

Reprinted from  
May-June 1970  
Volume 58  
Number 3  
pp. 290-297

# American Scientist

## The Interaction of Laboratory Science and Astronomy

J. V. Narlikar

# The Interaction of Laboratory Science and Astronomy

*Current astronomical research throws new light on well-known laws of science*

A look at the history of science through the centuries shows that a scientific theory can never be proved—it can only be disproved. Usually a theory is created when experiments and observations accumulate an appreciable number of unexplained but apparently related phenomena. A “good” theory will not only explain these phenomena but make predictions testable by further observations. If such tests support the predictions, the theory gains more acceptance. But no theory is likely to be perfect, and there may come a time when more sophisticated tests disprove the theory. Many well established theories have had to be abandoned when it was realized they could not explain all the observed phenomena. In this sense Nature has always managed to keep one step ahead of man.

*Jayant Vishnu Narlikar was born at Kolhapur, India, got his B.S. at Banaras Hindu University in 1957, and his higher degrees at the University of Cambridge. He is now on the staff of the Institute of Theoretical Astronomy at Cambridge University and is Senior Research Fellow at King's College. The Government of India honored him in 1965, and Cambridge University awarded him Smith's Prize for an essay on “Cosmological Models” and the Adams Prize for “Gravitation, Mach's Principle and Cosmology.” His scientific papers include some written in collaboration with Fred Hoyle.*

*Dr. Narlikar's research has dealt with the following aspects of cosmology: the interpretation of radio source count in the steady state cosmological model; establishing a connection between Mach's principle and the creation of matter in the universe; formulating a new theory of gravitation which explicitly takes Mach's principle into account; investigating various phenomena in relativistic astrophysics such as the gravitational collapse of massive objects, the relation of quasars to the creation of matter, the origin of cosmic rays, and the formation of galaxies; studying the connection between local electrodynamics and the large scale structure of the universe—most recently demonstrating how closely the laws of quantum electrodynamics may be connected with the behavior of the universe. Address: Institute of Theoretical Astronomy, Madingley Road, Cambridge, England.*

Observed phenomena can be classified into two categories: controlled and uncontrolled. Those in the first category include experiments that can be performed in the laboratory, where it is often possible to vary different parameters in the environment and thereby test the predictions of the theory extensively. The phenomena in the second category do not permit such freedom of maneuver. Here man can only observe events as they take place, without being able either to control them or to reproduce them in the laboratory. To obtain the maximum possible information from such phenomena often requires a great deal of patience and ingenuity on the part of the observer, and conclusions drawn from these observations do not have the degree of accuracy that one expects from a laboratory experiment.

Astronomy is based on observations of phenomena of the second category. There are few laboratory experiments that can be performed to test astronomical theories directly; they are tested almost exclusively by observations of the universe. To see the contrast between the approaches of an astronomer and a laboratory physicist, consider the following simple example. Suppose the physicist wants to test the validity of Ohm's law for conducting materials. He can examine voltages at the ends of a wire by producing different currents, and thereby confirm that the law holds over a wide range of currents. An astronomer is denied this facility by the very nature of his problem.

Suppose he wishes to test a law that relates the luminosity of a star to its mass. To begin with, he will test the law on the nearest star available, the Sun. However, this will not be enough.

To test the functional form of the law, he must examine stars of varying mass. Although the problem in principle is similar to that of Ohm's law, the practical aspects of testing it are vastly different. Since the astronomer cannot at will change the mass of the Sun and observe the consequent change in luminosity, he must use other, less direct, methods.

Because of this difference of approach, astronomy has stood apart from the rest of laboratory science. A few centuries ago there was not much laboratory science to speak of, but the interest in astronomy was considerable. Of the four known basic interactions in physics, the law of gravitation was the first to be discovered. It was inspired by and tested on the observations of astronomy. The success of the Newtonian law of gravitation in explaining the motions of the planets and satellites of the solar system provided a stimulus to laboratory physics. However, the balance then swung to the opposite side. While no dramatic progress was made on the astronomical front for a long time, laboratory experimentation made rapid advances. Discovery of the laws of electromagnetism, quantum theory, special relativity was made possible by laboratory experiments.

Over the last two decades, however, there has been a remarkable upsurge of interest in astronomy. The new, large optical telescopes and the birth of radio astronomy have considerably widened the horizons of the observing astronomer. Recent techniques in cosmic rays,  $\gamma$  rays, X rays, and infra red are also providing hitherto unexpected information about the universe. It is therefore of interest to ask whether astronomy can again

contribute toward the progress of fundamental science.

This question can be answered from two different points of view. According to one, all fundamental laws of science are to be found in the laboratory, and the astronomical observations merely provide a wider framework in which to test them. The second point of view is more radical and sees the local behavior of matter as influenced by the large-scale structure of the universe. In other words, the laboratory scientist can never isolate himself from the rest of the universe. We shall discuss these two views in turn.

#### From the local to the distant

Although with considerable ingenuity man has greatly widened the scope of laboratory experiments, he is still limited by his environment. He can test the behavior of physical laws over a range of variables within this limit; to situations beyond this range he can only extrapolate these laws. This is where astronomy makes a valuable contribution. Astronomical systems appear to contain much more extreme conditions than could ever be produced in a laboratory on the Earth. Would the laws of science, as we know them from our limited laboratory experience, work in such extreme conditions? We shall discuss some of these astronomical systems and see how far extrapolation from the laboratory has been successful.

*Motion of heavenly bodies.* From early civilizations man has looked at stars, planets, and satellites in the night sky and tried to analyze their complicated motions. The Greek astronomers saw intricate geometrical patterns in these motions. However, it was not until Newton that a real insight could be obtained into this problem. The simple inverse square law of gravitational attraction,

$$F_G = G \cdot \frac{m_1 m_2}{r^2} \quad (1)$$

in which  $m_1$  and  $m_2$  are the masses of the gravitating bodies,  $r$  is their distance apart, and  $G$  is the gravitational constant, and  $F$  the force of attraction, explained not only the drop of an apple but also these celestial motions. This was an instance of astronomy providing a testing ground for a law of physics.

Gravitation happens to be a very weak force, as can be seen by comparing the

force of gravitational attraction stated in (1) with the force of electrical attraction between two opposite charges  $e_1, e_2$ :

$$F_E = \frac{e_1 e_2}{r^2} \quad (2)$$

Both forces vary with distance as  $r^{-2}$ , but their relative strength is expressed by

$$\frac{F_G}{F_E} = \frac{G m_1 m_2}{e_1 e_2} \quad (3)$$

For an electron-proton pair this number is of the order of  $10^{-40}$ . In laboratory physics masses are small and electromagnetism dominates. In astronomy, however, we deal with large masses which are electrically neutral, and hence  $F_G$  is a dominant force. For this reason very few experiments in the laboratory deal with the law of gravitation; astronomical observations provide the bulk of evidence to test it.

A relatively recent example of this occurred when Einstein formulated the law of gravitation in his general theory of relativity. Einstein's law agrees approximately with Newton's law in the limit of weak gravitational fields. The difference between the two laws in this limit is too minute to be tested in the laboratory. The difference is detectable, however, when we consider the motion of planets in the solar system. Newtonian law predicts elliptical orbits for the planets under the influence of the Sun. These orbits are slightly distorted by the small influence of planets on one another. However, even taking these influences into account, a slight discrepancy remains in the motion of the planet Mercury. The perihelion of Mercury rotates at the rate of about 42 inches per century. (Similar but much smaller discrepancies have been found in the motions of other planets.) When Einstein's theory was applied to the motion of Mercury, the discrepancy was almost fully accounted for. Clearly the two theories differ by a very small amount in their predictions about the gravitational field in the solar system. To dramatize this difference and to test the validity of each theory we need to turn to strong gravitational fields; present laboratory techniques are quite inadequate for this. As we shall see later, astronomy is again likely to give the lead.

*Stellar evolution and nucleosynthesis.* In-

vestigations into the structure and evolution of stars provide an excellent opportunity to extrapolate laboratory laws of science to more extreme conditions. We have already seen that gravitational force becomes stronger as the mass of the object increases. With a star like the Sun the following situation arises. The Sun is made up of atomic particles, attracting one another according to the law (1). It will therefore have a tendency to shrink. The time scale for such a shrinkage is very small—of the order of an hour or so—provided there is no other force to combat gravitation. If in estimating the energy output from the Sun we argue that it comes from gravitational contraction, the Sun cannot be much older than a few million years. But the age of the Earth is a few *billion* ( $10^9$ ) years. Clearly something is wrong with this figure for the Sun. The question "What keeps the Sun shining and in a relatively stable state?" was not answered satisfactorily until it was realized that the Sun obtains its energy by burning nuclear fuel.

Briefly, what happens is this. The Sun generates nuclear energy in its interior by converting hydrogen to helium. This energy is accompanied by thermal pressures which hold the Sun in a hydrostatic equilibrium against its own gravitation. In a simple model the equilibrium equations are

$$\begin{aligned} \frac{dp}{dr} &= -\frac{GM(r)\rho}{r^2}, \quad \frac{dM(r)}{dr} = 4\pi r^2 \rho, \\ p &= \frac{R}{\mu} \rho T + \frac{1}{3} a T^4, \\ \frac{4}{3} a T^3 \frac{dT}{dr} &= -\frac{\kappa}{4\pi c} \frac{L(r)}{4\pi r^2} \rho, \\ \frac{dL(r)}{dr} &= 4\pi r^2 \rho \epsilon \quad (4) \end{aligned}$$

Here  $p$ ,  $\rho$ ,  $T$  denote pressure, density, and temperature at a distance  $r$  from the center of the Sun.  $M(r)$  is the mass interior to a concentric sphere of radius  $r$ .  $L(r)$  is the luminosity at distance  $r$ .  $R$  is gas constant,  $a$  the radiation constant,  $\mu$  the mean molecular weight, and  $c$  the velocity of light.  $\epsilon$  is the rate of generation of nuclear energy per unit volume.  $\kappa$  is opacity of the material. The first equation denotes hydrostatic equilibrium between pressure and gravitation; the second relates mass to density; while the third relates pressure to density and temperature: The fourth equation describes how

the energy generated in the interior is transferred outside. The last equation relates the energy generated to its nuclear source. The remarkable point about these equations is that they are all extrapolations of results obtained in the laboratory and that they give an accurate description of the Sun. This method can be applied to the study of other stars, and a relation can be obtained among their mass, luminosity and composition (7).

The chemical composition of a star changes as thermonuclear reactions take place inside it. Thus the star evolves, changing its radius and brightness with time. The general time scales involved in stellar evolution are very long compared to a human lifetime, and hence it is not possible to observe any given star through all its stages of evolution. It is possible, however, to observe different stars in various evolutionary stages. Although the subject of stellar evolution has by no means been fully studied, the agreement between theory and observations is very encouraging.

By changing the nuclear species inside, the star acts as a thermonuclear reactor. The extreme conditions of temperature and pressure inside a star have not yet been simulated in the laboratory. Theoretical nuclear physics tells us how nuclear reactions should proceed at temperatures of the order of  $10^6$ – $10^9$  °K. The predictions of this theory can be tested by looking at the elements formed inside stars at such high temperatures. This problem was investigated in detail by Burbidge, Burbidge, Fowler, and Hoyle (2). According to their findings it is possible to argue that, starting from the simplest element, hydrogen, the stars in their various stages of evolution are able to manufacture all the heavier elements found in the universe. Thus the elements which go into the equipment used by the laboratory scientist were at some stage or other made inside the distant stars!

One of the stages of stellar evolution that has aroused a lot of interest lately is that of the neutron star—a star which has managed to burn out all nuclear fuel. Gravitational contraction would set in here unless pressures were produced to stop it. A new kind of pressure—the so-called quantum degenerate gas pressure—becomes important at this stage. The Pauli exclusion principle tells us that we

cannot put two electrons in the same state. In a highly compressed electron gas the low energy states are filled completely, and the gas has a degenerate pressure from electrons in these states. Stars with degenerate electron gas have been known for some time and are called white dwarfs. The density of matter inside a white dwarf can be as high as  $10^8$  gms  $\text{cm}^{-3}$ . The neutron star represents a further stage of compression, when the density rises to something like  $10^{14}$  gm  $\text{cm}^{-3}$ , the highest density so far thought of by the theoretical physicist. Very little is known about the behavior of matter at such high densities, but it is no longer in the form of separate electrons and protons. Rather, these two particles merge to form the neutron. A neutron star may be half as massive as the Sun, but because of its high density its radius is only a few kilometers.

Neutron stars have not been directly observed, but the recently discovered pulsars may be neutron stars. The short period of pulses coming from the pulsars—one of which has a period of only  $1/30$  of a second—indicates that we may be dealing with highly compact objects. Since these objects are believed to be in our galaxy, neutron stars are thought to be the best candidates.

*High energy astrophysics.* In the early years of this century it was generally assumed that our galaxy was the one and only system in the universe. Bigger and better telescopes have since revealed a wealth of phenomena occurring outside our galaxy. Not only are there other galaxies like ours but there are also other kinds of objects. For instance, radio telescopes have revealed strong extragalactic sources of radio waves all over the sky. Cosmic ray observations indicate that the very high energy particles may be coming into our galaxy from outside. Recently some galaxies have been found emitting a hundred times as much radiation in the infra red region as our galaxy does in the optical region (3).

Radio sources have long posed a stiff problem to the theoretical astronomer. Looking at the various processes of electromagnetic radiation known from laboratory experience, we find that synchrotron radiation gives the best account of the radio waves in most strong sources. In this process electrons accelerated in a magnetic field

emit electromagnetic radiation. Using this theory, coupled with observed estimates of radio flux and the size of the source, we arrive at an energy reservoir of at least  $10^{62}$  ergs. This is a conservative estimate, which may be pushed up by one or two orders of magnitude. What is the nature of such a reservoir? How was it built up in intergalactic space? These questions are not yet satisfactorily answered. Indeed they are similar to those that faced the astronomer of the twenties who was trying to account for the Sun's energy reservoir. But now the orders of magnitude involved are much bigger, and nuclear energy does not appear to be the correct explanation.

The situation in respect of strong radio sources was made more dramatic by the discovery of quasi-stellar objects about seven years ago (4). These are highly compact and highly luminous (in radio or optical regions, or both), usually with large redshifts. Like the radio sources, the quasi-stellars are also enormous reservoirs of energy. Their compact nature suggests that gravitation may be a very important force in them. We have already noted that in the Sun gravitation is strong enough to balance the pressure produced by nuclear reactions. In a quasistellar, the mass involved may be a million times that of the Sun. At this level there is no known physical interaction which can satisfactorily cope with gravitation. What happens to such an object eventually?

*Gravitational collapse.* Simple Newtonian gravitation suggests that the object would begin to shrink. Einstein's more sophisticated general theory of relativity points to the same conclusion. This phenomenon is known as gravitational collapse. We have already noted the similarity between Newton's and Einstein's theories in case of a weak gravitational field. As the object contracts, its gravitational field rises. According to Einstein's theory the following situation develops. Suppose we station an observer, A, on the surface of the collapsing object (assumed to be spherical) and another observer, B, at a great distance from the object. As the object shrinks the gravitational field rises in the neighborhood of A but remains more or less constant in the neighborhood of B. Since according to general relativity the geometrical prop-

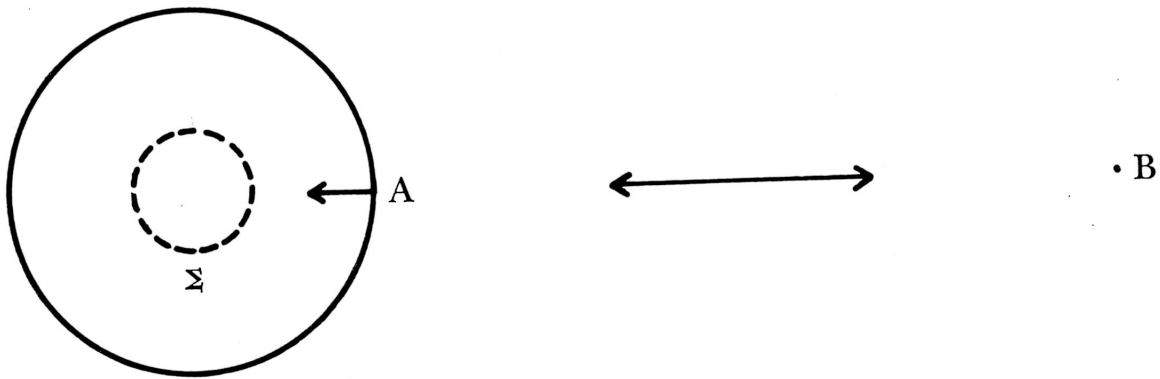


Fig. 1. Gravitational collapse. Observer A is situated on the surface of the collapsing object while the distant observer, B, is stationary. Signals sent by A at regular intervals reach B at successively longer intervals, as A approaches  $\Sigma$ , the Schwarzschild barrier. Once A crashes through the barrier, his signals no longer reach B.

erties of space-time are related to the gravitational field, these properties would be different at A and B. One way of describing this effect is through signal communication between A and B. If A sends out light signals to B at regular intervals according to his watch, B will receive them at successively longer intervals according to his own watch. Theoretically, there is a barrier such that if A penetrates through it his signals will no longer be received by B. This barrier is described by a sphere concentric with the object and having a radius

$$R_s = \frac{2GM}{c^2}, \quad (5)$$

where  $M$  is the mass of the object and  $c$  the velocity of light.  $R_s$  is called the Schwarzschild radius. Normally most objects have physical dimensions which greatly exceed their Schwarzschild radius. For the Sun, the actual radius is  $\sim 700,000$  km, whereas the Schwarzschild radius is only about 2 km. So these curious effects do not arise. However, in the very massive objects undergoing gravitational collapse these effects are bound to arise if we carry the interpretation of this theory to its logical conclusion.

There are two factors, however, which make one doubt whether the predictions of general relativity are valid in the extreme situation contemplated above. The first factor is theoretical and arises from the ultimate fate of observer A. It can be shown that in a finite time observer A will arrive at

a space-time singularity. This happens when the object has shrunk to a point. The density and the gravitational field become infinite and the geometrical properties of space-time break down. The appearance of singularities in a physical theory suggests inconsistency and room for improvement. The explanation that the fate of A will be unobservable by an outside observer like B after A has gone through the Schwarzschild barrier is not a very satisfactory one, since A himself is a physical observer and meets his doom in a comparatively short time.

The second factor is observational. If the gravitational field is attractive right to the end, we should be able to see signs of "implosion" in the very massive objects observed in the universe. The observations to date indicate the exact opposite. Such objects show outward motion near their center. Does this mean that gravitation becomes repulsive at some stage? If the observations continue to show this trend we may have to revise not only the law of gravitation but many other basic ideas in theoretical physics.

**Cosmology.** The biggest extrapolation of laboratory science was attempted when the general theory of relativity was applied to study of the structure of the universe as a whole. Models constructed by Friedmann (5) and by Robertson (6) and Walker (7) assumed large-scale homogeneity and isotropy. Under these assumptions the geometry of the universe is described by the line element

$$ds^2 = c^2 dt^2 - S^2(t) \left[ \frac{dr^2}{1 - kr^2} + r^2 (d\theta^2 + \sin^2 \theta d\phi^2) \right], \quad k = 0, \pm 1, \quad (6)$$

where the spherical polar coordinates

$r, \theta, \phi$  describe a typical galaxy (regarded as a point), and  $t$  is cosmic time.  $S(t)$  denotes a scale factor. If  $k = 0$  and  $S(t) = \text{constant}$ , we have the simple universe of special relativity and Euclidean geometry. The presence of matter in the universe, however, does not permit this solution. Instead we find that  $S$  varies with  $t$  and is at present an increasing function of  $t$ . This is loosely described by the statement that the universe is expanding.

In such a model if we consider light of wavelength  $\lambda$  as leaving a distant galaxy at the epoch  $t_1$  and arriving at the Earth at the present epoch  $t_0$ , its wavelength at reception is given by

$$\lambda + \Delta\lambda = \lambda \cdot \frac{S(t_0)}{S(t_1)} \quad (7)$$

If  $S(t)$  is an increasing function of  $t$ ,  $\Delta\lambda > 0$ , and all waves from such a galaxy are increased in wavelength by a factor  $(1 + z)$ , where

$$z = \frac{S(t_0)}{S(t_1)} - 1 \quad (8)$$

is called the "redshift." This prediction was in agreement with the redshifts actually being observed by Hubble (8) forty years ago. Moreover, the Hubble law

$$z = \frac{H}{c} D, \quad (9)$$

where  $D$  is the distance of the galaxy and  $H$  a constant, could also be accounted for by the theory.  $H$  is called Hubble's constant, and  $H^{-1}$  has the value  $\sim 10^{10}$  years.

If we follow the behavior of  $S(t)$  backward in time, we arrive at an epoch when  $S = 0$ . This is a singular epoch, when density of matter and of radiation was infinite. In fact the

singularity encountered here is very similar to that discussed earlier in connection with massive objects. In the case of the universe this epoch is identified with that of creation. The laws of science do not apply at  $S = 0$  but only at  $S > 0$ . The high density of matter and radiation, and the rapid rise in  $S$  just after  $S = 0$ , are expressed in popular language by the statement that the universe originated in a big bang.

*A big-bang universe?* The mathematical objections to singularity can be raised in this case too. There are also physical reasons why the big-bang models are not entirely satisfactory. One is the apparently low "age" of such a universe. The time elapsed since the big bang can be calculated and turns out to be less than  $H^{-1}$  i.e.  $10^{10}$  years. The age of our own galaxy is estimated at higher than this figure, and galaxies older than our own are also believed to exist. Either something is wrong with these age determinations or the constant  $H^{-1}$  may be in need of revision. Failing such corrections, we must discard the big-bang models. There are other physical objections to the models, which we shall discuss later.

Hence some cosmologists have looked for models of the universe which do not depend on the concept of a big-bang origin. These require a departure from general relativity. We shall describe one such model later. The interesting point to note is that astronomical observations and theory have reached a stage where the laws in the laboratory can be applied to distances of the order of  $10^{28}$  cms and time scales of the order of  $10^{10}$  years!

From the distant to the local

We come now to the second point of view mentioned earlier. To what extent is the local behavior of matter influenced by the large-scale structure of the universe? The experimental scientist working within the confines of his laboratory may regard the whole concept as ludicrous indeed. However, certain developments in theoretical physics which we shall describe tend to suggest that the influence of the universe on locally observed phenomena is not trivial. Two of these developments came well before cosmology was established as a branch of science.

*The Olbers paradox.* Why is the sky dark at night? This question was

raised by Olbers (9) in 1826. The simple answer, that we are facing in a direction opposite to that of the Sun, is not sufficient—as the following calculation will show.

Suppose in a static Euclidean universe we have a uniform density  $n$  of bright objects, each with luminosity  $L$ . Then the number of such objects in a shell of inner radius  $R$  and thickness  $\Delta R$ , with the Earth as the center, is

$$4\pi R^2 \Delta R \cdot n, \quad (10)$$

while the light received from each such object is

$$L/4\pi R^2 \quad (11)$$

by the inverse square law. The total light from all objects in the shell is therefore the product of (10) and (11), i.e.

$$\Delta R \cdot L \cdot n. \quad (12)$$

The result is remarkable in that (12) does not depend on the radius of the shell. Clearly, if we add the contributions from all such shells in an infinite universe, the brightness of the sky should be infinite! So our orientation relative to the Sun should not matter!

This paradox, known as the Olbers paradox, was in fact raised even before Olbers, by Halley (10) in 1720. No satisfactory resolution of the paradox could be obtained until the modern developments in cosmology. For instance, if we argue that the radiating objects are of finite size and therefore the nearer ones would block the radiation from the more distant ones, we do arrive at a finite result. The sky brightness then corresponds to that of each radiating object. If we take the Sun as a typical radiating object, the sky brightness would correspond to a temperature of some 6000 °K!

If, however, we use the Hubble law (9), we find that the light from a distant galaxy is diminished by a factor

$$(1 + z)^{-2} \quad (13)$$

over and above the inverse square law (11), where  $z$  is the redshift of the galaxy. The sky brightness then does turn out to be very small, and our orientation relative to the Sun becomes important.

The origin of the Olbers paradox, and its resolution, indicate that we cannot ignore the presence of the universe even in a discussion of the local environment.

*Mach's principle.* We are accustomed to the concept that inertia is a property of matter, and express this quantitatively by the mass we ascribe to any piece of matter. The concept itself dates back to Galileo, but is expressed formally by Newton's laws of motion. The first law states that an object will continue to be in a state of rest or of uniform motion unless some external force acts on it. That the amount of the change of motion, the acceleration, caused by a given force is inversely proportional to the mass of the object is the second law, which may be written in the form

$$\mathbf{P} = m\mathbf{f}. \quad (14)$$

Here  $\mathbf{P}$  is the applied force,  $\mathbf{f}$  the acceleration produced, and  $m$  the mass of the object. The more "inert" the object, the greater will be the force required to budge it.

In formulating the laws of motion Newton encountered a difficulty with regard to the frame of reference. To measure the velocity and acceleration of the object we need a frame of reference within which we can note down the displacement of the object at successive times. Suppose we call this  $S_0$ , and write the law (14) in this frame. If, however, we decide to use another frame of reference,  $S_1$ , which has an acceleration  $\mathbf{a}$  relative to  $S_0$ , our law of motion relative to  $S_1$  will be

$$\mathbf{P}_1 = m\mathbf{f}_1, \quad (15)$$

where  $\mathbf{P}_1$  and  $\mathbf{f}_1$  relate to  $S_1$ . But we also have

$$\mathbf{f} = \mathbf{f}_1 + \mathbf{a}, \quad (16)$$

so that for consistency we need

$$\mathbf{P}_1 = \mathbf{P} - m\mathbf{a}. \quad (17)$$

Thus if we want to use a new frame we must "correct" the force by adding to it an extra term,  $-m\mathbf{a}$ . Since this extra term depends on the mass of the object, Newton called it the inertial force. He argued that the second law (14) works in a special frame of reference  $S_0$ , and in all frames which are *unaccelerated* relative to it.  $S_0$  may be identified with Newton's absolute space and time, and all other frames which are unaccelerated relative to  $S_0$  are called "inertial" frames. A frame like  $S_1$ , which requires an inertial force correction, is called a noninertial frame.

To give an example, consider a stone tied to a string and whirled around in a circle. If we look at the stone in the

frame  $S_0$ , we see it going round in a circle and therefore accelerated toward the center. The force responsible for this acceleration is the tension in the string. Suppose we now look at the situation in another frame,  $S_1$ , in which we move with the stone.

Clearly the stone is unaccelerated in the frame. It still has the force of tension. To be consistent, we need an equal and opposite force. This is the so-called centrifugal force which is directed outward from the center of the circle.

*What is an inertial frame?* It appears therefore that  $S_0$  and other inertial frames have some special status. What is it that singles out these frames from all others? This remained a mystery at the time of Newton. Later astronomical observations however led, as we shall see, to the discovery of a remarkable coincidence about  $S_0$ .

There are two ways of measuring the Earth's rotation. One way is to argue that it is rotating relative to  $S_0$  and therefore a frame of reference fixed on the Earth would be noninertial. In that case inertial forces are called in. The influence of these forces can be detected in various ways. For example, if we set up a Foucault pendulum, we notice that its plane of oscillation rotates with an angular velocity

$$\Omega = \omega \sin \lambda \quad (18)$$

where  $\lambda$  is the latitude of the place of observation and  $\omega$  the angular velocity of the Earth relative to  $S_0$ . Knowing  $\lambda$  and  $\Omega$ , we determine  $\omega$ .

The second method depends on astronomical observations. We can measure the Earth's rotation about its axis relative to distant stars. The coincidence is that the angular velocity measured by this method is the same ( $\omega$ ) as that obtained by the first method. The two methods are, however, very different and apparently unconnected. The second depends on very distant parts of the universe, whereas the first involves a laboratory experiment.

The conclusion to be drawn is that *the frame  $S_0$  is determined by the distant objects in the universe*. This resolves, to some extent, the mystery associated with the special status of  $S_0$ . However, it also introduces a new feature. To give a consistent picture of Newton's

laws of motion we need the background of the distant parts of the universe.

Great significance was attached to this observation by Mach in the last century. He argued that the concept of inertia, which can be quantified by Newton's second law of motion, has a status solely because of the background provided by the universe. If there were no background, we could not identify  $S_0$  in preference to other frames. Consider a single object in an otherwise empty universe. In the absence of any force Newton's law would become

$$m\mathbf{f} = 0. \quad (19)$$

If we conclude from this that  $\mathbf{f} = 0$ , we find the object moving with uniform motion relative to  $S_0$ , which now has no other means of identification. Mach argued that the correct conclusion to be drawn from (19) is  $m = 0$ .  $\mathbf{f}$  is then indeterminate.

This conclusion implies that inertia is somehow related to the background produced by the universe. Remove the background, and the inertia disappears! So the inertia is not just a property of matter, as is usually assumed.

This idea is known as Mach's principle (17). It was not stated in a quantitative form by Mach, although others have since attempted to do so in various ways. I shall not go into the details of the various approaches to Mach's principle, but rather emphasize the difference between the Machian point of view and that usually adopted by the laboratory scientist. By relating the inertia of matter to the distant parts of the universe, Mach destroyed the purely local character of the laboratory. Because of this revolutionary outlook, his principle has remained a matter of controversy.

Although Mach's principle concerns inertia, the concept is capable of generalization. A striking application of it to another branch of physics—the electromagnetic theory—is discussed below.

*The absorber theory of radiation.* There are two ways of describing the electromagnetic interaction between charged particles. The better known method makes use of the concept of an electromagnetic field. Suppose we have two electric charges,  $a$  and  $b$ . The move-

ment of  $a$  causes disturbances in the ambient field. These disturbances travel outward from  $a$  with the speed of light  $c$ . If the charge  $b$  is at a distance  $r$ , it will experience these disturbances after a time  $r/c$ . Similarly the disturbances caused by the motion of  $b$  influence  $a$  after an interval  $r/c$ .

The motion of these disturbances in the field is described mathematically by *retarded* waves. The underlying equations are those of Maxwell and Lorentz. The field concept, ever since its origin in the latter half of the last century, has been very successful in describing the experimental data in electrodynamics. For this reason it has overshadowed the other method, which in its crude form came much earlier.

According to the second method the electric charges interact directly with one another. The law of interaction formulated by Coulomb was stated in equation (2), and resembles Newton's law of gravitation as stated in (1). However, this law assumes instantaneous interaction at a distance; it requires influences to travel at infinite speed. With increasing experimental data on rapidly moving electric charges, it became clear that the Coulomb law was not correct. One reason can be seen in the conflict with special relativity, which requires physical influences to travel at most with the speed of light. The law of action at a distance had therefore to be reformulated so that the interactions no longer traveled with infinite speed. Although Gauss had suggested the need for reformulation along these lines as early as in 1845, the solution of the problem had to wait until the present century. By that time the field concept had been well established, however, and interest in the second method had dwindled considerably.

Moreover the reformulation, as given by Schwarzschild (12), Tetrode (13), and Fokker (14), ran into further difficulty, which can be described as follows. Suppose in the case of the two charges  $a$  and  $b$  the action from  $a$  to  $b$  travels with the finite speed of light. Thus if  $a$  is set in motion at time  $t = 0$ , the action is felt by  $b$  at time  $t = r/c$ . This action of  $a$  on  $b$  must, however, be accompanied by an equal and opposite reaction of  $b$  on  $a$ . Such a reaction must travel backward from  $b$  to  $a$  not only in space *but also in time*. The reaction therefore starts at  $b$  at  $t = r/c$  and arrives at  $a$

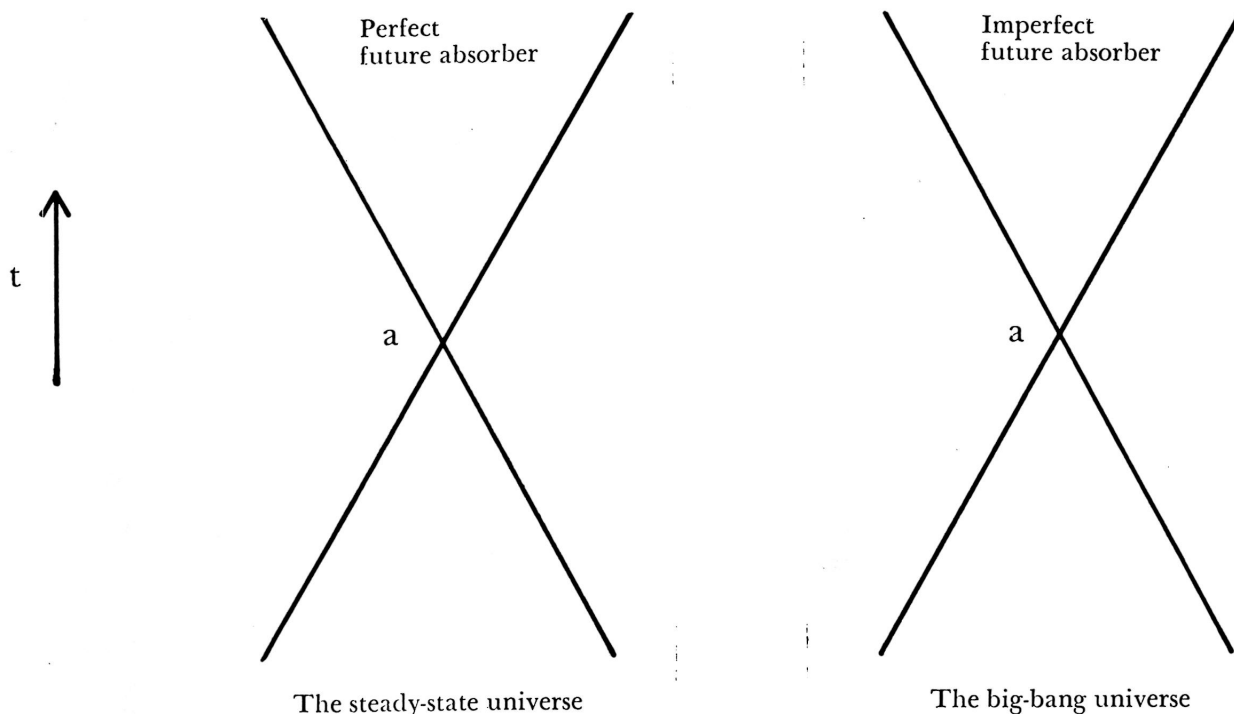


Fig. 2. Reaction from the universe. In the steady-state universe there is enough matter in the future absorber to produce the correct reaction. In a typical ever-expanding big-bang model the future absorber has vanishingly small density of matter as  $t \rightarrow \infty$  and hence does not produce the correct reaction.

at time  $t = 0$ . Since it is traveling *backward* in time, this reaction is described mathematically by *advanced* waves. Thus the theory is symmetric with respect to advanced and retarded waves. If, for example, we describe symbolically the retarded disturbance originating from charge  $a$  by  $F_{\text{ret}}^{(a)}$ , and the advanced disturbance by  $F_{\text{adv}}^{(a)}$ , the theory predicts that the charge  $a$  in fact radiates

$$\frac{1}{2}[F_{\text{ret}}^{(a)} + F_{\text{adv}}^{(a)}]. \quad (20)$$

We observe, however, only retarded disturbance,  $F_{\text{ret}}^{(a)}$ , when  $a$  is set in motion, and this is consistent with causality. The result (20) as given by the reformulated theory therefore appears to be wrong. Advanced and retarded solutions arise also in the first method, but there a freedom of choice is available to reject the advanced solutions. This choice is not

available in the second method where charges interact directly.

*Backward in time.* It was shown in 1945 by Wheeler and Feynman (15) that the second method is capable of giving the right answer if we take into account the influence exerted by the universe. In our example above we have already noted that if charge  $a$  is set in motion at  $t = 0$ , it receives reaction from  $b$  at  $t = 0$ , no matter what the distance of  $b$ . Thus in principle all the distant charges in the universe will send their reaction at  $t = 0$ . It therefore becomes necessary to take into account the large scale structure of the universe. Wheeler and Feynman performed their calculation for a static Euclidean universe with a uniform distribution of electric charges of both kinds. They found that the reaction from the universe can be described by

$$R^{(a)} = \frac{1}{2}[F_{\text{ret}}^{(a)} - F_{\text{adv}}^{(a)}]. \quad (21)$$

When (21) is added to (20) it gives the correct answer. Further, the reaction exerted by the universe on charge  $a$  is observable in a laboratory experiment. This is because the theory requires that a charge not interact

with itself. Therefore the motion of  $a$  will not be affected by (20) but only by (21). It is well known that an accelerated electric charge radiates electromagnetic waves and hence suffers a damping of its motion. This effect is usually described as the radiation reaction. In the above theory the damping occurs through the reaction force (21) from the universe. We therefore have another example of the universe directly influencing a laboratory experiment.

*The right type of universe.* We may ask: "What does this tell us about the structure of the universe?" If we accept the evidence that the universe is expanding, we must do the Wheeler-Feynman type of calculation in an expanding universe. This has been performed (16, 17), with the following interesting results.

For the theory to work, the universe must send back the appropriate reaction stated in (21). It is able to do this provided it absorbs all the retarded disturbances from charge  $a$  and the other charges excited by  $a$ . In other words the universe must be a perfect absorber in the cone which the

light rays from  $a$  generate as they go into the future. (All retarded influence of  $a$  is confined to the interior of this cone.) Does an expanding universe satisfy this requirement? None of the big-bang models we have discussed does. The reason is that as the universe expands its density diminishes, and hence there is less and less matter in a given volume as we go into the future. Thus there simply is not enough matter to fulfil the requirement of perfect absorption.

A model of the universe which does meet this requirement is the so-called "steady-state" model (18, 19). In this the universe expands according to

$$S(t) = e^{Ht}, \quad (22)$$

but its density remains constant. This is achieved by a continuous creation of matter. This universe has no big-bang origin and therefore no singularity. It has no beginning, no end, and as the name indicates, it presents the same large-scale view at all times. Such a model cannot be obtained from Einstein's equations without some modification of the existing ideas on matter and energy. However, the steady-state model provides enough density of matter in the future to ensure perfect absorption.

Thus if we adopt the theory of direct particle interaction we arrive at the conclusion that the observed electromagnetic phenomena in the laboratory are related to the large-scale structure of the universe. A big-bang universe is not consistent with the observed results of laboratory experiments, while the steady-state model is.

*Quantum theory.* These ideas have recently been extended to quantum electrodynamics (20). To give one example, consider the transitions of atomic electrons under the influence of electromagnetic radiation. It is well known that under radiation of the appropriate frequency the electron can make upward or downward transitions between the various energy levels. These are called induced transitions. Besides these, the electron also makes *spontaneous* transitions, even when there is no external radiation present. *Such transitions are always downward.* These are accompanied by the emission of electromagnetic radiation. These latter transitions are more difficult to understand. In the direct particle theory what happens is this. A quantum analogue of the response

(21) from the universe causes the electron to jump down. In the process it emits radiation which is absorbed by the universe and which evokes a response from the universe. Thus we have to work in a self-consistent cycle of arguments in which cause and effect are not directly separable. The main result that emerges again is that the universe must act as a perfect absorber in the future in order to produce the required response.

### Conclusion

The examples given above relate some of the current scientific theories to astronomical phenomena. In spite of their limitations and uncertainties, the astronomical observations have widened the scope of the laboratory scientist. The various astronomical systems provide conditions much more extreme than could be produced on the Earth, and indicate to what extent the laws of science are still applicable. This extrapolation has been largely successful, although there are now a few indications that some of the laws need revision. These suggestions must be substantiated by further observations before the laboratory scientist is convinced that a change is indeed necessary. For this reason future developments in observational astronomy will be of great interest.

The Machian idea that the local behavior of matter is intimately connected with the large-scale structure of the universe is, however, more startling to the laboratory scientist than any peculiar behavior of a particular astronomical system. He will accept such a point of view only if it is demonstrated that theories based on this concept work more satisfactorily than the purely local theories. We have seen above how the concept works in the description of electromagnetic phenomena. The local description of electrodynamics is known not to be entirely satisfactory. If the global description works better it must be preferred, by extension of the principle of "survival of the fittest" to scientific theories. Whatever the fate of these ideas, their evolution represents the most direct impact of astronomy on science.

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