THE BIG BANG

ANAND NARAYANAN

The Big Bang theory currently occupies the center stage in modern cosmology. And yet, half a century ago, it was only one among a few divergent world views, with competing claims to the truth. This article highlights a few trail-blazing events in the journey of the Big Bang model from the fringes to the centerfold of astrophysics, a journey that is ongoing and far from over.

"Who really knows, who can declare?
When it started or where from?
From when and where this creation has arisen
Perhaps it formed itself, perhaps it did not."

– Rig Veda (10:129), 9th century BCE.

These words were written over 2000 years ago. And yet, if they sound contemporary, it is because they echo a trait that is distinctly human; the highly evolved ability of our species to look at the world around us and wonder how it all came to be. How often have you asked these very same questions?

We assume that all things have a beginning. Could this be true for this vastly complex universe as well? If so, what was that moment of origin, and what could have triggered it? Also, does a beginning, in some way, mean that our universe will someday cease to exist?

Humans have always pondered about the origins of things around us – from the atomic to the cosmic. Poets and philosophers, theologists and scientists have all, in their own unique ways, tried to fathom the universe. But, it is only in the last 120 years or so, that science has made it possible for us to get closer to answering some of these long-standing questions.

The scientific study of the origin and evolution of the universe is called cosmology. From the early years of the 20th century, the observational aspects of scientific cosmology began to gather wide attention. This was because of a small series of startling discoveries made by scientists like Edwin Hubble that changed the way we understood the physical universe.

Hubble had an advantage which few astronomers in the early 20th century had – access to the Mount Wilson Observatory in California. This particular observatory housed the largest telescopes of that time and yielded high quality data. With the help of Milton Humason, a fellow astronomer who was adept at using the Mount Wilson telescope Hubble began observing nearly two dozen galaxies in the neighbourhood of the Milky Way.

Hubble and Humason had already calculated the distance from the Earth to each of these galaxies through a set of scrupulous observations. Now, they began recording the spectra (see Box 1)

Fig. 1. Edwin Hubble looks through the eyepiece of the 100-inch telescope at the Mount Wilson Observatory in California, USA. It was using this telescope that Hubble made his many seminal discoveries in the field of cosmology.

of each of these galaxies. Pouring over these observations, Hubble observed two striking trends. Barring a few exceptions, nearly every galaxy that he looked at exhibited a redshift, suggesting that it was moving away from us. This implied that the universe is not stationary. If it were, either none of the galaxies would show any movement relative to us, or an equal number of galaxies would be moving closer to our own. That the vast majority of galaxies are receding from us can only be true for an expanding universe. This important revelation was in stark contrast to the view held by many leading scientists of the period, including Albert Einstein (see Box 2), that the universe was stationary, neither expanding nor contracting.

Hubble noticed the second interesting trend when he plotted the velocity of recession of each galaxy against its distance from us (see Fig.4). These plots showed that the farther away a galaxy was from us, the faster it was receding. The relationship between the two quantities is almost linear (see Box 3). Hubble & Humason formalized this linear relationship, by writing it in the form of a mathematical expression:

$$v = H \times d$$

Where, **v** is the velocity of any galaxy relative to us, and **d** the distance to that galaxy. The two quantities are related to each other by a constant, represented by the symbol **H.** Astronomers started calling this constant, the Hubble's constant. Its value could be obtained

Fig. 2. A view of the Hooker Telescope at the Mount Wilson Observatory. It was this telescope, having a mirror with a diameter of 100 inches, which was used by Edwin Hubble to discover the expansion of the universe.

Source: Ken Spencer, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:100_inch_Hooker_Telescope_900_px.jpg.

Box 1. Red and Blue Shifts in Spectra:

We know that when white light passes through a prism, it splits into several different colours, corresponding to the different energies of photons (light particles) it contains. Astronomers measure the brightness of the light across this rainbow of colours to obtain the **spectrum** of the object emitting it.

The spectrum of a luminous object is a gold mine of information. The spectrum of a star, galaxy or a nebula, for example, helps in determining its temperature, chemical composition, pressure and density. It also allows the measurement of the object's velocity, if the object is moving relative to us. So, if an object emitting light is moving away from us, its spectrum will show a shift towards longer wavelengths and lower energies, called a **redshift**. If, instead, the object is moving towards us, its spectrum would show a shift towards shorter wavelengths and higher energies, called a **blueshift**. The greater the velocity of the object relative to us, the greater will be its shift in energy.

Fig. 3. White light passing through a prism produces a spectrum of colours.

Source: Vilisvir, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Optical-dispersion.png.

Consequently, recording the spectrum of astronomical objects has become a routine part of astronomy. This is done using an instrument called a spectrograph – with older models using a prism to split light into different energies of photons, and newer models replacing this with an optical device called a grating.

by calculating the slope of the linear trend between velocity and distance in Hubble's plots.

As it turns out, Hubble's constant is not just any other number. For over 90 years, astronomers have been trying to measure its value as accurately as possible because it can tell us something very important about the universe. We will come back to that in the section titled – Age of the Universe.

Understanding the expansion of the universe

Hubble's pioneering observations, taken at face value, can lead to a gross misconception about our universe. The spectra of galaxies show all of them moving away from us. Does this mean that we are the centre of this expansion? Intuitively, one may be tempted to say "yes", but such an assumption harks back to an old human folly.

There was a period in history, when even the greatest minds believed that the Earth was the centre of the cosmos. On hindsight, it may appear as a ludicrous notion. But realizing that it is so hasn't been easy. The Earth feels stationary to us, whereas the Sun, the Moon, and all the stars, appear as if they are going around the Earth. It took years of observation and much thought to hit upon the fact that it is the Earth, along with other planets, that is circling the Sun. The fact that even the Sun is not stationary was discovered much later. The Sun occupies a corner of our galaxy, and with billions of other stars, circles the galaxy's centre.

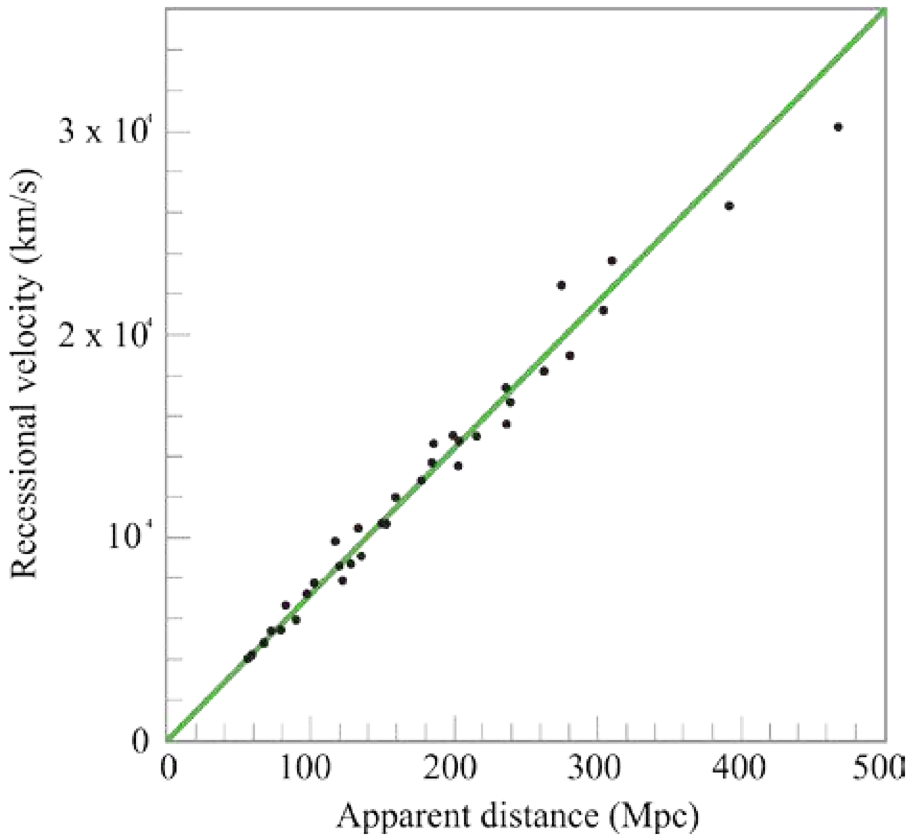

Fig. 4. A graph showing the velocity–distance relationship for galaxies, similar to the one plotted by Hubble and Humason. On the vertical axis is the velocity in units of kilometers per second. On the horizontal axis is the distance of these galaxies from the Milky Way in million parsecs (1 parsec corresponds to 3.26 light years). The black dots correspond to each individual galaxy in this sample. As one can see, the galaxies that are farther away from us also have higher velocities with respect to us. The spread of data in this plot suggests a linear relationship between relative velocity and distance. This linear relationship is represented by the thick green line. The slope of that line is Hubble's constant.

History is replete with such examples of science displacing us from our imagined significance in the cosmos. As a consequence, most astronomers were extra cautious about interpreting Hubble's results. To conclude that the Milky Way is the centre of the expansion would be the repetition of an old mistake. Instead, astronomers came up with a radical new idea that no matter which galaxy we look at the universe from, we should see the other galaxies rushing away from us. So, if an alien astronomer from some other galaxy were to do the same experiment that Hubble and Humason did, it would

Box 2. The biggest blunder of my life!

In 1916, nearly a decade before Hubble and Humason's path-breaking observations, Einstein had derived a set of mathematical equations that described gravity from a fresh perspective. One of the logical outcomes of these equations on general relativity was a universe that kept growing in size. In other words, the equations predicted a non-static universe. Einstein himself was appalled by this outcome, and did not know how to make sense of it. The prevailing notion of those times was that the universe was stationary; and there was no evidence to imagine it being otherwise. Einstein assumed that his model was imperfect. To correct for this, and to set the equations straight, he introduced a constant in his equations, upon learning of Hubble's discovery, Einstein happily threw away the constant, calling its forced insertion to his general relativity equations, "the biggest blunder" of his life.

Interestingly, some of Einstein's contemporaries, like Willem de Sitter, Alexander Friedmann and Georges Lemaitre, had used Einstein's general relativity equations to mathematically arrive at the same conclusion – the universe is expanding. Although they published their results in a various scientific journals, it was taken seriously by the scientific community only after Hubble & Humason's observations were widely replicated and proven.

Box 3. Linear relationships:

The relationship between two quantities that looks like the Hubble velocity–distance diagram is called a linear relationship. When one quantity doubles in its value, the other quantity also doubles. Similarly, when one quantity is halved, the other is also halved. Whenever such a trend is observed between two quantities, scientists try to codify it with the help of a straight line.

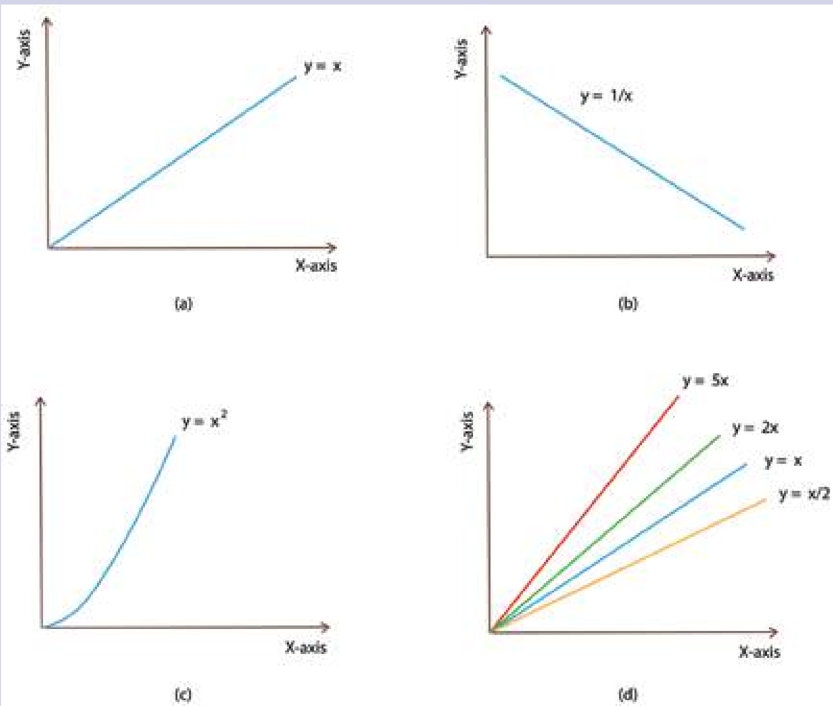

Fig. 5. Identifying a linear relationship. (a) This graph shows a positive linear correlation between the quantities along the horizontal and vertical axes. (b) This graph shows a negative linear correlation between the quantities along the horizontal and vertical axes. (c) This graph shows a non-linear relationship, where the quantity along the vertical axis varies faster than the quantity along the horizontal axis. (d) Four examples of positive linear correlation, with slopes of 5, 2, 1 and 0.5 respectively.

also arrive at the conclusion that the universe is expanding. In other words, there are no preferred locations in the universe. The universe would look the same at large physical scales, no matter where we observe it from. This notion, referred to as the **homogeneity** of the universe, has since become a central idea in cosmology.

The only way that the homogeneity of the universe can be explained is by concluding that space itself is expanding. As incredible as it may sound, this is exactly how astronomers understand the expansion of the universe. While the expansion of space is a dramatic idea that is beyond the scope of this article, one can get a conceptual handle on it through the following analogy. Imagine the three dimensional universe that we live in as being represented by a two dimensional grid system (see Fig. 6). While two galaxies would start out by being close to each other (see Fig. 6a), after some time, our fictitious universe would look different (see Fig. 6b). Seen from each galaxy, it would appear as if the other galaxy has moved away from it. The universe **has** expanded. And yet, if we were to ask where the centre of this expansion is, we would not be able to point our finger at any specific location. The moving apart of galaxies is a consequence of the expansion of space between them, and not so much due to the galaxies themselves travelling through space.

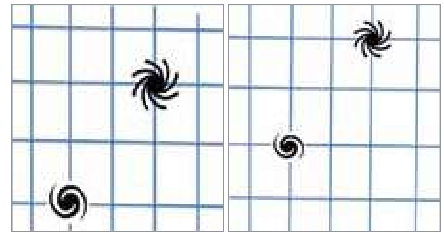

Fig. 6. Expansion of space.

Expansion as evidence of a beginning

The expansion of the universe was a landmark discovery in cosmology because it points in the direction of the universe having an origin. Our observations show us that at present, galaxies are moving away from each other. What would happen if we rewound time? Obviously, we should see space shrinking, galaxies coming closer to each other, and eventually everything collapsing to a single point of infinite density, encompassing the entire mass energy of the universe. This notion of an infinitesimally small entity, from which the entire universe of matter, energy, space and time emerged, was first proposed by a Belgian astrophysicist Georges Lemaitre. From that primordial state, the universe must have started expanding by some means. Astronomers refer to this beginning of the universe's expansion as the "Big Bang", to indicate that it could have been kicked off by an explosion.

The Big Bang has now become a commonly accepted term to refer to the origin of the universe. But the truth is, no one really knows what triggered the expansion, or whether it did, in fact, all start with a bang. With the means of observation available to us and our understanding of the laws of physics, it is very difficult to probe time periods close to the origin of the universe. What is certain, however, is that at present the universe is growing in size, and therefore it must have been smaller in the past.

The Age of the Universe

If the universe had a beginning, the obvious question is – how old is it?

Again, observations of the expansion of the universe provide an answer. To understand how, consider the following analogy:

> Imagine that you are rushing to a race course to witness a motorcar race. It's a busy day and pushing your way through heavy traffic, you finally arrive at the venue to find that the race has already begun. There are two teams competing, and as you take your seat in the gallery, you see that one of the cars has already advanced 80 km from the START line, while the other is lagging behind at 40 km. The display board shows the speeds of the two cars as 80 km/h and 40 km/h respectively (see Fig. 7). It would not take you too long to conclude that the race must have started about an hour ago. To arrive at this conclusion, however, you have to make the crucial assumption that the two cars have been travelling at a steady speed, without accelerating or decelerating at any point of time.

Let us apply this analogy to galaxies. Hubble found that a galaxy that had a relative velocity of 1400 km/s was at a distance of 6 million light years from us, whereas a galaxy that was moving with half that relative velocity had only travelled half that distance away from us. We can, therefore, calculate when the Big Bang must have occurred:

Age of the universe =

$$\frac{\text{distance of any galaxy from us}}{\text{velocity of the galaxy relative to us}} = \frac{1}{H}$$

This explains why calculating the value of Hubble's constant is so important. It offers a means to estimate the age of the universe. Of course, by doing so we make the crucial assumption that the universe has always been expanding at the same rate as what we measure today. The current best estimates of the velocities of the galaxies indicate that the universe is about 14 billion years old. That's how far back in time the Big Bang must have happened.

Fig. 7. When did the race between the two cars begin?

Box 4. The Big Bang!

Ironically, the term 'Big Bang' was coined by the astronomer Fred Hoyle, who found the idea that the entire universe had started off from an infinitesimal point, ridiculous. While Hoyle remained a staunch critic of the Big Bang theory till the end of his life, the name he gave it was too awesome to be ignored!

Beginning or no beginning

By the middle of the 20th century, there were two competing theories about the universe. The steady state theory, put forward by astrophysicists Hermann Bondi, Thomas Gold and Fred Hoyle, suggested a universe that was infinite in space and time. According to this theory, the universe has always existed and, therefore, it was meaningless to talk about an origin. The alternative to this was the Big Bang theory, developed by George Gamow, Ralph Alpher and Robert Herman (see Fig. 8), which favoured the notion of a universe with a beginning.

Fig. 8. George Gamow and Ralph Alpher, who along with Robert Hermann, developed the Big Bang Theory. Gamov was born in the Soviet Union. He moved to the US in the 1930s after spending a brief period in Europe. He later joined the faculty at the George Washington University in the US. Along with his student Ralph Alpher and co-worker Robert Hermann, Gamow worked a great deal on the Big Bang theory, also predicting the presence of the cosmic microwave background radiation.

The discovery that the universe is constantly expanding posed a serious threat to the steady state model. If the universe is expanding, and if it has been doing so for an infinitely long period of time, then individual galaxies should have moved so far away from each other that we should not be seeing any of them in the night sky at all. Clearly, that is not the case. Irrespective of which direction we orient our telescopes; we end up seeing many other galaxies.

Those who favoured the steady state theory tried to resolve this embarrassing contradiction by suggesting that even as the universe was expanding, matter was being spontaneously created from empty space. This is not a trouble-free idea. It violated the law of conservation of matter, for example, which suggests that whenever matter is spontaneously created out of an energy field, an equal amount of anti-matter is also formed. In reality, we see much less anti-matter than matter in the universe. In addition, the rate at which matter would need to be created to compensate for the expansion of the universe is so tiny (one hydrogen atom every trillion years) that it would be difficult to directly observe this phenomenon as it happens.

In science, ideas that cannot be experimentally or observationally verified have short lives. Such ideas do not qualify as scientific theories. Instead, they are called **hypotheses**, which, put simply, are educated guesses. Hoyle's hypothesis of the spontaneous generation of matter was met with only marginal enthusiasm in the broader scientific community. With the expansion of the universe becoming firmly established through repeated observations, the future prospects of the steady state theory started looking grim.

The strength of any scientific model lies in being able to make a prediction which can be observationally tested and verified. In one of the most sensational tales in the modern history of science, the Big Bang theory would go on to do just that, triumphing over the steady state cosmology a second time. The prediction was made in 1948, by George Gamow and his collaborators, in a scientific paper based on the Big Bang cosmology. It was observationally confirmed as being true, nearly 20 years later, and interestingly, by a sheer stroke of luck.

David Wilkinson (1935 – 2002) | **Robert Dicke (1916 – 1997)** | **Jim Peebles (b.1935)**

Fig. 9. Robert Dicke, David Wilkinson, and Jim Peebles from the Princeton University. These astronomers started an experimental campaign to detect the cosmic microwave background radiation predicted by George Gamow and his group.

The discovery of the oldest light in the universe

According to the Big Bang theory, a few seconds after it was formed, the universe was an extremely dense sea of highly energetic photons and fundamental particles. The photons in this sea were a billion times more energetic than the ones our eyes perceive as light. This early universe was also expanding. Physics tells us that expansion is a type of work. Any physical system that is isolated from everything else can do work only if it is willing to expend its own energy, called **internal energy**. This fact is fundamental to a branch of physics called thermodynamics. Our universe is also an isolated system. As far as we can tell, there is nothing outside of the universe for it to interact with, or borrow energy from. If it has to do any work, such as expand and become bigger, it has to use up its internal energy. This means that the photons that filled the universe, immediately after it was born, would have to lose their energy.

Following this train of thought, George Gamow and his collaborators predicted that if the Big Bang were true, the radiation (i.e., photons) from the earliest moments of its existence should be detectable even today. But, in the 14 billion years of expansion that followed the Big Bang, the energy of this radiation would have declined significantly. Gamow and his group suggested that this radiation would most likely be in the form of microwave photons, which are a thousand times less energetic than the light that our eyes perceive. If it existed, this radiation would pervade the universe, and therefore should be detectable from all directions in the sky. Gamow and his group called this the **cosmic microwave background radiation**, or CMBR for short.

Intrigued by the possibility of detecting the CMBR, a group of researchers at the Princeton University, headed by Robert Dicke, started fabricating a radio antenna-receiver system sensitive enough to detect photons of very low energies. This antenna would act like a bucket, collecting any radiation (photons) pouring in from the direction to which it is pointed. The receiver, which is typically tuneable to different energies, records the signal collected by the antenna. Simultaneously, Dicke and his colleagues David Wilkinson and Jim Peebles (see Fig. 9), started the long and rigorous calculations needed to estimate the kind of intensity one could expect from the CMBR at different energies. Even as Dicke and his group were making arrangements to test Gamow's prediction, the CMBR was discovered serendipitously by two young radio engineers from a place not far from Princeton.

In the 1960s, the American electronics research and product development company Bell Labs had built a 20-foot radio antenna meant to collect and amplify radio signals to send them across long distances. But, in a few years, due to the launch of new satellites, the radio antenna system became obsolete and was given away for research. Two radio astronomers – Arno Penzias and Robert Wilson, started using this Bell Labs antenna to measure the brightness of the Milky Way, and several other galaxies near it, at radio photon energies (see Fig. 10). Penzias and Wilson were unaware of Gamow's prediction of the CMBR, or the efforts at Dicke's lab to detect it.

As they began recording their observations, Penzias and Wilson were

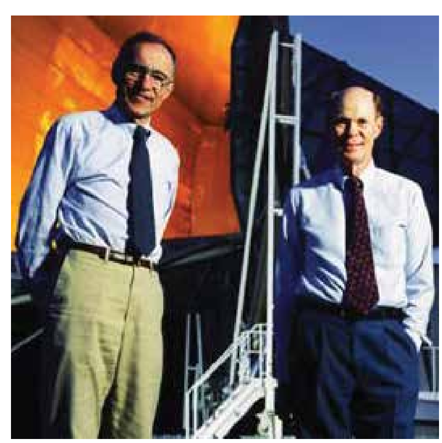

Fig. 10. Arno Penzias and Robert Wilson. They stand in front of the 20-feet long horn-shaped antenna and receiver system they used to discover the cosmic microwave background radiation.

confronted with a problem. Their antenna kept picking up a steady but faint source of noise, in the form of microwave photons, which was disturbing their measurements. The noise was persistent and seemed to be coming from all directions. It did not go away no matter which direction they pointed the antenna at. Assuming that it could be due to some problem with the electronic components of their instruments, Penzias and Wilson tried every means to improve the antenna set-up. To their great chagrin, the "noise" persisted. Nearly a year went by with no means to either explain or get rid of this problem.

Till one day, Arno Penzias heard of Gamow's work from one of his colleagues. Soon after, he and Wilson got in touch with Robert Dicke's group at Princeton. It didn't take Dicke and his colleagues much time to recognize that Penzias and Wilson had accidently discovered the cosmic microwave background radiations predicted by the Big Bang model. These radiations had the exact same properties that the model had predicted, thus becoming the ultimate cause for the triumph of the Big Bang theory. Arno Penzias and Robert Wilson went on to win the Nobel Prize in physics for the discovery of the CMBR.

The CMBR represents the oldest photons in the universe – the fossil relics of the Big Bang. There are hundreds of those photons in every cubic centimetre of space, and each one of them is nearly 13 billion years old. Although we are constantly being bombarded by the CMBR, we do not feel their presence (like the way we feel the heat from Solar photons), because of their very low energies. And yet, these whispers from the Big Bang hold precious information about the early universe – on what seeded the formation of galaxies, galaxy clusters, and similar large-scale structures that we see in the present universe. Because of their importance, we continue making observations of the CMBR, both from the ground, as well as from high-flying balloon experiments, and satellites.

A story far from over

The scientific awareness of the universe having a beginning is only a century old. From the discovery of the expansion of the universe, to the detection of cosmic microwave background radiation, the Big Bang theory has stood the test of many observations. Yet, there are many big gaps in our understanding of the physical universe. We do not really know what triggered the Big Bang, or the physical state the universe had at the very beginning. In one version of the Big Bang cosmology, the universe underwent a very rapid phase of expansion, called inflation, for a tiny fraction of a second. The inflationary model was invoked by scientists to explain certain problems posed by the cosmic microwave background radiation. But whether such a rapid growth phase truly existed; and if it did, what could have powered it is unclear.

And then, there are some even bigger questions. The cosmology of the last three decades has exposed two previously unknown components to the universe – Dark Matter and Dark Energy. Together, these two ingredients account for nearly 96% of the energy density of the present universe. In comparison, the ordinary matter that you, I, and all that we see around us – the planets, the billions of stars in our Galaxy, the trillions of galaxies in our universe, the cosmic microwave background photons – is composed of measure up to only 4% of the known universe. Science has no inkling what dark matter and dark energy are, or how they were generated in the first place. But with their discovery, our view of the universe has changed in ways that were unimaginable before. It has made us realize that in all these years of exploring the universe, we have only been scraping its surface. There is a lot more to the universe than what meets the eye. Scientists hope that astronomy of the 21st century will address and answer these big unknowns. What new challenges the answers might pose for the Big Bang theory remains to be seen.

Note: Credits for the image used in the background of the article title: Big Bang. Geralt, Pixabay. URL: https://pixabay.com/en/big-bang-explosion-pop-fireball-422305/. License: Public Domain.

Anand Narayanan teaches astrophysics at the Indian Institute of Space Science and Technology. His research is on understanding how baryonic matter is distributed outside of galaxies at large scales. He regularly contributes to astronomy-related educational and public outreach activities. Every so often he likes to travel, exploring the cultural history of South India.