Cosmology and Local Environment

Jayant V. Narlikar

LECTURES 88-90

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FOREWORD

The Indian Institute of Advanced Study has come to be associated with studies in humanities and social sciences, but only because very few scholars have come to the Institute as Fellows to work in the field of natural and life sciences.

The interests and objectives of the Institute are inclusive enough to welcome a 'scientist' in any field. It was a matter of gratification for us when Dr Jayant V. Narlikar agreed to come to the Institute as a Vistiting Professor to deliver a series of lectures on 'cosmology and local environment'. These lectures evoked a lively response from a large number of scholars who came to listen to him. The lucidity of his expression enhances their value. We are happy to publish these lectures as much for the general reader as for the specialist.

J.S. GREWAL
Director

PREFACE

These lectures highlight certain issues being discussed today in the frontier areas of science. Rather than go into quantitative aspects with formulae, diagrams etc., I have highlighted the underlying concepts and viewpoints. The hope is that non-specialists, even non-scientists, may be able to capture the flavour of the subject matter. Last word has not been said on any of the issues discussed in these lectures. There is no consensus, let alone a unique clearcut view, that is accepted by the scientific community. I have taken the liberty of emphasizing my own points of view in certian places.

The single theme running through these lectures is described by the overall title. I strongly believe that our existence and local environment that goes with it are linked with the large scale structure of the universe. A strictly local theory that ignores this long range interaction may be missing some vital clues.

It is a pleasure to thank Dr J.S. Grewal for giving me the opportunity of presenting these views at the Indian Institute of Advanced Study.

JAYANT V. NARLIKAR

1

MACH'S PRINCIPLE

Let me begin with a quotation:

> Nature does not begin with elements, as we are obliged to begin with them. It is certainly fortunate for us, that we can, from time to time, turn aside our eyes from the overpowering unity of the All, and allow them to rest on individual details. But we should not omit, ultimately to complete and correct our views by a thorough consideration of the things which for the time being we left out of account.

These are the words of Ernst Mach, philosopher scientist of the last century, taken from his famous book, *The Science of Mechanics,* published in 1893.[1] The idea expressed in these words will form the guiding theme of my lecture today, which will be mainly devoted to Mach's ideas on inertia of matter.

It was Galileo Gallilei who first appears to have appreciated the significance of the property of inertia. Inertia implies the tendency of a body to resist any change in its state. Although we use this word in several different contexts in our daily life, to the mathematical physicist, inertia has a specific meaning—the meaning given to it by Galileo, in the context of dynamics.

Galileo had a long controversy with the scientific-cum-religious establishment of the day. The establishment followed the precepts of the Greek thinker Aristotle. According to Aristotle a body in motion requires a force to push it along. Galileo, on the other hand, believed that force was needed not for maintaining a given state of motion but for changing it. In other words, the external force is related not to velocity. To produce acceleration that is to change the velocity of the body it becomes necessary to take account of its inertia. An elephant has bigger inertia than a cat because a

[1] E. Mach, 1893, *The Science of Mechanics*, Chicago, Open Court.

larger force is necessary to budge the elephant from its state of rest than that needed to shift the cat.

Galileo was proved to be right in the end, although it was Isaac Newton who gave the precise laws of motion. Newton's second law tells us that the force acting on the given body equals the product of its mass and acceleration. Mass is a quantitative expression of the inertia of the body. An elephant with the mass of five tons has 1000 times as much inertia as a cat of mass of five kilograms.

Newton took it for granted that inertia is an intrinsic property of matter and that the mass of a body will be the same regardless of its environment. In this context recall the standard school question: "What is the difference between mass and weight?" The weight of our elephant would depend on the force with which it is attracted towards the centre of the Earth. The same elephant taken to the Moon would weigh about one sixth of its weight on the Earth. The mass of the elephant, on the other hand, would remain the same on the Moon as it is on the Earth.

The successes of the Newtonian system in explaining the dynamics of terrestrial and astronomical phenomena naturally established the basic postulates of the system. The postulates, however, did not go unchallenged. In fact Newton himself was in difficulties as is seen by the following example.

THE BUCKET EXPERIMENT

The Newtonian laws of motion require measurements of velocities and accelerations, and these measurements are to be made against a frame of reference. Which frame of reference is really implied? I will give you an example to illustrate the problem.

Imagine a stone tied to a string and whirled round in a circle. An observer **A** at rest at the centre of this circle sees the stone in an accelerated state. The direction of motion of the stone is changing steadily. Mathematical calculation tells us that the acceleration of the stone is directed towards the centre of the circle. From Newton's second law of motion we know that the force acting on the stone must also be directed in the same direction. Indeed it is. The force is the tension in the string attached to the stone and it is directed towards **A,** the centre of the circle.

While this observer **A** at the centre of the circle finds everything consistent with Newton's laws, another observer **B** staying fixed on the stone has a different experience. Since the stone is at rest relative to him, he concludes that the stone has no acceleration. Nevertheless he would notice the tight string and conclude that there is a force of tension pulling the stone towards the centre of the circle. Why does the stone stay fixed in spite of the force? Clearly the observer **B** cannot reconcile himself to Newton's second law.

The above example illustrates the fact that not all observers are alike in their interpretation of the laws of motion. Newton himself gave the example of the rotating water-filled bucket. Newton's experiment is as follows. Imagine a water-filled bucket hanging from the ceiling by a rope. In the stationary state the level of water in the bucket is horizontal. When, however, the rope is given a twist and the bucket is set spinning the water level becomes concave, dipping at the centre and rising at the boundary. The observer **A** who sees the spinning bucket concludes that this is the result of accelerated motion. The observer **B** who is at rest relative to the spinning bucket is puzzled as to why the water level has become concave. Again **A** and **B** do not seem to have equal staus vis-a-vis Newton's law.

Newton rationalized the situation by postulating the existence of 'absolute space'. Only when measured against the reference frame of the absolute space do Newton's laws of motion have their familiar form. The observer **A** in each of the two examples described above is at rest in the absolute space. Whenever we talk of an observer like **B** in each of the above examples, with acceleration relative to the absolute space postulated by Newton, we have to introduce a new element into Newtonian dynamics. For, the Newtonian laws will not hold as they stand, in the rest frame of **B**. Here Newton introduced the concept of an *inertial force*.

In our example of the stone whirled round at the end of a string we can reinstate Newton's law in the rest frame of the stone by postulating an equal and opposite force which cancels the tension of the string. Such a force is therefore directed in the outward direction, away from the centre for the circle. Commonly known as the *centrifugal force* this postulated force is an example of Newton's inertial forces. It is the same force that accounts for the curvature of the water surface in a rotating bucket.

The Foucault Pendulum

Let me give another example of inertial forces, which is of a different nature from the centrifugal force just described. This example arises in the context of a Foucault pendulum.

An ordinary clock pendulum is constrained to oscillate in a vertical plane. It takes a fixed period to complete one oscillation. Imagine now that the pendulum is free to oscillate in any vertical plane. In practice this can be achieved if the suspension thread is attached to a joint which can move freely. The French physicist Leon Foucault had set up such a pendulum around 1851. If such a pendulum is set in oscillation in a given vertical plane, it is found that the plane of oscillation gradually shifts around the vertical axis of suspension. The plane of oscillation makes one complete rotation around the axis in a period which depends on the latitude of the place, ranging from one day at the poles to infinity at the equator.

Why should the plane of oscillation of a Foucault pendulum rotate? Again, the question can be answered by postulating inertial forces. Dependence of the rotation period on latitude gives us some hint that the force to be postulated arises from the Earth's rotation. Indeed, if we suppose that the Earth rotates relative to the absolute space we can deduce the type of inertial force needed for preserving the validity of the laws of motion on the surface of the Earth. This force is called the *coriolis force* and is directed in a transverse direction from the axis of rotation.

Foucault's pendulum therefore gives us a means of measuring the Earth's angular velocity of rotation relative to the absolute space. These observations tell us that the period of rotation is one day.

Is this result surprising?

The Local Inertial Frames

The answer, at first seems not so suprising. We learn at an early state in our life that the Earth revolves round its polar axis in one day. Surely, the Foucault pendulum is merely confirming that result in a more sophisticated way?

Closer examination reveals the real significance of the observation. We learn of Earth's revolution by observing the rising and setting of stars. The Earth, therefore, takes one day to revolve around its axis in relation to the background of distant stars. What Foucault pendulum tells us is the period of Earth's revolution round its north-south axis relative to the absolute space.

The equality of the two answers tells us that Newton's postulated absolute space is none other than the background provided by the distant stars.

Before we proceed further with the implications of this result, it is worth mentioning that twenty years after the publication of Newton's famous treatise *Principia,* Bishop Berkeley had criticised Newton's analysis of the bucket experiment, by pointing out that the role of the background had not been fully appreciated. The difference between the rotating and the non-rotating bucket was physically or observationally decided only in relation to the background. Absolute space introduced by Newton was fictitious and there were no independent means of detecting it.

Now we see that Bishop Berkeley was right in the sense that if we do away with the concept of absolute space and concentrate only on the stellar background, we have an operational definition of a reference frame in which Newton's laws of motion hold. Any other observer in uniform motion relative to this reference frame will also find that the laws of motion hold without modification. All such reference frames are called *inertial frames*. If we have observers accelerated relative to any inertial frame then in their rest frames it becomes necessary to postulate inertial forces. We will refer to such frames as *non-inertial frames*. The rest frame on the surface of the Earth is a non-inertial frame.

To decide whether a reference frame is inertial or non-inertial the operational procedure is to examine the motion of the background of distant stars. If the background is accelarated (for example rotating) then the frame is non-inertial and vice-versa.

What do we mean by 'distant stars'? As the astronomers expanded the range of their observations they first saw stars just beyond our local solar neighbourhood. Then their vision extended to remote stars in our Milky Way System or the Galaxy. In the third decade of the present century the 'background' receded still further to galaxies lying close to but outside our Galaxy. The modern telescopes take us to the background of galaxies so far that light takes thousands of millions of years to cover the intervening space between them and us.

But the remarkable thing is that the result of the Foucault pendulum experiment is found to be valid within the observational errors: the earth's revolution period relative to Newtons fictious absolute space is the same as it is to the background of distant galaxies.

Or, to put it differently, the inertial frames in our local neighbourhood are determined by the background of remote matter in the universe.

MACH'S PRINCIPLE

It is Ernst Mach in the last century who emphasized the point made earlier by Bishop Berkeley namely that the 'background' is important to any discussion of dynamics. In his text book *The Science of Mechanics* which I referred to in the beginning of this talk, Mach notes the important result which we just saw in connection with the experiment of the Foucault pendulum. That the local inertial frame is the one in which the distant parts of the universe are non-rotating was, according to Mach, not an accident but a consequence of some basic natural law.

We may look at Mach's reasoning in the following qualitative way. How do we measure the mass of an object? As seen earlier, the mass is a quantitative measure of inertia and is determined by measuring the acceleration produced in the body by an external force. But acceleration cannot be measured without a reference frame. Newton's postulate of an absolute space is hardly of any practical use since there is no independent way of identifying it. If however, we assume that the Newtonian laws are defined in a reference frame in which the distant parts of the universe are non-rotating, then we have a practical prescription for determining the local inertial frame.

It, therefore, follows that the measurement of inertia depends upon the background. Remove the background and we have no means of knowing what the inertia of a body is. Hence inertia is *not* intrinsic to the body but it also depends on the background of remote matter in the universe.

This reasoning is known as Mach's principle and so far as Mach was concerned, these ideas remained qualitative. For example, Mach did not specify *in what way* the mass of an object depends on the background. What is the prescription for determining the mass of the given body in a given model universe? Does mass remain constant in space and time, in a changing universe? If the mass changes, what are the observable consequences of such a change? Unless questions like these are answered, Mach's principle cannot be dignified by the appellation of a physical theory.

EINSTEIN AND MACH'S PRINCIPLE

Albert Elinstein was very impressed by Mach's reasoning and his attitude towards Mach, in the early days, was that of a disciple towards his mentor. While formulating his general theory of relativity Einstein had hoped to come up with a quantitative version of Mach's principle. In this effort he was not successful.

That general relativity does not reflect the spirit of Mach's principle can be seen in many ways. I will attempt to describe two features in a qualitative manner.

First consider what is meant by the motion of a test particle in an otherwise empty universe. By a test particle we mean a particle which has no gravitational influence of its own. In Einstein's general relativity such a particle describes what is known as a *geodesic*. A geodesic is a geometrical curve in space and time which is analogous to the Euclidean straight-line. We know that the straight-line between two points **A** and **B** on the Euclidean plane is the curve of shortest length. A geodesic connecting **A** and **B** in a general space time with a geometry which may not obey Euclid's axioms, is a curve along which the distance from **A** to **B** is *stationary*. By stationary we mean that if we alter the shape of the curve slightly, the distance measured along it remains unchanged.

Now there are several solutions of Einstein's equations for an empty universe with geometries that are non-Euclidean. A particle moving along such geodesics has definite trajectories. What do these trajectories mean? According to Mach, a single particle existing in an otherwise empty universe would not have any background against which to move. So complete indeterminancy should prevail in the motion of such a particle. Yet relativity prescribes definite trajectories!

Lest it is thought that an argument based on empty universe is unphysical, let us take a look at another feature of relativity.

Mach's principle, as we saw earlier, evolved out of the observation that the actual universe is seen to be non-rotating in the local inertial frame. Is it possible within the framework of general relativity to have a model universe not showing this property? In

1949, in the volume brought out by the Reviews of Modern Physics to celebrate Einstein's 70th birthday, Kurt Gödel (well known for his therorem on the logical incompleteness of arithmetic) contributed an article on the so called rotating universes.[2] In this article Gödel constructed a model from Einstein's equations of general relativity which was manifestly *anti-Machian*. That is, in the Gödel universe a local observer using an inertial frame would find the distant parts of the unverse rotating.

Gödel's universe has some undesirable properties which make it unphysical. For example, observations show that the light coming from distant galaxies undergoes an increase in wavelength. In Gödel's model this effect is not present. A somewhat peculiar property of Gödel's model is that it has closed timelike lines. This technically worded sentence means in effect that there are observers in Gödel's universe whose future meets their past, that is, they keep meeting themselves in the past and future!

Although Gödel's anti-Machian example could be discounted on these and other grounds, later work by T.V. Ruzmaikina and A.A. Ruzmikin from the U.S.S.R. produced anti-Machian models from general relativity which were free from any unphysical characteristic. Hence, we can argue that because the theory generates such anti-Machian models, Mach's principle does not follow from general relativity.

Einstein was naturally disappointed at such a conclusion and late in his life he began to lose his early regard for Mach's principle. His disillusionment was based largely on the fact that Mach's principle implies a connection between the local and the distant parts of the universe and such a connection cannot be achieved via local field theories. His belief that field theory provides a correct description of nature in preference to action at a distance was what led Einstein ultimately to reject Mach's ideas.[3]

THE HOYLE-NARLIKAR THEORY

A few scientists, however, did feel that Mach's principle is significant enough to be incorporated in physics. Although the influence of distant matter on local matter suggests action at a

[2] K. Gödel, 1949, Rev. Mod. Phys., **21**, 447.

[3] A. Einstein, 1949, Autobiographical Notes in *Albert Einstein: Philosopher-Scientist*, ed. P. Schilpp, New York, Tudor.

distance, such may not actually be the case. In fact the work of D.W. Sciama in the 1950's was dictated by the motive of providing a field theoretical description of Mach's principle.[4] However, in the true spirit of Mach one needed an action at a distance theory.

In 1964, Hoyle and I made such an attempt.[5] Using the same mathematical machinery which had earlier proved useful towards the understanding of action at a distance electromagnetism, we were able to describe how the inertia of a typical particle arises from the individual contributions of all other particles in the Universe. Although it took us several months to arrive at the final answer, by hindsight it now appears that our final answer was a unique one and that it arose in a straightforward manner from the various criteria imposed on the Machian theory.

The resulting theory was not only consistent with Machian philosophy about inertia, but it also yielded a theory of gravitation which was wider in its implications than Einstein's general relativity. Just as Newton's law of gravitation follows as a special case of general relativity, so did general relativity follow as a special case of our formulation.

There were certain other dividends from our approach which were unexpected. For example, both Newton and Einstein assumed that gravitation is an 'attractive' force. The constant of gravitation G is taken to be positive in both theories. In our theory 'G' is not an assumed constant, but it emerges as a property of the Universe; *and we could deduce that G must be positive.*

Another conclusion which emerged from our theory is that the cosmic force of repulsion, the so called λ-force postulated by Einstein in 1917, cannot exist. In general relativity such a force could be accommodated if needed. While a majority of cosmologists do not believe in the existance of the λ-force, observations are ambivalent on this score. This is why a clear-cut prediction of our theory is of interest.

Is *G* Constant?

At this stage I wish to recall the words of Ernst Mach quoted at the beginning of my talk, and consider them in the light of the

[4] D.W. Sciama, 1961, *The Unity of the Universe*, New York, Double Day.

[5] F. Hoyle and J.V. Narlikar, 1964, Proc. Roy. Soc. **A282,** 191; 1966, Proc. Roy. Soc. **A294,** 138; 1972, Mon. Not. R. Astron. Soc. **155,** 323.

gravitation theory proposed by Hoyle and myself. In the remainder of this talk I will refer to this theory as the HN theory of gravity.

Both the Newtonian and Einsteinian theories of gravity are local in character, in the sense that they relate the local gravitational influence to the local distribution of matter. The HN theory by contrast cannot be formulated without taking into account the structure of the universe. In practice such a theory might have been difficult to apply had the solution of each local problem of gravity demanded our knowing what the universe is like. Fortunately, this is not necessary. Because the HN theory reduces to relativity for most practical purposes we do not need to know all the details of cosmology.

I said 'most' not 'all'. As Mach argued, there are problems where the cosmological details cannot be left out. I will describe two such problems.

The first problem relates to *G*, the constant of gravitation. The strength of the gravitational interaction is measured by this constant. If *G* were ten times larger than what it is, the Earth would attract us with ten times its present force, thus making us all ten times heavier. But is *G* the same at all places and at all times?

According to relativity the answer to this question is 'yes'. In Newtonian gravity *G* could vary with time but not with space. What about the HN theory? In that theory there is no prima facie reason why *G* should be a constant, either in space or in time. It is determined from the overall properties of the universe which may evolve and change. Indeed in some model universes of HN theory *G* does change with time. (The assumption of a cosmological principle ensures that at a given time all parts of the Universe are physically alike. Such an assumption precludes the variation of *G* with space.)

Can this change in *G* be measured? The predicted rate is extremely small—a few parts in a hundred billion—per year. Improvement in low temperature technology is needed before such a small rate of change can be detected in a laboratory. Judging by the advance of present technology this improvement may not be impossible to achieve.

Barring direct year to year measurements, we may look for long term effects of a possible variation of *G*. Take for example, the Earth-Moon system. The size of the present orbit of the Moon around the Earth is related to the period of the orbit by a simple formula containing the constant of gravitation G. As G decreases, the gravitational pull of the Earth on the Moon loosens and they begin to move apart from each other. As the orbit size grows the period lengthens. Can we observe the Moon's orbits accurately enough to check whether the above effects do occur?

The use of accurate atomic clocks and the employment of laser technology have made such measurements possible. Van Flandern of the U.S. Naval Observatory had earlier concluded that there is some evidence for a slow decrease of G.[6] This conclusion is, however, controversial. Many people have argued that the tidal force between the Earth and the Moon would produce a similar effect as the decrease of G and so the observations are inconclusive. Here again we may have to wait a little longer for the situation to clarify. It is fair to say that the present state of data with their large error bars are consistent with an unchanging G.

Lastly, there are geophysical and astrophysical effects of the variation of G. The former affect the structure of the Earth and its evolution from a primitive stage[8] while the latter affect the evolution of stars.[9] I will not go into details of these effects here. So far as the Earth is concerned, a slow decrease in G implies that the gravitational force was stronger in the past than now so that the Earth was closer to the Sun. What is more, the Sun also was brighter in the past than it is seen to be now. The Earth's atmosphere must have played a protective role in the past to keep the surface temperature on the Earth within reasonable limits to permit biological evolution. Also if the Earth has been steadily growing in size, its surface crust would have broken up. Is that how the continents formed?

THE REDSHIFTS OF QUASARS

From these 'down-to-Earth' effects let us go over to the esoteric and remote effects of the HN theory which might explain a strange phenomenon in quasars. Quasars are starlike in appearence but are believed to be immensely more powerful than a

[6] T.C. Van Flandern, 1981, Astrophys. J. **248**, 813.

[7] R.W. Hellings; P.J. Adams; J.D. Anderson, M.S. Keesey; E.L. Lau; E.M. Stanelish, V.M. Canuto and I. Goldman, 1983, Phys. Rev. Lett. **51**. 1609.

[8] F. Hoyle, 1972, Q.J.R. Astron. Soc. **13**, 328

[9] V.M. Canuto and J.V. Narlikar, 1980, Astrophys. J. *236*. 6.

typical star. In fact a powerful quasar outshines a galaxy containing a hundred billion stars!

The important piece of information which decides how powerful a radiator a quasar is, comes from the measurement of its 'redshift'. The redshift is a measure of the fraction by which the wavelengths of certain well known lines in the spectrum of the quasar are found to exceed the wavelengths of similar lines in the spectra of light sources produced in the laboratory. For example, in the quasar with the catalogue number 3C9, the wavelength of Lyman-α line is found to be at about three times the laboratory wavelength of 1216 A (A = Angstrom = ten billionth part of a metre). The fractional increase in the wavelength is therefore 2, which is the redshift of the quasar.

According to a well known law first found by E.P. Hubble in 1929, the redshift of a remote object is directly related to its distance.[10] The larger the distance the larger is the redshift. Given the model of an expanding universe, the astronomer can tell the distance of an object like a quasar or a galaxy if its redshift is known. At least, this is what most cosmologists take for granted.

Some observations of quasars and galaxies are, however, beginning to threaten this sacrosanct belief. Such observations have come largely from the work of H. Arp.[11] A typical Arp observation shows quasars of varying and large redshifts close to a galaxy of low redshift. Suppose for example, we find two quasars **A** and **B** of redshifts 1 and 2 close to galaxy **C** of redshift 0.05. What do we conclude from such data?

If we apply Hubble's law, we have to conclude that the galaxy **C** is very close by while the quasars **A** and **B** are very distant, **B** being more distant than **A.** Yet Arp finds **A, B** and **C** closely grouped on the sky. Clearly, the apparent closeness of **A, B, C** must be an optical illusion: we see them close because **A** and **B** happen to be located along directions very close to the direction of **C.**

Now given, a random distribution of quasars on the sky the chance of the above three directions coming very close is rather small. Statisticians tend to reject a hypothesis if the porbability of observing the outcome of that hypothesis is small, say less than 1 part out of 100. Many of Arp's observed configurations suggest

[10] E.P. Hubble, 1929, Proc. Nat. Acad. Sci. (USA), **15**, 168.

[11] H Arp, 1987, *Quasars, Redshifts and Controversies*, Berkeley, Interstellar Media.

much smaller probabilities than this.

If we take these low probabilities seriously, we have reason to doubt the underlying hypothesis, namely Hubble's law. We have to argue that in spite of their large redshifts quasars are relatively nearby objects. In my example we have to assume that all three objects **A, B, C** are physically near each other.

Before proceeding further let me state that cosmologists have reasonably strong grounds for believing that Hubble's law holds for galaxies. It is the quasars that cause some doubt, which is why the conclusion in this example was that the quasars **A** and **B** being near the galaxy **C** must be at the same distance from us as **C** is, which in turn is given by Hubble's law *applied to* **C.**

In spite of Arp's data the majority of astronomers still believe that Hubble's law holds for quasars also and that all the quasar galaxy associations found by Arp are due to chance. Only time and more sophisticated observations will tell if this confidence in Hubble's law is justified.

I belong to the minority who thinks that the present data on quasars are sufficiently distrubing for this conventional Hubble-law based picture. The high redshifts of quasars are not due to their being very far away but are due to some other cause intrinsic to quasar structure. Naturally, any one departing from the conventional picture has to provide a clue to this 'other cause'.

It is here that the HN theory may be useful. A few years ago P.K. Das and I argued that if quasars are shot out of active galactic nuclei in gigantic explosions and if they are made of younger matter, then their redshifts will be higher than those of the galaxies from which they were ejected.[12] This conclusion emerges where Mach's principle is applied to newly created matter as per the HN theory.

Although our explanation can account for several of the peculiarities observed in the redshifts of quasars, I personally feel that we need more data before we can definitely assert that quasars are made of younger, more recently created matter than found in the rest of the Universe. The Space Telescope may well supply the much needed information.

[12] J.V. Narlikar and P.K. Das, 1980 Astrophys J **240** 401

To conclude, Mach's Principle implies a link between our local environemnt 'here and now' and the distant parts of the universe. The Foucault pendulum and the structure and evolution of the Earth as well as the mysterious properties of the far away quasars appear as different aspects of the same basic idea. The link in these cases is through the property of inertia operating as an action at a distance effect. In my next lecture I will talk of another effect that manifests itself as a result of the large structure of the universe responding to a local signal.

2

THE ARROW OF TIME

This subject is capable of rousing great controversies. Let me therefore make it clear at the outset that I wish to consider the problem entirely from the point of view of a physicist.

The world of physics is of four dimensions, three of space one of time. All known laws of physics are expressed in terms of partial differential equations with space and time as independent variables. These laws describe the behaviour of physical systems at different points of space and at different instants of time. The interesting thing is that the laws describing macroscopic physics obey certain symmetry rules. They are symmetric with respect to space and time. The laws themselves do not make a distinction between left and right, past and future. While in our every day experience the distinction between left and right is more from conventions, that between past and future is absolute. What causes this asymmetry in time?

At this stage it is possible to take two different points of view. One is to say that there exists in physics some law, as yet unknown to us, which is not time-symmetric. It is this law which makes a distinction between past and future. While it is premature to say that we know all about physics today, the above point of view strikes me as a counsel of despair. It does not take us any further—the answer provided by it is merely a restatement of the problem.

The other point of view is statistical and usually involves asymmetrical initial conditions. According to this view the asymmetry was introduced at the origin of the universe. This may be right; but again, it does not take us any further. The question still remains: 'Why, of all possible initial conditions, a perticular subset was chosen?'

A more fruitful line of investigation lies, in my opinion, in looking at different branches of physics where this asymmetry in time shows up. If we are able to correlate these apparently unconnected phenomena we may have made a significant advance towards answering the basic question 'Why an arrow of time'? I wish to discuss here an attempt along these lines.

Three Arrows Of Time

From our present day knowledge we can pick out at least three apparently unconnected arrows of time. These are cosmological, electromagnetic, and thermodynamic arrows of time.

Of these the cosmological arrow is based upon the concept of an expanding universe. Light from distant galaxies shows a red-shift in its spectrum which can be interpreted to mean that the galaxies are receding from one another. Suppose we take photographs of two galaxies at different instants of time. If these photographs are all mixed up, we can rearrange them in chronological order by noting the separation of the two galaxies. This chronological order has been determined purely from a cosmological phenomenon—there is no local direction of time involved.

The electromagnetic arrow of time is shown by phenomena such as electromagnetic radiation. When an electric charge oscillates it radiates electromagnetic waves and as a result suffers a damping of its motion. This, again, is a time-asymmetric phenomenon. If we film this event and run the film backwards, we would see an electric charge receiving energy from infinity and as a result oscillating more and more energetically. This time-reversed phenomenon, though perfectly permissible by Maxwell's equations, is never observed.

The third direction of time is the one shown by local theremodynamics. Here again, the laws of microscopic physics which are responsible for the observed phenomena, are time–symmetric. The macroscopic behaviour of a system is however, time–asymmetric.

Is there any connection between these three arrows of time?

The Wheeler-Feynman Theory

A way of connecting the cosmological arrow with the electromagnetic arrow is indicated by the work of Wheeler and Feynman.[1]

[1] J.A. Wheeler and R.P. Feynman, 1945, Rev. Mod. Phys., **17**, 157 Rev. Mod. Phys. 1949, **21**, 425.

In the Wheeler-Feynaman theory electromagnetism is described in terms of direct particle action. That is, any two charges interact with each other by an action which travels at the speed of light. There are no fields involved—rather, there are pseudo fields whose existence depends on the particles themselves.

In its elementary form this theory can lead to strange situations. Imagine two electric charges **A** and **B** situated one light hour apart. The action from **A** which starts off at, say 5 p.m. will reach **B** at 6 p.m. This action must have an equal and opposite reaction—implying that **B's** reaction starts at 6 p.m. and effects **A** at 5 p.m.! 1 If we call **A's** effect on **B** a 'retarded' effect, **B's** reaction is 'advanced'. Advanced and retarded effects go hand in hand in such a theory.

At first sight this looks like a drawback. In real life we do not encounter advanced effects—they conflict with the notion of causality. How to reconcile a theory which explicitly incorporates advanced as well as retarded effects? This drawback was turned into an advantage in a remarkable way by J.A. Wheeler and R.P. Feynman. They argued that the universe does not consist of just two particles **A, B.** Thus in the situation described above we are not right in taking into account the reaction from **B** alone. Indeed, we must include the advanced effects of all other particles **B, C, D,** etc. in the universe. By including these effects they were able to show that in a static infinite universe with a homogeneous distribution of charges, the combined reaction on **A** from all charges is just such as to provide the observed damping of its motion. Also, the combined effect of all charges including **A**, is purely retarded—again, in accordance with experience. For this argument to work, the universe must be a 'perfect absorber', i.e., it must have enough matter to obsorb and react to all the signals coming from the typical particle **A**. For this reason, Wheeler and Feynman called this theory 'the absorber theory of radiation'.

Thus the choice of retarded solution is not an arbitrary one, but dictated by the universe. This is a step foward, since it seems to indicate a connection between the local electromagnetic arrow and the universe as a whole. Yet nowhere does it incorporate the cosmological arrow of time I described before. In their calculations, Wheeler and Feynman assumed the universe to be static. A static universe is time–symmetric. We can therefore reverse the sign of time coordinate throughout their calculations and get a consistent result but now there will be pure advanced effects everywhere.

Indeed, within the framework of pure electrodynamics it is not possible to distinguish between pure advanced and pure retarded effects. To make a distniction, Wheeler and Feynman had to go beyond electrodynamics and to bring in statistical considerations of a kind found in thermodynamic arguments.

THE ROLE OF COSMOLOGY

This was shown to be unnecessary by Hogarth[2] and later by Hoyle and myself.[3] All one has to do is to repeat the Wheeler Feynman calculations in an expanding universe. Thus we have a time-asymmetric universe in which to work out a theory which is time-symmetric in its basic interactions. What is the outcome of carrying out such a procedure? The result depends very much on how the universe expands. I shall not go into the details of calculations. But it is easy to describe the crucial points.

First, let me briefly summarize the cosmological scenario. The models, currently the most popular ones describe the universe as expanding from a 'big bang' origin and *either* dissolving into infinity as all consituent galaxies recede from one another to infinite distance, *or* recontracting into a 'big crunch' which is the reverse of the big bang. These models were first conceived by A. Friedman[4] in 1922-24 and they involve no subsequent creation of matter, once the universe is created in a big bang.

A rival to these models is the steady state theory proposed in 1948 by H. Bondi, T. Gold and F. Hoyle.[5] In this model the universe being always in the same state is without a beginning and without an end. Its ever constant density is maintained in spite of expansion, by a continuous creation of matter.

Let us now consider the Wheeler-Feynman theory in these two types of universes.

As explained before, to get pure retarded effects we need a large number of practicles **B, C, D,...** on the future light cone of **A.** This requirement is not easy to meet in an ever expanding universe without continuous creation. In such a universe the den-

[2]J.E. Hogarth, 1962, Proc. Roy. Soc. **A, 267,** 365.

[3]F. Hoyle and J.V. Narlikar, 1963, Proc. Roy. Soc., **A, 277,** 1.

[4]A. Friedman, 1922, Z. Phys., **10,** 377 and 1924, Z. Phys., **21,** 326.

[5]H. Bondi, and T. Gold 1948, Mon. Not. R. Astron. Soc., **108,** 252; F. Hoyle, *ibid.* **108,** 372.

sity of matter in a proper volume falls as the universe expands. If there is continuous creation, however, this density remains constant and the future half of the universe fulfills the conditions of being a perfect absorber. To get pure advanced effects, we need a large number of particles **B, C, D,...** on the past light cone of **A**. This is satisfied in the Friedman universe but not in a universe with continuous creation and constant density. Thus in the steady state theory pure retarded-not advanced solutions are possible whereas in most of the so called 'big bang' universes pure advanced-not retarded solutions are possible. (In the big bang/big crunch models there is no clear cut solution in favour of either the retarded or the advanced solutions).

Assuming then that we live in the right kind of universe which (a) expands and (b) produces retarded electromagnetic signals, the phenomenon of electromagnetic radiation becomes explicable. It is the response of the universe that decides the local outcome. In such a universe, it is no accident or a matter of arbitary selection that an oscillating electric charge radiates energy. Indeed we can turn the problem round and argue that because we notice an electromagnetic time arrow we must live in the right kind of universe.

In subsequent work Hoyle and I extended these ideas to quantum electrodynamics.[6] Here one is explicitly confronted with the notion of the response of the universe to the quantum transitions. I will illustrate the result with the help of an example very common in atomic physics.

Consider an atom of hydrogen. It has an electron orbiting a central proton. Unlike in a classical dynamical situation, the electron orbit is not a clear-cut trajectory in space. Instead one talks of a 'quantum state' of the electron which only tells us the probability of finding it in any given volume of space. In a typical stationary state the electron has a fixed energy.

Quantum mechanics allows the electron to exist in states of specific energies only. The 'allowed' energies form a discrete set. If there is external inducement from an ambient radition the electron may change its state *either* by jumping 'up' to a state of higher energy, *or* by jumping 'down' to a state of lower energy. The rates of upward or downward induced transitions are equal

[6]F. Hoyle and J.V. Narlikar, 1969, Ann. Phys., **54**, 207 and 1971 Ann. Phys., **62**, 44.

and depend on the intensity of inducing radiation.

However, in addition, the electron can also *jump down* on its own and the rate of this spontaneous transition does not depend on how much external radiation is present. This is something of a mystery. Why does the electron jump at all? Why does it jump down and not up? These questions are dealt with by the conventional quantum field theory in a somewhat formal manner which ascribes a non-trivial behaviour to the vacuum. Instead, the Wheeler-Feynman theory relates the one way behaviour of the electron to the response from the expanding universe. Hoyle and I were able to explain spontaneous transitions in this way: provided we lived in the right kind of universe.

Thus the so called spontaneous transition of an atomic electron from a state of higher energy to one of lower energy is not an isolated process in the atom but it involves a link with the large scale structure of the universe. The probability of what a quantum system will do is decided only by taking into account this link.

The point of view I wish to put forward next is that the *third* arrow of time, the thermodynamic one also follows the sense of the electromagnetic and cosmological arrows of time. An expanding universe is far from being in a thermodynamic equilibrium. For any 'hot' system, e.g. a star, it provides a sink. However, the mere existence of a sink is not sufficient. There should be an actual flow of energy from the system to it. This is made possible via radiation. In other words, retarded potentials together with the expansion of the universe should account for the local thermodynamic effects.

Why An Arrow?

This brings me to the final question, 'Why is there an arrow of time?' Even if we 'reduce' everything to the basic phenomenon of the expansion of the universe, the question still remains as to why should the universe expand. The equations of cosmology are also time symmetric. A contracting universe should also be a solution of the equations. *It is* in fact. But the difference between an expanding and a contracting solution is no longer physical at this stage. One can be obtained from the other by a change of sign of the time co-ordinate. The difference would have been crucial if we had another, indpendent, arrow of time to compare with. The argument given above has done away with the need for one. Indeed, it leads us further to speculate about a fourth arrow of time, the biological one.

Suppose we link our experience of 'ageing' with a biological arrow of time. At present we know very little about the physics of living systems. Nevertheless the so called one-sidedness of the ageing process may be linked with the thermodynamic arrow of time. In other words, the biological arrow is also aligned with the three arrows I have so far described and hence the time asymmetry we 'experience' can be ascribed to this overall alignment.

Perhaps I can illustrate this difference better by considering a time-symmetric model of the universe which is given by the cosmological equations.

In this model the universe constracts at one end of the time axis and expands at the other. It is stationery at one instant which we denote by $t=0$. Suppose we say, arbitararily, that at one end $t \rightarrow -\infty$ and at the other $t \rightarrow +\infty$. At either end, the universe is asympotically in steady state. At $t \rightarrow +\infty$ it is expanding with creation of matter, at $t \rightarrow -\infty$ it is contracting with destruction of matter. A random observer along the t axis will most porbably be at $t = \pm\infty$. Suppose he is at $t = +\infty$. He sees an exapanding universe, retarded electromagnetic signals and conventional thermodynamics, as we do. If he is at $t = -\infty$ the universe would appear to contract, the electromagnetic signals would be advanced and the thermodynamics would go in the reverse direction to what we are accustomed to. However, if he decides to measure time in the direction in which he grows older, he would reverse all the three arrows. His experience would then coincide with that of the observer at $t \rightarrow = +\infty$. It is only a rare observer, at a finite value of t, that has no definite sense of arrow of time. For such an observer the question 'why an arrow?' has no meaning. Perhaps there is no biological evolution in this phase of the universe.

AN ELECTROMAGNETIC MACH'S PRINCIPLE

In my first lecture I had begun with Mach's philosophical ideas on inertia. There I linked up the property of 'mass' of a body to the large scale structure of the universe. Here we see another link in the context of the arrow of time. Our local experience of time is related to the fact that the universe is expanding and to the way it is expanding. We may therefore call the Wheeler-Feynman theory another expression of Mach's principle so far as electromagnetic effects are concerned, just as the Hoyle-Narlikar theory gave a quantitative expression to Mach's principle in the context of inertia.

In my third lecture I will describe an entirely new principle which seeks to relate our local existence to the large scale features of the cosmos.

3

THE ANTHROPIC PRINCIPLE

In the ancient times man had looked at the universe from a personal point of view. Located here on the earth he saw the Sun, the Moon, the stars and the planets rise and set and rise again in unending cycles, with the Earth as the central point. The so called 'geocentric' point of view was therefore natural as the starting point of any theory of the cosmos. Even in modern terminology brought in by the special theory of relativity, each observer has his own 'rest frame of reference' as the natural frame in which he makes his observation.

The difference between the old geocentric view and the modern rest frame of reference lies in the significance attached to each. The former had a certain absolute status which placed the Earth at the centre of the universe and man the observer as a special observer. The relativistic point of view on the other hand attaches no special status to a particular observer. Thus two observers can very well describe the cosmos in their respective rest frames, but if they are in relative motion each can transform his observations to the other's. Neither has the pretensions of being more 'special' than the other. The basic laws of science are expected to be 'covariant', i.e., describable in a form that does not change from observer to observer.

Thus we can take two observers, one at rest on the Earth and the other at rest on the Sun (assuming that he survives there for the purpose of this argument!) Both are entitled to describe the solar system (and the rest of the cosmos) in their respective rest frames. We may call the former Ptolemy and the latter Copernicus. The considerable debate between Ptolemy's geocentric theory and Copernicus's heliocentric theory might have been avoided had it been realized that both are correct in their own ways and that their observations are transformable one to the other.

Nevertheless, the convenience of understanding the nature of the solar system tilts the balance in favour of Corpernicus. The planets (including the Earth) move in the gravitational field of the Sun which hardly moves under the combined gravitational field of the planets. Because of its enormously larger mass* the Sun dominates the overall physical behaviour of the solar system. Thus a Copernican observer finds studies of the solar system considerably simpler than his Ptolemyic counterpart on the Earth.

The simplicity and elegance of the Copernican picture, however, proved to be the thin end of the wedge in eroding man's position as a special observer in the cosmos. Even the Sun as a star is not of any special importance when viewed against the backdrop of the Milky Way. The astronomers William and John Herschel (father and son) after a careful mapping of stars in the Milky Way, placed the Sun at the centre of the whole system. However, by the first two decades of this century the Sun was 'dethroned' from this special status! Today it is seen as one of some 100-200 billion stars in our Galaxy (that is seen as the Milky Way when viewed from the Earth) and it is located about two thirds of the way towards the circumference of the galactic disc. The disc itself is so large that light would take about 100,000 years to transverse its diameter. (for a comparison light takes eight minutes to travel from the Sun to the Earth!)

Is our Galaxy the centrepiece of the universe? No way! The large telescopes of this century have probed the universe so far out that the remote corners we see today are as they were billions of years ago: light takes that long to reach us from where they are (or were). And the vast space is populated by billions of galaxies of which ours is just one ordinary member.

We may therefore. enunciate a Copernican principle of perfect democracy in the cosmic population with no special status for man, his planet, his Sun, his Galaxy. Indeed, a last ditch attempt to restore a special status to our galaxy was made when in 1929 Edwin Hubble discovered the phenomenon of nebular redshift.[1] Hubble found that the spectrum of light coming from a typical galaxy shows a shift towards the red end of its seven colours. A simple interpretation of this result was that all galaxies are reced-

* The Sun's mass is approximately 99.87% of the total mass of all objects in the solar system.

[1]E.P. Hubble 1929, Proc. Nat. Acad. Sci. (USA), **15**, 168.

ing from ours. Did this not confer a special status on our galaxy?

Unfortunately not. A proper assessment of the data revealed that exactly the same picture would emerge if we observed the universe from any other galaxy. A Hubble-type observer located there would again notice the rest of the galaxies flying away from him. And so, we are back with the Copernican principle in which all galaxies as vantage points, are alike. There is no preferred position, no preferred direction in the universe.

Did this mark the end of man's special role in the universe? Curiously, not so! Over the last two decades a reaction to the Copernican principle is emerging, in the form of the 'anthropic principle'—a principle that takes special cognizance of the fact that man is present as an observer in the universe at this epoch. Stated in simple language this principle says that the universe must be so constructed that man is here to observe it today!

Let us examine the scientific motivation and content of what appears to be a human chauvenistic remark.

The Anthropic Principle

Although science has made considerable progress in our understanding of nature, it has to postulate certain basic laws within whose framework all its explanations are given. These laws contain certain 'fundamental' constants whose values are determined experimentally. As a mark of progress one tried to reduce the number of such constants by trying to explain some of them in terms of others.

For example, in thermodynamics there are constants like the radiation constant, the Stefan constant, the gas constant, the Boltzmann constant etc. which play a key role in explaining the properties of gases and radiation. In spectroscopy there are the Rydberg and fine structure constants whose values have been measured accurately from several experiments. The question is, are all these constants 'prescribed' by nature or would they turn out to be related. Progress, as mentioned above consists of discovering their interrelationships so that the actual number of independent constants is much less. In the above examples this has been achieved to a large extent.

Thus we have at present a fewer number of constants than the physicists of the last century had for explaining the same phenomenon. The gravitiational constant G of Newton, the speed of light c, the Planck constant h, the charge of the election e are such constants. Physical theories do not determine their values; they have to be measured experimentally. So the question is, why do these constants have these particular values and none others?

Let us consider the case of G. What would have happened if G were different from the value it is known to have? To answer this question we have to examine all phenomena in which G plays a key role. One such is the structure of a star. The luminosity of a star depends on a fairly large power of G.

The star is a ball of hot plamsa which is held in equilibrium under two balancing forces: its internal pressures which resist compression and its self gravity which tends to shrink the star. Stars of large mass exert greater gravitational compression and so require higher internal pressures which in turn imply higher temperatures. Now stellar physics further tells us that the core temperature in a typical star exceeds the threshold level where nuclear fusion reactions set in—reactions in which four hydrogen nuclei combine together to generate a nucleus of helium thereby releasing energy. The higher the temperature the higher the rate of release of energy. Thus we have the following chain of consequences for stars:

Higher mass ==> Higher self gravity ==> Higher internal perssures ==> Higher temperatures ==> High rate of energy generation ==> Higher luminoisity

In other words, stars of higher mass radiate energy at a higher rate.

The consequence of this chain is seen in a distribution of stars in the so-called 'H-R diagram' first prepared independently by two astoronomers Hertzsprung and Russell. We find stars of higher luminosity having surface temperatures and those of low luminosity having lower temperatures. Now, surface temperature determines the surface colour of the star. Thus the Sun is yellowish because of its surface temperature of around 5500 Celsius. Stars more massive than the Sun would be hotter and tend to look bluer while stars less massive will be cooler and redder in appearance. The H-R diagram clearly displays such a relationship.

It is also the fact that because of their much faster fusion rates the blue stars tend to burn out sooner than the red stars. Thus the 'life' of a blue star is the shortest and of a red star the longest, with the Sun lying in between with an age of approximately five billion years and an overall life span about twice that.

To link all this to human existence we next examine what star is suitable as a typical source of energy needed for sustaining life on a nearby planet. Red stars, being too weak are unsuitable as are blue stars which are too short lived. For, to sustain life and let it evolve to a sophisticated level requires the energy source to be strong enough and to last long enough. It is therefore no accident that we humans find ourselves near the Sun which is a medium kind of star.

To bring the anthropic principle into the argument imagine another universe in which G is higher. This would mean that the inward pull of gravitaional contraction would be larger, requiring higher internal pressures and temperatures. The stars would therefore tend to behave like the blue stars in the H-R diagrams and would not be able to sustain life on a neighbouring planet. Had G been lower than its actual value it would have led to all stars being like red stars. In neither case therefore would life have developed to the state we find it in here on the Earth.

In short, our very existence as reasonably advanced life forms leads to the conclusion that the constant of gravitation could not have a value much different from what it is found to have. The strength of this agrument depends on the sensitive way that a star's internal structure and luminosity depend on the value of G.

This argument was first given by Brandon Carter[2] in 1974 to illustrate the result that the constants of nature are probably tuned to their present values not by accident but because 'we are here to measure them'. It was Robert Dicke, however, who in 1961 had coined the word 'anthropic principle' as a general premise of which the above is one particular illustration.[3]

I will now describe another example which preceded this date and which has the merit of having predicted a physically significant result.

[2]B. Carter, 1974 in *Confrontation of Cosmological Theory with Observational Data* ed. M.S. Longair Dordrecht, Reidel, p. 291.

[3]R.H. Dicke, 1961, Nature, **192,** 440.

FRED HOYLE'S PREDICTION

As human beings we are made of many chemical elements of which the elements carbon (C) and oxygen (O) are certainly very important. In fact the nearly equal abundances of C and O in the universe play a crucial role in life-maintenance processes. First, we have the carbon monoxide (CO) as a common molecule. In association with hydrogen, another abundant element, it produces formaldehyde HCOOH. Then, with only a slight rearrangement of several such molecules one has sugars and carbohydrates.

These are crucial to the metabolic life sustaining processes. The question is, where do we get C and O in the first place?

This question is part of a wider one about the origin of elements. How, when and where did the elements found today in the universe originate? The question was first addressed in 1946 by George Gamow who was one of the proponents of the big bang universe. This model of the universe, soon after its origin in a big explosion, passed through an era of very high temperature that declined rapidly in the course of time. In the first three minutes of its existence, the universe was hot enough to support fusion of nuclei. Gamow's hope of building most of the observable abundances of elements in that hot era was not, however, completely fulfilled. Only light nuclei like deuterium, helium, lithium, beryllium etc. could be made in the 'hot big bang'.

The fusion of nuclei requires hot sites and it was natural for astrophysicists to turn to stars for the continuation of the nuclear building process. Here too there was a difficulty. It was easy enough to make helium from fusion of hydrogen in Sun-like stars: but could the process continue further? To make bigger elements we would need to bring either two helium nuclei together or one each of hydrogen and helium. In both routes we encounter nuclei that are unstable and break apart.

This was where Hoyle entered the picture. For reasons given above it is imparative that the universe contains C and O. To explain the existance of life one had to find *some way* of making C and O in stars. The atomic mass of carbon is three times the atomic mass of helium. Could we form carbon directly from three helium nuclei thus bypassing the unstable elements in between?

Earlier attempts along these lines had failed largely because the 'three body encounter' of helium was very rare. Thus the chance of making carbon appeared too thin to succeed. Some compensafory effect was needed to boost up the rate of carbon production. In 1954 Hoyle found it.[4]

According to Hoyle, the three helium nuclei should fuse not into the standard C-nucleus but into an *excited* state of it and that excited state should have an energy almost exactly matching the combined energy of the three helium nuclei. In such circumstances we are in a state of resonance, so that the reaction converting helium to carbon would proceed fast. Hoyle calculated the energy of the required excited state and asked nuclear physicists to find it. *They did find it*, exactly as Hoyle had predicted. Thus a way was found for creating C. What about O? This was possible by adding a further helium nucleus to the carbon nucleus just formed.

As Hoyle had pointed out, several circumstances have been responsible for achieving the right balance of C and O in the universe: all of these relating to the nuclear structure. Thus two helium nuclei cannot make a stable nuceus of beryllium—had they done so the composition of the universe would have been entirely different. The C-nucleus has an excited state at the right energy level and the same holds for energy of the O-nucleus. Had these numbers been slightly different the universe would have ended up having either too much C and no O or vice versa.

Some of these arguments may appear to spring from hindsight. However, most of them were not when Hoyle was working on the problem. Rather he used the anthropic necessity of making C and O to predict the required energy levels.

Thus the anthropic arguments start with the fact of human existence at the present level of evolution and work back to the basic laws and try to explain why their parameters have to values they happen to have.

A Critique

The proponents of the anthropic principle bring to bear several facts of human existence on the numerical ranges of physical constants of the type I mentioned earlier. Various plausibility arguments are given to say that had these ranges been different man would not be here to observe the universe theory. As Livio Grat-

[4]F. Hoyle, 1954, Astrophys. J. Suppl. **1**, 121.

ton[5] has put it, the principle 'is a *solipsistic* way of reasoning, it does not explain anything; it cannot be verified (nor falsified)'.

Let me describe some of these critical views.

By 'solipsism' Gratton means the assumption that the very existence of an unthinking being consists in being perceived. It follows from this that the condition for the existence of the whole universe is the existence of a perceiving (human) mind in some place and at some time, as we are here and now. Gratton argues that this kind of philosophy originates from the endless discussion which went on in the seventeenth century regarding primary and secondary properties of matter. It has not produced a falsifiable statement that is the hallmark of a scientific theory.

A second criticism comes from the fact that many properties of the universe—on the large or small scale—are deduced from observations that do not require the hypothesis of human existence at all. For example, how much helium is produced in the hot era of the big bang universe can be tested by observations and certain models can be ruled out, *without any recourse to the need for human beings to exist.*

The proponents of the anthropic principle often take recourse to the argument that such and such scenario is necessary to understand the harmony of nature. What exactly is the 'harmony' implied here? The aesthetic criteria have evolved over the years both regading our perception of nature and the basic laws of science. 'Could it be possible for the Nature to be as absurd as it appeared in those atomic experiments?' Wrote Heisenberg to Bohr. Yet with the development of quantum mechanics, those absurdities fell into a pattern that had its own elegance and simplicity. Thus one cannot place too much emphasis on the aesthetic criteria.

Finally, why human beings? We know very little about the existence of life in the universe. It is not certain that we are alone in the universe. More intelligent, technologically more advanced life forms may very well exist in the universe. If there is an anthropic principle for us, should there not be another similar principle for them? If the universe and its laws are fine tuned to our existence, it would be surprising if they are also fine tuned to theirs! Carrying this argument further one must conclude that

[5] L. Gratton, 1989, in *The Anthropic Principle*, eds F. Bertola and U. Curi, Cambridge, p. 101

there are no life forms radicallly different from ours in the universe. This seems a sweeping conclusion to draw!

POPPER'S CRITERION

Perhaps the most unsatisfactory feature of the anthropic principle is that it fails to meet Karl Poppers criterion of a scientific theory that it is falsifiable. The way science has progressed is through the unending chain

→ observations → interpretation → theory → experiments → observations →

in which the predictive power of theory is very important. It is not enough that theory explains only existing observations. It must make new predictions that can be tested: and the predictions must be of a nature that can be falsified. (A prediction that a coin when tossed, will fall either heads-up or tails-up, is not falsifiable).

The anthropic principle is not of this kind: it only seeks to explain what is already known in terms of its premises. An example of its limitations will suffice. Astronomers today believe that there is considerable matter in the universe that is dark, i.e. unobservable by any kind of telescope. Considerable conjecturing is going on about its composition. Can the anthropic principle *predict* what it will turn out to be?

I will end with another principle that is completely Popperian: the Perfect Cosmological Principle (PCP). This will illustrate the difference between the two principles.

The PCP says that the universe is unchanging in space and time. That means, if we sample the nearby region we should know what the universe was like a long time back and far away from here. This concept can be tested in principle by sampling a remote region and comparing it with our local neighbourhood. For example, a group of very far away galaxies should look no different from a nearby sample. The so called steady state theory of the universe was proposed by Bondi and Gold[6] from this predictive principle. They always exphasized that the strongest point in favour of the steady state theory is that it is dispovable.

[6]H. Bondi and T. Gold, 1948, Mon. Not. R. Astron Soc **108** 252

We do not find this predictive feature in the anthropic principle—with the exception of Hoyle's prediction of the excited state of the carbon nucleus—a prediction that was made *before* the anthropic principle was even enunciated!