The globular cluster M-13 is approximately 200 light years in diameter.

Interior of Orion nebula known as the Trapezium.

THE EXPLODI

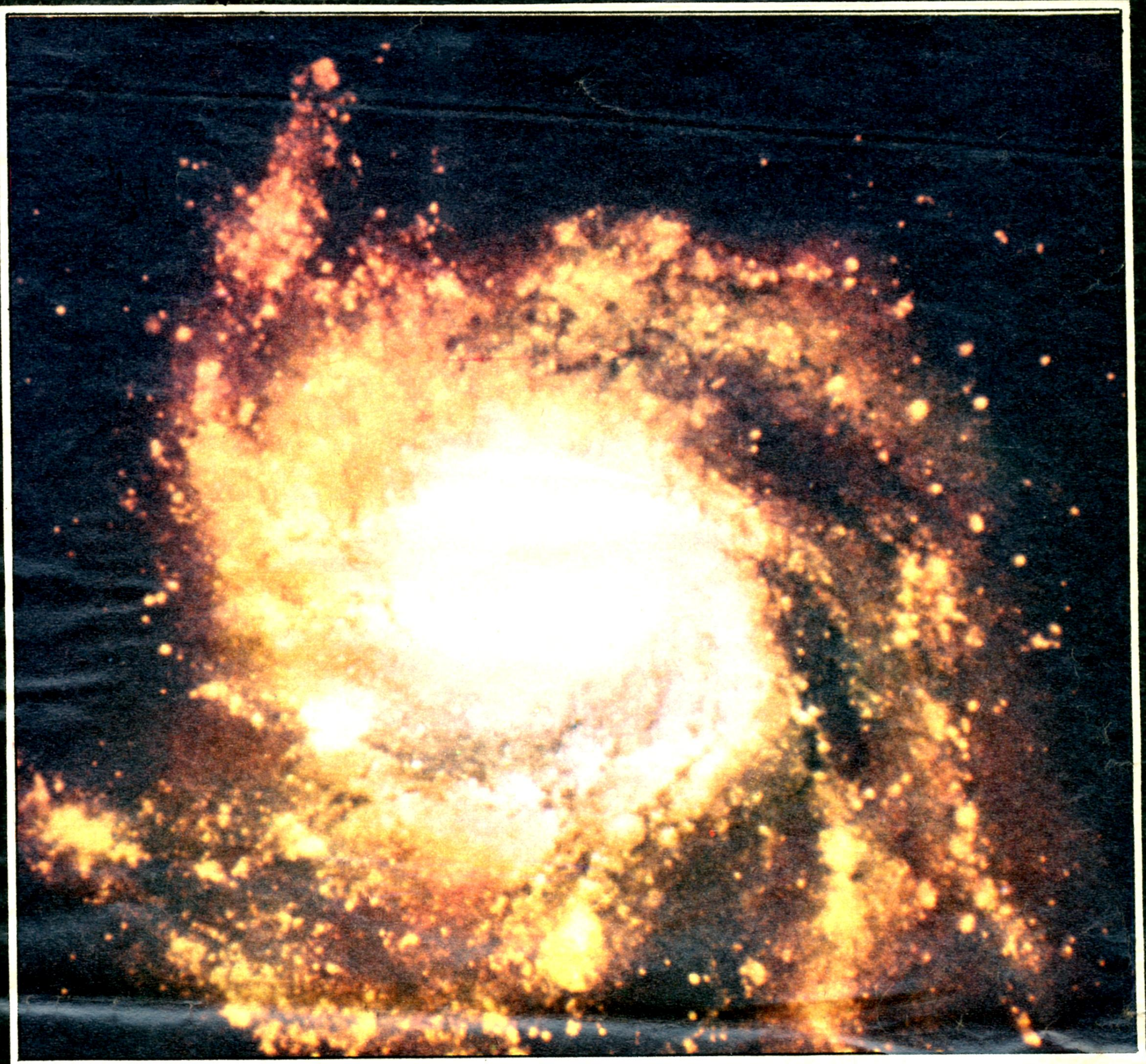
THE WEEKLY COVER STORY/JAYANT NARLIKAR

How big is the universe? How did it begin? How long will it survive?
Are there other planets like ours? Other suns? Other moons?

No one knows for sure. But some of the finest minds have spent their entire lives trying to find out more about this universe in which we find ourselves, and yet know so little about. Theories have led to newer theories. Discoveries have spawned newer discoveries. As the technology of skygazing becomes more refined, more and more of the universe is opening up.

Jayant Narlikar, the internationally renowned astrophysicist, describes this unravelling of the universe in our cover story. He takes us on a guided tour of its mysteries, explaining in the process the subtleties of the various theories in existence.

All of which attempt to explain how the universe was born, how it's growing, and how one day it will die. To be reborn perhaps.
A fascinating journey into our past and our future. And one you cannot miss, whether you are interested in science or not.



A galaxy in motion, typifies the dynamic processes apparent in spiral galaxies.

NG UNIVERSE

At the beginning of this century a heated debate took place at an international meeting of astronomers. The point at issue was: "How far does the observable universe extend?" The majority of astronomers were firmly of the opinion that all that they saw was part of the Milky Way. "Not quite!" argued a handful who shared the view expressed by the nineteenth century astronomer R A Proctor. Proctor believed that a few faint nebulae picked up by the telescopes did not belong to our gigantic Milky Way, but lay far beyond it.

As it happens at astronomical meetings even today, the majority view prevailed on that occasion. However, as Galileo put it more than three centuries ago: "In questions of science the authority of a thousand is not worth the humble reasoning of a single individual."

The scientific technique of 'experiment- observation- inference' has a built-in safety mechanism, which takes effect sooner or later displacing wrong theories. By 1924 the observations by Edwin Hubble with the newly constructed 100 inch telescope at Mount Wilson clearly demonstrated that Proctor was right. However, Hubble's observations revealed something far more startling and dramatic than what Proctor could have ever imagined.

Let us first consider our own galaxy seen in the sky as a diffused white band, which is responsible for its name 'Milky Way'. The galaxy is disc shaped with a diameter of about one lakh light years and it contains billions of stars including the sun. Nebulae are not pointlike sources of light like stars but are diffuse in appearance. There are several bright nebulae in the Milky Way. But what about the bright Andromeda nebula?

It is such nebulae that caused the controversy mentioned in the beginning. The Andromeda nebula is not a small system containing a star or two; it is a galaxy in its own right, containing hundreds of billions of stars. It looks small and faint because of its enormous distance from us — some two million light years!

In the 1920s Hubble and his colleague Milton Humason found several such galaxies lying well beyond our own and which clearly demonstrated that Andromeda is one of our *near* neighbours. The visible universe extends far beyond Andromeda where distances have to be measured in hundreds of millions of light years. Astronomers can photograph clusters of galaxies located at distances of hundreds of millions light years away.

While we may be inspired by awe at this gigantic size of our universe, there is more to come. Hubble's survey revealed more startling facts about the universe, facts on which the modern subject of cosmology rests. But before describing them let us briefly try to understand why the astronomers were deceived about the size of the universe, eight decades ago.

The clue to this puzzle is contained in the dark patches seen in the photographs of the Milky Way. These patches arise because of absorption of starlight by particles of dust. This interstellar pollution was not known and therefore not taken into the calculations by the early astronomers. It was Proctor's conjecture that such absorbing dust exists, that was verified in the 1920s. The bigger and better telescopes of the post World War I period could look beyond this darkening screen and make out clearly the extragalactic nature of many faint nebulae.

In the 1920s, there were two

methods by which the astronomers could study heavenly bodies. In one process the light from a star or a galaxy would be collected for a sufficiently long time to form images on photographic plates. In the second method,the light was split into different wavelengths much in the same way as a glass prism splits sunlight into a spectrum of seven colours.

Hubble and Humason examined side by side, the spectra and images of several galaxies. In the spectrum of a galaxy dark lines appear in isolated places against a bright continuum. These are caused by absorption of light of certain fixed wavelengths by atoms in the gas present in the object itself. Atomic physicists can tell, from the wavelength of the dark line, which atom was responsible for it. The so called H and K lines of calcium are often found in the spectra of astronomical objects, their wavelengths having a mean value of 3950 A° (1 A° = Angstrom = hundred millionth part of a centimetre) in the terrestrial laboratory.


The Milky Way

The peculiarity of the spectra examined by Hubble and Humason lay in the fact that in all of them the wavelengths of the H and K lines were systematically increased above their laboratory values. Since in a typical spectrum the red colour appears at the longest wavelengths and the blue/violet colour at the shortest wavelengths, we say that such spectra are *shifted* towards the *red* end. The fraction by which the wavelength appears to have increased in a particular spectrum is called the 'redshift' of the spectrum. Sometimes the astronomer expresses this shift by multiplying the redshift by the speed of light (which is around three lakh kilometres per second). Thus the galaxy in Hydra cluster is estimated to have a redshift corresponding to 61,000 km per second.

There is a rough and ready way of interpreting this shift, through the well known *Doppler effect*. This effect states that if a source of light is moving away from the observer, the light waves from it are seen redshifted. If we apply this rule to the galaxy in Hydra, we come to the conclusion that it is moving away from us with the speed of 61,000 km per second!

This is fantastic speed even for an astronomical object. Earlier astronomers were accustomed to seeing redshifts in the spectra of stars, but these amounted to no more than a few tens or hundreds of kilometres per second. That something very unusual is in the offing became clear to Hubble and Humason when they discovered such large redshifts in the spectra of galaxies.

The peculiarity does not end here. When data for several galaxies accumulated it became clear that the velocity of recession seems to increase with the faintness of the object. By arguing that the fainter an object is,the farther away it is, Hubble arrived at a simple law: the speed of recession of a galaxy increases in proportion to its distance from us. The nebula in Hydra for example, is about five times as far away from us as the nebula in Virgo. The corresponding recession velocity has also increased five times in going from Virgo to Hydra.

What does it all mean? Hubble's law appeared to hold for almost all galaxies in his survey and it seemed to suggest that all galaxies are running away from us, as if there was some explosion at our location. Did this confer a special status on our galaxy?

We may recall that the ancient Greeks believed the Earth to be at the centre of the universe. That belief was shattered by Copernicus and Galileo. The Earth turned out to be just one of the many planets going round the Sun. However, even the Sun did not enjoy its special status for long. It became clear that it was just one of the hundred billion stars in our galaxy and that it did not even have a central position there. The Sun is in fact, located about two thirds of the way out from the galactic centre. Could our galaxy at least claim to be *the* centre of the universe — a centre of gigantic explosion?

Not quite! Theoreticians in the 1930s soon realised that far from conferring a special status on the galaxy, Hubble's law imposed a totally democratic system on the universe: a system in which the view of the cosmos would be the same from wherever we look. Thus if we imagine another observer located on a distant galaxy looking at the universe, he would find the same Hubble law. All other galaxies including our own would appear to him to recede from *his* galaxy.

The subject can be best understood with an analogy, the analogy of a dotted balloon being inflated. As it expands, all dots move away from one another without there being a unique centre of the whole system of dots. Likewise we now argue that the entire three-dimensional space with the galaxies embedded in it is expanding.

THE BIG BANG

Remarkable though Hubble's observations were, something even more remarkable had preceded them on the theoritecal front. In 1915, 14 years prior to Hubble's discovery, Albert Einstein had proposed the general theory of relativity.

General relativity is regarded by many physicists as the greatest intellectual achievement in science for all times. It would be hard, indeed impossible, to do justice to this theory in an article of this kind. Suffice to say that through this theory Einstein identified the gravitational phenomena with the geometry of space and time.

It is Euclid's geometry that we learn at school and apply in practice. Mathematicians of the nineteenth century knew other geometries, but only as abstract subjects without any relevance to reality. Einstein demonstrated that if his theory was correct, the space time geometry would indeed be non-Euclidean. He himself constructed in 1917, a model of the universe whose spatial geometry was that of the three-dimensional surface of a 'hypersphere'. Just as a man walking straight on the two-dimensional spherical surface of the Earth eventually returns from his travels to the starting point,so does the ray of light flashed in any direction in the Einstein universe eventually return 'from behind'. Such a space is called 'closed', there is no escape from the outside, even though its volume is finite.

In 1922, the Russian physicist Alexander Friedmann constructed models of the universe which were different from the Einstein model. The Einstein universe was static: the galaxies in it stayed put and did not move away from each other. The Friedmann models had the universe expanding, with galaxies receding from one another.

Nobody took much notice of Friedmann's models in the early days because in the 1920s astronomers were not prepared for the concept of the expanding universe. However, Hubble's observations showed that Einstein's model was wrong and that Friedmann's models were closer to reality. Einstein himself conceded that his static model was incorrect.

Accepting the Friedmann models to be correct, the astronomers could extrapolate them backwards in time and ask what the universe was like in the past. The answer was,that a finite time ago the entire universe was compressed literally into a point from which it exploded violently. The present expansion is a slowed-down version of that violent explosion, often called the 'big bang'. Cosmologists who take these models seriously argue that the big bang or the pointlike state signifies the 'creation' of the universe. Thus it is meaningless (or beyond the power of physics) to answer the question 'What existed before the big bang?'

What about the future of the universe? Here the Friedmann models offer two alternatives. If the universe contains matter with density beyond a critical value, the space is *closed* as in Einstein's static model. Such closed models will continue to expand at a decreasing rate until the expansion stops and gives way to contraction. The contraction will proceed at an ever increasing rate and the entire universe would merge into a point. This 'big crunch' signifies the end of the universe.

The other alternative arises, if the matter density is less than the critical density and in this case,the space is 'open'. Thus, a ray of light sent out from here will keep going away from us for ever. An open universe will continue to expand for ever, but at a steadily diminishing rate, until it dissolves into the infinite!

At this stage the reader may want to know answers to some questions. "How old is our universe?" "Is it open or closed?" "Will it continue to expand for ever?" Modern cosmology indeed tries to answer questions like these. But before considering them let us move on from the 1930s to 1940s and look at two exciting developments in the cosmological saga.

As the phrase 'big bang' implies, the primeval explosion must have been a highly turbulent and disturbed one and the Friedmann models indicate that the temperature of the universe must have been very high in the early epoch. How high?

The answer to this question can be given provided we have enough confidence in the validity of physical laws we know at present — confidence, enough to extrapolate these laws in the rather extreme situations of the early universe. In 1946 George Gamow had the boldness to make this calculation and to explore its consequences.

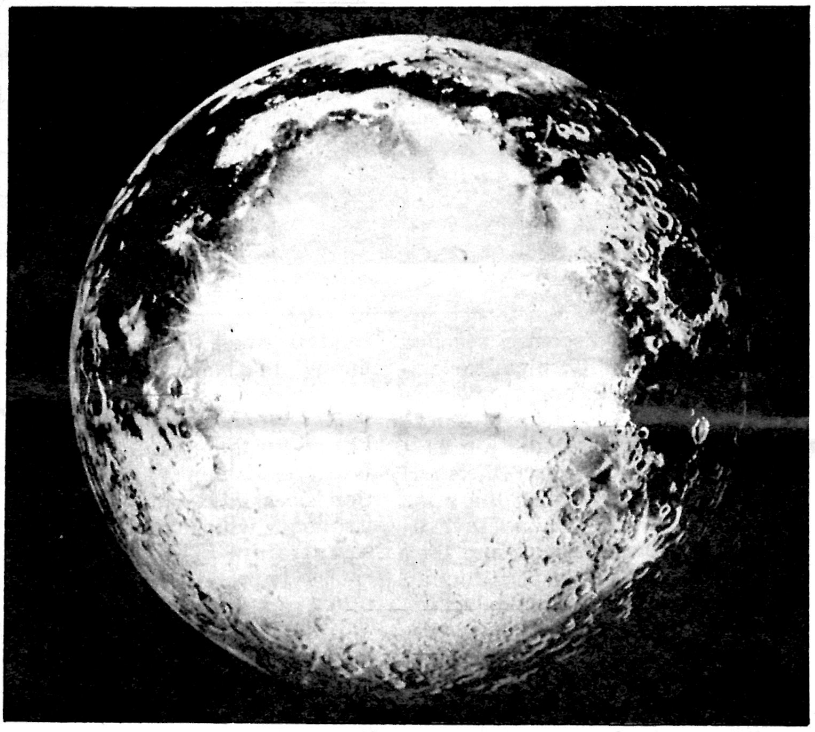
For example, Gamow found that when the universe was only one second old,its temperature was around ten billion degrees kelvin. (Kelvin is the absolute scale of temperature. The zero of this scale is at - 273°C and a step of 1 kelvin equals a step of 1 degree Celsius.) At such a high temperature,matter could not exist as solid lumps or even as a liquid. It was in the form of gas made of particles like protons, neutrons, electrons, neutrinos and of course, photons, the packets of energy in the form of pure radiation. All these particles moved almost freely, although they did collide inside their dense population.

Gamow felt that the situation at this stage was remarkably similar to that inside a fusion reactor which builds up atomic nuclei from collisions and combinations of protons and neutrons. For example,the nucleus of deuterium (heavy hydrogen) contains one proton and one neutron bound together by the nuclear force. At the temperature of ten billion degrees the protons and neutrons are moving too fast to be bound. However, as the temperature drops with the expansion of the universe the nuclear binding becomes more and more effective and deuterium begins to be formed. The process continues and eventually leads to the formation of the helium nucleus which contains two protons and two neutrons.

It was Gamow's hope that even bigger nuclei would be formed this way. His colleagues Ralph Alpher and Robert, Herman collaborated with Gamow to present a plausible theory of primordial nuclear fusion. And in the course of this work they made an important prediction. The radiation which was present at this hot epoch, would cool down and would be observable even today, they said. They estimated that this radiation would be predominantly in the form of microwaves.

Microwave technology was sufficiently developed in the 1950s for some one to construct a suitable antenna for detecting the predicted relic radiation. However, no one undertook to make this important measurement.

By hindsight sociologists of science have debated why this happened. There may be two reasons. Gamow's hope of cooling all types of atomic nuclei in the first few minutes of the existence of the universe (after the big bang) proved to be futile. Astrophysicists found that it was not possible to progress much further than helium along the path offered by Gamow. The rapidly cooling universe just did not offer the right environment for this purpose. So they lost interest in the whole theory. Secondly, thirty years ago physicists did not take cosmology as seriously as they do today, considering it a highly speculative subject.



The Moon

THE STEADY STATE THEORY

In 1948 three British theoreticians produced a rival cosmological model, which they claimed, did not have some of the inherent defects of the Friedmann models.

One defect, if we may so term it, lies in the notion of the big bang itself. The idea that the entire universe is compressed to a point is not only hard to imagine, it is impossible to quantify mathematically. Mathematicians term such instances, where their mathematical processes break down as 'singularities'. In the Friedmann model there is a singularity of space and time at $t=0$, the epoch of creation.

Physicists consider such singular instances as defects of the underlying description, and find ways of improving the theory so that such instances are avoided in the new description. In 1948 Hermann Bondi, Thomas Gold and Fred Hoyle attempted to give such an improved description which they called the 'steady state model' of the universe.

In the steady state model the universe is ever expanding, having no instance of 'beginning' or of 'end'. Just as the capital invested in a business grows rapidly under a compound interest scheme, so does the volume of space bounded by several galaxies grows rapidly as the universe expands. However, the density of the universe remains constant in the steady state model, as the adjective 'steady' implies. How is this achieved?

The authors of the theory argued that this was the outcome of continuous creation of matter. Normally, as the universe expands its density would tend to go down. The continuous creation of matter serves to fill the gaps left by expansion and thereby maintains a constant density. Almost from its birth the steady state model attracted hostile criticism.

The pro-big bang astronomers attacked this model for one reason while the physics community criticised it for another. During the 1950s and the early 1960s several astronomical observations were put forward to 'disprove' the steady state theory. The observations were of remote parts of the universe. When we see a remote object we see it as it was in the past, because light travels with a finite velocity. When the image of a galaxy 1 billion light years away is formed on a photographic plate, the light reaching the plate left the galaxy 1 billion years ago. So, if the universe is in a steady (that is, unchanging) state, the remote maps of the heavens should look similar to the nearby maps.

The astronomical observations referred to above claimed that the remote maps were not similar to nearby ones. However, close examination showed such claims to be either false or full of uncertainties.

In 1960,I became a student of Fred Hoyle. I recall, that when as a fresh graduate student, I expressed the desire to work on the steady state theory, Hoyle discouraged me with the comment that the theory was controversial and hence not suitable as a Ph.D. topic which is normally chosen in an uncontroversial line of research. Nevertheless, I was drawn into cosmological controversy and found myself lined alongside Hoyle in defending the steady state theory against the observations of radio sources made by Martin Ryle and his colleagues.

The Ryle attack, just like the earlier ones from other sources could be successfully countered and the steady state theory lived on.

The objection from the physicists was of a different nature. The notion of continuous creation, they felt, violated certain basic conservation laws, for example, the law of conservation of matter and energy. This objection could, however, be countered by demonstrating that matter creation took place from a reservoir of negative energy radiation, which we termed the 'C-field'. Working on the C-field in the mid-1960s, Hoyle and I felt that although the law of conservation of matter and energy was still valid, another law, that of conservation of baryon number must break down in a steady universe.

What is the baryon number? All atoms in matter are made of nuclei containing the heavy particles, neutrons and protons, surrounded by orbits of electrons (which are light compared to protons or neutrons). The heavies are the baryons, and they come in many types although the protons and neutrons are the most common types. The baryons could be transformed from one type to another by particle interactions, but according to the law of conservation of baryon numbers, they could not be created anew or destroyed totally. In short, the total number of baryons in the universe must be fixed.

Twenty years ago the physicists believed in the validity of this law so firmly that they discounted any theory that broke this sacred rule. And so, the steady state theory was under a cloud of suspicion. By hindsight we can say that the steady state theory came two decades too soon. I will return to this comment again later in the article.

The steady state theory is credited, even by its detractors with two beneficial effects on cosmology. The first is, that by providing a rival alternative to the big bang and by making definitive observational predictions it inspired many observers to undertake difficult cosmological observations. Thus, by mid-1960s the astronomy of galaxies and the universe in general had attained sufficient maturity to discard the adjective speculative.

The second contribution of the theory was to promote work on origin of atomic nuclei inside stars. Since in the steady state theory there was no 'hot' epoch in the past, the Gamow-type process could not be invoked to build elements from protons and neutrons. Therefore, there had to be alternative sites in the universe where this process goes on. Where? The classic work of Geoffrey and Margaret Burbridge, William Fowler and Fred Hoyle in 1957 showed that the interiors of stars were ideal sites for the fusion of nuclei. Not only light nuclei but heavy ones also could be made in stars and distributed out in stellar explosions.

In 1965, however, the steady state theory received an unexpected blow from which it has yet to recover. Two physicists at the Bell Telephone Laboratories at Holmdel, New Jersey (USA) were testing their equipment in order to make measurements of microwave radiation from certain parts of our galaxy. The equipment was a big horn shaped antenna and for testing purposes it was tuned to the wavelength of 7.3 cm.

When the two physicists Arno Penzias and Robert Wilson analysed their observations they were in for a surprise. After accounting for various sources of radiation, they found that what their antenna received was a residual radiation coming equally strongly from *all* directions. This radiation therefore could not be identified with any specific source. Rather it seemed to be 'noise' generated on a cosmic scale. What could be the cause of this noise?

We may recall that in the early 1950s George Gamow and his colleagues had predicted the existence of microwave radiation as a relic of the hot big bang. Was the radiation background discovered by Penzias and Wilson by accident, this very relic radiation?

In an age of rapid circulation of scientific information it seems strange that Penzias and Wilson were unaware of Gamow's prediction. They, therefore, did not immediately put two and two together. In fact, although they had made the discovery in 1964, they did not publish it immediately, thinking that their results might be due to some undiscovered instrumental fault (including pigeon droppings on the antenna!) When the rumour of their discovery reached Princeton University, there the scientists Robert Dicke and Jim Peebles immediately spotted the possible significance of this radiation as a relic of the big bang. In fact Dicke and Peebles were working on the same problem that Gamow had investigated fifteen years earlier and they were in the process of constructing an antenna of their own to detect the cosmic relic radiation.

The Earth

Thus, in 1965 the Penzias-Wilson paper appeared in the *Astrophysical Journal* under the somewhat unpretentious title, *A Measurement of excess antenna temperature at 4080 Mc/s.* But the cosmologists saw in it the long awaited evidence of the big bang. The discovery was considered important enough to merit a Nobel prize in 1978 for its authors.

Certainly, if the relic interpretation is correct the discovery is as important for cosmology as Hubble's discovery of the expanding universe. (If cosmology were considered respectable enough in the 1930s, Hubble would definitely have received a Nobel prize.)

The relic interpretation required the spectrum of this radiation to follow a certain law, known as the black body law. A black body ideally is a hot enclosure from which no radiation can escape outwards. In such an enclosure, the light photos get bounced, scattered and mixed thoroughly so that the distribution of photons of different energy attains a steady value. In this distribution photons of a specific frequency are most numerous. The inside of a heated oven is probably close enough to a black body enclosure (if we ignore the heat lost through the walls). When we say that the oven is heated to a temperature of 250c what is implied is that the inside distribution is peaked at photons of a specific frequency which corresponds to this temperature. This frequency increases in proportion to the temperature, expressed on the absolute scale. Thus 250c is equivalent to 523k and the peak frequency corresponding to this temperature is about 30,000 gegacycles per second. Penzias and Wilson found that the background temperature is about 3k and the black body peak would be at the microwave frequency of about 180 gegacycles per second.

THE EARLY UNIVERSE

The agreement between theory and observations looks good enough to make a prima-facie case for the hot big bang model. Gamow's calculations re-done with modern inputs from nuclear theory show a reasonably good agreement between theoretical values and the observed abundances of light nuclei. Heavier nuclei are believed to have been made inside stars.

The aim of science is to push back the existing frontiers of knowledge. Applying this objective to cosmology we can ask the following question: "Assuming, on the basis of the evidence of relic radiation that Gamow was right about the cooking of light nuclei in a primordial fusion reactor, can we not investigate the state of the universe before the fusion process came into operation?"

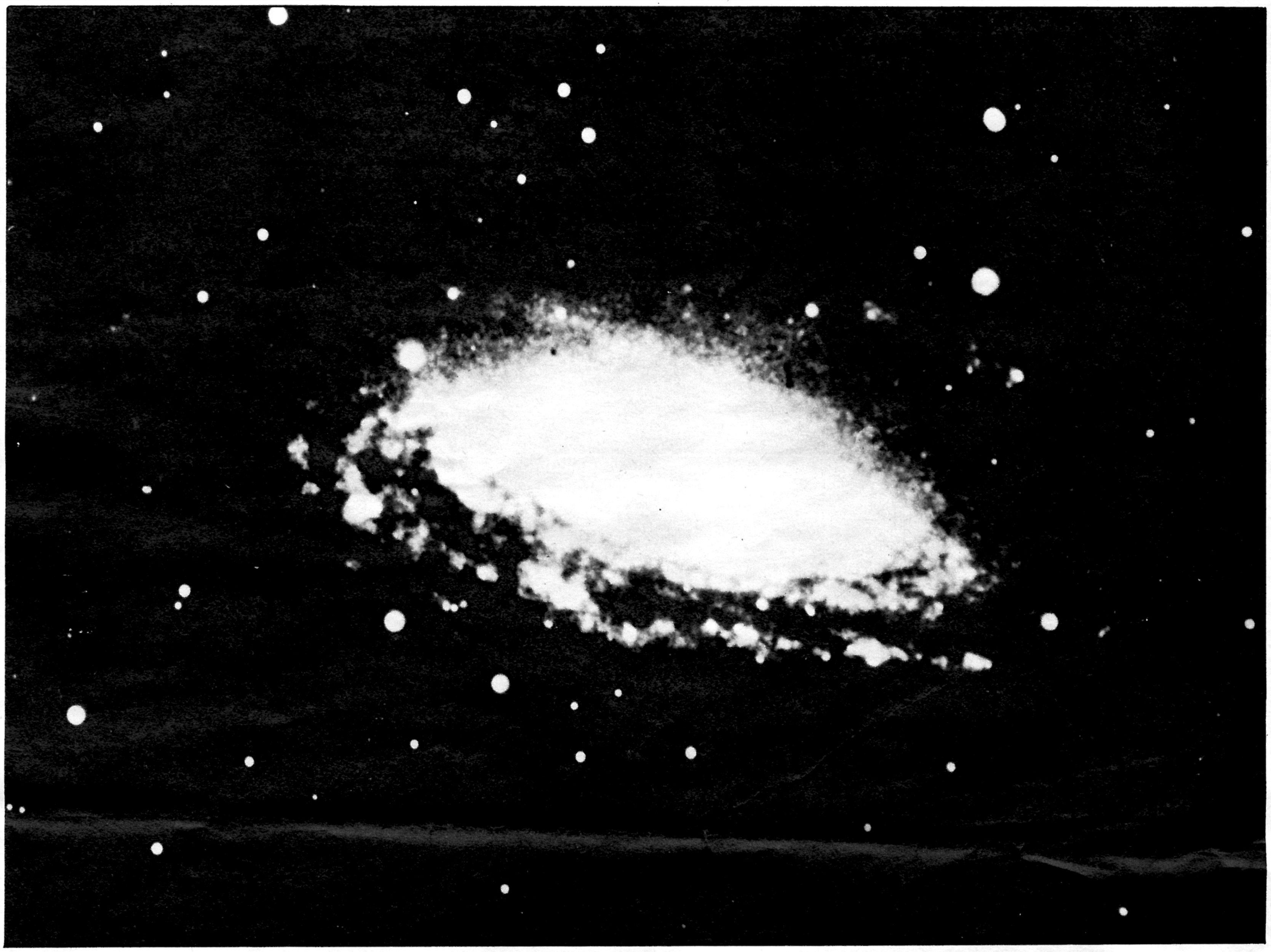
Recall that the cooking of light nuclei took place, according to the hot big bang model, as the universe cooled from a temperature of a few billion degrees to a temperature of a few hundred million degrees. This phase, according to present calculations lasted from the epoch when the universe was a few seconds old, to the epoch when it was about three minutes old. At the beginning of this phase, it was assumed that the universe had protons and neutrons already in existence as the primary building blocks of atomic nuclei.

The cosmologists today, are asking these questions: "How did these building blocks come into existence? Were they created at the time of the big bang, or did they form out of something else in the first few moments of the existence of the universe?"

Particle physicists believe that neutrons and protons, or baryons in general, are formed from combinations of (as yet undiscovered) particles called quarks. Quarks according to theorecticians come in many types, 'colours' and 'flavours', but three quarks glued together make a baryon. To make or destroy a baryon, we must therefore be able to form or split the 3-quark combinations. Theorists believe that the gluing force is so strong that this is not normally possible. And out of such a belief came the conservation law of baryon number stated earlier. Hence, till a decade ago particle physicists would have argued that the primordial neutrons and protons which Gamow talked about were not formed *after* the big bang but *with it.*

However, exciting developments in particle physics in recent years have led to a revision of this belief. These developments are prompted by the search for a 'grand unified theory' (GUT) of basic physical interactions. To understand the motivation for GUT let us briefly review the four known basic interactions of physics.

The oldest of the four is gravitation, first quantified as a physical force by Isaac Newton in his *Principia* in 1687. This force is universal, acting between any two pieces of matter, and is responsible for diverse phenomena like planetary motions, the structure of stars, tides on oceans and so on. Next to be discovered was the electromagnetic theory which is primarily responsible for the structure of atoms and molecules which form the ordinary matter we see around us. The other two forces, the strong and weak interactions are of short range and their effects are felt only on the scales of subatomic particles. In 1915 when Albert Einstein invented the general theory of relativity to describe the phenomenon of gravitation, only two interactions



The Spiral Galaxy

out of these four were known. It was Einstein's hope to produce a unified field theory which would combine these two, namely electromagnetism and gravitation, a hope that was not realised during his lifetime

In the 1970s, however, experiments verified that the theoretical attempts of Abdus Salam and Stephen Weinberg to unify the electromagnetic theory with the weak interaction were along the right lines. This unified theory, called the electroweak theory, generated the belief that a grand unified theory including the electroweak and the strong interactions in a single framework could be formed. As of today, there are several version of GUT and the last word remains to be said. Attempts are also underway to form a Super-GUT, which includes gravitation also.

However, all GUTs agree that baryons can be created and destroyed, and this possibility has opened up two lines of attack. The experimental approach involves erecting huge piles of matter interpersed with sensitive detection to look for the decay of the most abundant baryon, the proton. The first such experiment to report likely events which could be interpreted as proton decay events is from India. The apparatus is located deep underground in a gold mine at Kolar Gold Fields.

The second approach is theoretical, making use of various GUT models. Unfortunately, all such approaches suggest that GUT predictions are of interest only if we have particles of phenomenally high energy colliding. Only at such high energies could the baryon be stripped apart. How high is this energy requirement?

The largest man-made accelerator is the Fermilab particle accelerator at Batavir, Illinois. Built at a cost of the order of billion dollars this accelerator generates particles of energies upto a thousand billion electron volts. (Electron volt is a measure of energy. If an electron is totally annihilated at rest position, the energy generated would be about five lakhs electron volts.) To test the predictions of GUTs we need accelerators that can produce particles million, million times as energetic as those produced by Fermilab. This is not a practical proposition either technologically or financially.

The only alternative for GUT-physicists, therefore is to look to astronomy for likely sites in the universe where such energetic particles might be present. So far astronomers can point to only one example, that of the early universe. Very shortly after the big bang, the violence of the explosion was capable of generating particles of such high energy, although for a very short time. The shortness of these time intervals is beyond human comprehension: it is of the order of a billion-billion-billion-billionth part of a second!

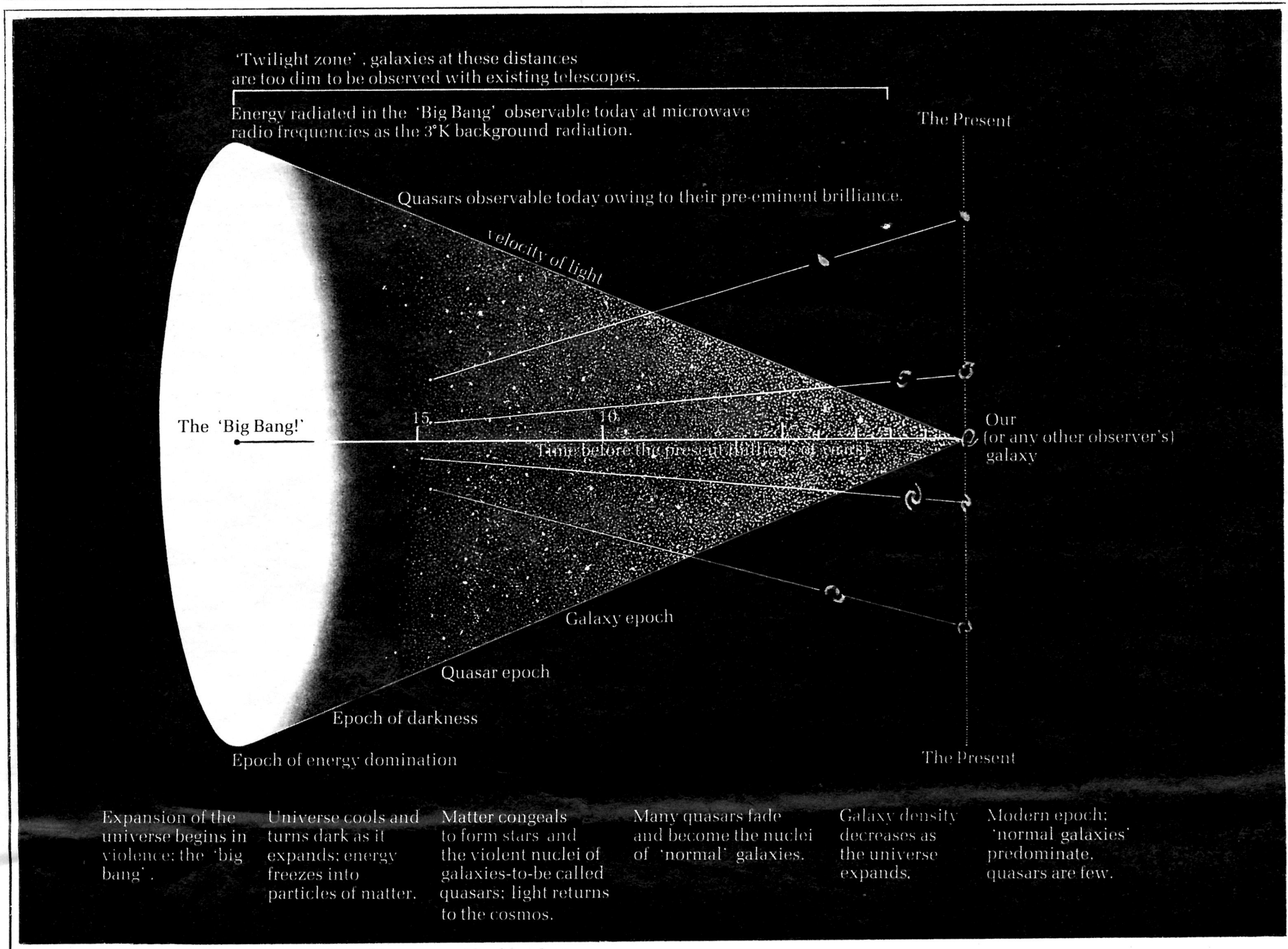
For a fleeting moment of this order after the big bang, the particle energies were high enough to experience the full force of the grand unified theory. The present composition of the universe would have been settled in that wink of time.

The questions that cosmologists and particle theorists are trying to come to grips with are how, why and when this composition was decided in the early universe. In particular they are trying to see how and in what quantity the baryons were created in that crucial epoch: a problem that the steady state cosmologists two decades ago were criticised for tackling on the grounds that it defied the laws of physics!

QUANTUM UNIVERSE

Dare one go even further back in time, closer to the so-called creation epoch? General arguments suggest that in the first hundred-million-million- million- million- million-million-millionth part of a second, the behaviour of the universe was governed by the laws of quantum theory, the theory that is normally called upon to solve problems of microscopic systems like atoms, molecules etc.

Quantum theory introduces the important notion of 'uncertainity', first discussed in the 1920s by Werner Heisenberg. Classical physics, developed since the days of Newton, implicitly assumed determinism in the following sense. Given sufficient information about the pre-



The expanding, evolving universe viewed in terms of lookback time

SUHAS BAWDEKAR

sent state of a physical system it is possible to predict its immediate future behaviour, with the help of physical laws. Not quite, said Heisenberg, with his so-called uncertainty principle. The laws of physics have certain limitations on what can be completely specified and so, there is an inherent uncertainty in their predictions. Hence, instead of specifying how the system will behave definitely, the physicist can assign relative odds to the various alternative courses of evolution the system can take.

The uniqueness of classical physics therefore, gives way in quantum theory to a range of possible alternatives for the future behaviour of a system.

In cosmology, we can turn the problem around and argue that, in quantum epoch the past history of the universal was not unique and definitive. Instead, there were a whole range of possible histories the universe could have passed through, and we cannot say for sure which particular history it did have. Can we assign odds to the various alternative histories in much the same way that an atomic physicist assigns odds to which orbit an atomic election will follow?

There have been several approaches to quantum cosmology, not all of which agree in their answers. I will briefly outline an approach I developed during the last six-seven years. This approach concentrates on deciding the history of the scale factor of the expanding universe. In the classical Friedmann models the scale factor, characterizing the distance between two typical observers at any given epoch, increases steadily from its zero value at the big bang. In quantum cosmology we ask the question: "What are the odds for this particular history of the scale factor?" More importantly we wish to know if the odds were overwhelming that the scale factor was zero at some epoch in the past. If the answer is 'yes' then we can assert that the universe, in all likelihood, did originate in a big bang.

Interestingly, my calculations suggest the reverse! The odds that the universe emerged from a state of zero volume turn out to be almost zero! Thus the big bang origin indicated by the classical Friedmann solution turns out to be an exception rather than the rule. The universe is more likely to have a finite (but different from zero) size in the past and hence it need not have had a beginning at all! Strangely, this result is in intellectual sympathy with the steady state theory which also did not have a beginning for the universe.

In his classic book *The Realm of the Nebulae* Edwin Hubble said that, 'the history of astronomy is a history of receding horizons'. In the six and a half decades since Einstein's classic paper, the cosmologists have pushed the horizons considerably further. Both Hubble and Einstein, had they been alive today, would have been impressed by the advances in observational and theoretical cosmology in recent years.

I have highlighted in this article the theoretical approach to cosmology. The theoretical developments have however, come because of the observational inputs from various branches of astronomy, from telescopes mounted on satellites as well as from telescopes on the *terra ferma*. A major achievement of space technology, the space telescope, is to be launched in two or three years from now. Many astronomers hope that it will augment our vision of the universe as much more as the very invention of telescopes, three centuries ago did in the past. Will the present view of the universe survive the inputs from the space telescope and the other next-generation instruments planned for the 21st century?

Although the big bang theory is very much the accepted theory today it has chinks in its armour. The age of the universe computed from the theory is around 8-12 billion years and is uncomfortably low. For our galaxy itself may have exceeding the upper limit quoted above and even older galaxies exist in the universe. How can we have 'children' older than the 'parent'?

The strongest evidence in favour of the big bang, the microwave background radiation, itself has some problems of interpretation. Most cosmologists believe that the formation of galaxies took place out of growth round inhomogeneities that existed in the universe when this radiation background was formed. If so, some mark of these discontinuities would have appeared on the observed background.

USIS

THE ACHIEVEMENTS OF SUBRAMANYAN CHANDRASEKHAR

The 1983 Nobel Prize for Physics has been shared by two astrophysicists, both of them past the age of 70; Subramanyan Chandrasekhar (b 1910) from the University of Chicago and William Fowler (b 1911) from the California Institute of Technology.

Chandrasekhar is the fourth Nobel Laureate in science from this subcontinent, the previous three being C.V. Raman, Hargobind Khorana and Abdus Salam. Statisticians point to several examples of close relationships (father-son, mother-daughter, teacher-pupil) amongst Nobel prize winners. Chandrasekhar adds to the list; he is the nephew of C V Raman.

It is not often, that astronomers and astrophysicists have got the Nobel prize. Probably the Physics community still feels that these subjects are speculative in spite of their many advances in the recent past. The award to Chandrasekhar, therefore, reflects the respect and confidence his work enjoys internationally. Indeed many scientists feel that he should have got the award long ago.

Chandrasekhar was born in Lahore and educated in the Madras Presidency College before going to Cambridge University in 1930 for research in astrophysics. Like many great scientists he did his outstanding work while in his twenties, at Cambridge.

This work, which is today part of astrophysics text-books and which is now considered respectable enough for a Nobel award, was received with ridicule and hostility when it was first presented. What was it all about?

In the 1920s two important developments took place which were to affect Chandrasekhar's work significantly. The first was in astrophysics itself and it arose out of the work done by the Cambridge astronomer Arthur Stanley Eddington. Eddington set up equations describing the internal structure of a star like the Sun. These equations described how the star maintains equilibrium under two opposing forces, the force of contraction due to its own gravity and the outward forces of pressure produced by the hot furnace in its core. It was Eddington's conjecture that the furnace was kept fuelled by thermonuclear fusion.

The second development was of quantum mechanics which prescribed laws governing the behaviour of subatomic particles. These laws altered many preconceptions of physicists who were brought up on Newton's laws of motion. One of the 'strange' consequences of quantum laws was the so-called 'exclusion principle' which forbade two identical particles like the elections to be present together in the same state.

To see the connection between these two developments and their relevance to Chandrasekhar's work imagine what would happen to a star which has exhausted all its nuclear fuel. Will such a star be able to keep itself in equilibrium against the contracting force of gravity? The visually faint but highly dense and compact stars called the white dwarfs indicated that the answer should be 'yes'. But how?

The answer lies in the exclusion principle. The tendency of a star to contract means more and more particles in the same small volumes. The exclusion principle puts limits on how closely we can pack the matter together. Out of such restrictions a new pressure emerges which opposes further contraction.

Chandrasekhar used this idea together with the modifications needed by special relativity theory and showed that provided the star was not very massive it could be maintained in equilibrium by the above pressure. This limit on the star's mass which emerged from Chandrasekhar's calculations is called the *Chandrasekhar limit* and it equals 1.44 times the mass of the Sun. Thus, all white dwarfs must respect this mass limit in order to survive!

Contrary to Chandrasekhar's expectations this elegant result was ridiculed and criticised by a person no less than Eddington himself. This is indeed ironical since, in the 1920s, Eddington's ideas of thermal fusion were also criticised by the established atomic physicists of the day.

However, the result gradually gained its due recognition while Chandrasekhar moved on to new things. His later works on stellar dynamics, stability of liquid masses and on Einstein's general relativity are all internationally recognised. In each case his in-depth studies formed subject matters for his books, all of which are regarded as land-marks in their fields. Recently he completed a mammoth volume on black holes.

He brought the same thoroughness and attention to detail, into the famous *Astrophysical Journal* whose managing editorship he carried for nearly two decades.

Last year when I met him during his tour of India, I asked him "What new field will you now take up after finishing the book on black holes?" He replied, "At the age of 72, it is hardly the time to take up new fields of research."

Judging by his past performance, I would tend to disagree! In his seventies, despite a serious but successful open heart surgery, Professor Chandrasekhar is as active in scientific research as he ever was before.

The agreement between the observed spectrum of the microwave background and the predicted black-body curve is found not to be good enough when subjected to statistical scrutiny. Could this imply that the spectrum is not that of relic radiation, but was formed at a later epoch? Alternatives to the relic interpretation are not popular, but they are being taken more seriously.

Needless to say, that if it is established that the microwave background is of recent origin, then the steady state theory will receive a new lease of life.

The investigations of the early universe have also thrown up a number of difficult problems. One problem relates to unwanted monopoles. Classical electromagnetic theory tells us that there are no free magnetic poles in existence. The poles always appear in a North-South (dipole) combination. However, GUTs lead one to expect that a large number of massive monopoles formed in the early universe. Where are those monopoles today? Theoreticians are working hard on scenarios in which the monopoles are somehow reduced greatly in number, if not eliminated altogether. For, their presence today can lead to many drastic effects.

The reader may have noticed a serious omission in the write-up on cosmology: there is no mention of biology and of the living system besides those on the Earth. It seems hard to believe that life originated in an isolated fashion on our planet. Does it exist elsewhere, in outer space? What are the characteristic time scales for origin and evolution of life? How do they compare with cosmological time scales? Fred Hoyle and Chandra Wickramasinghe have argued that the cosmological time scales are far too short for biological purposes. They have invoked such arguments to suggest a universe without a beginning and also the existence of a superior intelligence which manipulates organic molecules to generate life forms.

Whether or not this line of reasoning is correct, it is hard to find fault with a philosophical argument of Hoyle's. Taking into account the complexity of human brain and its intrinsic limitations of thinking and generating ideas, Hoyle feels it inconceivable that it should have solved the ultimate problem of the origin of the universe *now*. The nature of the universe is far too profound for the human brain to grasp it in entirety. Time and again, man working at the limits of his imagination is deluded into thinking that he has solved it. The big bang cosmologists beware!

In any case, if you hear a cosmologist tell you in no uncertain terms 'how it all began' remember these words of the physicist Landau. "Cosmology is often wrong but never in doubt."

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