And Gamow said, Let there be a Hot Universe

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Soon after Albert Einstein published his general theory of relativity, in 1915, to describe the nature of space and time, the scientific community sought to apply it to understand the nature and origin of the Universe. One of the first people to describe the Universe using Einstein's equations was a Belgian priest called Abbé Georges Edouard Lemaître, who had also studied mathematics at Cambridge with Arthur Eddington, one of the strongest exponents of relativity. Lemaître realised that if Einstein's theory was right, the Universe could not be static. In fact, right now, it must be expanding.

Working backwards, Lemaître reasoned that the Universe must have been a much smaller place in the past. He knew about galaxies, having spent some time with Harlow Shapley at Harvard, and knew about Edwin Hubble's pioneering measurements of the spectra of nearby galaxies, that implied that almost all galaxies are moving away from each other. This would mean that they were closer and closer together in the past. Going further back, there must have been a time when there was no space between the galaxies. Even further in the past, there would have been no space between the stars. Even earlier, the atoms that make up the stars must have been huddled together touching each other.

Lemaître imagined that there was a time in the past when the entire Universe was packed into a space a few times larger than the Sun. He called this the "primeval atom", even though at that time, in 1927, he was unaware what an atom was really made of. This atom, thought Father Lemaître, would have "exploded" into fragments, which would later become particles, stars and galaxies. The impulse of this initial spurt of ex-

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pansion would be felt even today, in the form of galaxies moving away from each other as seen by Hubble, though their relative speeds would have been considerably slowed down due to the gravity of matter, much like a stone thrown upwards progressively slows down due to the backward pull of the Earth's gravity.

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This proposal caused a sharp reaction from the scientific community of the time. The doyen among theoreticians, Arthur Eddington of Cambridge found this notion unpleasant. Einstein in his heart believed that the Universe is static, and he found the argument of Lemaître, who was also a Catholic priest, strongly reminiscent of the Christian dogma of Creation. The debate between cosmology and religion took the form of a polemic that would last several decades.

Meanwhile, the most important challenge came from Eddington's successors in Cambridge, who came up with a far more aesthetic theory called the steady state theory. First postulated in 1948 by Fred Hoyle, Hermann Bondi and Thomas Gold, this theory states that the universe had no origin, and that although it does expand, matter is being continuously created in just the right amount so that the overall density of the universe remains constant. This avoided the unpleasant notion of the Universe being created out of nothing, and thus was far more popular than Lemaître's notion of the Universe hatching out of a cosmic egg.

In Leningrad, another mathematician named Alexander Friedmann had independently solved Einstein's equations to come to conclusions very similar to those of Lemaître, but being a pure mathematician hadn't really been interested to make connections with the real Universe, and didn't live to see Hubble's observational confirmation of the expanding Universe. However, he had managed to instill into his PhD student George Gamow an interest in the subject.

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The energies involved here have to be very high since both the proton and the atomic nucleus are positively charged, and so would naturally repel each other. Ruther ford's students, Cockcroft and Walton, followed this idea and built the first particle accelerator to achieve this. However, the idea of banging nuclei against each other hard enough to overcome their repulsive elctrical force had given Gamow another, much bigger idea. This concerned the state of the new-born Universe, just after the Big Bang.

Fusion, not Fission

Lemaitre had suggested that after starting off as the 'primeval atom', the Universe would split into subatomic particles by repeated fission. Yet, spectra of stars and galaxies showed that most of the Universe is made of the two simplest elements, hydrogen and helium. Hydrogen has just a proton for a nucleus, with an electron around it, and the helium nucleus has two protons and two neutrons, with two electrons whizzing around. If Lemaitre's primordial atom broke up into smaller particles, why would most of it be in such simple form? Gamow set about making up the Universe the other way around. The Universe would have to evolve not through fission, but fusion. If you start with a proton, which is a hydrogen nucleus, you explain three-quarters of the Universe straight away.

The proton is a very stable particle, but if you leave a neutron around, it would spontaneously turn ('decay') into a proton and an electron with a half-life of thirteen minutes. So if the Universe started off with protons and neutrons, having a Universe that is predominantly made of hydrogen doesn't sound unlikely. So where did the other elements come from? After Gamow had left Soviet Russia and taken up his first long-term appointment at George Washington University in the USA, he assigned this problem to his graduate student, Ralph Alpher.

Gamow named this state "Ylem", a word he found in the Webster's dictionary to mean 'the first substance'.

Together, the basic idea they developed is as follows. The Universe started from a 'singular state', when its density and temperature were practically infinite. As the Universe expands, it cools, and also gets less dense, because of course as the volume of the Universe increases, no new matter is being created. So, in the past, the Universe must have been hotter and denser. Instead of a 'cosmic egg', the early protons, neutrons and electrons must have been swimming around in this very hot, very dense 'primordial soup', a few minutes after the birth of the Universe. Gamow named this state "Ylem", a word he found in the Webster's dictionary to mean 'the first substance'.

Since the newborn Universe was so small, there was little available space, and the particles must have been colliding very often. Gamow's theory of colliding particles could then be applied to show that under these very special and ephemeral conditions, a proton and a neutron would overcome electrostatic repulsion and stick together to form the deuterium nucleus, or the tritium nucleus could form from one proton and two neutrons. Tritium is unstable, so one neutron breaks down to form a proton, spitting out an electron in the process. Now we have two protons and a neutron in the nucleus, and all it now needs is to capture another neutron to become the helium nucleus, the element after hydrogen in the periodic table. Frequent collisions made this possible in the primordial soup. So helium has been made from hydrogen, thus accounting for 99% of the visible matter in the Universe. Nevertheless, it was here that Gamow's theory got stuck.

Climbing the Periodic Table

The helium nucleus is of course the alpha particle, which had earlier brought fame to Gamow in the physics community. It is one of the naturally occurring by-products of radioactivity because it is a remarkably stable particle, and there is no stable nucleus with five particles. So it looked like the rest of elements could not be made by the above process.

However, Alpher's PhD thesis with Gamow worked out that the chain could move on by the alpha particle being struck simultaneously by two particles (neutron or proton) to produce higher elements, and continue making up heavier elements. When submitting this work to the *Physical Review*, Gamow played his most famous scientific joke. "It seemed unfair to the Greek alphabet to have the article signed by Alpher and Gamow only", he later wrote in his book *The Creation of the Universe*, "so the name of Hans A Bethe was inserted." This paper, which is the first detailed exposition of the physics of the Universe immediately after the Big Bang, has since then been known as the 'alpha, beta, gamma' paper.

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In the same year (1948) Hoyle, Bondi and Gold published their alternative scenario for the Universe, that of an expanding steady state. Ironically, it was Hoyle who would later show how to make the heavier elements in the Universe, not in the primordial soup but much later in stars, from the hydrogen and helium cooked up in Gamow's early Universe. For the next twenty years, the two theories, represented by Gamow and Hoyle, remained rivals, with the Steady State Universe being more popular because of its avoidance of the initial singularity. In a BBC radio programme in the 1950s, it was Fred Hoyle who jokingly referred to Gamow's theory of the creation of the Universe as the 'Big Bang' The name stuck.

Cold Soup – Billions of Years Old

Which describes better the history of the Universe – Big Bang or Steady State? To both camps, the theories were abstract mathematical games: nobody knew how to experimentally resolve the debate. But Gamow had a prediction. As the Universe gets bigger and colder, there will be a lot of the primordial soup left, and it will be rather cold.

Gamow carried out a very rough but clever calculation, without the use of his complicated nucleosynthesis ideas, and came up with a value of 7 degrees Kelvin for the current temperature of the primordial soup (see *Box* 1). His ex-student Alpher, along with Robert Herman, subsequently calculated this properly, such that the right

Box 1. How Gamow Calculated the Temperature of the Cosmic Microwave Background

Long before anybody else, George Gamow estimated the temperature of the remnant of the 'primordial soup' using very basic physics. He might have been lucky with some of the numbers he had chosen, such that in spite of his ignoring his own theory of early nucleosynthesis, Gamow came up with an estimate of 7 degrees K, in a paper that was published in an obscure Danish journal in 1953.

Gamow started off by imagining the Universe as a sphere filled with matter and radiation, which expands such that its size R grows as $R \propto t$.

At the present time, most of the stuff of the Universe is in matter. Early on in its history, when the Universe was much hotter, it must have been dominated by radiation. Somewhere in between, the density of matter ρ_{mat} must have been equal to the density of radiation ρ_{rad}.

Gamow assumed that the Universe is 3 billion years old (too small by a factor of 4 by current standards), i.e., $t_0 = 10^{17}$ seconds, and the current density of matter is $\rho_{\text{mat}}(t_0) = 10^{-30}$ g cm^{-3} (too small by a factor of 8 from current estimates).

Box 1. continued...

As the Universe expands, the total mass of the Universe doesn't change, so the density of matter changes as the volume of the Universe, implying that as a function of time,

$$\rho_{\text{mat}}(t) = \rho_{\text{mat}}(t_0)\left(\frac{t_0}{t}\right)^3 = 10^{21}\frac{1}{t^3}\ \text{gcm}^{-3}.$$

In a tour de force, Gamow pulled off a similar calculation about the density of radiation. Since the entire Universe could be safely assumed to be a blackbody, the Stefan-Boltzmann law applies. This means that the energy density of radiation is $\varepsilon_{\text{rad}} = \sigma T^4$, except that, since $E = mc^2$, the corresponding 'mass density' of radiation is $\rho_{\text{rad}} = \sigma T^4/c^2$.

The Universe expands adiabatically, so the temperature of the radiation in the early radiation-dominated Universe would fall off as $T \propto 1/R$, where R is the size of the Universe. Gamow borrowed an approximate result from classical mechanics to show that in the early stages of expansion, the value of R would depend on time as $R \propto 1/\sqrt{t}$. Thus, he calculated that the density of radiation would behave as

$$\rho_{\text{rad}}(t) = 4.5 \times 10^5 \frac{1}{t^2}\ \text{gcm}^{-3}.$$

Thus, Gamow found the age t_* of the Universe at the time when $\rho_{\text{rad}}(t_*) = \rho_{\text{mat}}(t_*)$, i.e. when the energy density of radiation was the same as that of matter in the Universe, as

$$t_* = 7.3 \times 10^7\ \text{yr},$$

which is 73 million years after the Big Bang. At this time, the density would be $\rho_{\text{rad}} \equiv \rho_{\text{mat}} = 9.4 \times 10^{-26}$ g cm^{-3}. From the Stefan-Boltzmann law he used above, he could then calculate the temperature at this time to be

$$T(t_*) = 320\text{K}.$$

It follows from Gamow's initial assumption of the growth of R that

$$T(\text{now}) = T(t_*)\left(\frac{t_*}{t_0}\right) = 7\text{K}.$$

If he had used the currently favoured values of the age of the Universe $t_0 = 1.2 \times 10^{10}$ yr, and the current density of matter $\rho_{\text{mat}}(t_0) = 8 \times 10^{-30}$ g cm^{-3}, he would have got the temperature of CMBR to be about five times larger. His largest source of error would have come from his approximate formula of the growth of the early Universe $R \propto 1/\sqrt{t}$, something that his student Alpher had done properly later to come to an estimate of 5 degrees K.

Suggested Reading

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[2] George Gamow, *My World Line*, Viking, New York , 1970.

proportion of hydrogen to helium was produced in the early Universe, and came up with a very similar prediction: 5 degrees K. This soup would emit blackbody radiation from everywhere in the Universe, since it is equally pervasive in all directions.

Gamow hadn't thought that observing this background radiation would be possible. Looking back, it is evident that many people had come tantalisingly close to confirming Gamow's prediction. In 1940, W S Adams and Andrew McKellar had observed spectral lines of the cyanogen radical (CN^-) in absorption in interstellar space, and had concluded that interstellar clouds must be at a temperature of about 2.3K. But even Gamow (or Hoyle, who later documented a discussion with Gamow about this observation) did not interpret the coldest temperature encountered in the Universe to be that of the Universe itself.

Robert Dicke of Princeton University had realised that the radiation that was left over from the early Universe would always be like a blackbody, and if the Universe were now at a temperature as Gamow predicted, it would emit mostly microwaves. So he developed an instrument to detect microwaves in late 1940s (a design that is still widely used), but could not detect any isotropic radiation, and concluded that the temperature of the Universe must be lower than 20K. The paper outlining Dicke's measurement appeared in the same volume of *Physical Review* as Gamow's paper on early nucleosynthesis, yet neither realised the connection between the two.

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Pigeon Droppings?

That the temperature of the Universe itself could be measured was thus considered unfeasible until the day two electrical engineers at Bell Labs suspected that their research was being hampered by pigeon droppings. Arno

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Penzias and Robert Wilson had been experimenting with inter-continental telephone transmission using the earliest of communication satellites (the Echo series of metal-covered high-altitude balloons). They found that there was a static radio hiss they could not get rid of, no matter which direction they pointed their antenna to. They suspected the pigeon droppings.

Another interpretation was that there was an all-pervasive radiation that came from a blackbody of temperature 3K, which sounded too weird to them. Unaware that they were the first people to have detected the Universe, Penzias called the Chairman of Physics at Princeton University, 30 km away, who happened to be a man called Robert Dicke.

The Nobel Prize for detecting the remnant of the primordial soup, or what is now known as the Cosmic Microwave Background Radiation (CMBR), was awarded to Penzias and Wilson. Following Gamow's suggestion, a large number of people had by then independently made estimates of the temperature, but their contribution went unrecognised.

The CMBR – the Rosetta Stone of Modern Cosmology

One of the consequences of the discovery of the CMBR was that it proved to be the demise of the popular steady-state theory, which had no inherent way of coming up with a mechanism to produce such a remarkably uniform low-energy background radiation. On the other hand, the CMBR was a direct prediction of Gamow's theory of Universe starting off with a hot Big Bang.

In fact, the discovery of the CMBR brought together the two major contributions of George Gamow to the understanding of the origin of our Universe. It confirmed how hot the Universe had been in its early stages, and thus supported Gamow's estimates of how hydrogen and helium had formed from nuclear fusion in the early Universe.

George Gamow's 1948 model of the hot Big Bang has come a long way since then. In 1980, after Gamow's death, Alan Guth introduced the idea of 'inflation', to solve the 'horizon problem', something Gamow had thought was the main worry with his model. The CMBR had turned out to be too uniform in all directions. How does one end of the Universe know the temperature of the end that is diametrically opposite, if light would take twice the age of the Universe to go from one end to the other?

Had he been alive, Gamow would have been happy with Guth's elegantly simple explanation that solved both paradoxes at the same time.

There was also the 'flatness problem', which refers to the overall geometry of the Universe, which appears to be very nearly flat. The general curvature of the fabric of the Universe depends on its overall density. Given that the Universe has been expanding for so long and its density has been constantly dropping, the critics of the Big Bang would say, why is this that we happen to live just at the time when the Universe has turned flat? Gamow and a growing number of comologists had been uncomfortable with such a coincidence.

Had he been alive, Gamow would have been happy with Guth's elegantly simple explanation that solved both paradoxes at the same time. Guth postulated that there must have been a very rapid phase of expansion of the Universe at an early stage, which means that all of the Universe that we see now would have come from a small, causally connected chunk of spacetime. Also, the rapid inflation caused the Universe to become flat very early on (imagine how suddenly pulling a wrinkled bedsheet to many times its size would make the wrinkles vanish).

The cosmic microwave background radiation, first predicted by George Gamow, has proved to be the richest source of cosmological information for experimentalists. Recent observations of the CMBR have provided us with

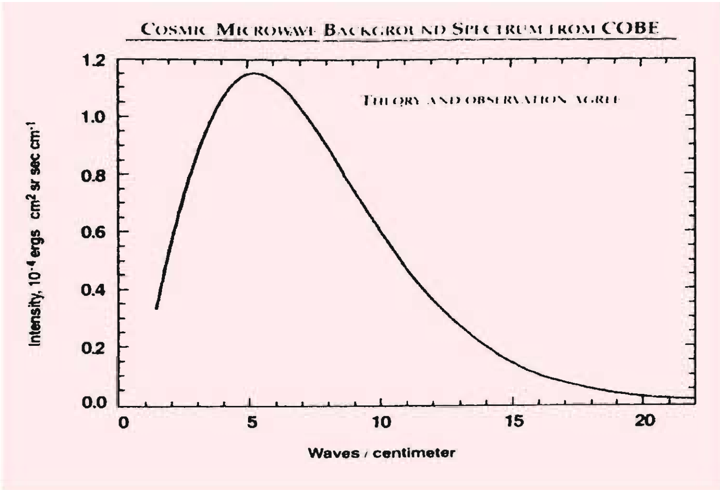

Figure 1. The blackbody fit to the spectrum of the CMB.

The 'primordial soup' of the Universe in which the hydrogen and helium were synthesized is very cold at the present time. As Gamow had predicted, it has been now detected as the cosmic microwave background radiation, which behaves as a perfect blackbody at a temperature of 2.7 Kelvin.

(Picture courtesy: NASA)

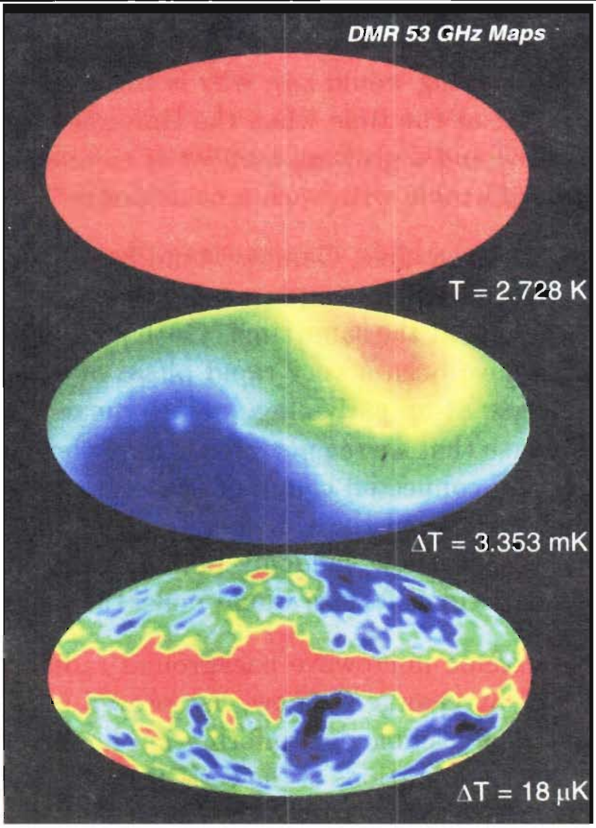

Figure 2. The COBE monopole-dipole-quadrupole map.

The CMBR is remarkably homogeneous, i.e. its temperature is the same, (to two places of decimal in Kelvin), in all directions in the sky. But our galaxy is moving with respect to it, since it is being pulled by neighbouring galaxies. This causes a 'dipole' pattern in the CMBR as seen from inside the Milky Way. After correction for it, variation in the CMB temperature is only found in the fifth decimal place, revealing the fluctuations in the primordial soup that have grown to form the structures that we see today in the Universe.

(Picture courtesy: NASA)

a view of how the large-scale structures of galaxies, that we see today, evolved from random tiny inhomogeneities in the cosmic soup very early on in Gamow's hot Universe. It has also provided us with accurate measures of the flatness of the Universe, and its material content.

When the *Planck* satellite goes into orbit in a few years, we will have a view of the microwave sky which is almost as detailed as the optical pictures of today, and this will allow us to measure cosmological quantities far more accurately, and fill in the few fuzzy areas in Big Bang cosmology.

In the distant future, one hopes that somebody in the higher echelons of NASA or ESA would be wise enough to name the next generation of cosmological observatories after George Gamow, the colourful character who started it all.

Suggested Reading

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A stamp portraying Lemaître

This stamp was issued by Sweden to commemorate the discovery of the cosmic microwave background radiation.