was an angular symmetry in the motion. Hubble also showed the recession increased with distance. Both factors can be accounted for if the distance between any two points in the Universe increases by an overall scale factor; a natural consequence of a relativistic model of the Universe. In addition, this expansion will look the same from all points, building in translational symmetry. This seems to imply preferred observers, who see the expansion the same in all directions, whereas General Relativity does not have preferred observers. The symmetry of the expansion arises because we have set the initial conditions for the model such that there are preferred states which see the symmetry. We will return to this later.

The expansion of the distance between points can also be a cause for concern. Is space itself being stretched? General Relativity only tells about the relation between points, not about the interval between them. Empty space is empty space so there is nothing to stretch.

Finally, if we extrapolate the expansion backwards in time the distance between any two points will tend to zero, and the density of points will become infinite. This has been interpreted by some as the actual creation of the Universe. In fact, as we shall see, our understanding of the physics of the early Universe breaks down long before this, so this is extrapolation beyond what we know.

(ii) Big-Bang nucleosynthesis

In the 1940s Russian physicist George Gamow, and later in 1957 Geoffrey and Margaret Burbidge, William Fowler and Fred Hoyle, developed the idea that if the Universe had been smaller in the past any radiation in it would have been at a correspondingly higher temperature. At some time in the past the Universe would have been hot enough to initiate thermonuclear fusion, just as it had recently been shown to power the Sun. But while stellar nucleosynthesis could explain the production of heavier elements, it had failed to explain why nearly all stars are made of around 25% helium. Gamow's calculations, and subsequent refinements, were able to show that given an initial abundance of hydrogen in the Universe, thermonuclear fusion in an expanding universe would spontaneously proceed to form deuterium, helium, lithium and beryllium in the first few minutes of the Universe. The relative abundances of these predictions, and in particular the 25% abundance of primordial helium, were compared with and found to be in very good agreement with the measured primordial abundances.

The relative abundance of the heavier elements depends rather sensitively on the initial density of baryons in the form of hydrogen. Taking the observed abundances of primordial elements implies a density of baryons that would contribute on around 5% of the value needed to make the Universe spatially flat. This startling discovery was the first indication that normal matter was only a small part of the Universe.

Knowing the temperature that primordial nucleosynthesis would take place at, and by estimating the density of matter required to produce enough Helium, Gamow was able to predict that the radiation at the time would have cooled by today to a few degrees Kelvin, leaving behind a microwave remnant of the early Big-Bang Universe.

(iii) Cosmic microwave background

One of the most powerful arguments for the Big-Bang model, and the one that killed off the Steady-State model, was Gamow's prediction that if the Universe was in a hot enough state to initiate nucleosynthesis in its distant past then matter and photons should have combined at high temperature to form a plasma. As the Universe cooled, well after nucleosynthesis, this plasma would have broken down allowing atoms to form and the photons to travel freely across the Universe. Assuming that nothing got in the way of the photons they would travel unhindered until they hit a detector on the Earth. A detector on the Earth it would see a uniform bath of radiation, now in the microwave range, coming from all directions.

The serendipitous discovery of this cosmic microwave background (CMB) radiation by Arno Penzias and Robert Wilson at Bell Laboratories in 1965, and its correct interpretation by Robert Dicke and Jim Peebles at Princeton, was seen as conclusive proof that the Universe had been hot and in thermal equilibrium, and that all that had happened to the radiation is that it has cooled due to the expansion of the Universe. The discovery by Penzias and Wilson of the CMB led to their award of the Nobel Prize for Physics and the establishment of the Big-Bang model.

1.4 THE INITIAL CONDITIONS OF THE UNIVERSE

Having observationally established the Big-Bang model of the Universe, attention naturally moved towards the events surrounding the very earliest moments of the model. But if one extrapolates the model backwards in time the scale factor goes to zero, implying that the density of the Universe everywhere becomes infinity. Some have mistakenly taken this to be an actual model for creation (hence the name Big Bang, a term of ridicule coined by Fred Hoyle) and assumed that one can ask no more. In fact the Big-Bang model does not explain the origin of the Universe: it is a model for its subsequent evolution. An analogy can be made with the theory of projectiles which can accurately describe how a cannon ball will travel through the air, but does not provide us with an explanation for how cannons work. To see why we cannot extrapolate the Big-Bang model back to the start we need to consider the limits of our knowledge of nature.

The quantum-gravity era

At high enough energies we expect all of the known laws of matter and spacetime to break down. In particular we expect that when energies become high enough, or on very small scales, gravity should come under the rule of quantum physics. Consider a massive particle. In General Relativity there is a length-scale, the Schwarzschild radius given by the mass of the particle, which tells us when we must consider the effects of curved space and time. This is the size the particle or object would be if it were a black hole. Usually the size of the object is much bigger than the Schwarzschild radius and we ignore space and time curvature. Quantum physics also tells us that the wave-like nature of this particle can be associated with a quantum wavelength, the de Broglie wavelength, after the French physicist Louis de Broglie. This is inversely proportional to the particle's mass (or energy). If we increase the mass (or energy) of the particle the Schwarzschild radius will increase while the de Broglie wavelength will decrease. At some point the de Broglie wavelength will become smaller than the Schwarzschild radius – we now have a quantum object where we need to consider the effects of curved space time. This happens at a scale called the Planck length where we expect quantum effects on spacetime itself to become important. Unfortunately we do not yet have a theory for how to combine quantum theory and General Relativity; a