The Mystery of Dark Matter and Dark Energy: A Cosmological Challenge

Jayant V. Narlikar
IUCAA, Pune

Professor Jayant Vishnu Narlikar is an internationally acclaimed astrophysicist, known for his work in cosmology, in championing models alternative to the popularly believed big bang model for the creation of the universe. His work has been on the frontiers of gravity and Mach's principle, quantum cosmology and action at a distance physics. He is the founder Director of the Inter-University Centre for Astronomy and Astrophysics, Pune, which, under his direction has acquired a world wide reputation as a centre for excellence in teaching and research. He has won several national and international awards including the Bhatnagar prize. In 2004 he was decorated Padmavibhushan by the Government of India. He is a Fellow of the three national science academies as well as of the Third World Academy of Science. Apart from his scientific research, Professor Narlikar has been well known as a science communicator through his books, articles and radio and TV programmes. For these efforts he was honored by the UNESCO in 1996 with the Kalinga award.

Let us begin with a well known story.

The Danish writer of the nineteenth century, Hans Christian Andersen wrote several fairy stories and folk tales, but none of them came closer to describing the current situation in cosmology than the well known Emperor's New Clothes. We begin by recounting the story in brief.

An emperor was fond of trying new dresses and spent a fortune on various fashion designs. One day a couple of dressmakers from a far away land came to his court promising the emperor clothes made of such fine silk that only the virtuous and the righteous could see them. The emperor was pleased by this offer and accorded them liberal funds and facilities to make the royal dress. Taking considerable time over the process the tailors eventually returned carrying their handiwork.

The King sent one of his ministers as an emissary to examine the dress. When the packet was opened, the minister could see nothing in it. However, recalling the makers' admonition that only the righteous and virtuous could see them he felt that if he admitted to seeing nothing, he would be treated as a sinner and dismissed from his job. So he reported to the emperor praising the dress in glowing terms. So, the King decided to wear the new clothes himself and parade in them through the main street of his capital.

He too could see no dress, however; but the tailors went through elaborate motions of placing it on his body, commenting on how well it looked on His Majesty. So, he too felt that admitting seeing nothing would lead to his forsaking his kingdom as not being virtuous and righteous. Thus he accepted the garment and got ready to head the procession followed by his courtiers all of whom were full of praise for the new suit, since none wanted to be fired from his job.

As the procession went through the town, people gathered on the street to applaud. Although they saw their emperor naked, they dared not say so for fear of being branded sinners. It was finally left for a simple child, who had no personal stake in the matter, to come out with the fact when he asked his mother: "Why, the Emperor is not wearing anything?" That was when everybody realized that the Emperor and his court had been taken for a ride!

With this introduction we return to modern cosmology, to perhaps its most important issue as to just how much matter and energy are present in our universe. And, how much of it we can see and how much we cannot see.

Evidence for dark matter

What is the meaning of 'dark' or 'unseen' matter? In the old days there was the adage: "Seeing in believing". This implied that only the evidence that you can see with your eyes can be trusted. The science of astronomy evolved through the process of 'observing' with naked eye, and later with telescopes. Even when using the telescope for the first time, several persons were uncomfortable with the findings made with its help, as they showed many more objects than were visible to the naked eye, some of which did not fit into the then belief system.

Galileo's telescope, and others that followed his pioneering instruments monopolized viewing to the form of light that our eyes are sensitive to. By the end of the nineteenth century, physicists were aware that electromagnetic radiation can come in other forms too with wavelengths vastly different from those which give the visible light. The twentieth century gradually brought those other forms of light to the service of astronomy and 'seeing' now means using any of the different forms of light for observing.

So what do we mean by dark or unseen matter? It means the matter that cannot be seen but whose existence can nevertheless be inferred by indirect observations. The historical example of the discovery of planet Neptune, shows that the existence of the planet was inferred by noticing its perturbing effect on the motion of its neighbouring planet Uranus. Thus the existence of the new planet could be deduced even before it was seen in the conventional way. And the interaction that played a crucial role in the episode was the gravitational interaction.

In modern times, gravitational interaction plays a similar role in revealing the existence of matter that could not otherwise be seen by using any form of light. It is this type of matter, and it may be in several different forms, that is labelled dark matter. How does it get detected?

An analogy from the field of economics is worth recalling in this context. Think of a country which has two economic systems in force. The first is the official one based on declared incomes and expenses; one which is on the records of the Internal Revenue Department. The second, parallel economy is run by the so-called black money, based on incomes and expenditures not reported to the taxman.

Now, even though the black money is not declared or recorded, experts can form a shrewd judgement of its extent. This is estimated by its visible impact on the country's economy. The construction activity, election campaign expenses, massive entertainment events, etc. are the dynamical effects of black money... the economic activity generated by it that give the clue as to the amount of black money in circulation.

Dark matter in astronomy is like black money in economics. Although not directly observed, its gravitational influence on the visible matter in its neighbourhood can give astronomers good estimates of its total amount. Perhaps the most dramatic example of this type is the black hole. A black hole is a highly compact object whose gravitational pull is so strong that not even light can leave its surface. A very massive star may shrink under its own gravity and become a black hole when its surface gravity has grown powerful enough to pull back its own radiation. A black hole can therefore never be seen. Yet its gravitational influence will help to reveal its presence in space. For example, consider a star having a planet going round it. If the star shrinks and shrinks and becomes a black hole, it will be invisible. Yet the planet will continue to feel its gravitational attraction and will keep orbiting round it. So if we see a planet going round and round but no star that is visibly controlling its movement, then we conclude that the planet is going round a black hole. By observing details of the planetary motion, theoreticians can tell where the black hole is located and what is its mass.

We now come to cosmological evidence for dark matter, mainly from two different types of systems.

Rotations of spiral galaxies

Consider the galaxies spiral in shape of which our Milky Way is one. We see one example in the adjoining figure. As the name implies, a spiral galaxy has two or more arms winding outwards like the spring of a classical wind-up clock. The arms are the regions where stars are concentrated. The gaps between arms are relatively less populated with stars, although they may carry gas and dust. The picture shown also indicates that there is no sharp boundary to the galaxy...it merges into darkness as one goes farther and farther from the more populated central region.

Astronomers believed (and justifiably so!) that the darkness engulfing the galaxy in the outward parts is indicative of its gradual but definitive approach towards a boundary. Thus they assume that beyond some specified perimeter, there is no mass belonging to the galaxy. Certainly there are no shining stars, nor are there any indications of gas or absorbing dust either beyond the assumed boundary. With the advent of radio astronomy, however, they discovered that there are small or large clouds of neutral hydrogen gas in circulation round the typical spiral galaxy. These clouds are located far and near, extending well beyond the assumed boundary of the galaxy.

Fig. 1 Spiral galaxy M 101

From the early days of radio astronomy it was recognized that hydrogen gas in its atomic state radiates radio waves at a wavelength of twenty one centimetres. Radio waves of this wavelength are emitted when the spinning orbiting electron in the hydrogen atom changes its state. From the state in which it spun parallel to the spin of the proton it changes to a state where it now spins in the opposite direction. This process results in a state of lower energy and so the energy lost appears as a radio wave of 21cm length. Thus, if we see a cloud of gas radiating at this wavelength, we can be pretty sure that it is made of neutral hydrogen gas. However, if we find that the wavelength of the radiation is slightly longer than 21 centimetres, say about a tenth of a percent longer, what can we conclude?

Using the Doppler effect, we would be entitled to argue that the cloud of neutral hydrogen is moving away from us with a speed of a tenth of a percent of the speed of light, that is, with the speed of 300 kilometres per second. Similarly if we see a cloud radiating at a wavelength shorter than the 21 centimetres by a fraction of a tenth of a percent, then we would argue that it is moving towards us with a speed of 300 kilometres per second.

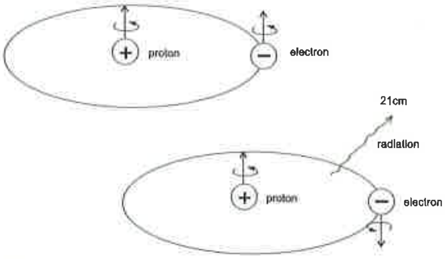

Fig. 2 The two states of the H-atom

In the 1960s and 70s radio astronomers were able to measure speeds of such clouds and relate them to the galaxy around which they might be moving. We may use here the analogy of the planets moving round the Sun in our own planetary system. We know from measurements of speeds of these planets that the farther they are from the Sun the slower they orbit. For example, Mercury, the nearest planet, has an orbiting speed around 48 kilometres per second, whereas for the most distant dwarf-planet Pluto the speed is less than a mere 5 kilometres per second. Applying this analogy, astronomers expected the clouds farther and farther away from the galaxy to have rotational speeds smaller and smaller.

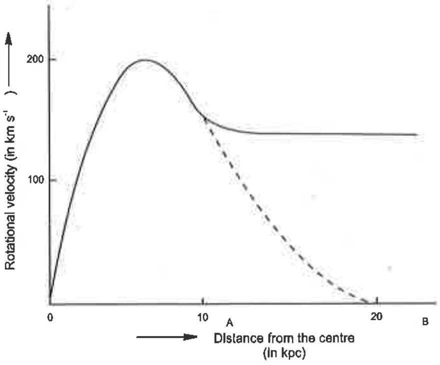

Fig. 3 Atypical flat rotation curve

They were in for a surprise. The speeds did not seem to be dropping off; rather they stayed constant over a very long range. The figure 3 below shows typical behaviour for several galaxies. As they remained flat over a long distance, these rotation curves came to be known as 'flat rotation curves'. To resolve this mysterious behaviour, let us go back to the solar system example. There the speed drops off because we know that the planets are moving under the attraction of the Sun and this attraction drops off as one moves away from the centre of attraction. There is a definitive formula which tells us how the rotational speed of a planet should drop off with its distance from the Sun. The speeds of all planets from Mercury to Pluto follow this rule. Indeed this was the classic discovery of Johannes Kepler in the early seventeenth century for which Newton's law of gravitation provided the mathematical explanation. But the same law applied to the neutral hydrogen clouds attracted by the galaxy, does not seem to be working. Why not? And, more importantly, even the more sophisticated Einstein's theory of gravity fares no better.

Why is dark matter necessary?

Whenever there is a conflict between a well established law and observations, two possible courses of action suggest themselves:

1. Re-examining the observations in case something crucial is missed out
2. Change the law for something deeper and more subtle.

The latter option calls for a fundamental rethinking and is usually put off as the last resort, especially if the existing law or paradigm has served well until this particular discrepancy. The Newtonian laws of motion and gravitation have served so well, as has Einstein's theory of relativity, that replacing or modifying them would be a high price to pay. Nevertheless there have been attempts to modify them with a view to understanding the flat rotation curves. The so-called Modified Newtonian Dynamics (MOND) proposed by Mordehai Milgrom is perhaps the most talked of attempt in this direction, although it is very much a minority view. In the MOND theory the second of Newton's three laws of motions gets modified when applied to objects with very small accelerations.

What the majority of physicists and astrophysicists would like to follow is the first alternative. This involves admitting that our observations of galaxies are incomplete and that there is invisible matter present which extends well beyond the visible part of the galaxy. In terms of distances, we can argue for our own Milky Way like this. The visible matter made of stars, dust and gas may extend over a disc of radius 15 kiloparsecs. However, the dark matter is expected to be present well beyond this radius. It is because of this extra matter that the gravitational influence of the Galaxy extends much farther, and so the rotation speeds of neutral hydrogen clouds extend without attenuation out to distances of 50 kiloparsecs or even beyond.

What would the dark matter be made of? Black holes? Since these are very efficient in holding back light, this alternative suggests itself. We could have black holes formed from remnants of massive stars that stopped shining after their nuclear fuel stocks were spent up. A second possibility could be planet-like objects that are not self-luminous. Any object with mass not exceeding around the tenth of a solar mass cannot shine on its own because its core temperature is not high enough to ignite a nuclear reactor. Such objects are called Brown Dwarfs and these would not be seen by normal telescopes. We could also have planetary masses as large as Jupiter. These are examples of 'conventional' types of dark matter. Given the hypothesis that dark matter exists, these are the options one may think of in the first instance. Indeed, till about 1980 these were the strong contenders for the status of dark matter.

However, there are other more esoteric options, which are lumped together under a class called Non-Baryonic Dark Matter (NBDM). These options are, by definition, made of particles that do not form parts of atomic nuclei. Atomic nuclei contain neutrons and protons which are called baryons and almost all matter we see in the universe consists of these as well as light particles like electrons and neutrinos. Thus masses of black holes or brown dwarfs are mainly made up of baryons. As yet there have been no particles so far discovered by high energy physicists that could be classified as NBDM. In the 1980s the possibility that neutrinos may have a fair amount of mass (corresponding to an energy of up to about 30 electron volt) had raised the option that dark matter may be accounted for by neutrinos. However, those indications have gone. Although neutrinos may have mass, it would still be far too small to explain the dark matter in galaxies. We will return to this issue of what the dark matter is made of later, after we have described another line of evidence for dark matter on an even grander scale.

Clusters of galaxies

In the adjoining figures we show a couple of clusters of galaxies. A typical cluster contains several hundred galaxies and they are all moving randomly within the cluster. These random motions are of the order of 250-500 kilometres per second. These motions are over and above those arising from the expansion of the universe. Thus a typical cluster takes part in the overall expansion process, and additionally has galaxies moving within it at random speeds.

If we assume a cluster is an isolated dynamical system of many bodies which have been moving under one-another's gravitational attraction for a long enough time to settle down to some steady state, then we can deduce a simple result from Newton's laws of motion and gravitation. It is that the energy of motion, the so-called kinetic energy of all moving galaxies is comparable in magnitude to their total gravitational potential energy.

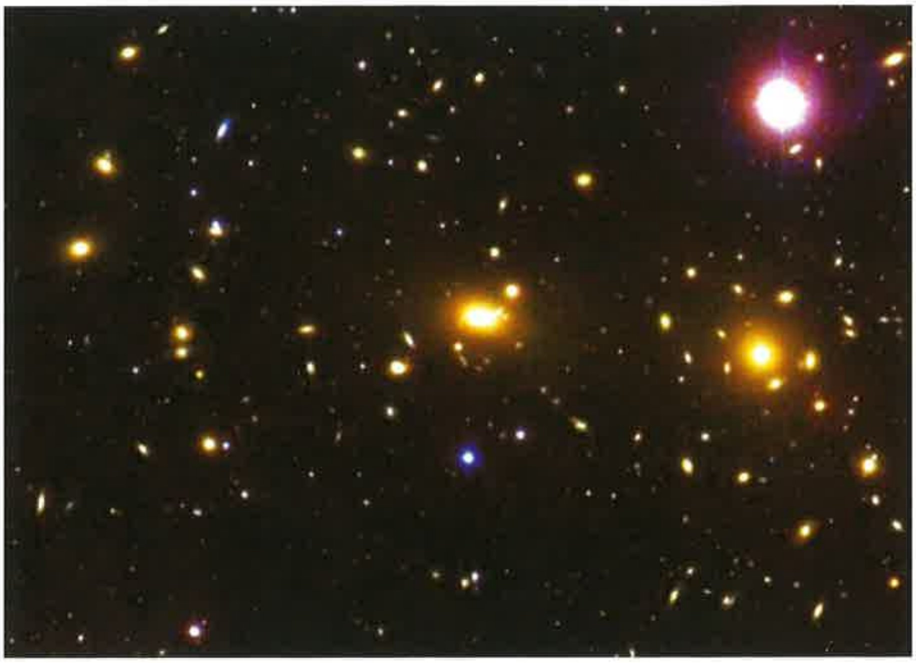

Fig. 4 The Coma Cluster of galaxies has nearly 1000 galaxies

If we denote the kinetic energy by T and the potential energy by V, then in the final state of equilibrium we have

$$2T + V = 0.$$

This is known as the virial theorem. So if we estimate the two energies for clusters, we can verify if the virial theorem does apply to them.

For most clusters it does not. The energy residing in motions of the visible galaxies is much higher than the energy residing in their gravitational attraction. The discrepancy is large enough to make one think. One possible conclusion can be that the clusters have not yet had time to settle down and so the virial theorem does not apply to them. This could happen if the cluster is all round expanding or contracting. The Armenian astrophysicist Viktor Ambartsumian had concluded back in the early 1960s that the clusters are expanding, having been created in an explosion. Based on his assessment of the data, Ambartsumian concluded that the clusters are examples of explosive creation of matter. We will return to this conclusion later.

The majority view, however, is different. The view is that the clusters have indeed settled down to an equilibrium state and the reason we have a deficiency of gravitational energy is because we are not able to see all the matter present in the cluster. Suppose there is a lot of dark matter within the cluster which is not moving fast. Such matter will not contribute much kinetic energy, but would give rise to large gravitational energy by virtue of its mass. This is why we notice a deficiency of gravitational energy.

This argument has therefore suggested to the theoreticians that they can add as much dark mass as they need to make up the energy deficiency. The amount of dark matter to be added this way far exceeds the visible matter. Whereas in the case of rotation curves of spiral galaxies the ratio of dark to visible matter may be around 3 to 1 or so, in the case of the clusters the ratio may go up to 10 to 1 or even more.

So, now we come back to the question posed earlier...what is such dark matter made of? Even though it is not seen, we can argue for the options like black holes or brown dwarfs. However, there are problems with these options. First one has to argue for a physical scenario that led to so much of matter being in this form. This may or may not be a very difficult problem...with sufficient ingenuity, the theoretician may come up with a plausible scenario. But even if successful, a large class of theoreticians would reject this solution. These theoreticians adhere to the big bang model.

The big bang cosmology

We may briefly recall what the big bang model is. The classical solution of Einstein's equations of general relativity first obtained by Alexander Friedmann (1922-24) and later independently by Abbe′ Lemaitre′(1927) shows a large scale expansion of the universe which we may denote by an increase of the scale factor S (denoting the length scale associated with the universe). The scale factor in the simplest solution increases with time t , according to

$$S \ \alpha \ t \ \tfrac{1}{2}$$

in the initial radiation dominated phase and as

$$S \ \alpha \ t \ \tfrac{2}{3}$$

in the later matter dominated phase. The big bang is identified with the state at the epoch when S was zero. As Lemaitre first found, the effect observed by a typical observer at any later time is the velocity v – distance D relation

$$v \ \alpha \ D.$$

The constant of proportionality was observationally found by Edwin Hubble, two years later. Known as Hubble's constant (and the linear relation as Hubble's law), it is sumbolically denoted by H. Its value is currently estimated as around 72 km/s/Mpc.

The temperature of radiation background in the universe falls as

$$\theta \alpha S^{-1}$$

Thus dropping from very high values in the early epochs to low values today. In fact the thermal background observed today at a temperature of 2.7K is considered a strong vindication of the big bang hypothesis. A strong confirmation of the early hot era is given by the correct prediction of abundances of light nuclei by nucleo-synthesis of neutrons and protons, provided these baryonic particles do not exceed a certain critical density.

The classical picture of this model was revised in the early eighties with the introduction of inflation. Inflation represents a rapid expansion of the universe in the form $S=\exp(at)$. This is believed to have happened when the universe was around 10^{-36} second old, being caused by the phase transition effected by the 'grand unified theory' that is believed to have controlled physical interactions. Inflation lasted for a very limited period but long enough to blow up the scale factor by a huge factor of the order of 10^{55}. Such a phase helps in solving some fundamental problems of big bang cosmology. Shortage of space prevents us from discussing these in detail. For an overall description of this cosmology see a standard textbook on cosmology: for example, the author's book An Introduction to Cosmology (Cambridge).

We remind the reader that the three states of the universe described above, command different levels of credibility. The matter dominated phase is the current one and astronomical observations enable us to view the more recent parts of the universe. The physical understanding of those epochs is available in terms of well tested theories of physics. The radiation dominated phase uses standard well-tested physics although it lacks direct astronomical observations. The inflationary part on the other hand is not based on standard physics since physicists are far from being in the state where they can claim to have a grand unified theory valid and confirmed. Nor does it have observational confirmation of those early epochs. At best one could claim a coherent and consistent picture but lying in the realm of speculation. The theorists in this field therefore look at recent observations that would be consistent with the speculations of the early universe.

The big bang theorists would indeed be worried if all the observed dark matter existed in these relatively normal forms like black holes, brown dwarfs, Jupiter-like planets, etc. For these forms are all made of baryonic matter. If there were so much of baryonic dark matter (BDM) around, a difficulty arises with the big bang scenario of explaining how the light nuclei, especially deuterium, were made. For, if we begin to allow all or most of dark matter in clusters and galaxies to be baryonic, the critical limit mentioned above, would certainly be exceeded.

To find a way out therefore, big bang cosmologists have supposed that the bulk of dark matter in or out of the clusters is non-baryonic. The non-baryonic dark matter (NBDM) is an esoteric option which has to be adopted because there is no other alternative for survival of the big bang nucleosynthesis scenario. An alternative name given to such a NBDM particle is "weakly interacting massive particle" or a WIMP!

There is another reason why so much of matter in baryonic form will be an embarrassment for the big bang model. Baryons interact with light and fluctuations in the density of BDM will lead to far greater fluctuations of radiation background than indicated by observations. So the big bang theorists would want to limit BDM to as small abundance as possible. Hence the bottom line is that bulk of dark matter nust be bon-baryonic.

Why do we call NBDM esoteric? Because there has been no laboratory demonstration of it. Nor has it been detected in any astronomical scenario. Rather, the theoretical possibilities for such matter come from the as yet untested theories of very high energy particles.

But to proceed further, once one accepts the paradigm of NBDM, then one's imagination leads to further speculations. Is the NBDM hot or cold? Big bang cosmologists talk of two kinds of non-baryonic dark matter. The hot dark matter (HDM) consists of particles which were in close interaction with normal baryonic matter in the early times, and when their interaction ceased, they were still moving fast, with speeds near that of light. The other species of dark matter is the cold dark matter (CDM) which is made of particles which had slowed down to almost the state of rest by the time they ceased to interact with ordinary (baryonic) matter.

The particle which comes nearest to a realistic example of an HDM is the massive neutrino. The neutrino interacts with ordinary matter very weakly, and theory tells us that when the universe was less than a second old, the neutrinos stopped interacting with other light particles like the electrons in any significant way. At that stage the typical neutrino was still moving very fast and so the neutrino is a particle of HDM type. Depending on its mass (still not reliably determined) it would slow down; but this would have happened much later.

What are examples of CDM? These would depend on a typical high energy particle theory. The menu of possible particles is quite extensive, the more popular ones being the photino, gravitino, the axion, etc. Rather than go for a specific particle, the cosmologist proceeds in the opposite way. He asks, what should such a particle do in order to be consistent with the requirements of the cosmological theory? These requirements include the scenario of formation of galaxies and the tiny fluctuations observed in the microwave background. In this sense, the approach has no scientifically predictive power. It only asks for overall consistency of the picture. Since no CDM particle has been found, the issue is wide open for speculating what it should be like. Indeed, since the late 1980s, CDM has held centre stage in the drama of dark matter.

However, speculations in modern cosmology do not end there.

Dark energy

In the early stages of cosmology, Einstein had introduced the cosmological force in his equations, to obtain the mathematical model of a static universe. Later when he discovered that observations favoured an expanding universe and that his original equations did yield expanding models, he more or less abandoned this extra force.

Cosmologists have since had a love-hate relationship with the cosmological force. Whenever they feel that their models are threatened by new observations they invoke the cosmological force, perhaps with reluctance, only to abandon it if later it is discovered that the observations were not threatening after all. The intensity of this force is typified by a constant often denoted by λ or, Λ. The constant in today's universe is very small and this indicates that the force of repulsion implied by it is very small on the terrestrial, stellar or galactic scale. However, on the scale of the universe as a whole, it is significant. A positive Λ means the force is of repulsion and on a large scale it makes the universe accelerate. Is the universe really accelerating?

Extensive work by Allan Sandage to check on this very fact in the 1960s and 1970s, involved results of studies of distant galaxies, and these indicated that the universe is decelerating, that is, its rate of expansion is slowing down. At the time, the Friedmann models without the Λ-term were popular and these indicated the same conclusion. The only model that stood apart was the steady state model that implied that the universe is *accelerating*. Later this test fell into disuse as it was realized that there were several imponderables, i.e., observational errors that made any definitive conclusion impossible.

However, the test was revived in the 1990s when it became possible to make dedicated studies of exploding stars, called supernovae lying in distant galaxies. A particular class of supernovae, called Type Ia supernovae seemed to have the property that they provided a standard candle for measuring galactic distances. Let us first try to understand what this statement means.

The figure here shows the photograph of a Type Ia supernova. Typically, a supernova of this type represents a highly compact star blowing up as it loses its internal equilibrium. The intensity of the star shoots up after the explosion and it reaches a peak in luminosity within a few days. The typical light curve of such a supernova is shown in Fig. 6.

Fig. 5 photo of a Type Ia supernovae: the bright spot is the supernova

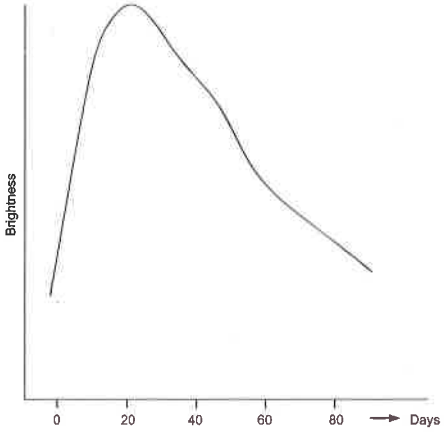

Fig. 6 Supernova light curve

The important thing to note is that the supernova becomes very bright and may outshine the entire galaxy in which it is housed, but for a few days. The peak luminosity therefore makes it easy to spot a supernova even if it is located in a very distant galaxy. And, it seems that the maximum brightness attained by the star is more or less the same from one Type Ia supernova to another. So we can use the method of measuring distances commonly used in astronomy, to estimate the distances of galaxies in which the supernovae are located. The fainter the supernova the further away it is, as per the rule that farther candles look dimmer. The assumption that the peak intensity for all Type Ia supernovae is the same is called the 'standard candle hypothesis'.

A 'Supernova Cosmology Watch' programme was set up to observe and record any such sudden eruptions in galaxies with redshifts ranging up to around 1-1.5. These redshifts are higher than those of galaxies used by Sandage in his earlier studies, which went up to around 0.5. Thus we are in principle able to sample a more remote part of the universe with the help of supernovae.

The method is then to look at supernovae at different distances and see how their redshifts change with distance. Redshifts are obtained by studying the spectra of galaxies, while distances are estimated by using the standard candle of Type Ia supernovae. Broadly speaking, we expect that if the universe is decelerating the distances will increase with redshift more slowly than if the universe were accelerating.

If the observers hoped to find a confirmation of the earlier results that the universe is decelerating, they were in for disappointment. The distances as estimated from supernova standard candle seemed to increase faster with redshift than allowed by any decelerating model. Rather the indications were that the universe seems to be accelerating! The typical decelerating model produces the lower curve in Fig. 7 whereas what is observed is the upper curve.

At this stage it would have been fair on the part of observers to have acknowledged that the conclusion in favour of an accelerating universe was consistent with the prediction of the much-maligned steady state universe. Even though in the 1990s, the steady state universe was no longer in serious contention, a note of this historical fact would have been only fair, and as per normal practice in science. However, the result was simply announced as favouring the standard big bang model with a non-zero cosmological constant.

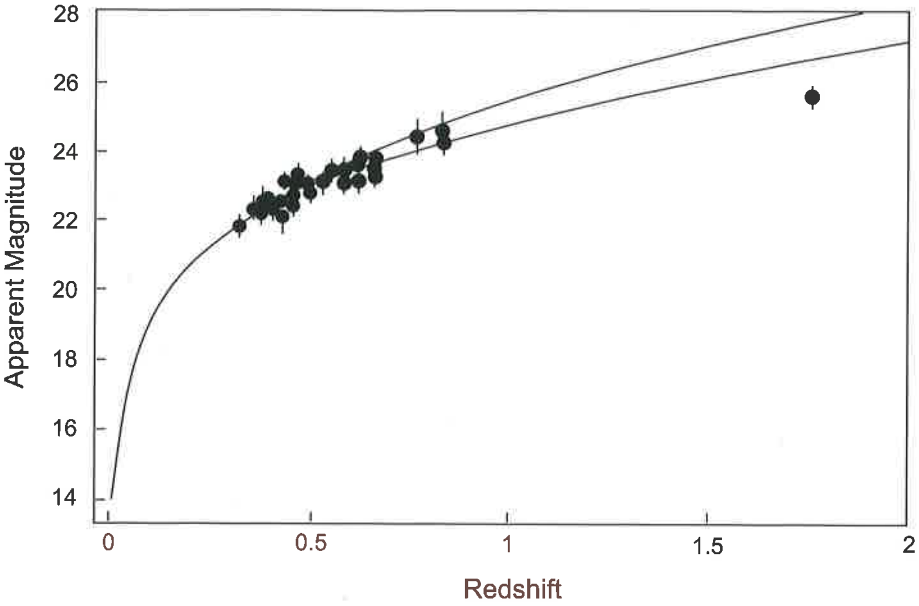

Fig. 7 Supernova data and accelerating universe

That this was a volt-face on the part of the big bang establishment can be seen from the fact that as late as 1997, the popular belief was that there is no cosmological constant and that the universe is decelerating. While changing the model so significantly from what had been previously in vogue, an acknowledgement should have been made that such a change was being forced on the theory by observations. That the present approach has no predictive value is seen from the circumstance that today's observers ask the following question: *What value of the cosmological constant will give a good fit to what is observed?...* instead of first determining theoretically the preferred model and then asking if observations support it.

Like good salesmen for inflationary hypothesis, the cosmologists announced this finding as confirming the inflationary paradigm by arguing that the results bore support for the conclusion that the universe is flat, i.e., with $\Omega = 1$. What was not emphasized was the result that the data gave the best fit to the value $\Omega = 1.3$ *not supported by inflation.*

According to current wisdom, the density parameter Ω these days is made up of three components: (1) visible (baryonic) matter (2) cold dark matter (CDM) and (3) dark energy. We have already elaborated upon the first two of these. The third component is related to Λ, the magnitude of the cosmological constant. After studying the supernova results and also the fluctuations of the microwave background, cosmologists have come to the conclusion that the contribution to Ω from these three components can be quantified quite precisely as follows: (1) The contribution of baryonic matter is 4%, (2) the contribution of NBDM is 23% and (3) the contribution of dark energy is 73%. This conclusion is referred to as 'precision cosmology'. The impression is created that with such precise details the long-standing cosmological question: 'What is our universe made of?' is finally answered.

If these 'precise' values are to be believed, then cosmologists are telling us that the only form of matter and energy that astronomers see, or the physicists experiment on, accounts for only 4% of all matter-energy budget of the universe. The remaining 96% is made of the esoteric dark matter and the even more esoteric dark energy. Like the emperor, the universe apparently requires invisible clothes!

What is dark energy?

The revival of the cosmological constant has raised fresh issues. If we assume, following Einstein, that the cosmological constant has been constant at all times, then we run into a new difficulty vis-à-vis inflation. The universe was driven to inflate because of the extra energy it obtained from a phase transition. That energy was very similar to the dark energy and the inflation of the universe was very similar to that in the classic 1917 model of de Sitter. Thus there was an effective cosmological constant that drove the inflationary universe. Only the time scale for inflation was very short and so the corresponding cosmological constant was very large, compared to its present value. How large? It was large by a factor 10^{108}. So prima facie one is forced to conclude that after the inflation was over, the extra energy almost disappeared, leaving behind an extremely tiny fraction of the order of one part in this large number! Further, this left-over has to be very finely tuned, otherwise, the whole expansion of the universe would go astray.

This is ironical, since one of the reasons for invoking inflation had been to avoid fine tuning of precisely this nature. The flatness problem required fine tuning to one part in 10^{55} and to avoid that inflation was proposed. Now it appears that inflation brought its own fine tuning to an even greater degree! To avoid this problem one needs to have a dynamical mechanism which would reduce the cosmological constant from its initial very large value to what is required today.

Naturally theoreticians are busy trying to provide a respectable mathematical model to patch up this defect. At the time of writing there is no satisfactory model achieving this, although the confidence with which the existence of dark energy is believed in exceeds confidence in Newtonian gravitation.

Concluding remarks

We can summarize as follows. It is clear that the important observations of flat rotation curves of galaxies opened up the pandora's box of dark matter. The evidence for dark matter is certainly there if one continues to have faith in the laws of Newton and Einstein. However, how much dark matter is really warranted? If one is not prejudiced by belief in inflation then one need not have Ω=1. One can manage with much less matter. Can it all be baryonic as our experience of the rest of astronomy would have us believe? If you are not committed to the notion of primordial nucleosynthesis, then the answer is "yes". But if one is firmly of the view that inflation did take place and that light nuclei were made in a primordial nucleosynthetic process, then one is driven to postulating that a lot of dark matter is esoteric and non-baryonic.

Coming to dark energy, the major argument in favour of it rests on inflation and the observations of distant supernovae. But there too the chain of reasoning may have glitches. Are we sure that the standard candle hypothesis is valid? If there is significant variation in the peak intensity of light from Type Ia supernovae, then the distance measurement on which the test rests is not so reliable. When we infer the distance of a supernova from its observed faintness, we ignore the presence of any absorbing intergalactic dust. Our knowledge of intergalactic medium is still very primitive, and by ignoring intergalactic dust in estimating distances, we may be committing the same error that galactic astronomers committed a century ago when they were estimating stellar distances without knowledge of interstellar dust. Intergalactic dust will make a supernova look dimmer than in the absence of dust and so if we ignore this effect we will overestimate the distance of a supernova and this error will grow the further away the supernova is. So instead of the cosmological constant causing an accelerated universe in which all distances get enhanced, it may be the absorption by dust that makes high redshift supernovae look dimmer.

Even if we discount the dust alternative and stick with the accelerating universe, we find that data do not really fit the simple model in which a constant Λ accelerates the universe. One needs a variable Λ, thus making the hypothesis messier. For, more recent evidence apparently points to acceleration over a limited period. Thus theoreticians are getting lost in more and more complex models of dark energy, which have no predictive power. The reader will find a similarity between the account of how everybody wants to pay court to NBDM and dark energy and the new clothes that the Emperor ordered.

Given this history of standard big bang cosmology, and its current bag of speculations, we feel that there are certainly no firm grounds for assuming that it provides a factual account of the real universe. It may well turn out that all of today's speculative element will be borne out by facts at a later stage. If that happens we can accord full support to this cosmology. Till then, however, a skeptic may be justified in thinking that reality may lie elsewhere.