5 Astronomy and Laboratory Physics

J. V. Narlikar

Introduction

A look at the history of physics through the centuries shows that a physical theory can never be proved — it can only be disproved. Many well established theories had to be abandoned when it was realized that they could not explain fully the observed phenomena. In this sense Nature has always been one step ahead of man.

The observed phenomena can be classified into two categories — the controlled and the uncontrolled. The phenomena in the former category include experiments that can be performed in the laboratory. In such experiments it is often possible to vary different parameters in the environment, and thereby to test the predictions of a theory extensively. The phenomena in the second category do not permit such freedom of manoeuvre. Here man can only watch events as they occur in Nature, without being able to reproduce them in the laboratory. Such phenomena are found in astronomy. To obtain the maximum possible information from such phenomena requires a great deal of patience and ingenuity on the part of the observer. Also, the observed results do not have the same degree of accuracy that one expects from laboratory experiments.

For this fundamental difference, astronomy has stood apart from laboratory physics, although both have contributed and will contribute towards the progress of fundamental physics. A few centuries ago, laboratory physics was practically nonexistent, and the theories of physics were tested on the astronomical observations. Since then the balance has swung in the opposite direction. While no dramatic progress was made in the astronomical techniques, the science of laboratory experimentation made rapid advances. Thus it was that while Newton's law of gravitation arose because of astronomical observations, the Maxwell equations, the theory of relativity, the quantum theory, all have been contributed by laboratory experiments.

Over the last two decades, however, observational astronomy has prospered remarkably. The use of new and big optical telescopes and the birth of radio astronomy have considerably widened the horizons of the observational astronomer. Moreover, recent techniques in cosmic rays, γ-rays and X-rays also promise to add to our information about the universe. It is therefore of interest to ask whether astronomy can again contribute towards the progress of fundamental physics.

We follow the discussion from two points of view. According to one point of view theoretical physics is guided by laboratory experiments alone, and the astronomical observations merely provide a wider framework in which to test the laws obtained in the laboratory. The second point of view is that we cannot talk of laboratory physics in isolation; and that the behaviour of the local system is influenced by the universe in a non-trivial manner. We shall consider the two points of view in that order.

From the Local to the Distant

Although with considerable ingenuity man has greatly widened the scope of the laboratory experiments, he is still limited by his environment. Thus he can test the behaviour of physical laws over a limited range of variables and then rely on an extrapolation of these laws to conditions outside the range of his experiments. This is where astronomy can make a valuable contribution. Because of the vast dimensions of space and time involved in the astronomical phenomena, we have an opportunity of testing the various laws of physics in situations that cannot be achieved in the laboratory. Below we shall discuss some of these situations and see how far the extrapolation from laboratory has been successful.

(i) *Motion of heavenly bodies* — As mentioned before, astronomy provided an excellent testing ground for Newton's laws of gravitation. The simple inverse square law

$$F = G\,\frac{m_1 m_2}{r^2} \tag{1}$$

which explains the drop of an apple, can also account for the motions of planets and satellites which so much puzzled the early Greek astronomers. Because of the weak nature of the gravitational interaction it has not been possible to test this law in the laboratory as extensively as for instance Coulomb's law could be tested. The big masses of astronomical objects generate appreciable gravitational forces. Indeed, gravitational force is the major known force considered in the motion of stars and galaxies.

Although the law given by (1) worked very well in astronomical dynamics, the first hint that all is not well came also from astronomical observations. Newton's law predicts that planets, moving under the attraction of the Sun, follow elliptical orbits. These orbits are slightly disturbed when the interaction between planets is taken into account. The paths of the planets as predicted by the theory can be compared with the observed data. A slight discrepancy was noticed in the case of planet Mercury. A rotation of some 42″ per century of the perihelion of Mercury could not be accounted for. The discrepancy could, however, be explained by Einstein's general theory of relativity. In general the differences between the predictions of the two theories is so minute that laboratory experiments are difficult to devise to differentiate between them. The above example shows how astronomy can be useful under such circumstances. [There are two other astronomical tests which distinguish between Newton's and Einstein's theories. These are the bending of light by a massive object and the redshift of light waves travelling from strong to weak gravitational fields. But the actual observations are not accurate enough.]

(ii) *Stellar evolution and nucleosynthesis* — The structure and evolution of stars provides an excellent example of the difference between laboratory science and astronomy. In the laboratory gravitational force is weak while the nuclear force is strong. The two are, however, comparable in a star. In fact the question 'What keeps the Sun shining?' could not be answered until it was realized that the Sun obtains its energy by burning nuclear fuel.

In a simple model of the Sun, its equilibrium equations are

$$\frac{dp}{dr} = -\frac{GM(r)\rho}{r^2}, \qquad \frac{dM(r)}{dr} = 4\pi r^2 \rho,$$

$$p = \frac{R}{\mu}\,\rho T + \tfrac{1}{3} a\, T^4, \qquad (2)$$

$$\tfrac{4}{3} a T^3 \frac{dT}{dr} = -\frac{K}{4\pi c} \cdot \frac{L(r)}{4\pi r^2}\,\rho,$$

$$\frac{dL(r)}{dr} = 4\pi r^2 \rho \epsilon.$$

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 shows how the energy generated in the Sun is transferred from inside to outside, while the last equation relates the energy output to the nuclear energy source. The remarkable point about these equations is that they are the extrapolations of results obtained in the laboratory, and that their solution gives a very accurate description of the Sun!

This method has been applied to other stars to obtain the relations between their mass and luminosity and mass and radius. The results depend naturally on the chemical composition of the star. This changes as the star burns its nuclear fuel. Thus a star evolves with time, changing its luminosity and radius. Although the change in a given star during man's lifetime is very small, different stars in various evolutionary stages have been observed. The agreement between theory and observation is encouraging enough to justify the application of laboratory physics to astronomy.

By changing the nuclear species inside, the star acts as a thermonuclear reactor. The extreme conditions of temperature and pressure in the star have not yet been simulated in the laboratory. Stars in different stages of evolution provide us with information about the working of different thermonuclear reactions. The predictions of the theory can be tested by comparing the calculated abundances of different elements with the observed ones. The problem was first considered in detail by Burbidge, Burbidge, Fowler and Hoyle (1957).

(iii) *High energy astrophysics* — The high energy phenomena in astronomy provide even more extreme conditions than those found in the stars. Here the extrapolation of laboratory physics has not been so successful. For example, we are as yet not able to account for the energy reservoirs of strong radio sources. Synchrotron process gives the best explanation of this type of radio emission. Using the synchrotron theory and the observed estimates of radiation flux, we can estimate the energy in the source in the form of magnetic field and the charged particles. Taking into account various efficiency factors, we arrive at a required reservoir in the region of 10^{62} erg. for a strong radio source. How is such a reservoir built up? Here we are in the same position that the astrophysicists were in, when they were trying to account for the energy generation in stars before the advent of nuclear physics.

The situation in respect of strong radio sources was made more dramatic by the discovery of quasi-stellar objects. These are highly compact, highly luminous (in radio or optical region or both) objects with usually large redshifts. If we interpret the redshifts as cosmological, these objects must be very distant. We then have to explain enormous reservoirs of energy (of the order of 10^8 solar masses) in very compact forms. Severe difficulties are encountered when we take into account the rapid fluctuation of energy output from these objects. In some cases the time scale is of the order of a few days. This sets an upper limit to the size of the object since we do not expect the disturbance to travel faster than light. Thus in some cases we may be dealing with objects of linear size 10^{16}-10^{17} cms only! These difficulties have prompted some to suggest that these objects are not so distant. Their redshift could be due to Doppler effect if they were thrown out in an explosion or to the presence of strong gravitational fields. In the latter case, very large redshifts ($z \sim 2$ in some cases) point to the radius of the object being close to its Schwarzschild radius. Such a situation has not been encountered in other massive objects in astronomy, let alone in the laboratory. It would be interesting therefore to investigate whether general relativity remains valid under such extreme conditions.

Observations of cosmic rays, γ-rays and X-rays from astronomical objects provide information about elementary particle physics at high energies. Particles of energies far higher than those produced in the laboratory accelerators are observed in cosmic ray showers. Many of these observations have not been understood in terms of what is known in the laboratory. The problem of the origin of cosmic rays still remains a mystery.

(iv) *Cosmology* — The biggest extrapolation of laboratory physics was attempted when the general theory of relativity was employed to construct models of the universe. Models considered by Friedmann (1924) and by Robertson (1935) and Walker (1935, 1936) assumed large scale homogeneity and isotropy. Under these assumptions the geometry of the universe is described by the line element

$$ds^2 = c^2dt^2 - S^2(t)\left[\frac{dr^2}{1-kr^2} + r^2\,(d\theta^2 + \sin^2\theta d\phi^2)\right], k = o, \pm 1, \quad (3)$$

where r = constant, θ = constant, ϕ = constant denote the world line of a typical galaxy, and t is the cosmic time. The surfaces t = constant are homogeneous and isotropic. $S(t)$ denotes a scale factor. The light from a distant galaxy is redshifted, a fact which can be interpreted in these models by saying that $S(t)$ increases with t. An increase of $S(t)$ with t is loosely described as the expansion of the universe.

These models were successful in accounting for Hubble's law for small redshifts :

$$Z = \frac{H}{c} D, \quad (4)$$

where Z is the redshift from a galaxy at distance D and H is Hubble's constant. The value of H could not be determined by Einstein's equations. It could, however, be related to the mean density of matter in the universe.

These models suffered from one drawback. They had a singular state at $S = 0$. Since this corresponds to a singularity of space time, all physical processes, as we know them, break down at this instant. Some interpret this moment as the moment of creation. According to them physics operates only from $S > 0$. Others assume that a way of avoiding this state would eventually be found — perhaps through a modification of physical laws at very high densities. Neither point of view can be regarded as satisfactory.

From the Distant to the Local

We now return to the second point of view mentioned in the introduction. To an experimental physicist working within the confines of his laboratory the idea that his experiments are influenced by the behaviour of the universe may seem ludicrous indeed. Below we shall consider certain developments in physics which tend to suggest that the role of the universe in the behaviour of local phenomena may be non-trivial. Two of these developments came well before cosmology was established as a science.

(i) *The Olbers Paradox* — Why is the sky dark at night? This question was raised by Olbers in 1826. According to Olbers' calculations it appeared that the sky brightness should be enormously high — so high in fact that whether we were facing the Sun or not made no difference. This can be seen from the following simple argument.

In a static Euclidean universe with a uniform density n of bright objects, each of luminosity L, the flux of light received from objects located between distances R and R + dR is,

$$4\pi R^2 dR . n . \frac{L}{4\pi R^2} = nLdR. \tag{5}$$

Thus the total flux from all bright objects in the universe would be infinite! A more careful calculation taking into account the finite size of each object gives a finite result. The sky brightness is then the same as that on the surface of each object. If a typical bright object is like the Sun, the sky brightness would correspond to a temperature of $\sim$ 6000°K!

This paradox — known as the Olbers paradox — was in fact raised long before Olbers by Halley (1720). A satisfactory resolution of the paradox had to wait until the concept of the expanding universe. In the models described in the last section, the flux received from an object of distance $R = rS(t)$ is not $L/4\pi R^2$ but,

$$\frac{L}{4\pi R^2(1+z)^2} . \tag{6}$$

Thus the redshift factor in the denominator cuts down the radiation from distant objects faster than the inverse square law, and is responsible for convergence. The sky brightness contributed by the universe then turns out to be very small and consistent with the observations.

The Olbers paradox clearly demonstrates how our local environment can be controlled by the universe.

(ii) *Mach's principle* — In the last century Mach put forward the controversial idea that inertia is not the intrinsic property of matter, but is the effect of the background provided by the distant matter in the universe.

Mach was led to this concept through his criticism of Newton's laws of motion. Newton's second law of motion provides a quantitative expression for the inertia of matter — a concept which dates back to Galileo. This law is written in the form

$$P = mf \tag{7}$$

and states that the force P acting on a material body of mass m produces the acceleration f. The mass m measures the inertia of the body. The more 'inert' the body the greater is the force needed to provide a given acceleration.

In formulating the laws of motion Newton encountered the difficulty of a reference frame. Suppose (7) is true when the motion is measured relative to a reference frame S_0. Then relative to a reference frame S_1 which has an acceleration a with reference to S_0, the law would become

$$P - ma = mf_1 \tag{8}$$

where f_1 is the acceleration measured relative to S_1. Thus extra terms appear in the law of motion, suggesting that S_0 has some special status. Newton postulated that such a special reference frame does indeed exist and called it the absolute space. All frames with $a = 0$, in uniform relative motion with respect to S_0 are called inertial frames. The frames like S_1, with $a \neq 0$ are called non-inertial frames. These can always be detected through the presence of the extra term $- ma$ in the law of motion. This extra force being dependent on the inertia of the body, is called the inertial force. Newton describes the well known 'bucket experiment' in this connection.

Although S_0 was so postulated the mystery remained as to why such a special frame should exist at all. The mystery was heightened by another astronomical observation — that of measurement of Earth's rotation. This can be measured relative to S_0 by the Foucault pendulum. The value is the same as that measured relative to the background of the distant objects in the universe!

Mach argued that this observation has deep significance. It tells us that S_0 is determined by the background of the distant objects in the universe. Since S_0 is essential for the quantitative description of inertia through (7), Mach concluded that the concept of inertia is somehow connected with the background. If there were no background there would be no inertia.

These ideas are designated by the name 'Mach's principle'. It is not our intention to go any deeper into this principle at present. Rather we would like to emphasize the difference between the Machian point of view and that discussed in the previous section. The concept of inertia and inertial frames plays a vital role in most laboratory experiments. In stating that these are determined by the behaviour of the universe at large distances Mach destroyed the purely local character of the laboratory. Because of this revolutionary outlook Mach's principle has remained a matter of controversy.

Although Mach's principle is about inertia, the concept that the universe interferes in local affairs is capable of generalization. Below we discuss a striking example of this concept in another branch of physics — the electromagnetic theory.

(iii) *The absorber theory of radiation* — There are two ways of describing the electromagnetic interaction beween charged particles. In one the electric charges influence one another through the medium of the electromagnetic field, the influences travelling through the field at the speed of light. In the other, the charges interact directly with each other.

Although the concept of direct interaction between particles is historically the older of the two, it is not very popular. When first formulated, the concept was that of instantaneous interaction. This was contrary to the requirement of special relativity and led to conflict with experiments. It was subsequently reformulated to make interactions travel with the speed of light. Although this met the requirement of relativistic invariance, a new type of difficulty arose. The new formulation was time symmetric, and was in conflict with causality. Thus when we disturb a charge *a* we expect the field generated by *a* to travel into the future, i.e. to be described by the 'retarded' solution $F^{(a)}_{\text{ret}}$. This formulation, however, gives the field generated by *a* as

$$\tfrac{1}{2}\, F^{(a)}_{\text{ret}} + \tfrac{1}{2}\, F^{(a)}_{\text{adv}}. \tag{9}$$

The presence of 'advanced' solutions appears to violate causality, although it is consistent with, and indeed required by Newton's third law of motion.

Advanced and retarded solutions also exist in field theory but the former can always be got rid of by a special choice of solutions. This choice is not available to the direct-particle-interaction theory.

This presented a stumbling block to any further development of the theory of direct interparticle action, until a breakthrough was achieved by Wheeler and Feynman (1945, 1949). They pointed out that although advanced interactions are present between particle pairs, they can be cancelled out altogether under certain circumstances. These are when the universe as a whole acts as a 'perfect absorber', i.e. it absorbs all electromagnetic disturbances generated by individual particles. In such a case the field* acting on particle a is given by

$$\sum_{b \neq a} \frac{1}{2}\left(\mathrm{F}^{(b)}_{\mathrm{adv}} + \mathrm{F}^{(b)}_{\mathrm{ret}}\right) = \sum_{b \neq a} \mathrm{F}^{(b)}_{\mathrm{ret}} + \frac{1}{2}\left[\mathrm{F}^{(a)}_{\mathrm{ret}} - \mathrm{F}^{(a)}_{\mathrm{adv}}\right]. \quad (10)$$

The right hand side shows that all particles $b \# a$ act on a only through their retarded fields. The only advanced effect to survive is that in the second term. This denotes the radiative reaction on the particle. Although it appears to arise from the motion of a directly, it is in fact the outcome of the complete absorption by the universe. In the field theory the radiative damping is ascribed to self-action; in the present theory it is the response of the universe to the particle motion.

Wheeler and Feynman were able to show that the static Euclidean universe is a perfect absorber. Thus (10) would hold and no conflict with causality would be encountered. However, the universe is time-symmetric and the entire argument can be reversed to show that purely advanced fields also offer a self-consistent picture! In fact it is meaningless to distinguish between the two pictures in the absence of an independent arrow of time. Wheeler and Feynman recognised this and sought to relate the electrodynamic time-asymmetry to the thermodynamic arrow of time.

It was subsequently pointed out by Hogarth (1962) that the appeal to thermodynamics is unnecessary if one takes into account the expansion of the universe. An expanding universe is time-asymmetric and this removes the time-symmetry of the whole argument! Hogarth and later Hoyle and Narlikar (1963) were able to show that this is indeed the case for the well known

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* The word 'field' in this theory means the 'direct particle field', i.e. the field generated by specified particles.

cosmological models. Thus the steady state model gives retarded solutions, but not advanced solutions, in a consistent way. The ever expanding Friedmann models give exactly the opposite result. This is because in the former the continuous creation of matter ensures that there is enough absorbing matter present along the future light cone. In the Friedmann models the matter density steadily decreases as the universe expands.

If we adopt the direct particle theory as a correct description of electromagnetism we have the following advantages. First, we are able to understand why retarded — not advanced — solutions operate in the laboratory. This is not a matter of choice (as in the field theory) but a requirement imposed by the universe. Thus, provided we live in the right type of universe, we can establish a direct connection between the electrodynamic and cosmological arrows of time. Second, this theory is free from the concept of self action and the associated infinities that beset the classical field theory.

There has so far been one respect, however, in which field theory could claim superiority. This was in relation to quantum theory. Field theory has been quantized and the resulting subject of quantum electrodynamics can claim several successes. Until recently there was no quantum electrodynamics of direct interparticle action. Recent work (Hoyle and Narlikar 1968) has shown, however, that the field theory can no longer claim this superiority. We conclude this section with a brief description of this work.

(iv) *Quantum electrodynamics* — A survey of problems in quantum electrodynamics shows that there are two types of problems in which the theory of direct interparticle action is likely to run into difficulties. These are problems of the vacuum and the problems associated with self action.

The former type of problems arise in quantization of electromagnetic fields. In the usual theory the fields are independent entities, and can be quantized. In this case the state of vacuum — i.e. with no fields present — has non-trivial properties. These properties play an important part in explaining diverse phenomena such as the spontaneous transitions of atoms, line widths, resonance fluorescence, etc. In the direct particle theories fields have no independent existnce and therefore we cannot follow the same procedure. How then do we explain the above phenomena ?

The problems connected with self action lead to difficulties in classical field theory. These difficulties are present also in the quantum field theory. However, ingenious renormalization procedures are devised to extract finite answers from apparently divergent expressions. That these finite answers are in excellent agreement with experiments (e.g. in the case of the Lamb shift in a hydrogen atom) is claimed to justify the somewhat nonrigorous nature of the renormalization programme. It is also regarded as an evidence of the action of an electric charge on itself. Can such experiments be explained in the direct particle theory which denies self action?

It is not possible to go into the details of the recent work which shows how these difficulties can be surmounted. The clue lies in the second term of the right hand side of (10) which denotes the response of the universe. A similar 'response' term exists in the quantum calculations and is able to account for the various phenomena described above. For this it is essential that the universe acts as a perfect absorber along the future light cone.

Conclusion

Having considered the two points of view in the two previous sections it seems that both are essential for the progress of physics. There is no doubt that astronomy has gained a lot from laboratory physics. The use of astronomy, on the other hand, provides laboratory physics with a valuable extension of its horizons. The laws tested in the confines of man-made walls can be tested in vastly different surroundings. At the same time it appears wrong to ignore the influence of the universe on local environment altogether — as shown by the Olbers paradox. To what extent the universe influences the local conditions is a matter of controversy at present. If the global outlook proves to be successful in our understanding of the laws of Nature — as seems in the case of electrodynamics — the theoretical physicist may well have to widen his outlook considerably.

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