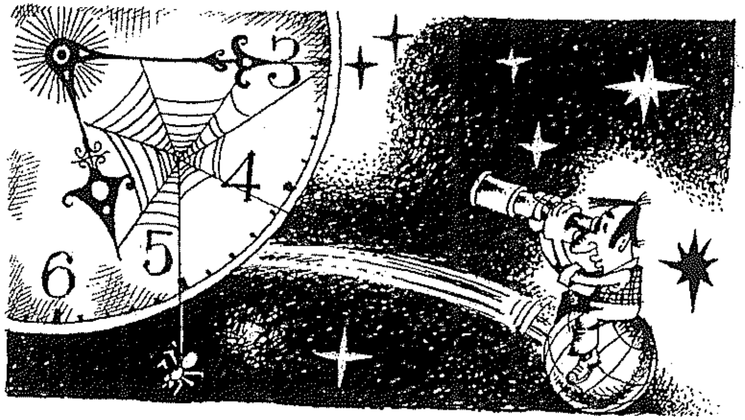


I. Novikov

1: *What is a black hole?*

Stars that the world cannot see

A black hole is a creation of gravitation. It is thus logical to start the account of the discovery of black holes at the time of Isaac Newton, who discovered the law of universal gravitation. This law determines the force acting on absolutely everything. All other types of physical interaction are connected with concrete properties of matter. For instance, the electric field acts only on charged bodies while neutral ones are perfectly indifferent to it. Gravitation is the only interaction that reigns supreme in nature. It acts on everything: on small-mass and large-mass particles (in precisely the same way if initial conditions are identical), even on light. Newton hypothesized that light is attracted to massive bodies. It is with this understanding of the fact that light is also subject to gravitational force that the early history of black holes begins, the history of prediction of their astonishing properties.

One of the first scientists to come up with the prediction was the famous French mathematician and astronomer Pierre Laplace, an illustrious personality in the history of science. First and foremost, he was the author of the enormous five-volume *Treatise on Celestial Mechanics*. This work, written and published over a period from 1798 to 1825, presented the classical theory of motion of bodies in the Solar System, based solely on the law of universal gravitation.

Before that, some observed peculiarities in the motion of planets, the Moon, and other bodies of the Solar System could not be completely understood. It even seemed that they contradicted Newton's law. Elegant mathematical analysis performed by Laplace proved that all these finer points are caused by the mutual attraction of celestial bodies, by the effects of the gravitation of planets on the motion of other planets. He asserted that the only force reigning in the skies is the force of gravitation. In the preface to his *Treatise*, Laplace wrote that from the most general standpoint, astronomy is the grand problem in mechanics. Note that he was the first to suggest the term 'celestial mechanics', now firmly rooted in the language of science.

Laplace was also one of the first to realize the need in a historical approach for explaining the properties of systems of celestial bodies. He advanced, after Kant, a hypothesis of the formation of the Solar System from the originally rarefied matter.

The principal idea of Laplace's hypothesis of the condensation of the Sun and the planets from a gas nebula still forms the foundation of currently developed theories of the origin of the Solar system.

Much was written in the literature and in textbooks about these achievements, as well as about Laplace's proud reply to Napoleon's question about no reference to God in *Celestial Mechanics*: 'I did not need this hypothesis.'

The point that was little known until recently was that Laplace predicted the existence of invisible stars.

The prediction was made in his monograph *Exposition of the System of the World* published in 1795. In this book – which would be considered 'popular' by today's standards – the famous mathematician chose not to resort to either formulas or drawings. Laplace's profound conviction that gravitation affects light in the same way that it acts on other objects led him to the following spectacular conclusion:

> A luminous star, of the same density as the Earth, and whose diameter should be two hundred and fifty times larger than that of the Sun, would not, in consequence of its attraction, allow any of its rays to arrive at us: it is therefore possible that the largest luminous bodies in the universe may, through this cause, be invisible.

The book did not give the proof of this proposition. It was published several years later.

How did Laplace reason? Using Newton's theory of gravitation, he calculated what we now call the escape velocity. This is the velocity

that we have to impart to a body (any body) in order for it to break away from the gravitational pull of a star or planet and fly away for ever into space. If the initial velocity of the body is less than the escape velocity, gravitational forces will decelerate its motion, stop the body, and then make it fall back on the gravitating center. Everybody is supposed to know in this age of space flight that the escape velocity on the surface of the Earth is 11 kilometers per second. The greater the mass and the smaller the radius of a celestial body the greater is the escape velocity on the surface. This is clear: as mass increases, gravitation is intensified, and as the distance from the center increases, gravitation is weakened.

The escape velocity equals 2.4 km/s on the surface of the Moon, 61 km/s on Jupiter, 620 km/s on the Sun, and reaches one half of the velocity of light, that is, 150 000 km/s, on the surface of so-called neutron stars whose mass is close to one solar mass but whose radius is only about ten kilometers.

Laplace argued like this: take a celestial body on whose surface the escape velocity exceeds the velocity of light. Then the light from this star cannot overcome gravitational pull and escape into space, and will not reach a remote observer, so that we would be unable to see the star even though it does emit light!

If the mass of a celestial body is increased by adding to it matter of the same mean density, the escape velocity increases in proportion to the increase in radius (or diameter).

Now the conclusion drawn by Laplace is clear: for gravitation not to let the light out, a star of the Earth's density must have a diameter 250 times that of the Sun, that is, 27 000 times that of the Earth. Indeed, the escape velocity on the surface of such a star is also greater by a factor of 27 000 than on the surface of the Earth, nearly equal to the velocity of light. Hence, the star becomes invisible.

This was a spectacular prediction of one of the properties of the black hole: to confine light, and thus be invisible. To be fair, we should remark that Laplace was not the only one and indeed not the first to come up with this prediction. It was recently established that a similar proposition was made in 1783 by the British priest and geologist John Michell, one of the founders of scientific seismology. His arguments were very similar to those of Laplace.

A half-joking, half-serious (and sometimes serious) debate took place some time ago between the French and the British about who was to be honored as the discoverer of the possibility of existence of invisible stars: Laplace of France or Michell of Britain? Laplace's

221

paper with the proof of the possibility of existence of black holes was cited in 1973 by the English physics theorists Stephen Hawking and George Ellis in a book devoted to special mathematical aspects of the structure of space and time; Michell's work was not known to specialists at the time. In the autumn of 1984, the English astrophysicist Martin Rees said at a conference in Toulouse that although what he had to say might not sound too nice in France, the truth was that the first man to predict invisible stars had been the Briton John Michell; Rees displayed a photograph of the title page of Michell's paper of 1784. This remark was greeted by the participants with applause and smiles.

Doesn't it resemble the debate of the French and the English about who predicted the coordinates of the planet Neptune on the basis of perturbations in the motion of Uranus, the Frenchman Le Verrier or the Englishman Adams? It is well known that they both calculated independently and correctly the position of the new planet. Le Verrier was luckier that time. Many a discovery has shared this fate. They are frequently made simultaneously and independently by several people. As a rule, a discovery is accredited to the one who demonstrated more profound comprehension of the problem, but sometimes it happens by a mere whim of fate.

Actually, the prediction made by Michell and Laplace was not yet the true prediction of black holes. Why not?

The point is that the science of the time did not yet know that nothing in nature is allowed to move at a velocity greater than that of light. Not in a vacuum, anyway. This was proved by Albert Einstein in special relativity theory but only in this century. For Michell and Laplace, therefore, the star that they considered was only black (nonemitting) since they were not aware that such a star loses any chance of 'communicating' with the outside world in any way, of 'informing' the world of any events occurring in the star. In other words, they could not know that it is not only 'black' but also a 'hole' into which one could fall but out of which there was no escape. Now we realize that if light cannot escape from some region of space, then nothing at all can emerge from it; we refer to this region as a *black hole*.

Another reason that detracts from the rigor of Michell's and Le Verrier's arguments is that they considered gravitational forces of enormous strength in which a falling body is accelerated to the velocity of light and the emitted light is confined, while at the same time applying Newton's law of gravitation.

Einstein was able to show that Newton's theory of gravitation is not valid for such fields, and developed a new theory, valid for superstrong and for rapidly varying fields (for which Newton's theory fails completely!); this theory is known as *general relativity*. If we want to prove that black holes can exist and to study their properties, it is this theory that we have to use as the tool.

General relativity is an astonishingly beautiful theory. It is so profound and elegant that everyone mastering it cannot but feel aesthetic delight. The Soviet physicists Lev Landau and Evgeny Lifshitz wrote in their textbook *The Classical Theory of Fields* that it is 'the most beautiful of all existing physical theories.' The German physicist Max Born said once that he enjoyed general relativity as he would an object of art. And the Soviet physicist Vitaly Ginzburg wrote that this theory makes him experience 'something akin to what one feels when contemplating the masterpieces of painting, sculpture, or architecture.'

No doubt, the numerous attempts at the popular exposition of Einstein's general relativity have created a general impression of its beauty. But let us be frank: the impression is as remote from the fascination imparted by the comprehension of the theory as a look at a reproduction of Raphael's *Sistine Madonna* is remote from the emotional experience you go through when contemplating the original created by the genius of the painter.

Nevertheless, if enjoying the original is impossible, one can (and ought to!) get acquainted with the available, preferably high-quality, reproductions (their merits do vary greatly).

A brief outline of some corollaries of Einstein's theory of general relativity is needed to make understandable the unbelievable properties of black holes.

Gravitational radius

What are the differences between Einstein's and Newton's theories of gravitation? Let us begin with the simplest case. Assume that we are on the surface of a spherical nonrotating planet and are to measure the attractive force exerted by this planet on some body, using a spring balance. We know that, according to Newton's law, this force is proportional to the product of the planet mass and the mass of the body, and inversely proportional to the squared radius of the planet. The radius can be found, for instance, by measuring the length of the equator and dividing it by 2π.

But what does Einstein's theory of gravitation have to say about

222

this force? It predicts that the force is slightly greater than the value yielded by Newton's formula. We will later elaborate the meaning of 'slightly greater'.

Now imagine that we can gradually reduce the radius of the planet by compressing it while preserving its total mass. The gravity on the surface will increase (since the radius decreases). According to Newton, contraction by a factor of two increases the force fourfold. Einstein's theory says that the force will increase slightly faster: the smaller the planet radius, the greater the difference.

If the planet is compressed to such a degree that the gravity becomes superstrong, the difference between the value calculated in Newton's theory and the true value predicted by Einstein's theory starts to grow catastrophically. In the former theory, gravity tends to infinity as the body is compressed to a point (the radius is nearly zero). In the latter theory, the conclusion is very different: the force tends to infinity as the radius approaches the so-called gravitational radius. This value of the radius is determined by the mass of the celestial body: the smaller the mass, the smaller the gravitational radius. In fact, it is very small even for gigantic masses. Thus it equals only one centimeter for the Earth. Even the Sun's gravitational radius is only three kilometers. As a rule, the dimensions of celestial bodies are much greater than their gravitational radii. For example, the average radius of the Earth is 6400 km, and that of the Sun is 700 000 km. If the actual radii of bodies are much greater than their gravitational radii, the differences between forces calculated in Einstein's and in Newton's theories are extremely small. On the surface of the Earth, for example, this difference is one billionth of the value of the force.

The differences become appreciable only when the radius of the compressed body approaches the gravitational radius and the gravitational field becomes very strong; as mentioned above, the actual strength of the gravitational field becomes infinite when the radius of the body becomes equal to the gravitational radius.

Before discussing the consequences of this behavior, let us look at some other conclusions of Einstein's theory.

The essential point of the theory is that it connected into an inseparable whole the geometric properties of space and time and the gravitational forces. These connections are complex and diverse. We shall now single out two important features.

According to Einstein's theory, time in a strong gravitational field goes slower than time measured far from gravitating bodies (where

gravitation is weak). Readers will certainly have heard that time can progress at a different pace. Nevertheless, this is something difficult to get used to. How can the pace of time vary? According to our intuitive feeling, time is the duration, something common to all processes. Time is like a river whose flow is unaffected by anything. Some processes may be faster or slower, and we can affect their rates by changing external conditions. For example, heating can accelerate chemical reactions, and freezing can slow down the functioning of an organism, but the motion of electrons in atoms will not change pace in response to these factors. It seems to us that all processes exist within the river of absolute time whose flow is unlikely to be affected by anything. Our notions allow the removal of all processes from this river, after which time will continue flowing as empty duration.

These notions reigned in Aristotle's and Newton's times, in fact, until Einstein. In Aristotle's *Physics* we find: 'Time flowing in two similar and simultaneous motions is the same time. If the two time intervals were not simultaneous, they would nevertheless be identical ... Hence, motions can be different and independent of one another. Time is absolutely the same in the former and latter cases.'

Newton, believing that he was speaking of a self-evident truth, wrote: 'Absolute, true, and mathematical time, of itself, and from its own nature, flows equally without relation to any thing external.'

A suspicion that the concept of absolute time is not so obvious was sometimes expressed even in ancient times. Thus Lucretius wrote in the poem *On the Nature of Things* in the first century BC:

> E'en TIME, that measures all things, of itself
> Exists not; ... for of TIME
> From these disjoined, in motion, or at rest
> Tranquil and still, what mortal can conceive.

It was Einstein who proved that absolute time is fiction. The flow of time depends on motion and, which is especially important for us here, on gravitational field. In the gravitational field all processes – absolutely all of them, regardless of their nature – slow down for an outside observer. This means that what is slowed down is that which is common to all processes: time.

The amount of this slowing down (time dilation) is usually very small. Thus time on the surface of the Earth ticks slower than in deep space by the same fraction of one part per billion that we had when calculating the force of gravity.

It is remarkable that this minute time dilation in the gravitational

223

field of the Earth was directly measured. A similar effect in the gravitational field of stars was also measured, even though this effect is also extremely small. Time dilation becomes considerably greater in very strong gravitational fields and tends to infinity as the body radius becomes equal to the gravitational radius.

The second important conclusion of Einstein's theory states that strong gravitational fields change the geometric properties of space. Euclidean geometry, which we are so accustomed to, becomes invalid. This means, for example, that the sum of the angles in a triangle is not equal to two right angles, and the circumference of a circle is not equal to the distance from the center times 2π. The properties of ordinary geometric figures change as if they were drawn on a curved surface. It is for this reason that space in gravitational fields is said to become 'curved'. Obviously, this curving becomes appreciable only in strong gravitational fields, when the size of a body approaches its gravitational radius.

Undoubtedly, the image of curved space is as difficult to reconcile with our deeply rooted intuitive notions as that of different rates of time flow is.

Newton wrote about space in terms no less definite than those concerning time: 'Absolute space, in its own nature, without relation to anything external, remains always similar and immovable'. He thought of space as of an infinitely large 'scene' on which unfold 'events' that do not affect this 'scene' in any way.

Nikolai Lobachevsky, the discoverer of a non-Euclidean, 'curved' geometry, had already expressed the idea that not Euclidean but his, Lobachevsky's, geometry may manifest itself in certain physical situations. Einstein's calculations demonstrated that space is indeed 'curved' in a strong gravitational field.

This conclusion of the theory was also supported by direct measurements.

Why, then, is it so difficult to accept the conclusions of general relativity on space and time?

It is painful because the everyday experience of mankind, and even the experience of exact sciences, dealt for centuries with conditions under which changes in the properties of time and space were completely unnoticeable and thus were neglected. The body of our knowledge is founded on everyday experience. Hence, we are thoroughly used to the millennia-old dogma of absolutely unchanging space and time.

In our epoch, mankind became aware of conditions under which

the effect of matter on the properties of space and time could not be ignored. We have to get accustomed to this peculiar situation despite the inertia typical of our thinking. New generations of people accept the predictions of general relativity much more easily than the generation of several decades ago when even the most enlightened minds had difficulty in mastering Einstein's theory. I will add another remark on the conclusions of relativity. Its author proved that not only the properties of space and time can change but that space and time merge into an inseparable whole: the four-dimensional 'spacetime'. It is this unified manifold that undergoes curving. Obviously, visual images are even more difficult to work out in this four-dimensional supergeometry; we will not spend time on it here.

Let us return to the gravitational field around a spherical mass.

We have to specify what is meant by the radius of a circle, for example, of a planetary equator, because the geometry in a strong gravitational field is non-Euclidean, curved. In conventional geometry there are two ways of determining the radius: first, as a distance from points on the circumference of the circle to the center, and second, as the length of the circumference divided by 2π. As a result of 'space curvature', these two quantities do not coincide in non-Euclidean geometry.

The second way of determining the radius of a gravitating body (not of the distance from the center to the circumference) has a number of advantages. To measure the radius, one need not approach the center of a gravitating mass. This is an important feature; for instance, it would be quite difficult to reach the center of the Earth when measuring its radius but not too difficult to measure the length of the equator.

In the case of the Earth, there is no need to measure the distance from the center directly: the gravitational field is not strong, Euclidean geometry holds for us with high accuracy, so that the length of the equator divided by 2π equals the distance from the center. This is not so, however, in superdense stars with strong gravitational fields: the difference between 'radii' determined by the two methods may be considerable. Furthermore, we will later see that in some cases the gravitational center is unreachable in principle. For this reason, we will always refer to the radius as the length of the circle divided by 2π.

The gravitational field around a spherical nonrotating body, discussed above, is known as the Schwarzschild field, after the

224

scientist who solved the equations of general relativity for this case immediately after Einstein published his theory.

The German astronomer Karl Schwarzschild was one of the creators of modern theoretical astrophysics; he also made important contributions to practical astrophysics and to other branches of astronomy. Schwarzschild died when he was only 42 years old; at the session of the Prussian Academy of Sciences devoted to his memory, Einstein gave the following appreciation of Schwarzschild's contribution to science:

> The most impressive characteristic of Schwarzschild's theoretical papers is a perfect command of mathematical tools of analysis and the ease with which he uncovered the core of an astronomical or physical problem. The combination of such profound mathematical knowledge and common sense with Schwarzschild's flexibility of reasoning is a very rare gift. It was this talent that allowed Schwarzschild to carry out important theoretical work in the fields whose mathematical obstacles scared away other theorists. It appears that the stimulus behind his inexhaustible creative effort was not so much the urge to perceive the hidden relationships of nature as the joy of an artist who discovers a subtle web of interconnections between mathematical concepts.

Schwarzschild obtained the solution to Einstein's equations for the gravitational field of a spherical body in December 1915. We have already mentioned that Einstein's theory, being based on completely novel, revolutionary concepts, is a very complicated one, but it is also extremely complicated 'technically'. Newton's formula of the law of gravitation is famous for its classical simplicity and brevity; in contrast, the new theory required that the gravitational field be found by solving a system of ten equations, each containing hundreds [*sic*] of terms. Moreover, these are not just algebraic equations but second-order partial differential equations.

Nowadays the entire gamut of electronic computers is employed to handle problems of this class. Of course, no such help was available in Schwarzschild's time, pen and paper being the only tools.

In fact, work in general relativity may require in certain cases – even today – a great many hours of painstaking mathematical manipulations 'by hand' (without computer assistance); they are often tedious and repetitive because of the staggering number of terms in the formulas. However, this crude labor is unavoidable. I often suggest to students (and sometimes to postgraduate students and young research fellows), fascinated by the brilliance of general relativity as taught by textbooks and wishing to work in it, that they

start with calculating 'by hand' at least one relatively simple quantity arising in problems of this theory. Not every one of these young people strives to devote his or her life to general relativity after many days (sometimes months) of such calculations.

To defend this 'test for love', I should confess that I myself was subjected to it in this very manner. (Incidentally, legends show that ordinary love between two people also used to be tested by heroic deeds.) In my student days, my instructor in general relativity was a well-known specialist and exceptionally modest person, Professor Zelmanov. The problem he chose for my diploma assignment was connected with a fascinating property of the gravitational field: the possibility of 'cancelling' it anywhere, if we wish. 'Oh, no!' I hear the reader protest, 'Textbooks insist that gravitation cannot in principle be shut off by any screen, and that "cavorite" invented by H. G. Wells is pure fiction, forbidden by nature.'

All this is true; as long as we are at rest with respect to, say, the Earth, its gravitational pull cannot be eliminated. But the effect of this force can be completely cancelled if we start falling freely in this field. Free fall produces weightlessness. There is no weight inside a spaceship orbiting the Earth with engines shut down: astronauts and their equipment float in the cabin and feel no weight. We have watched this picture quite a few times on television screens. Note that no other field, for instance, electromagnetic, allows such simple 'cancellation'.

This property of gravitation is related to a very complex problem of the theory: the problem of the energy of the gravitational field. Some physicists are of the opinion that this problem has not yet been solved. The formulas of the theory make it possible to calculate for any mass the total energy of its gravitational field in the whole of space. However, one cannot specify where this energy resides, or how much energy is located at a specific point of space. In physicists' jargon, the concept of gravitational energy density at a point of space cannot be introduced.

The task of my diploma assignment was to prove by direct calculations that the mathematical expressions known at the time for gravitational energy density gave meaningless results even for observers not in free fall, say, for observers at rest on the Earth who definitely sense the force exerted on them by the planet. The mathematical expressions I was to operate with were even more cumbersome than the equations of the gravitational field discussed above. I even asked Professor Zelmanov to give me an assistant who

225

would carry out the same calculations in parallel: I was afraid of overlooking a mistake. However, Professor Zelmanov knew (and I did not) that the ultimate goal was not only to obtain results of concrete calculations but also to bring up a young researcher. He said in his usual gentle manner, but quite definitely, that I would have to do the job single-handedly.

When everything was over, I realized that the routine work had taken several hundred hours. Almost all calculations had to be carried out twice, sometimes more. By the day the result of the diploma assignment was to be presented, the pace of the work grew rapidly, just like the velocity of free fall in the gravitational field. In all fairness, I have to say that the essential point of the work was not reduced to direct calculations. As it proceeded, I had to think of and solve problems of principle.

This was my first publication on general relativity.

Let us return to Schwarzschild's paper. Using elegant mathematical analysis, he had solved the problem for a spherical body and sent the solution to Einstein for presentation to the Berlin Academy. The solution fascinated Einstein because by that time he himself had been able to obtain only an approximate solution valid for weak gravitational fields. In contrast, Schwarzschild's solution was exact, that is, valid for arbitrarily strong gravitational fields around a spherically symmetric mass; this was a very important result. In fact, neither Einstein nor Schwarzschild himself knew at that time that this solution contained something much greater. It was later found that it contained the description of a black hole.

We shall resume the discussion of escape velocity. What velocity is to be imparted, according to Einstein's equations, to a rocket starting from the surface of a planet in order that it break away from the gravitational forces and escape into space?

The answer proved to be very simple: the formula given by Newton's theory remains valid in Einstein's case. Therefore Laplace's conclusion on the impossibility of light escaping from a compact gravitating mass was confirmed by Einstein's theory of gravitation which states that the escape velocity must become equal to the velocity of light right at the gravitational radius.

A sphere whose radius equals the gravitational radius is known as the Schwarzschild sphere.

Prediction

According to Einstein's theory, therefore, light is unable to leave the surface of a body and reach a distant observer once the radius of this body decreases to the gravitational radius; the body becomes invisible. However, the reader will of course have noticed that this extremely unusual property is certainly not the only 'miracle' that has to happen to a body whose size decreases to the gravitational radius. As we explained in the preceding section, the gravity on the surface of a star that reaches the gravitational radius must become infinitely large, and so must the acceleration of free fall. What will be the consequences of this situation?

To answer this question, recall first why ordinary stars and planets do not get compressed to a central point by the gravitational force but form equilibrium bodies.

The centerward compression is balanced out by the forces of internal pressure of matter. In the case of stars, this is the pressure of very hot gas that tends to expand the star. In Earth-type planets, these are the forces of tension, elasticity, and pressure that also counteract the compression. The equilibrium of a celestial body is maintained by this very equality of the forces of gravitation and forces counteracting it.

These latter forces depend on the state of matter, that is, on its pressure and temperature. Compression increases them. If, however, the matter is compressed to a finite (but not infinitely high) density, pressure and temperature remain finite as well. The gravitational force behaves differently. As the body size approaches the gravitational radius, the gravity on the surface tends, as we already know, to infinity. Now it cannot be balanced out by the finite counteracting pressure and the body must irresistibly contract towards the center.

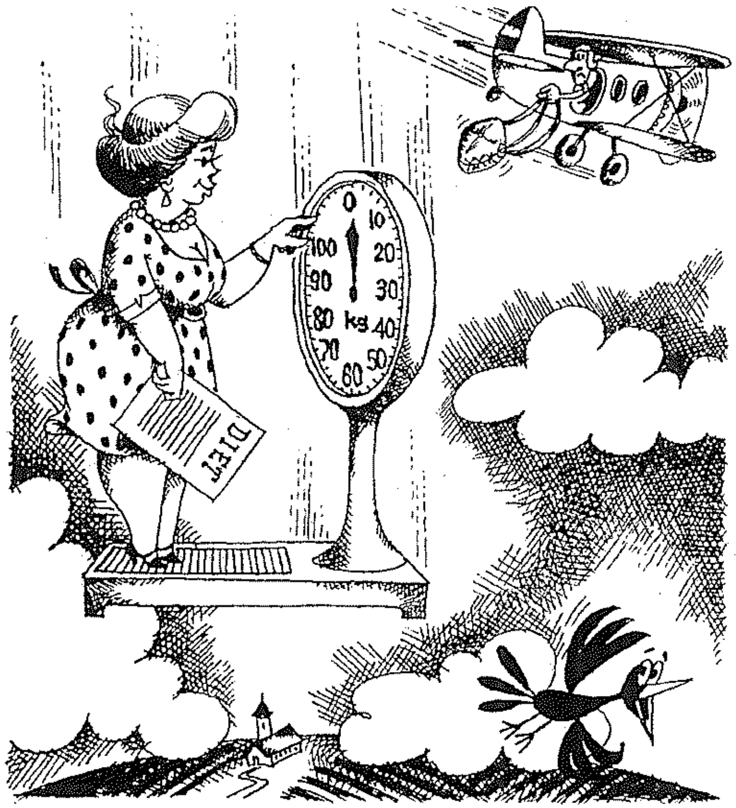
An extremely important conclusion of Einstein's theory thus states: a spherical body whose radius reaches the gravitational value or smaller than this value cannot be at rest but has to contract centerward. 'But wait,' asks the reader, 'if gravity is infinitely high at the gravitational radius, what will it be when the body size drops to below the gravitational radius?'

The answer is fairly obvious. So far we have discussed the gravitational force on the surface of a static body that is not contracting at a given moment. But this force depends upon the state of motion. We have already said that free fall results in weightlessness: a freely falling body does not undergo gravitational force at all.

226

Hence, no gravitational pull is exerted on the surface of a freely contracting body (both within and without the Schwarzschild sphere). The matter forced to fall by gravitation cannot stop at the Schwarzschild sphere (otherwise it would be subject to infinitely high gravity). Stopping inside the Schwarzschild sphere is all the more prohibited. Any particle, say a rocket with no matter how powerful an engine, must fall on the center irresistibly once it has fallen to a point less than the gravitational radius from the gravitational center.

We have thus answered the question about the consequences of the infinite growth in the gravitational force as the body approaches the Schwarzschild sphere: it produces a catastrophic, unstoppable compression. Physicists refer to this phenomenon as the *relativistic collapse*.



It is thus sufficient to compress a body to the size of its gravitational radius for the further compression to be self-sustained. This process produces an object that is now known as a *black hole*.

The process of relativistic gravitational collapse described above was first rigorously calculated by the American physicists Robert Oppenheimer and Hartland Snyder in 1939. Their paper is a classic of succinct and lucid presentation. It gives a complete and stringent description of the phenomenon while occupying only a few pages.

Oppenheimer was well known far beyond the physics circles. He took part in the development of the American atomic bomb and headed the famous Los Alamos Scientific Laboratory in 1943–5. Later he realized the danger implied by the development of the hydrogen bomb and by the armaments race and spoke up for the utilization of atomic energy for peaceful purposes only; in 1953 he was stripped of all his governmental positions as a politically unreliable American.

The Oppenheimer–Snyder paper must be regarded as the rigorous prediction of the possibility of the generation of black holes. As for the term 'black hole', it was coined much later, at the end of the 1960s. Its inventor was the American physicist John Wheeler. In the USSR, for example, they were known for some time as 'collapsars'; this word was then rejected as non-euphonious in English. To be frank, the term 'black hole' led to dubiousness too, despite its precise and clear image.

In 1988 at an international conference in Leningrad, Professor Remo Ruffini of Rome University, who obtained many important results in black hole physics, and I recalled the initial stages of the stormy growth of this science. In 1972 several specialists, myself included, lectured on black hole theory at the International School in the vicinity of Les Houches in the French Alps. After the School ended, the lecturers got together to discuss details of publishing the lectures in a single volume. We had to choose the title of the volume. All agreed that the book was to be called *Black Holes*. Unexpectedly, the technical secretary of the school – a nice and pretty young woman from France – who was to prepare the texts for publication, blushed and said that this title would create serious difficulties. The point was that the book had to have on the title page the title both in English and in French (indeed, the entire text was in English and the school was organized in French). The secretary explained that *Black Holes* would look extremely odd in French. (Of course, we all communicated in English which long ago became the international

227

scientific tongue and hardly any of the lecturers were fluent in French.) The secretary was absolutely adamant, stating that no publishing firm of high repute would print a science book with this title in French. We had to compromise. When published, the book had the English title *Black Holes* and the French title *Etoiles Noires* (*Black Stars*) which – you would agree – is something quite different. In fact, we will see later that this object is not only black, not letting any light out, but is precisely a hole in space and time!

We will conclude this chapter with the following remark.

In principle, a black hole could be produced artificially. We need to compress any mass to the size of its gravitational radius, after which it will contract of itself, undergoing gravitational collapse.

Actually, this endeavor would meet with enormous technical difficulties. The smaller the mass we want to transform into a black hole, the tinier the size to which it has to be compressed, since the gravitational radius is directly proportional to the mass. Thus we know that the gravitational radius of the Earth is roughly one centimeter; a mountain of, say, one billion tonnes would be converted into a black hole if compressed to the size of an atomic nucleus!

Subsequent chapters will show that large masses may spontaneously transform into black holes in the course of the natural evolution of the Universe. Before coming to that, however, we will continue outlining the fantastic peculiarities of black holes.

2: Around a black hole

A hole in time

We have mentioned that the theory of gravitation predicts that the closer the clock is to the gravitational radius the slower the flow of time will be. This means that no matter what processes proceed in a strong gravitational field, an observer located far from a black hole will see that their pace has slowed down.

Thus he will find that oscillations in atoms that emit light are slowed down so that photons originating at these atoms reach the observer 'reddened', at a reduced frequency. This phenomenon is called the gravitational red shift (it served as the basis for one of the tests of the validity of Einstein's theory). What is important for us for the moment is that the closer the emission region lies to the boundary of a black hole (to the Schwarzschild sphere) the greater the time dilation and reddening of light will be. Here time gets slower and then 'stands still' for a distant observer. If the observer follows a stone falling onto a black hole, he will find that close to the Schwarzschild sphere the stone starts to 'decelerate' and gets to the black hole boundary only after an infinitely long time.

A distant observer will see a similar picture in the very process of generation of a black hole, when the stellar matter is pulled by gravitation towards the center. For this observer, the surface of the star takes an infinitely long time to reach the Schwarzschild sphere