

Gravitational collapse

THE discovery of strong radio sources outside our own galaxy has presented modern astronomy with a wealth of fascinating problems. The most crucial of these questions is: "From what do these sources derive their enormous energies?" Estimates indicate that energies of the order of 10^{60} ergs—equivalent to the nuclear energy output of some hundred million suns—are spent during the lifetime of a radio source. Most theories about the origin and nature of radio sources fail to provide such large reservoirs of energy.

About a year ago, Fred Hoyle and William Fowler put forward the remarkable hypothesis that this energy could be obtained from the gravitational collapse of a super-star. Such an object would have to be very massive—about a hundred million times as heavy as the Sun—and it would be situated at the centre of the galaxy (*see Fig 1*).

Shortly after this, thanks to the combined efforts of the radio and optical astronomers, two radio sources were identified with very bright, star-like objects. One of these—the source classified as 3C 273 in the third Cambridge catalogue of radio sources—is the brightest known object in the universe. Work on optical identification has since revealed more objects of this kind; at the time of writing nine of these star-like sources are known.

These exciting developments in theory and observation were considered so important that an "International Sym-

Fig 1 Dark blob in the centre of galaxy M 82 is the location of a radio source. During their lifetime these radio sources expend the equivalent of the nuclear energy produced by about 100 million Suns. This energy may be liberated by gravitational collapse—a vast 'implosion' of cosmic dust

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Star-like objects a hundred million times as heavy as the Sun were recently discovered in the distant parts of the universe. Their vast energies may be caused by an 'implosion' of cosmic dust at fantastic speed. As one of the most important discoveries in the history of astronomy, this calls for a new analysis of the fundamentals of relativity

posium on Gravitational Collapse" was held in Dallas last December to discuss the many issues arising out of them. Are these unusual objects the outcome of a gravitational implosion? How is the gravitational energy converted into radio waves? And last, but not least from a theoretician's point of view, does gravitational collapse lead to an indefinite contraction and a 'singularity' in space-time itself?

It is the last of these questions that I will be concerned with in this article. The possibility that objects so massive as these can exist in nature has compelled theoreticians to reconsider their ideas based on the General Theory of Relativity.

Towards infinite density

Imagine a spherical cloud of dust, every particle in which attracts the rest according to Newton's law of gravitation. The cloud as a whole will begin to contract—and will go on doing so unless some other forces are brought into play. Suppose for the moment that no other forces are present. A simple calculation then shows that the cloud shrinks to a point in a finite time. If the starting density of the cloud is one gram per cubic centimetre, it will take about half an hour for the whole cloud to collapse to an infinitely small size.

The question naturally arises as to why every object in sight does not collapse under its own gravitation. The obvious answer is that other forces are present. Gravitation is a very weak force compared with these other forces. To give an example, the electrical force between two electrons is more than 10^{40} times bigger than the gravitational force between them. Gravitational collapse therefore does not occur in the case of ordinary bodies.

The situation is different, however, in the case of very massive objects such as those contemplated by Fowler and

Hoyle. The larger the mass, the stronger will be the gravitational force. Indeed, for such objects the gravitational force is so strong that no known forces seem able to prevent a gravitational collapse.

According to the Newtonian theory, if gravitational collapse is allowed to go on indefinitely, all matter gets concentrated into a point—leading to a state of infinite density. Are we justified in relying on Newton's theory right up to this stage?

Relevance to relativity

Newton's theory of gravitation, in spite of its successes in describing the gravitational phenomena on the Earth and in the Solar system, is not altogether free from logical difficulties. For example, according to Newton the gravitational interaction is instantaneous; it propagates with infinite speed and its effects are felt instantaneously. This is inconsistent with the Special Theory of Relativity which requires no interaction to propagate faster than light. However, a theory of gravitation which is consistent with Special Relativity and also agrees in many respects with the Newtonian theory, was put forward by Einstein about fifty years ago. This is the General Theory of Relativity.

The General Theory of Relativity makes use of the remarkable property of gravitation that it cannot be 'switched off'. It is always there and will affect *all* material particles. In this respect it differs from all other known forces in physics. An electric force will affect only charged particles. An electron (negative charge), a proton (positive charge) and a neutron (no charge) will all behave differently in an electric field. In a gravitational field, on the other hand, they would move in exactly the same way. This was realized by Galileo more than three hundred years ago, when he said that all bodies fall with equal rapidity, regardless of their mass (see "Our debt

to Galileo" DISCOVERY, February, 1964).

Einstein interpreted this property of gravitation to mean that gravitation is intimately connected with the nature of space and time. Newton's first law of motion says that a body continues in a state of uniform motion in a straight line unless an external force acts on it. Suppose a gun is fired at an angle of 45° to the vertical. If there were no gravity from the Earth, the bullet would continue to travel in a straight line at an angle of 45° to the vertical (see Fig. 2). The presence of gravity, however, causes the bullet to follow a curved parabolic path. As gravitation is something that cannot be got rid of, it is somewhat pointless to talk about laws of motion in the absence of gravitation. The above example shows that in the presence of gravitation—but absence of any other forces—particles do not move along straight lines, but along curved lines. However, we can call these curved lines "straight lines" if we change the rules of geometry. This is what General Relativity seeks to do. The presence of gravitation implies that the geometry of space-time is non-Euclidean—a result quantitatively expressed by Einstein's equations (see Fig. 2).

The Schwarzschild solution

Einstein's equations describe how the distortion of space-time—its non-Euclidean character—is related to the distribution of matter. Though the underlying ideas are simple and elegant, and the equations can be written in a compact form, the solution of any explicit problem in General Relativity is extremely difficult, largely because of the non-Euclidean nature of space-time. As a result, not many problems in the theory have been solved *exactly*. However, one important solution was given by Karl Schwarzschild in 1916.

According to this solution the gravitational field at a large distance from the

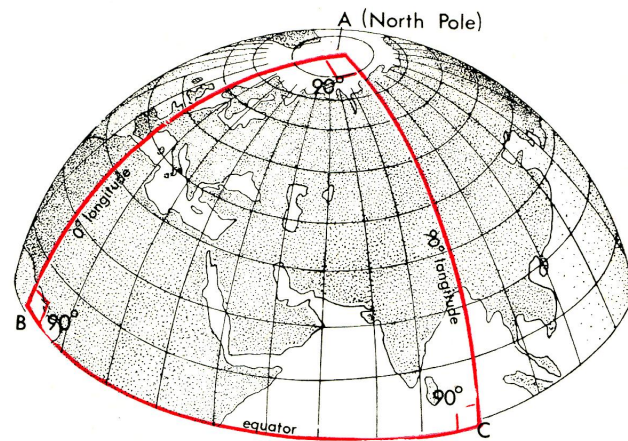
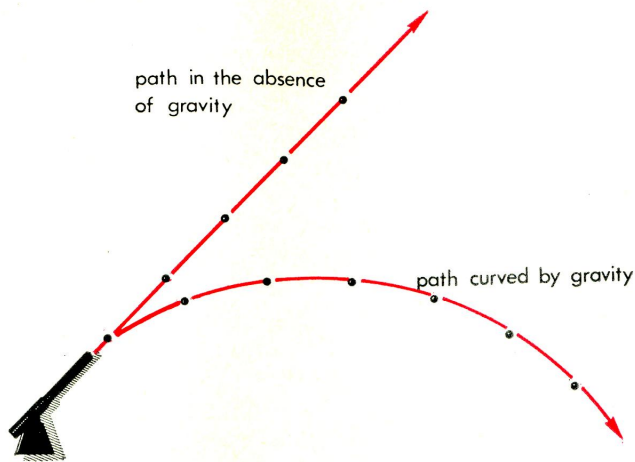


Fig 2 Einstein regarded the force of gravity as being intimately connected with space and time. Although the flight of a bullet in a gravitational field appears as a curve (left), general relativity pictures it as a straight line in the curved geometry of space-time

In the same way, lines drawn on a sphere such as the Earth appear curved (right), although they are by definition 'straight': they represent the shortest distance between two points but appear curved because they are drawn on a non-Euclidean geometry

body is more or less the same as that given by the Newtonian theory. In other words, it approximates fairly closely to the well known "inverse-square law". However, the difference from the Newtonian result becomes more and more significant as we get closer and closer to the attracting mass. As we would expect, the gravitational attraction becomes stronger and stronger. But—and this is not predicted by Newtonian theory—the strong gravitational field is also accompanied by a strong distortion in the space-time geometry.

Consider for the moment the most drastic case where the attracting mass is concentrated at a point. The distortion of space-time then give rise to a very interesting situation, most easily understood with the help of Figure 3. Around the mass we can construct a sphere of a definite radius, known as the Schwarzschild radius, which acts as a sort of signal-barrier. No physical signal can go from inside the barrier outside; but signals from outside can come in!

Can such a situation arise in practice? The answer is that it can, provided the body is so small that it lies inside its Schwarzschild sphere. This requirement is not met by the bodies we see around us. The Schwarzschild radius of the Sun, for instance, is only about three kilometres, whereas the actual radius of the Sun is 700,000 kilometres.

However, provided there is gravitational collapse, a body can shrink to a size so small that it eventually goes inside its Schwarzschild sphere. What

happens then could well form the basis of a science-fiction novel.

A space-time singularity

We go back to the simple example of a dust cloud collapsing under its own gravitation. This problem can be worked out exactly in terms of the theory of General Relativity and the answer is somewhat disturbing. Suppose at the start we station two observers, *A* and *B*, to record the subsequent events as the cloud shrinks. *A* remains where he is but *B* hangs on to one of the particles of the cloud and falls in with it. *A* and *B* arrange to communicate with each other via light (or radio) signals (see Fig. 4).

A will find that the cloud gets smaller and smaller; but *he will never live to see it collapse to a point*. The reason for this curious result lies in the distortion of space-time. As the cloud contracts the gravitational field near it becomes stronger and stronger, and the geometry of space-time is more and more non-Euclidean. Physically this effect is felt in the following way. Suppose *B* sends two signals at an interval of 1 second by his watch. These signals do not arrive at *A* at an interval of 1 second by *A*'s watch—they arrive at a much longer interval. And this interval gets longer and longer as *B* approaches the Schwarzschild sphere. Once *B* crosses into the sphere no signal sent by him will ever reach *A*—even if *A* were immortal! *A* therefore sees the body approach its Schwarzschild sphere more

and more slowly, but he never sees the body actually reach the sphere or shrink past it. In particular, he will never know what happened to *B* as he crossed this barrier.

The experience of *B* is even more interesting. If *A* finds events moving slowly at *B* as *B* approaches the Schwarzschild sphere, *B* sees the exact opposite happening to *A*. To him events move fast at *A*—and as he crosses the Schwarzschild sphere, he sees the entire future of *A* go by in a few seconds! But even greater experience is in store for him. Calculation shows that the time taken by the body (by *B*'s watch) to shrink to a point is exactly the same as given by the Newtonian theory. So, if the cloud started with a density of 1 gram per cubic centimetre, it would reach this stage in about half an hour! In a time of this order, *B* will be crushed with the rest of the collapsing cloud.

This state of infinite density has more serious consequences in the Theory of Relativity than in the Newtonian theory—for the simple reason that, in the former, gravitation is intimately connected with space-time. The state of density, therefore leads to infinities in the geometry of space-time itself. This is sometimes stated in these words: "*the space-time becomes singular*". The Theory of Relativity therefore leads to the remarkable result that for an observer of the type *B*, space-time becomes singular in about half an hour!

At this stage it is possible to take the

view that in the above simple example the singularity develops only for the observers of the type *B* who collapse with the body. An external observer like *A* never sees this happening; for him the cloud never contracts below its Schwarzschild radius. From this point of view the ultimate fate of an object under gravitational collapse is of no immediate importance.

However, a physical theory must consider all possible consequences and it is a perfectly valid question to ask whether the Theory of Relativity indeed leads to space-time singularities for observers like *B*? Can the singularity be averted by halting the gravitational collapse of any object at an earlier stage?

Can singularity be prevented?

I mentioned earlier that, owing to the weak nature of gravitation, other forces in nature are able to support ordinary objects against their own gravitation. It is only in the case of very massive objects that the problem of gravitational collapse becomes a serious one. Until recently, the largest objects whose equilibrium was considered by scientists were stars. The observational evidence mentioned earlier indicates that objects a

hundred million times (or more) as massive as stars are likely to exist in nature. It is therefore worth considering whether the forces that are able to support ordinary stars can also support these massive super-stars.

The stars are supported against gravitation by internal pressure. Indeed, the balance between pressure and gravitation must be exact—otherwise the star would collapse rapidly. The central pressure required in the Sun is about 10^{12} lbs per square inch—enormous by terrestrial standards. If such a high pressure was not provided for, the Sun would collapse in a matter of hours.

The high pressure and temperature inside a star are produced by nuclear reactions. In the Sun, energy is produced by the conversion of hydrogen into helium. This will be followed by helium burning, and so on. Eventually all nuclear fuel in any star will be exhausted and the star will contract. Calculations show that if the mass of the star does not exceed 1.44 times that of the Sun, a new kind of pressure, developed inside the star, is able to halt that contraction. This is called the degenerate electron-pressure, and can be predicted from the quantum theory. It states, in effect, that electrons cannot be compressed too closely together.

The more the material is squashed, the higher is this pressure.

The masses of the super-stars considered by Fowler and Hoyle are much larger than this limit. No pressure—thermal or degenerate—can support these objects against their gravitation. Clearly, new considerations have to be introduced into the General Theory of Relativity, if the singularity of space-time is to be prevented from developing inside these massive objects as they undergo gravitational collapse.

Why does gravitation always win in the end? The reason for this can be seen in the following way. If we pull a rubber band, we store energy in it. When released, the band shrinks under the elastic forces and the energy stored in it is given out to be used for other purposes. However, once this energy is taken out, the force responsible for the shrinkage disappears. This situation is typical of all known forces *except gravitation*. In the case of gravitation, the exact opposite takes place. When a system collapses under its gravitation, it increases rather than diminishes the effect of gravitation.

Another way to look at it would be to regard gravitation as having negative energy. If we extract something positive

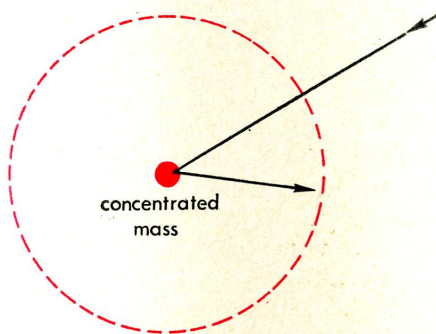
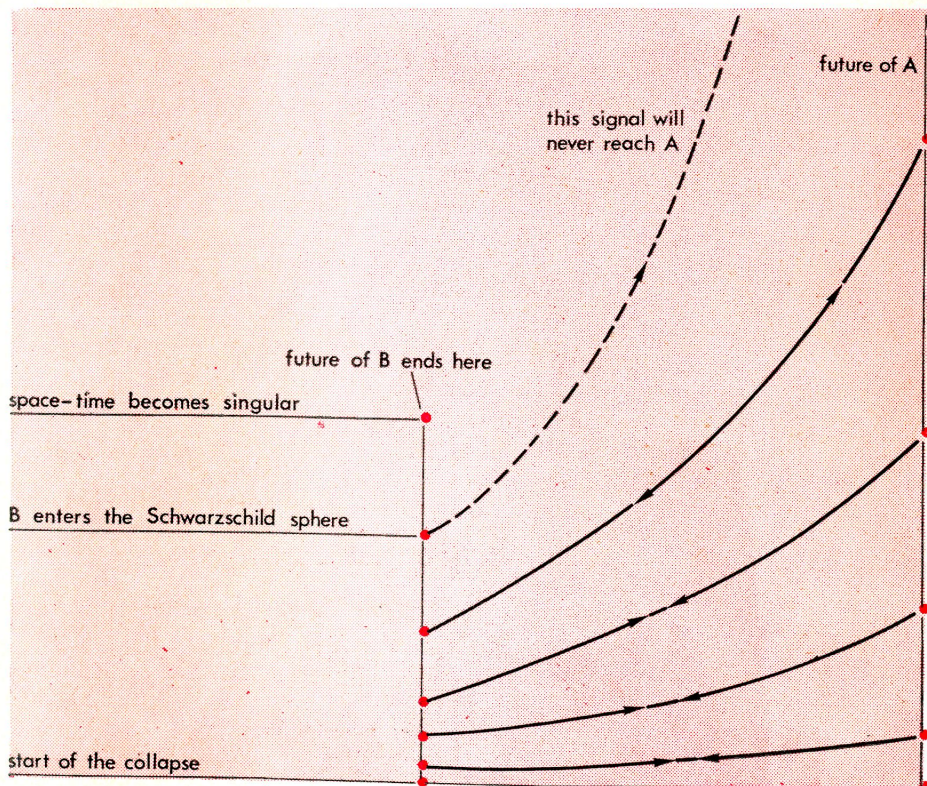


Fig 3 If a body contracts to within its own Schwarzschild sphere, light or radio signals can never escape from it. But to do this the body must be very dense—Schwarzschild radius for the Sun is 3km

Fig 4 Communication between observer *B*, stationed in a collapsing galaxy, and observer *A* stationed outside, is only possible before *B* enters Schwarzschild sphere. *A* can never know what happened to *B* as he crossed this barrier. *B* will see the whole future of *A* pass by in just a few seconds



from a negative reservoir, we make the reservoir even *more* negative. This happens to the gravitational energy of a collapsing body.

This suggests that the collapse to a space-time singularity can be avoided, perhaps, by a negative energy field which grows even stronger than gravitation as the object begins to contract. Has a negative energy field with this property been contemplated by physicists before?

An analogy with the universe

The answer is 'yes'. Such a field has been used in cosmology to represent the continuous creation of matter. One of the difficulties of the Steady State Theory of the Universe, when it was first

put forward, was to explain quantitatively the phenomenon of continuous creation. As the Universe expands, the density of matter would decrease unless new matter appears. In the Steady State Universe the density of matter must always remain the same—hence the need for the continuous creation of matter.

Where does the matter come from? It cannot come from radiation or any other source of positive energy. Any such source would soon be exhausted by the double effect of matter creation and the expansion of the universe. Fred Hoyle therefore put forward the idea that matter is created from a source of negative energy. If the matter is taken out from such a source, it will be made more negative. It is made less negative, on the other hand, by the expansion of the universe. The two opposing effects would balance each other to produce the steady state. This source of negative energy is called the "Creation Field". It is interesting, in this connection, to consider a cosmological analogy. The very simplest of models of the expanding Universe, given by General Relativity, have a singular origin. Such models show (see Fig. 5) that the universe started off from an infinitely dense state by an explosion. The receding galaxies that we see are fragments of the explosion flying apart. For this reason, the models are sometimes referred to as the "Big Bang" origin of the universe.

Supposing we make a film of the expanding Big Bang Universe and run the film backwards. We would then see a contracting universe in which different galaxies are coming closer and closer together. All matter would eventually come to be infinitely concentrated. This in fact represents the gravitational collapse of the entire universe. Exact calculation shows that the simple case of the collapsing dust cloud is formally identical to a miniature Big Bang Universe run backwards in time.

Now, the space-time singularity of the Big Bang Universe is avoided in the Steady State Universe by the continuous creation of matter. The Steady State Universe has no singular origin. Following the above analogy, if we reverse the direction of time in the Steady State Universe we should see contraction and continuous *destruction* of matter. The Universe itself never reaches a space-time singularity. Can the same

phenomenon operate in the massive objects known as super-stars?

Fred Hoyle and I explored this idea and found that such a solution exists. As the body contracts, the creation field in it would grow, but at the same time it would destroy matter. The two processes can be made to balance so that the density of matter in the body remains constant. A singular state is never reached. This solution, however, had two properties which made it appear implausible in describing the ultimate fate of these massive bodies. First, the above process worked only when the density of matter inside the body was very small—about 10^{-29} gram per cubic centimetre. This is about the density of intergalactic space and we expect the body to be very much more dense than this. Second, the time scale of the whole process was of the order 10^{10} years. This is very slow indeed. Observations indicate a much shorter time scale.

There exists, however, a more interesting situation, in which the Creation Field does not actually destroy matter but is simply squashed by gravitation. However, as it is squashed it grows at a more rapid rate than gravitation itself and in the end halts the collapse. Instead of falling into a space-time singularity, the body oscillates between states of high and low densities.

The maximum density reached may be as high as 10^{30} grams per cubic centimetre. Even a body one thousandth as small as a pin head would then weigh about a million million million tons! Such enormous densities have not been contemplated before. Even nuclear physics gives no real guidance about what happens to matter when crushed to this degree.

This gives rise to a number of problems of interest to high energy physics and astronomy. Does the observed variation in intensity of these super-stars indicate an oscillatory state? If so, could this be interpreted as an evidence for the Creation Field?

Many astronomers believe that the discovery of massive star-like objects is one of the most important events in the history of astronomy since Hubble's discovery of the expansion of the universe. Considering the implications it could have for astronomy and the Theory of Relativity, this may well turn out to be so.

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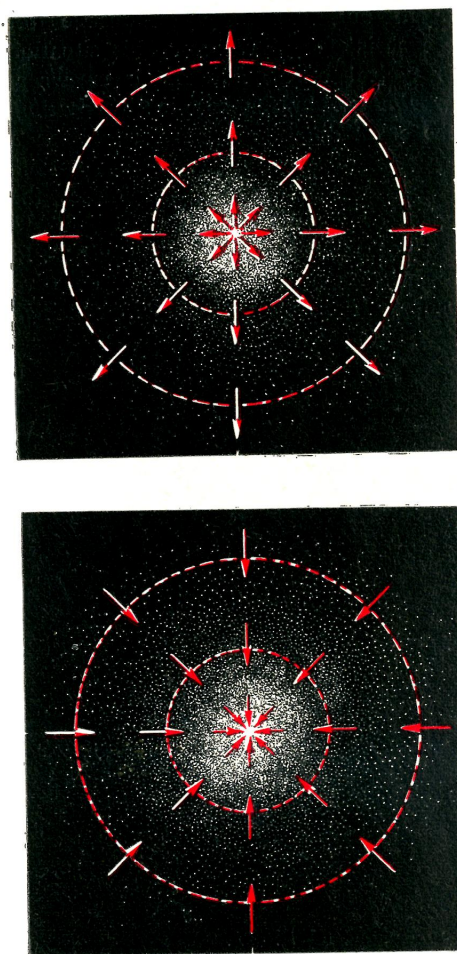


Fig 5 Schematic diagram of the expansion of the Big Bang universe. The arrows represent receding galaxies (top). Bottom diagram shows the same situation reversed in time—galaxies come closer and closer together until 'singularity' is reached