

## Some conceptual problems in cosmology

Jayant V. Narlikar

*Inter-University Centre for Astronomy and Astrophysics Ganeshkhind, Pune-411007, India*

*jvn@iucaa.ernet.in*

### 1. Introduction

Today the standard model for cosmology is one in which the universe was born with an enormous explosion in a state of high energy, in which it had infinite density and temperature. In fact no physically meaningful description is available for that initial state. Nevertheless most cosmologists like to work on the very early universe with huge extrapolations of physics known and verified today and of the astronomical data observed today. Not surprisingly such an approach leads to serious conceptual difficulties.

In this opening lecture I will highlight some of these issues. Given the limited time for this talk I will confine myself to two basic problems: dark matter and dark energy.

### 2. Dark matter

What is the meaning of 'dark' or 'unseen' matter? In the old days there was the adage: "Seeing is 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 telescope. Even when Galileo used his new invention, the telescope for the first time, several viewers were uncomfortable with the findings made with its help, as they showed many more aspects of the universe, than were visible to the naked eye. Thus doubts were expressed about the reality of craters on the Moon, the spots on the Sun, and Jupiters satellites when seen by Galileo's telescope.

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 light can come in other forms too with wavelengths vastly different from those which give the visible light. 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.

It is against this background that we now describe the difficulty associated with 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 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 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 (visible) 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 make a shrewd estimate 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. Thus the economic activity generated by it gives the clue 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.

## 2.1 Evidence for dark matter

We will now come to cosmological evidence for dark matter, mainly from two different types of systems: spiral galaxies and clusters of galaxies.

### 2.1.1 Rotations of spiral galaxies

Our Milky Way belongs to the class of *spiral* galaxies. 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 typical picture of a spiral galaxy also indicates that there is no sharp boundary to the galaxy...it sort of 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 assumed 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, astronomers 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.

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 planet Pluto (now designated as a dwarf planet) the speed is less than a mere 5 kilometres per second. Theoretically this result can be understood with the help of Newton's laws of motion and gravitation. Applying the same laws, astronomers expected the clouds farther and farther away from the galaxy to have smaller and smaller rotational speeds.

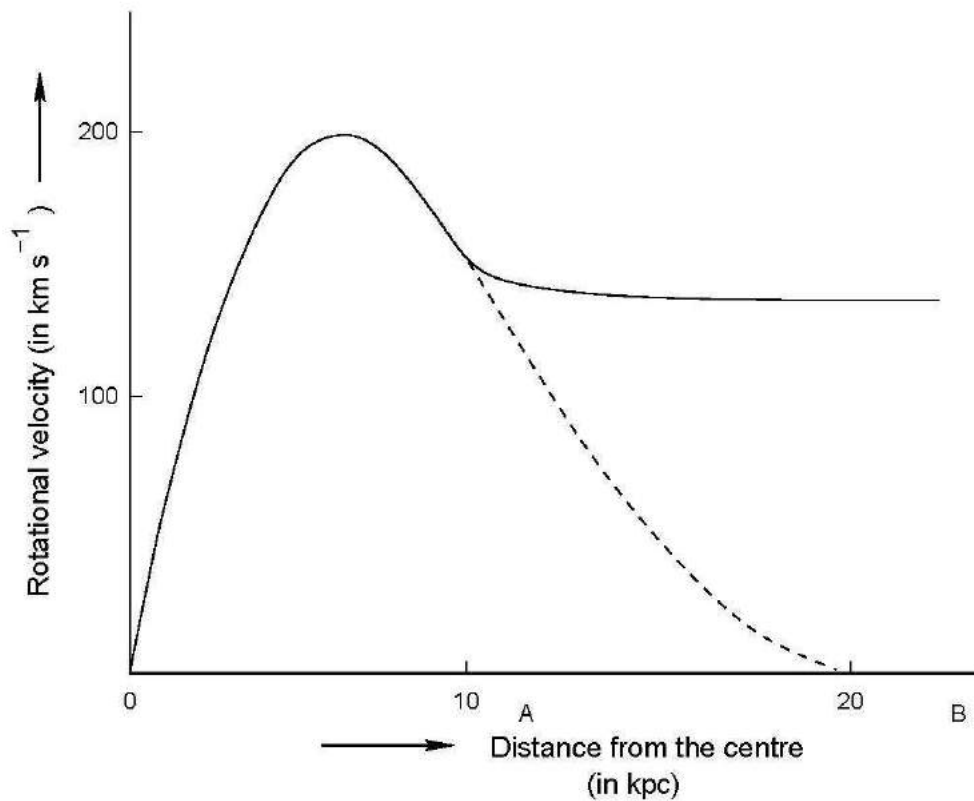
They were in for a surprise. The speeds did not seem to be dropping off; rather they stayed constant over a very long range. The figure 1 below shows results for a typical spiral galaxy. As the rotation curve showed a constant speed over a long distance, it came to be known as 'flat rotation curve'.

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 distance from the Sun. The speeds of all planets from Mercury to Pluto check out OK on this formula. 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? Even the more sophisticated Einstein's theory of gravity fares no better.

### 2.1.2 The need for dark matter

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...



**Figure 1.** Flat rotation curve of a typical spiral galaxy.

## 2. Change the law for something deeper and more subtle.

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 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. 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 early 1980s these were the main options before the cosmologists.

However, today cosmologists favour 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 options have now fallen by the wayside. 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 the second line of evidence for dark matter on an even grander scale.

### 2.1.3 Clusters of galaxies

In Figure 2, we show a photograph of a typical cluster of galaxies. A typical cluster contains several hundred galaxies and they all apparently move 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.



**Figure 2.** A typical cluster of galaxies.

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. 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 motion of the visible galaxy is much higher than the energy residing in 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 expanding or contracting all round. 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.

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 10:1 or even more.

#### 2.1.4 What is dark matter made of?

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 cosmologists who adhere to the big bang model, object to this possibility.

The big bang theorists would be worried if so much dark matter existed in these relatively normal forms. For these forms are all made of baryonic dark matter (BDM). If there were so much of BDM around, a difficulty arises with the big bang scenario of how light nuclei, especially deuterium were made. In the process of primordial nucleosynthesis first proposed by George Gamow, and later worked on by several other astrophysicists, one crucial conclusion was that if the density of baryons exceeded a critical limit, *practically no primordial deuterium would be made*. And it also became clear that if we begin to allow all or most of dark matter in clusters and galaxies to be baryonic, that critical limit would certainly be exceeded. Thus no deuterium would be formed.

In fact, a difficulty of even greater magnitude awaited the big bang theorist when he resorted to the inflationary scenario. It is believed that the phase transition leading to a break down of symmetry at the time of the end of epoch of grand unification, the universe had an inflationary phase. The outcome was that the universe had a flat geometry with a density

$$\rho = 3H^2/8\pi G$$

which far exceeded the deuterium limit. Thus, if the inflation did happen, it would leave the universe with a density very close to the critical density. If all this matter were normal baryonic matter, its density would be 25-30 times higher than the limit tolerated by deuterium synthesis process. We shall use the density parameter  $\Omega$  to denote the ratio of the actual density to the flat density mentioned above.

So the conventional big bang theory runs into a serious problem. If it allows inflation, it runs foul of deuterium production in the primordial nucleosynthesis. It also ends up with far more dark matter than the evidence from galaxies and clusters suggests. This latter difficulty can be resolved by supposing that there exists dark matter not only inside clusters but also in the space between them. However, the first problem was more serious. 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!

Why do we call NBDM esoteric? Because there has, as yet, 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. Man made accelerators do not reach these kinds of energies. So what we are effectively asked to accept is that bulk of the matter in the universe is of this strange kind, far exceeding the normal kind of matter that astronomers are familiar with.

### 3. Dark energy

We recall that in the early stages of cosmology, Einstein had introduced the cosmological force of repulsion 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 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  $\lambda$  or  $\Lambda$ . Thus the force of repulsion between two masses separated by distance  $r$  is simply  $\lambda r$ . 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  $\lambda$  means the force is of repulsion and on a large scale it makes the universe accelerate. Is the universe really accelerating?

Extensive work on this question was done by Allan Sandage in the 1960s and 1970s, and the results of his studies of distant galaxies indicated that the universe is *decelerating*, that is, its rate of expansion is slowing down. At the time, the Friedmann models without the  $\lambda$ -term indicated the same conclusion and so were in favour. 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, including observational errors that made any definitive conclusion impossible. Indeed, summarizing the overall cosmological data in the 1986 Symposium on cosmology at Beijing, Malcolm Longair concluded that the data did not require a nonzero cosmological constant.

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 Type Ia supernova typically, 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 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 of astronomical objects 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 fact 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...those 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 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!*

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 had been predicted by 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 should have been made. However, the result was simply announced as favouring the standard big bang model with a non-zero cosmological constant.

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 general 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, it should have been admitted 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?*

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 for the value  $\Omega = 1.3$ .

According to current wisdom, the density parameter  $\Omega$  these days is made up of three components: (1) visible (baryonic) matter, (2) cold dark matter (CDM) and (3) dark energy. Of these we have already elaborated upon the first two. The third component is related to  $\Lambda$  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  $\Omega$  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%.

If these precise values are to be believed, then cosmologists are telling us that the most familiar form of matter and energy that astronomers see, occupies only 4% of all matter-energy in the universe. The remaining 96% is made of the esoteric dark matter while the lions share is taken up by dark energy, which is still more esoteric. The ironical aspect of these conclusions is that the major components in the above distribution have not been found so far.

This situation will remind those who have read Hans Andersen stories, of the emperor who was offered new clothes that only non-sinners could see! For those who have not read the story *The emperor's new clothes* here is a synopsis of the same.

#### 4. The emperor's new clothes

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 clothes made of such fine variety that only the virtuous and the righteous could see them: those who lived a sinful life would not be able to see them. The emperor was pleased by this offer and accorded them liberal funds and facilities to make a royal dress. Taking considerable time over the process the tailors returned carrying their handiwork.

The king sent an emissary, a minister, 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 branded a sinner and dismissed from his job. So he reported to the Emperor praising the dress in glowing terms. Thus the Emperor was all eager to try on the new clothes himself and parade in them through the main street of his capital.

When he came to try them on, the Emperor too could see no dress; but as the tailors went through elaborate motions of placing it on his body, commenting on how well it looked on His Majesty, he too felt that admitting seeing nothing, would lead to his forsaking his kingdom as not being virtuous and righteous. So he got ready to join the procession followed by his courtiers who were all 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 too dared not say so for fear of being branded sinners. Finally, it was left to a simple child, who had no personal stake in the matter to come out with the fact when he asked his mother: "Why is the Emperor not wearing anything?" That was when everybody realized that the emperor and his court had been taken for a ride!

Modern cosmology, has brought us to a similar situation when we ask: 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*?

#### 5. Concluding remarks

To end this account, we summarize it 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  $\Omega = 1$ . 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 wedded to 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, 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 more than 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 the effect of dust absorption, we will be overestimating the distance of a supernova and this error will grow 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  $\Lambda$  accelerates the universe. One needs a variable  $\Lambda$  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.

Perhaps we should leave the last say with the Pythagoreans, the learned followers of the Greek mathematician philosopher Pythagoras more than two millennia ago who hypothesized that the Earth goes round *not the Sun*, but round a 'Central Fire'. When quizzed about why we don't see the central fire, they further hypothesized that another body, which they called *Counter Earth* lies between the central fire and us, So the skeptics began to ask: Why don't we see the Counter Earth? To this query their answer was that Greece was on the other side with respect to the Counter Earth and so we cannot see it. However, this defence also collapsed as people could 'go to the other side' and see that there was no central fire and no counter earth.

Cosmology may eventually acquire its own unprejudiced interpreters of the universe.