25 years Ago

Summer Programmes were organized for school children from 26th April to May 1st, 1993. It included lectures on astronomy, space science and a visit to the Vainu Bappu Observatory, Kavalur.

Astronaut Rakesh Sharma seen with the then Director Dr. G S D Babu and participants after a session "Face to face with astronaut", which was the highlight of the program.

COSMIC PERSPECTIVES

-C.V. Vishveshwara

Hubble’s Realm

In the year 1934, Oxford University awarded Edwin Hubble the honorary degree of Doctor of Science. Part of the citation alluding to Hubble’s achievements reads,

“Here is a man who has discovered worlds far removed from ours.
And he defined the laws of their motion – for the more distant they are the faster they seem to be running away from us”.

This was no exaggeration, since it was Edwin Hubble who revealed the true expanse of our universe and discovered its dynamic nature. His book *The Realm of the Nebulae* comprising his findings heralded the coming of age of modern cosmology.

Earlier around 1918, Harlow Shapley, another pioneer of modern cosmology, had determined the size and the shape of our Milky Way galaxy.
Let us recall that on the galactic and cosmological scales distances are measured in light years. A light year is the distance traversed by light in one year travelling at the phenomenal speed of three hundred thousand kilometers per second. A light year is equivalent to about ten trillion kilometers, a trillion being one followed by twelve zeroes. Shapley demonstrated that the Milky Way is shaped like a disk with a central bulge. The diameter of this disk is about 100,000 light years with our solar system tucked away at around two-thirds the distance from the centre to the outer edge.

The Milky Way is composed of no less than some two hundred billion stars. No wonder then that Shapley and many others believed that this was the sum total of our entire universe with nothing beyond.

Hubble’s work dramatically altered this worldview. The giant leap that launched the cosmic voyage was one single measurement – that of the distance to a small hazy patch in the constellation of Andromeda.

Situated at a distance of more than a million light years as Hubble showed, it lies way beyond our Milky Way. As a matter of fact, it is a galaxy like our own. Our Milky Way was not the entire universe after all. Soon, measurements of distances to many more galaxies were to follow opening up man’s vision to millions and billions of galaxies swarming within the observable range of as many light years. The immensity of the realm of the galaxies, making up our universe, is awesome.
They discovered that the spectra of different galaxies were shifted systematically towards the red. This phenomenon is akin to the Doppler Shift observed in the case of sound waves. The pitch or the frequency of the sound goes down perceptibly if the source is moving away from the observer at a speed comparable to that of sound. Similarly, it was concluded that the galaxies were rushing away from us with speeds comparable to the speed of light. In fact, it was found that the velocities of the galaxies are directly proportional to the distances of these galaxies from us. This is the celebrated Hubble law.

Relation between red shift and distance

The universe, on a large scale, is dynamic and not at all static then. One can therefore legitimately think of the evolution of the universe with time.

Many of the spectacular observations, conclusions and problems in modern cosmology are centered around two measurements, namely the distances to the galaxies and their redshifts. The galactic recession is explained by the extraordinary idea that the universe itself is expanding. If so, going back in time we should arrive at the moment when all the contents of the universe were concentrated together. This is the very birth of the universe, an event which immediately engenders the notion of the age of the universe. Then again, there are other questions that arise naturally. How about the future of the universe? What controls the cosmological evolution? Is it the matter and energy content of the universe? If so, how? These and many more are the profound questions stemming from Hubble’s observations. In order to discuss these issues, one needs a mathematical model for the large-scale structure of the universe. This is provided by the general theory of relativity formulated by Einstein, the theory of gravitation based on spacetime structure that marked a total departure from the good old Newtonian gravity.

Einstein’s World

In the year 1905, Einstein put forward his special theory of relativity. It ushered in a revolution that radically altered man’s view of the physical world.

Till then, all laws of nature had been based on the Newtonian idea of all pervading absolute space and absolute time that flowed uniformly without beginning or end. Space and time were separate entities.

According to Einstein, for a proper description of the physical world, time has to be treated on almost equal footing with space. The three spatial dimensions and one temporal dimension combine to form a four dimensional spacetime. In the usual three-dimensional space each point, characterized by three coordinates, specifies the location of, say, a particle or some happening. Now, in the four dimensional spacetime a three dimensional point is replaced by a four dimensional point or an ‘event’ which is characterized by not only the conventional three spatial coordinates but also the time coordinate. A four dimensional event therefore tells us not only where something happened but also when. A curve in the four dimensional spacetime could represent the history of a particle in motion or its worldline as it is called. Special theory of relativity deals with spacetime without gravitation. In the absence of gravitation and other forces, particles move with constant velocities and this defines the natural force-free motion. The worldlines of these particles are obtained by plotting their positions against time. It is easy to see that they are straight lines in four
dimensions. Spacetime itself may be visualized as made up of these straight lines. Now in two dimensions, a flat sheet of paper may be considered to be composed of the straight lines drawn on it. Analogously, the four dimensional spacetime of special relativity made up of straight worldlines is considered to be flat, a characterization borne out by many of its mathematical properties.

In 1915, after ten years of concentrated work, Einstein incorporated gravitation into his spacetime picture. This geometric theory of gravitation, the general theory of relativity, is considered to be one of the most beautiful creations of the human mind. The four dimensional trajectories of particles moving under the influence of gravitation are curved. Einstein hypothesized that this is so, because the spacetime itself is curved.

Even light rays imbedded in the curved spacetime have to be curved leading to the bending of light. This curvature of spacetime is brought about by the source of gravitation, namely matter and energy.

In order to visualize the spacetimes of the special and the general theories of relativity, let us take a look at a two dimensional example, namely the safety net used by acrobats.

When none has fallen onto it, the net is flat with straight ropes that can form a coordinate grid.

When an acrobat falls onto the safety net, it becomes curved.

Particles roll because of this curvature which is equivalent to gravitation. When the source of gravitation moves rhythmically, waves are set up in the spacetime, as would be in the stretched net if the acrobat jumps up and down. These are the gravitational waves predicted by Einstein himself. If the mass concentration is too high, particles and light rays are caught up in the highly curved region and can never come out. We have then a black hole. These and other phenomena are exclusive to the general theory of relativity and were undreamt of in Newtonian physics.

Einstein derived a complex but rich set of equations governing the curvature of spacetime in relation to the matter-energy content of the spacetime generating the curvature. When he tried to apply these equations to the structure of the universe, it inevitably led to a dynamic cosmos. This was in appalling contradiction to the age-old belief - and Einstein's own- that the universe was static. In order to remedy the situation, he introduced an extra term to his equations involving a constant, known as the cosmological constant. By adjusting this term, the universe could be made static. In the meantime, Alexander Friedmann in Russia and Georges Lemaître in Belgium had independently taken the bold step of accepting a dynamic cosmos and derived models based on Einstein's equations without the cosmological constant. And Hubble, through his observations, demonstrated that the universe is in fact expanding. Einstein dubbed his introduction of the cosmological constant as the 'biggest blunder' of his life. A hasty judgement perhaps, since this term has re-appeared in recent times as we shall see. But, first let us take a look at the generic mathematical models of the universe that were derived by H. P. Robertson and A. G. Walker that have formed the framework for explaining observations and the platform for theoretical discussions.
Needless to stress, the grandest application of space-time geometry lies in the description of the universe as a whole. The material building blocks of the universe are taken as the galaxies or the clusters of galaxies. The observational input that goes into the construction of cosmological models is that the universe, on the galactic scale, appears the same in all directions, that is the universe is isotropic as we see it. This does not tell us how the universe looks like when viewed from other points. To get around this, one invokes the so-called Copernican Principle which holds that we occupy no special place in the universe. The universe must, therefore, appear isotropic from every point of observation. One can show that this, in turn, leads to the conclusion that the universe is homogeneous. This means that on a large scale the physical properties like the density and the distribution of galaxies are the same at all points of the universe. This elementary requirement, surprisingly enough, sharply narrows down the possible geometries of the cosmic spacetime. The models that emerge thus are of only three types. The intrinsic geometry of the spatial section at any given moment of time varies among these models. One of them – the closed model – has closed spatial section, the spatial geometry curling up on itself. One can think of the surface of a sphere as a two-dimensional analogue of this, but it is impossible to visualize a closed three-dimensional space. The other two are open models infinite in their spatial extensions. The two-dimensional analogues of these spatial sections are the flat plane and the hyperboloid, the latter resembling the surface of a saddle.

Which of the three models corresponds to the actual universe we live in depends upon the amount of matter content of our universe. If the density of all types of matter and energy put together exceeds a critical value, the spacetime curvature can become high enough to produce a closed universe. If the density is equal to or less than the critical value, the spatial sections will be flat or hyperbolic respectively. All three models start expanding from an initial singular state in which the spacetime curvature is infinite. The spatially closed universe can expand only up to a maximum size and then it contracts to another singular state perhaps to resume its expansion once again. It can thus go through cycles of expansion and contraction. The other two open models, on the other hand, expand indefinitely since the matter content, and consequently the gravitational attraction, is not sufficient to slow them down. The mathematical structure of the geometry and the evolution of these three cosmological models are both simple and beautiful. Their geometries have provided a firm framework for describing various physical processes occurring on cosmological scales.

We shall now discuss some of the important issues in cosmology with reference to the three possible models we have described. We shall touch upon what is known as well as unanswered open questions.

(This is the first part of the article by Prof C V Vishveshwara, written on an invitation by Prof. Jesus Moya for translating it into Spanish.)

Tales from The History of Physics (Part 1)

- S.Lokanathan

In the first year of my college days, I took course on History of physics. It was largely a narrative history, of Hippocrates, the Greek Physician, of the growth of Astronomy in different cultures, of Harvey's discovery of the circulation of blood, of the nature of heat and so on. This style is out of fashion these days in two ways. First, there are those who have a grand view that you cannot really studying an 'internal history of science' do so with a more ambitious goal of how ideas emerged in context. I recall a funny story, probably apocryphal, about a physics teacher of the forties telling his students about the nucleus consisting of electrons and protons when one of his students interrupted to say that he had heard that there were no electrons in the nucleus. 'What there are none these days? (Aaj kal nahin hai kya?)' said the harassed teacher. Today's philosophers of science no longer dismiss that as merely a joke, they
want a scholarly discussion on the transience of theories and the nature of truth!

Pierre Duhem, the French Scientist who had made significant contributions to Chemical Thermodynamics, later became an admired philosopher of Science in his later years. In ‘The Aim and Structure of Physical Theory’ published in 1962, he made the major point that no single theoretical hypothesis can be conclusively falsified by observations. That sounds excessive but one should place it in context. His idea was that an experiment was more than a mere observation of a fact. Whatever certainty there is of a physical experiment is constantly subordinated to the confidence inspired by a whole group of theories. Duhem’s point is, in my view, more sophisticated than Karl Popper’s who placed the role of falsification as the central theme of crucial experiments acting as a sort of critical guardian of Scientific advance. For Popper there is an asymmetry here – no finite set of experiments can ever verify, but they can falsify a theory. For Duhem there is no such sharp asymmetry. I thought that I would like to examine such ideas in the light of a few specific examples and see what lessons they have to offer us as teachers of Science.

1. Charge of the Electron: Millikan’s Experiment

My first example is the famous Oil Drop Experiment of R. A. Millikan to determine the charge of the electron. The first definitive results were published in the Physical review in 1911. The ‘discovery’ of the electron, usually credited to J.J. Thomson, was only a little over a decade earlier. But long before, in Michael Faraday’s time it was known that a gram-atomic weight of a monovalent material was deposited on an electrode if a definite quantity of electricity passed through the electrolyte (about a 96,500 Coulombs, the so-called Faraday constant) and this led to the conjecture that perhaps these charged units (ions) all carried the same charge e, so that Ne ~ 10^N where N is the Avogadro number whose value was known to a fair approximation by now – thanks to Einstein (for one) who had proposed a variety of methods for its determination. I quote Millikan from his 1911 paper on the major aim of his experiment: “To present a direct demonstration of the correctness of the view that all electrical charges however produced are multiples of one definite elementary charge.” In other words Millikan was clear that the determination of the value of e was not the big deal but the strengthening of the entire edifice of a theory that was building up, namely, that charge came quantized and in multiples of e.

The oil drop experiment was performed by Robert A. Millikan and Harvey Fletcher in 1909 to measure the elementary electric charge (the charge of the electron).

Tiny electrically charged droplets of oil located between two parallel metal surfaces, forming the plates of a capacitor were observed. The plates were oriented horizontally and a mist of atomized oil drops was introduced through a small hole in the top plate. With zero applied electric field, the velocity of a falling droplet was measured. At terminal velocity, the drag force equals the gravitational force. As both forces depend on the radius in different ways, the radius of the droplet, and therefore the mass and gravitational force, could be determined (using the known density of the oil). Then, a voltage, inducing an electric field, was applied between the plates and adjusted until the drops were suspended in mechanical equilibrium, indicating that the electrical force and the gravitational force were in balance. Using the known electric field, Millikan and Fletcher could determine the charge on the oil droplet. By repeating the experiment for many droplets, they confirmed that the charges were all small integer multiples of a certain base value, which was found to be 1.5924×10^-18 C, about 0.6% difference from the currently accepted value of 1.602176487(40)×10^-19 C. They proposed that this was the magnitude of the negative charge of a single electron.

Recall, briefly, Millikan’s set up. Oil drops (which evaporate less instead of water as used hitherto) were sprayed by an atomizer between two parallel metal plates spaced by a little over a centimetre. The speed of the charged drops was noted in a telescope between the plates in electric field which could be varied. The major achievement of Millikan was that he could keep a single drop under observation for several hours so that he was determining the charge on a drop – not the average over a whole cloud of drops as done
hitherto. The drops chosen were of the order of a micron (millionth of a metre) in size. This was important for two reasons. First, a small drop was much more likely to hold just a few charges from which it could be deduced that they were multiples of \(e\). Had it been, say a thousand fold the charge \(e\) on average, charge would have merely appeared as a continuum in the experiment. Second, a micron was just about the smallest size that Mallikan could see in the set up.

It so happens that the original data of this experiment from the notes of Millikan have been subjected to detailed analysis in recent years by Professor Gerald Holton of Harvard \(^5\) and there is evidence that Millikan had ignored data from some drops for reasons that are not quite free from controversy. That is a little poignant because about the same time as Millikan's experiment, a Viennese Physicist Ehrenhaft produced evidence from his experiments of much smaller values of the charge compatible even with a charge continuum hypothesis. I do not wish to go into this controversy now. The point is that Millikan's own published data allow for a range of values of \(e\). It is a moot point at what stage you would regard the experiment as conclusive demonstration of the discrete nature of \(e\) let alone its appearance as a fundamental constant of nature. The sage of 20th century Physics Paul Dirac said in 1977, i.e. some 65 years later, that Ehrenhaft was not really a good Physicist. Dirac may be right but his comment is hardly helpful in establishing criteria for whom to believe. In the event, it is unquestionable that the developments of physics over the last century have given us confidence in Millikan's experiment and that perhaps is Duhem's point that the context of an experiment is far wider than of a single hypothesis.

4. Millikan acknowledged, in a long footnote in his paper, the contribution of a Mr. J Y Lee who had developed the atomizer a few years earlier for studying Brownian Movement.
most knowledgeable about the most familiar things. Secondly, that even a commonplace object like a candle, in the hands of a diligent observer can be transformed into an object of scientific curiosity. In fact, Faraday himself sets the tone at the very beginning of the lecture series when he says:

“There is no better, there is no more open door by which you can enter into the study of natural philosophy than by considering the physical phenomena of a candle.”

What follows is a wonderful excursion into the history of candle making, the structure and behaviour of the flame, the mechanism by which molten wax is carried to the tip of the wick. There are many interesting questions Faraday poses and goes on to answer them through excellent demonstrations. The one that illustrates the mechanism of wax rising up the wick is very good. I guess, not many students would be aware of the finer aspects involved in this phenomenon. The wax steadily rising through the wick is much more than the capillary action that is often invoked to answer the question.

Here is a description of the flame by Faraday that goes on to show the sharp observation acumen he possessed:

“It is steady and equal, and its general form is that which is represented in the diagram, varying with atmospheric disturbances, and also varying according to the size of the candle. It is bright, oblong, brighter at the top than towards the bottom, with the wick in the middle, and besides the wick in the middle, certain darker parts towards the bottom, where the ignition is not so perfect as in the part above.”

Faraday, then goes on to elucidate every observation with further experiments to understand the phenomenon. The interest, intensity and the tempo is more or less the same throughout the six lectures. There is hardly a dull moment in the book. A very wide range of phenomena are covered with a candle as the prop. Combustion, factors affecting combustion, products of combustion. The experiments leading to identifying the composition of the products of combustion are very interesting and appear easy only after having read them. At the end, one may be left with a feeling, “Well, even I could have thought of these experiments.” Make no mistake. Experiments are simple. But, it takes a Faraday to come out with such ideas.

Though all the lectures are good, the last two are very engaging. The fifth lecture dealing with the nature of the atmosphere and its properties and the last one comparing the process of combustion with that of respiration have very good but less popular demonstrations. Faraday sends a powerful message, actually a reminder, when he says:

“So are we made dependent not merely on our fellow-creatures, but upon our fellow existers, all Nature being tied together by the laws that make one part conduce to the good of another.”

The book is an excellent material to study not only the chemical history of a candle but to illumine us on Faraday, the supreme observer and an experimenter par excellence.

(The book has been published by Vigyan Prasar)