1

THE BIG BANG: HISTORY OF A SCIENTIFIC THEORY

> The evolution of the world can be compared to a display of fireworks that has just ended: some few red wisps, ashes and smoke. Standing on a well-chilled cinder, we see the slow fading of the suns, and try to recall the vanished brilliance of the origin of the worlds.
>
> **Georges Lemaître (1950)**[1]

The Beginnings of Modern Cosmology

Did the universe have a beginning in time or has it always existed? What were the conditions that enabled life to develop in the universe? Is the universe finite or infinite in extent? Does it always stay the same or is it changing over time? These are fundamental questions but in order to answer them we first need to take a step back in history, because our perspective on these issues has changed completely since the beginning of the twentieth century.

The 25th of November 1915 was a momentous day in the annals of science and in the whole history of human intellectual endeavour. This was the day on which Albert Einstein presented to the Prussian Academy of Sciences a new theory of gravity that would supersede the theory of Newton. Einstein called his breakthrough the "general theory of relativity".

Newton had pictured space as an infinite container in which massive bodies attracted each other instantaneously with the force of gravity according to his famous inverse square law. Einstein's theory is radically different and mind-bendingly hard to picture. Matter, space, and time are now intimately linked together: the presence of matter causes the fabric of space–time to curve, and the curvature of space–time tells matter how to move.

Newton's theory had bequeathed a significant problem to cosmology, the study of the universe as a whole. If space were an infinite container, as Newton conceived it, containing infinitely many stars, we would be unable to determine the gravitational force on any particular star. On the other hand, if there were only a finite number of stars, the universe would collapse in on itself under gravity. In other words, the universe would be unstable. Einstein set out to solve this problem with his new theory.

To solve his equations of general relativity as applied to the whole universe, and hence begin to answer some of the questions posed in my first paragraph, Einstein and others during the same period made certain simplifying assumptions. One assumption was that the universe is homogeneous, that is to say, the matter of the universe is distributed evenly across space. A second was that the universe is isotropic, meaning that it looks the same in all directions. Of course, these are only approximations. The universe is clearly not totally homogeneous, since it contains galaxies surrounded by near empty space, stars within the galaxies, and so on, and we would not exist if it were totally homogeneous. However, for simplicity, the universe on the largest scale can be treated as a medium of uniform density. It has proved highly profitable up to the present day to make these simplifying assumptions.

Einstein realized that a great advantage of curved space–time is that it allows for the possibility that the three-dimensional universe is finite in size. This is hard to picture, but a two-dimensional analogy can come to our aid (Figure 1.1). Thus the convex surface of a sphere is finite in size, and it is conventional to describe it as having "positive curvature". The surface of a sphere has no boundary or edge and one can travel all the way round it and arrive back at the same place. That would also be possible in a three-dimensional positively curved space, which would bend back on itself in a similar (though hard to picture!) way. A finite universe, Einstein reasoned, might also be stable.

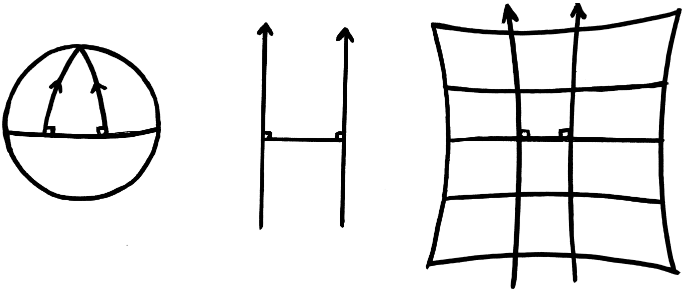

Figure 1.1 In positively curved space, parallel geodesics meet; in our familiar flat Euclidean space, they remain equidistant from each other; and in negatively curved space, they diverge away from each other.

In two dimensions the surface of a sphere has positive curvature, a flat plane has zero curvature, and a saddle shape, which is concave, has negative curvature. We know from our familiar school geometry that the shortest distance between two points is a straight line and that parallel lines in a plane never meet. On curved surfaces, the shortest distance between two points is called a "geodesic". On the surface of a sphere parallel geodesics do meet, and for a saddle shape they diverge away from each other. These surfaces all have their equivalent in three dimensions, though in this case they are much harder to visualize. We have naturally assumed in the past that three-dimensional space is "flat", like the plane in two dimensions, but Einstein is telling us that this naïve picture might be wrong!

Einstein wanted a stable universe and, for philosophical reasons, he also wanted a static universe, a universe that was everlasting, always looking essentially the same. In order to achieve that, in 1917 he introduced an extra term into his equations, which he called the “cosmological constant”. This is generally denoted by the Greek letter Λ (capital lambda) and essentially acts like a repulsive force to stretch space. It is thus a kind of anti-gravity force pulling space in the opposite way to gravity. To get a static universe, Einstein had to set this constant Λ arbitrarily to a single unique value, Λ_E (the E subscript denoting the Einstein value), so that gravity and the repulsion were exactly balanced. Einstein was unhappy that the introduction of Λ detracted from the beauty of his theory and later called it a mistake.[2] It turns out that introducing Λ was not a mistake, but setting it to a particular value to obtain a static, eternal universe was.

An important alternative to Einstein’s solution was found by the Dutch astronomer Willem de Sitter, also in 1917. This was an empty universe but with a positive cosmological constant. That certainly sounds odd, and Einstein dismissed it as physically unrealistic. Nowadays de Sitter’s model is interpreted as an expanding universe solution and a good approximation to the real universe when the matter content has become thinly dispersed due to the expansion.

Enter the Roman Catholic Cleric

In 1927 the Belgian priest Georges Édouard Lemaître came up with a realistic expanding universe solution as an alternative to Einstein’s static universe. We now know for sure that the universe is indeed expanding, so this was a vital step in the right direction.

Lemaître had originally trained as an engineer and served in the First World War with distinction, although there is a story of him falling foul of a gunnery instructor when he pointed out an error in the ballistics manual! After the war, Lemaître took up physics, mathematics, and theology. He was ordained priest in 1923 and spent 1923–24 working on his doctoral thesis in Cambridge with the great British astronomer Arthur Eddington, who was famous for verifying general relativity by observing one of the theory’s main predictions, the bending of light by the sun. Eddington was a Quaker and a pacifist and risked imprisonment during the First World War. It is fascinating that during the war he wanted to maintain friendship with German scientists, and that immediately after it, in May 1919, he led the solar eclipse expedition that confirmed Einstein's prediction.

I was pleased to discover, not long after arriving at St Edmund's College, Cambridge, myself, that Georges Lemaître had almost certainly resided at the college during the academic year he spent in Cambridge. St Edmund's is only a stone's throw from the University Observatory where Eddington lived and worked. Moreover, in Lemaître's time, St Edmund's House, as it was then known, was a place of residence for Roman Catholic clergy and laity studying and working in the university, with a Roman Catholic chapel where priests could say daily Mass. Now a full college of the university, St Edmund's nevertheless retains, uniquely in Cambridge, a Roman Catholic chapel with a Roman Catholic dean.

The solution to Einstein's equations that Lemaître discovered had in fact already been found in 1922 by the Russian physicist Alexander Friedmann. Indeed Friedmann found a complete set of solutions and gave examples in which the age and mass of the universe were remarkably close to presently accepted values. However, Friedmann had treated all this as simply a mathematical exercise and had never thought to look for observational support. Yet as early as 1912 there was some support for the expanding universe from observations of Doppler shifts in distant nebulae made by Vesto Slipher at the Lowell Observatory in Flagstaff, Arizona.

Doppler shift (Figure 1.2) is the difference between the frequency of light (or sound) received from an object in motion compared to that for the same object at rest. The high-pitched sound of an approaching train becomes lower in pitch when the train is receding. When we observe a distant nebula, we examine the colour spectrum of the light entering our telescopes. This spectrum is crossed by dark lines due to the absorption of light at certain frequencies by the atoms of various chemical elements.

These absorption lines occur as light from the hot interior of stars is absorbed by cooler material in their atmospheres, and the effects from many stars are combined for a nebular spectrum. Slipher observed a preponderance of redshifts (i.e. shifts to lower frequency or, equivalently, higher wavelength) over blueshifts in these absorption lines, indicating that most nebulae were receding from us.

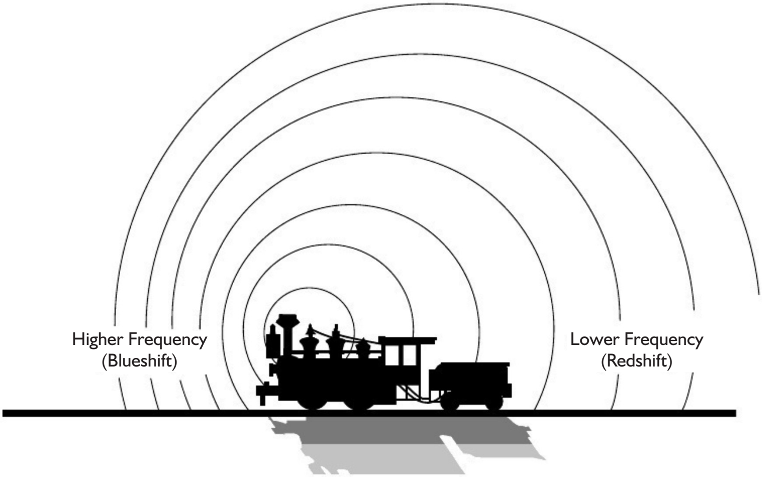

Figure 1.2 Doppler shift is the change in frequency of sound or light waves received from an object in motion. The frequency is higher for an approaching object and lower for a receding object.

In 1929 Edwin Hubble, working with the 100-inch telescope at Mount Wilson in California, verified the result already found by Lemaître. Hubble measured both the distances and redshifts of distant nebulae, now believed to be galaxies like our own Milky Way galaxy. The redshift determines the velocity, and Hubble showed from this that the velocity of recession of the distant nebulae was directly proportional to their distance. This is known as the Hubble law (Figure 1.3) but was in fact predicted by Lemaître in his 1927 paper. Lemaître had even calculated a value for what is now known as the "Hubble constant", a parameter that measures the rate of expansion, and his value was not very different from Hubble's a couple of years later.

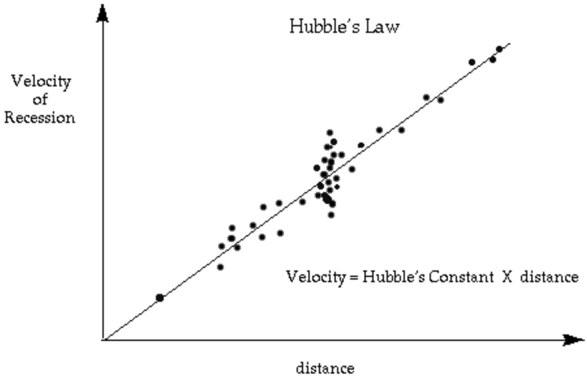

Figure 1.3 Hubble's law: velocity of recession is proportional to distance.

Thus by 1929 Lemaître and Hubble, building on the work of Slipher and others, had shown that, on the largest scale, the galaxies are moving away from each other. In reality, it would be more accurate to say that, according to general relativity, it is the expanding space that is carrying the galaxies with it, rather than the galaxies moving relative to one another. It is like when a balloon is blown up and dots painted on the surface are pulled apart by the expansion of the fabric of the balloon (Figure 1.4).

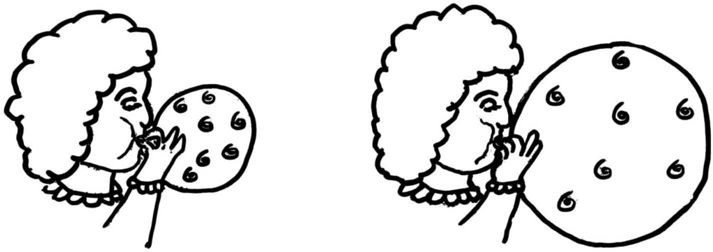

Figure 1.4 When the balloon is blown up the fabric expands to pull apart the dots (galaxies) painted on it.

The Primeval Atom

We are now on track in the quest for a realistic model of the universe, which we now know to be the Big Bang. However, Lemaître's 1927 model, rediscovered independently of Friedmann, was not yet a Big Bang model. The universe expanded from a finite size, not from a "singularity" of zero size or even a highly compact initial state. There was no definite beginning in this 1927 model, but as one looks back in time the universe approximates more and more closely to an Einstein static model of radius about 900 million light years. In the far future it is more realistic and tends to a de Sitter empty-space model.

Einstein described Lemaître's model as "abominable"![3] The mathematics was fine, but Einstein hated the idea of an expanding universe. However, in 1930 Eddington published a paper in which he recognized that Lemaître had shown Einstein's own model to be unstable.[4] This was particularly devastating since of course one of the motivations for Einstein's model in the first place had been to avoid the instability of Newton's cosmology.

In 1931 Eddington went on to secure the publication of an English translation of Lemaître's 1927 paper in *Monthly Notices of the Royal Astronomical Society*.[5] This would bring Lemaître's work to a much wider audience than could the original paper, which had been published in a relatively obscure Belgian journal. Of course by this time there was increasing evidence in Lemaître's favour from the Hubble expansion.

Figure 1.5 Einstein and Lemaître discussing the origin of the universe at Pasadena, California, in 1933.

The year 1931 also saw Lemaître's publication of a new model of the universe, this time with a real temporal beginning.

It was published as a letter to *Nature* and bore the title "The Beginning of the World from the Point of View of Quantum Theory".[6] He envisaged the initial state of the universe as a single atom with the total mass of the universe, which, being unstable, would divide and divide into smaller atoms by a "kind of super-radioactive process". And, later in the year, at the British Association for the Advancement of Science, Lemaître described how "The whole universe would be produced by the disintegration of this primeval atom."[7]

Lemaître's "primeval atom" provided the first ostensibly physical Big Bang model, comprising the two components of expansion and a beginning in time, and was described in yet another momentous paper of 1931.[8] Whereas Lemaître called it the primeval atom, the term "Big Bang" was coined later by another great British astrophysicist, Fred Hoyle, who hated the idea. Indeed there was a great deal of ideological suspicion of the idea that the universe had a beginning. This suspicion lasted from the time such theories were first mooted until the Big Bang was finally established beyond reasonable doubt by observation of the predicted cosmic background radiation in 1965. This is a story we need to examine in more detail, including the most recent debates, but of course the question lurking in cosmologists' minds was, if the universe had a beginning, did it not therefore require a Creator?

An Unavoidable Singularity?

Interestingly, the new Lemaître model of 1931 retained a cosmological constant, like the model of 1927 (now renamed the Lemaître–Eddington model), whereas Einstein abandoned the cosmological constant in 1931 on the grounds of its ugliness. George Gamow reports Einstein as telling him that he considered the introduction of the cosmological constant Λ his "biggest blunder".[9] That may be apocryphal, but in a letter to Lemaître in 1947 Einstein did write the following, which underlines how important it is to scientists that their theories should be mathematically beautiful:

> Since I have introduced the term I had always a bad conscience. But at the time I could see no other possibility to deal with the fact of the existence of a finite mean density of matter. I found it very ugly indeed that the field law of gravitation should be composed of two logically independent terms which are connected by addition. About the justification of such feelings concerning logical simplicity it is difficult to argue. I cannot help to feel it strongly and I am unable to believe such an ugly thing should be realized in nature.[10]

John Polkinghorne is fond of saying that seeing beauty in mathematics is "an austere form of aesthetic pleasure"! That may resonate with readers who are not mathematically minded, but it is certainly true that mathematical beauty is an important criterion for physicists in evaluating alternative theories.

In 1932 Einstein and de Sitter came up with a further significant solution, which was to them simpler than Lemaître's 1931 model. The Einstein–de Sitter model has zero cosmological constant Λ, but "flat" geometry. Significantly it is also a Big Bang model with a beginning in time from a point of zero size. But it was Lemaître whose pioneering work on the primeval atom led to him being dubbed the "Father of the Big Bang". How pleased he would have been to know that the 2011 Nobel prize for physics was awarded to two teams of astronomers who discovered that the expansion of the universe is accelerating, indicating that the cosmological constant is indeed non-zero as Lemaître continued to maintain. Nowadays, many cosmologists interpret the cosmological constant as something called "dark energy". This is the energy associated with the vacuum in quantum theory, the theory of the very small. Although we tend to think of a vacuum as empty space, in quantum theory it is a sea of activity with particles spontaneously coming into existence and annihilating.

The step Lemaître did not take was to accept Einstein's equations at their face value and conclude that the size of the universe shrinks literally to zero as one takes time back to the origin. For Lemaître the universe began with the primeval atom. The equations on their own, however, indicate that there is what cosmologists refer to as a "singularity" at the beginning – a point at which the density of matter becomes infinite as all the universe's mass is crushed into the singular point. In the 1930s physicists generally thought such a notion was unphysical – and Einstein and Lemaître were among them. Nowadays, thanks largely to the work on "singularity theorems" of Stephen Hawking and Roger Penrose, it is recognized that a singularity is formed by gravitational collapse at the end of the lifetime of some types of star. The resulting object is called a "black hole", and giant black holes are singularities found at the centres of galaxies.

Which Universe Are We in?

As a result of the epochal work of this period, modern cosmologists can classify all the possible models of the universe that result from solving Einstein's equations of general relativity applied to the whole universe under certain simplifying assumptions. These include the assumptions of homogeneity and isotropy we met earlier, namely that the universe looks the same at all places and in all directions. In addition to the persons already mentioned above, two further significant contributors are H. P. Robertson and A. G. Walker. Robertson and Walker worked out the formula for the distance between two points for a homogeneous, isotropic universe. This formula is called the metric and is the generalized form of Pythagoras's theorem for such a four-dimensional space–time. It describes the geometry of space–time, in particular whether space–time is positively or negatively curved or flat. These models of the universe are therefore variously known as Friedmann–Lemaître–Robertson–Walker (FLRW) models, or Friedmann–Robertson–Walker (FRW), or simply Robertson–Walker (RW) models.

Since there is still some doubt as to which precisely of these models most closely applies to the real universe – which, even with the latest observations, lies tantalizingly close to the border between them – it is worth briefly summarizing them at this point. They can be classified according to two parameters, namely the curvature of space–time, which can be negative, positive, or zero (i.e. "flat"), and the cosmological constant Λ, which can also be negative, positive, or zero.

Whether space is curved positively, negatively, or is flat depends on the density of the universe, assumed as noted above to be uniform across space, but in general varying with time. The overall density includes contributions from matter, radiation, and the cosmological constant.

There is a certain critical value of density (varying with time) that gives rise to a flat space–time. If the density is above this value, it will stay above it and space will be positively curved. If below it, space will be negatively curved. For convenience, cosmologists define the parameter Ω (capital omega) to be the mean density divided by the critical value. Then space is flat if Ω is equal to one; space is positively curved if Ω is greater than one; and space is negatively curved if Ω is less than one.

It is important to note that if space is positively curved the universe will be finite in size, like the surface of a sphere in two dimensions: such spaces are called "closed". Models of zero or negative curvature are spatially infinite and in two dimensions resemble a flat plane or a saddle shape respectively: these spaces are called "open".

Effect of the Cosmological Constant

If the cosmological constant Λ is negative, Λ no longer represents a repulsion but an attraction and it reinforces gravity. All the models, of whatever curvature, then begin at a singularity, expand to a maximum size, and recollapse to a "Big Crunch", a final singularity.

If Λ is zero, a positively curved universe will expand from a singularity and then ultimately recollapse. However, in zero and negatively curved universes gravity will not be strong enough to cause recollapse and these universes will expand forever. The flat (zero curvature) model with zero Λ is the Einstein–de Sitter universe and, while this universe does indeed expand forever, the rate of expansion is always decreasing with time. It is just about the simplest model, which is why Einstein favoured it, and for many purposes it is a very good approximation to our own universe. In the Λ zero and negatively curved universe the expansion rate tends to a constant value over time.

If Λ is positive, as now appears to be the case, there are several possibilities. One is the empty de Sitter universe, which simply expands, getting ever faster, forever. Another, when Λ takes the Einstein value Λ_E, is the Einstein static universe of constant radius, eternally existing and unchanging. As described above, the Eddington–Lemaître model (Lemaître's original 1927 model) starts from an Einstein universe and expands forever. The Lemaître "Big Bang" model has Λ greater than the Einstein value. It starts explosively but the expansion rate slows down, then finally it speeds up. This is because gravity dominates to begin with to slow the expansion, but then the cosmological constant takes over and ever more strongly dominates gravity.

The Einstein, Eddington–Lemaître, and Lemaître models all have positive curvature, which means they are finite in size. But there are also models with flat and negatively curved geometry, and matter, which, like the Lemaître model, start from a singularity, slow initially and then accelerate as the cosmological constant dominates. However, the universes described by these models are infinite, whereas the Lemaître model is finite.

Since the present universe is very close to being flat, it remains tantalizingly difficult to ascertain whether it is precisely flat or just curved positively or negatively. Still, we have come a long way, and even by the 1930s it was looking promising that some of the questions posed at the beginning of this chapter were amenable to scientific answers. But then a group of Cambridge cosmologists threw a spanner in the works and challenged the whole Big Bang concept. Maybe we are not in any of the universes I have described.

A Rival on the Block[11]

By the 1940s, the evidence of the redshifts, interpreted as due to the expansion of the universe, seemed to indicate that some version of the Big Bang theory was correct. The Einstein static, eternal universe did not seem to reflect reality. However, a major challenge remained. The age of the universe had been estimated from the Hubble law to be a couple of billion years or even less. However, this was smaller than the estimated age of stars and galaxies, and indeed of the earth itself. It was pretty troubling that cosmological theory gave an age of the universe less than that of some of the objects within it! More accurate observations came much later, from the early 1950s on. Today, observations from the European Space Agency's Planck satellite yield an estimate of the age of about 13.8 billion years, comfortably older than the objects within it, and the three significant figures[12] indicate how far cosmology has advanced as a science of measurement. Incidentally, this figure updates the earlier remarkably accurate estimate of 13.7 billion years obtained by the WMAP (Wilkinson Microwave Anisotropy Probe) satellite.

Possibly even more important than this age problem was the ideological objection to the idea that the universe had a beginning. We have seen that Einstein disliked the idea. Eddington, who, although a Quaker, wanted to keep religion and science apart, was equally critical, writing in 1931 that "philosophically, the notion of a beginning of the present order of Nature is repugnant to me."[13] And Helge Kragh writes that astronomers in general preferred to speak of the "cosmic time scale" rather than to date the present epoch from an absolute beginning of time.[14] Indeed "most astronomers preferred to neglect what may seem to be a natural consequence of the evolutionary, relativistic worldview."[15]

In 1948 the view that there was any kind of evolution at all was challenged by a new theory, which ran directly contrary to the Big Bang idea. As formulated by Thomas Gold and Hermann Bondi in that year, it was based on a metaphysical principle called the "perfect cosmological principle".[16] This principle states that not only does the universe on the largest scale present a uniform aspect at every place within it, but it presents the same uniform aspect at every time in its history. Previous cosmological models had assumed uniformity across space, but to assume uniformity at all times as well was new. Put simply, the universe looks the same at any place and any time, always excluding local irregularities. It should be stressed that this is indeed a metaphysical or philosophical principle, not an empirical scientific principle derived from observation or experiment.

In order to account for the observed expansion it was necessary in the steady-state theory that new matter come into existence in the space created between the receding galaxies, and at just the right rate. In fact, other steady-state continuous creation models had arisen in the pre-war period, quite often associated with a metaphysical preference for God to be continuously creating rather than, as it were, winding up the universe at the beginning and letting it run down. Physicists such as Robert Millikan and many others put forward such highly speculative steady-state type theories, and in 1933 such ideas were endorsed from the theological perspective by W. R. Inge, the well-known Dean of St Paul's Cathedral.[17]

Inge (pronounced, as he said himself, to rhyme with "sting" not "whinge") was something of a maverick. He was an advocate of Christian mysticism and wrote popular and witty columns for several newspapers. He was known as "the gloomy Dean" for his pessimism about the state of modern society. In his book *God and the Astronomers* he hoped that some such scheme as Millikan's would be found whereby some process compensated for the expansion. He was unhappy with the idea of the Creator starting the universe off and saw the divine origin of the universe much more in terms of its orderly and value-laden character.[18]

Despite all this, there seems to have been an atheist agenda behind the steady-state theory proper put forward by Bondi, Gold, and, significantly, Fred Hoyle, who simultaneously came up with a rather different version of the theory. Nevertheless the steady-state theory still attracted Christian support, notably from the cosmologist W. H. McCrea. Moreover, the Anglican theologian E. L. Mascall noted how it was entirely in keeping with Aquinas's notion of God both bringing things into existence and preserving them in existence so that "if he withdrew his action from them, all things would be reduced to nothing."[19]

Kragh tells us that it was particularly Hoyle who objected to a singular creation event which was beyond the realm of scientific understanding.[20] In his 1948 paper Hoyle wrote: "For it is against the spirit of scientific enquiry to regard observable effects as arising from 'causes unknown to science', and this is in principle what creation-in-the-past implies."[21] Another reason the trio rejected standard cosmology was the time-scale problem. This could be solved in the Lemaître and other evolutionary models but at the unacceptable cost of fine-tuning the cosmological constant. This was deemed a fudge which ought to be unnecessary in a true theory, though it is interesting that Hoyle, in a lecture in 1960, acknowledged that Lemaître's model could do the trick.[22]

Interestingly enough, Hoyle initially objected to matter creation, as suggested by Gold, and this delayed progress on the steady-state theory.[23] After all, matter creation would constitute a violation of the law of conservation of energy. In the event, this would mean that two versions of the steady-state theory would emerge, both in 1948, one authored by Hoyle and the other by Bondi and Gold. Another very significant difference within the trio is that, unlike Hoyle, Bondi and Gold regarded general relativity as suspect when extrapolated to apply to the universe as a whole.

In his version of the theory, Hoyle modified Einstein's equations of general relativity by replacing the cosmological term with a "creation tensor", which did, after all, violate the law of energy conservation! The rate of matter creation governed by the creation tensor just matches the rate at which matter disappears across the horizon of the visible universe. But Hoyle preferred his approach to that of Bondi and Gold who started instead from the abstract "perfect cosmological principle". For Hoyle, that principle was a consequence of his theory rather than an unproved assumption you start from like an axiom in mathematics. In contrast, Bondi and Gold judged it necessary to ensure that the laws of physics did not change over time, and they claimed that without such a principle cosmology could not be counted a science.[24]

At this stage I could suggest that perhaps a theological principle would have done what Bondi and Gold wanted! They are right that some metaphysical principle is required to undergird the constancy of physical laws. Theologians would say that this principle is the faithfulness of God. The constancy of physical laws is a sign of God's reliability in maintaining those laws, and the God of the Christian religion is not capricious but faithful. This kind of view informed the natural philosophers of the "scientific revolution", such as Johannes Kepler who reputedly saw himself "thinking God's thoughts after him" when uncovering the laws of planetary motion. No science at all is possible without some sort of presupposition about there being order and law-like behaviour out there to be discovered. Why that should be the case is not explained by science, but it is explained by theology. However, it is not an explanation that would have appealed to the atheistic proponents of the steady-state theory.

The perfect cosmological principle implies that the Hubble expansion rate we observe today is the same as that at all times, past, present, and future. This enabled Bondi and Gold to calculate, very straightforwardly and without any appeal to general relativity, the rate of creation of matter required to balance the expansion. In Bondi's book, which utilized an up-to-date figure for the Hubble constant, he gave an imperceptibly tiny rate of something like the equivalent of one hydrogen atom per litre coming into existence every 500 billion years.[25] Hoyle put it more graphically in his 1950 radio broadcasts as one atom per year in a volume equal to that encompassed by St Paul's Cathedral. Clearly this is many orders of magnitude below any detectable threshold![26]

One of the most bitter disputes in all cosmology was occasioned by Hoyle's defence of the steady-state theory. It involved the future Nobel prize-winning Cambridge radio astronomer Martin Ryle and was mainly concerned with counts of radio sources, once these were established to be extragalactic (which Ryle originally denied but Hoyle rightly asserted), relative to their brightness. If the steady-state theory is correct then sources of a given brightness should be uniformly distributed throughout space. There is then a simple and easily derivable formula for the number of sources having a brightness greater than any particular value.[27] This formula can easily be tested by drawing a simple graph based on actual observations.

From about 1954 onwards Ryle sought to catalogue radio sources and to disprove the steady-state theory. Indeed, he apparently achieved results which did that, obtaining a graph different from that which the steady-state theory predicted. The trouble was that the survey results Ryle presented in 1954 (from the second of a series of Cambridge surveys) were unreliable; they were contradicted by observers in Australia, and the survey results of 1958 (from the third Cambridge survey) were still disputed. However, by 1961 further results were much more accurate, were confirmed by other observers, and did indeed seem to refute the steady-state theory. These latter results were further confirmed by the complete fourth Cambridge survey carried out between 1958 and 1964, though the steady-state advocates stuck to their guns despite the mounting evidence. It was in reality the discovery of the cosmic microwave background radiation in 1965 that provided the clinching evidence in favour of the Big Bang, and we return to that in the next chapter.