

A new look at gravitation

At the Royal Society last week, Professor Fred Hoyle and the author presented their new theory which implements in modern terms the idea of the 19th-Century German philosopher Mach, that the mass of a particle results from the effect of the rest of the matter of the universe

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MODERN physics can be said to have begun about three centuries ago with Newton's law of gravitation. Yet gravitation remains, to this day, one of the least understood phenomena in physics. Last week, Fred Hoyle and I proposed a new approach to this problem. The point of view leading to the present theory can be best described in the background of the evolution of physics since Newton.

Newton formulated his law in the form of action at a distance. The force of attraction between two material particles is proportional to the product of their masses and inversely proportional to the square of their distance apart. The constant of proportionality, the gravitational constant G , was determined by experiment. The remarkable successes of this law accustomed physicists to think in terms of instantaneous action at a distance; and when electromagnetism was discovered, it too was described in terms of action at a distance.

However, it soon became clear that instantaneous action at a distance did not give a complete description of electromagnetism — especially where non-steady phenomena such as radiation were concerned. The indication was that action should propagate with a finite speed. In a letter on 19 March 1845, the German pioneer of electromagnetic theory, J. K. F. Gauss wrote:

"I would doubtless have published my researches long since were it not

that at the time I gave them up I had failed to find what I regarded as the keystone, . . . namely the derivation of the additional forces — to be added to the interaction of electrical charges at rest, when they are both in motion—from an action which is propagated not instantaneously but in time as is the case with light."

The failure to give a mathematical description was largely due to the fact that special relativity had yet to come and physicists were not accustomed to thinking of interactions travelling with a finite speed.

The problem was solved, though in an entirely different way, by Maxwell in the 1860s. Maxwell's theory, the first field theory in physics, gives a description of electromagnetism in terms of charges and electromagnetic fields. The motion of a charge is given by the value of the field at that point. The fields are related to the motion and distribution of charges by Maxwell's equations. The important point is that the field theory is local in character—in direct contrast to action at a distance. In Maxwell's theory, two charges interact, not directly, but through a field. Any disturbance in the electromagnetic field propagates with a finite speed, the speed of light.

The success of Maxwell's theory heralded a new era in physics. Action-at-a distance fell into disrepute and fields came to stay. Maxwell's theory

also served as the forerunner of the special theory of relativity. Maxwell's equations, which at first looked rather cumbersome in the 19th-Century notation which separates space from time, took on new elegance when expressed in the four-dimensional form of special relativity.

Newtonian gravitation, with its instantaneous action at a distance which had proved so attractive and successful before, now looked inconsistent with the ideas of field theory and special relativity. In formulating his theory of gravitation, known as general relativity, Einstein therefore looked for a field theory.

Unlike electromagnetism, gravitation has the property of "always being there". The electric field of a positive charge can be cancelled by that of a negative charge. A similar cancellation cannot be effected in the case of gravitation. Einstein interpreted this result to mean that gravitation is the property of space-time.

In Einstein's theory, the presence of gravitation alters the geometrical structure of space-time. Thus, instead of saying that planets move in elliptical orbits round the Sun, we should say that they move in "straight" lines, but the rules of geometry which determine what is a "straight" line are changed. In other words, the rules of Euclidean geometry do not hold. Einstein's equations describe how the geometry is modified by the presence of matter.

There is a clear analogy with Maxwell's theory, in which matter can be likened to electric charges, and the variables describing the non-Euclidean nature of geometry are comparable with the electro-magnetic fields. It turns out that, when the gravitational field is not very strong, Einstein's equations reduce to Newton's.

In spite of the successes of field theory, sporadic attempts to revive action at a distance were made in the early part of the present century. The problem which baffled Gauss was finally solved by Karl Schwarzschild, H. Tetrode and A. D. Fokker. Fokker was able to express, in a precise mathematical form, the concept of action between two electric charges propagating at the speed of light. This theory, however, met another stumbling block, which can be described in the following way. Imagine two charges, A and B, situated one light-hour apart. The action leaving A at, say, 5 p.m. gets to B at 6 p.m. The theory then predicts that B's reaction to A leaves B at 6 p.m. and reaches A

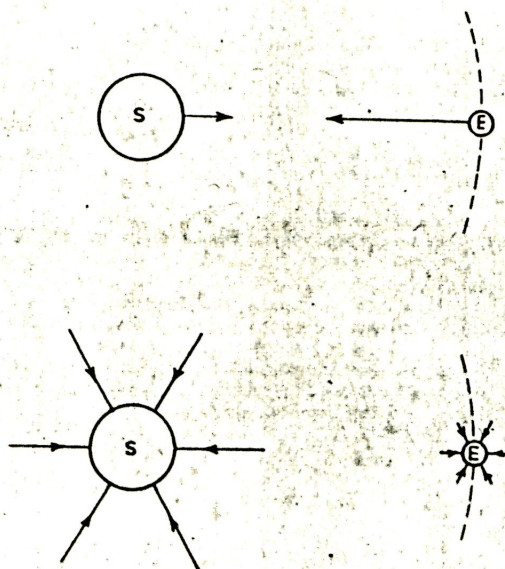
at 5 p.m. There is thus a lack of causality here. How can one reconcile such a theory with experience?

This difficulty was resolved in a very elegant manner by J. A. Wheeler and P. Feynman about twenty years ago. They argued that the universe does not contain just two particles. In the above example, one must add the reactions of all the remaining particles C, D, E... of the universe. They demonstrated that, when all the reactions are added properly in a static universe, the result given by the theory does indeed accord with experience. In doing so, they also cleared up one problem which remained unsolved in Maxwell's field theory. This difficulty was associated with the "self-action" of an electric charge.

Experience shows that, when an electric charge oscillates, it radiates energy to the universe and as a result suffers a damping of its motion. This damping arises from the motion of the charge itself and is known as self-action. Now, it is possible to give a description of this phenomenon within the framework of Maxwell's theory. But owing to its time-symmetry, the theory also predicts the reverse phenomenon, in which an oscillating charge gains energy from the universe. Why does nature make an arbitrary choice in favour of the former? Moreover, the formula for self-action can lead to absurd results such as infinite self-acceleration of an electric charge. How is this to be avoided?

Both these questions are answered by the Wheeler-Feynman theory. The concept of self-action is replaced by that of reaction from the universe, and the awkward infinities do not arise. Moreover, the choice in favour of radiation and damping is not arbitrary, as in the field theory, but is accounted for by the interaction with the universe.

In their calculations, Wheeler and Feynman had assumed the universe to be static, and therefore inherently time-symmetric. In order to get their result they had to introduce a time asymmetry by making particular assumptions about the initial conditions. J. E. Hogarth showed that this "dodge" to be unnecessary. He argued that the required asymmetry did not have to be postulated but was indicated by observations; the universe is not static but is expanding. The Wheeler-Feynman theory should therefore be worked out in an expanding universe. This calculation was done by Hogarth—and later, in a different form, by Hoyle and myself. It turned



The idea of action at a distance: two objects for example the Sun and the Earth, interact with one another directly across a great distance. At first it was thought to be instantaneous.

The idea of a field: the Sun (and the Earth, too) is surrounded by a gravitational field of force. The Sun's field, not the Sun itself, acts on the Earth.

FIGURE 1. Action at a distance, or field?

out that the result of the calculation depends critically on what model of the universe is assumed. We found, for example, that results in agreement with experience (and causality) follow in the steady-state universe (which is essentially uniform and unchanging in space or time) and not in the "big-bang" Einstein—de Sitter universe (which is finite and evolving).

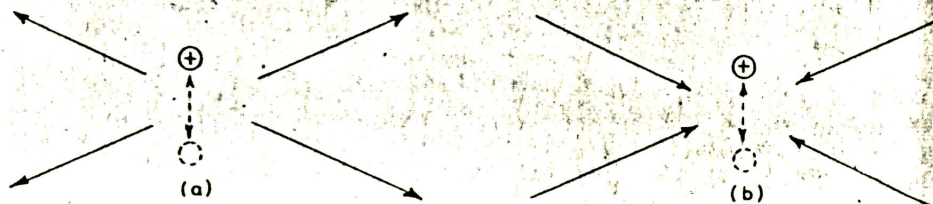
We were very impressed by this result. The action at a distance theory had not only cleared its old obstacles but had also proved more informative. It became possible to draw conclusions about cosmology from apparently local phenomena. This has never been possible in a field theory, which only relates purely local quantities.

If action at a distance is a fruitful way of looking at electromagnetism, there is no reason why it should not be extended to other parts of physics. We were soon able to express the C-field, which describes the continuous

creation of matter required by the steady-state theory, in the form of action at a distance. We were then encouraged by this success to consider gravitation.

The idea that local behaviour of matter is influenced by the distant parts of the universe was put forward by the philosopher Ernst Mach in the last century and is known as Mach's principle. Various physicists have interpreted this idea in different ways. Einstein himself was greatly impressed by it and had hoped that it would be incorporated in general relativity. His ambition was not realised and one of the main reasons was the inherent field-character of general relativity. Mach's ideas, as was seen above in the case of electromagnetism, can be incorporated more directly in a theory of action at a distance.

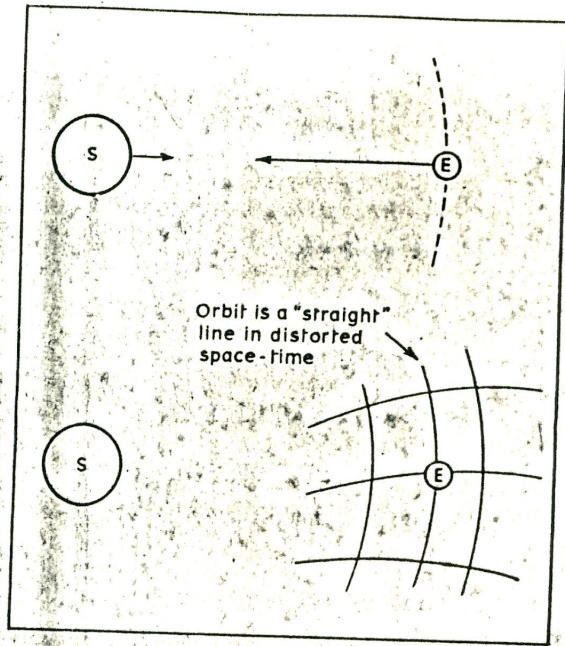
In our approach to gravitation we have followed the Einstein view that gravitation is to be attributed to the



Time-symmetry: We know that an oscillating electric charge radiates energy to the universe as in (a), and loses energy. In Maxwell's electromagnetic theory, it is just as plausible that the oscillating charge should gain energy from the universe — the film could, as it were, be run backwards. To be convincing, theory has to exclude (b).

FIGURE 2. The bugbear of time symmetry.

A new look at gravitation *continued*



Newtonian theory: Gravitation is a property of matter: any particle (m_1) attracts any other particle (m_2) by action at a distance, with force = $G \frac{m_1 m_2}{r^2}$

G is determined experimentally (it is 6.67×10^{-8} c.g.s. units)

General relativity: Gravitation is a property of space-time: particles travel in "straight" lines in space-time but, as space-time is distorted by the presence of matter, the path appears as a curve in ordinary Euclidean space. Reduces to Newton's theory when the effects are weak. G is determined experimentally.

mass, electromagnetism, C-field, etc does not change.

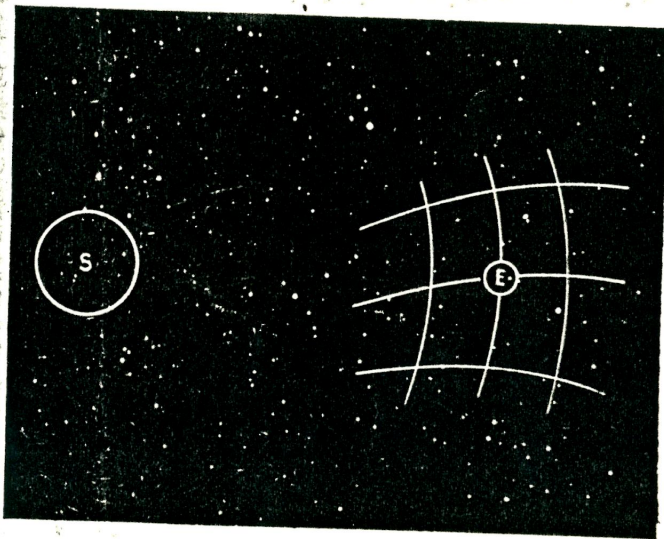
The interesting thing is that, in the present theory, the equations describing gravitation follow, once the action between particles that leads to the property of "mass" is defined. In general relativity, an extra term has to be introduced and Einstein's resulting equations have then a somewhat ad-hoc character.

The equations of the present theory are more complicated than those of general relativity. They do, however, admit of a simplification in which mass is constant in space and time. The equations then become those of Einstein! The constancy of mass is therefore closely linked with the validity of Einstein's equations. Moreover, because of the similarity of description of mass, electromagnetism and the C-field, there is the hope of a more complete theory in future which unifies the three. This would be the analogue of a Unified-Field Theory linking gravitation and electromagnetism, so much sought after over the last half century though, of course, this new theory is without fields!

I shall end by noting some points where the present theory differs from general relativity and Newtonian gravitation. In the two earlier theories the sign (i.e. attraction or repulsion) and magnitude of the constant of gravitation G are fixed from local observations—formally, G can be anything. In the present theory, gravitation is inevitably "attractive" and the value of G follows from a determination of the mean density of matter in the universe, in accordance with the Ideas of Mach.

This difference can be best expressed by the following "thought experiment": What will happen to the solar system if half the universe is suddenly removed? In Newtonian and Einsteinian theories, nothing. In the present theory, the value of G will go up by a factor of two, the Sun will become some hundred times brighter and the Earth will be fried to a crisp!

A more formal point of difference relates to empty space. A number of results of general relativity and of Maxwell's theory describe interesting situations in empty space. Such situations could not arise in the present theory for the simple reason that it takes two particles (at least) to form an action. In other words, there would be no "physics" if the number of particles in the universe were less than two!



The new theory: Gravitation is a property of the universe, because the mass of a particle, and hence the distortion of space-time it produces, arises from the effect of the rest of the particles in the universe. Reduces to Einstein's theory when mass is constant. G is deduced from the density of matter in the universe.

FIGURE 3. Theories of gravitation.

non-Euclidean geometry of space-time. The difference comes in the interpretation of the inertial mass of a particle. In general relativity, this is the intrinsic property of the particle; in the present theory, mass arises from the rest of the particles in the universe. Following the analogy of electromagnetism described above, it is possible to give an expression for the mass of the particle in terms of the rest of the particles in the universe.

The gravitational equations are derived from the principle of stationary action (sometimes wrongly called "least action"). This mathematical principle has, in the past, proved immensely useful in the derivation of new physical laws. In the present case this principle states:

The actual space-time structure is such that if we alter it slightly (in an arbitrary way) the action describing various physical phenomena, such as