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Black holes, wormholes, and time machines

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Abstract. **Three major predictions of Einstein's General Relativity — black holes, wormholes, and time machines — are reviewed for their development and current status.**

Keywords: black holes, wormholes, time machines, Einstein relativistic theory

Albert Einstein's General Relativity (GR), formulated one hundred years ago, is the greatest modern scientific theory. Immediately after its creation, three outstanding theoretical predictions were made:

(1) black holes;
(2) wormholes;
(3) time machines.

Black holes in GR were predicted in 1915 (of course, not under that name, which was coined by Wheeler in 1968 [1] [see [2] for more details]) by the German physicist and astronomer K Schwarzschild (see [3, 4]), who solved the Einstein equations for a spherical black hole in a vacuum. The properties of this solution were extremely unusual. First of all, a black hole turns out to have no material surface, but is bounded in empty space by the so-called gravitational radius $r_g = 2GM/c^2$, where M is the mass, G is the gravity constant, and c is the speed of light. The gravitational force tends to infinity at r_g. Bodies and radiation can enter the sphere with that radius, but nothing can escape. The time for an observer at rest slows down near r_g and stops completely at r_g. The geometry of space is non-Euclidian and is like a three-dimensional funnel.

These properties are so unusual that at that time physicists did not take black holes seriously.

K Thorne writes: "Black holes just didn't 'smell right'; they were outrageously bizarre.... Nobody was pushing black holes as a serious prediction" [3, p. 134].

The years went by, but without any significant progress in black hole studies.

"In the 1930s, ... black holes began to be taken seriously .... [but] the 'opinion setters' began to express unequivocal opposition to these outrageous objects" [3, p. 135].

What was the reason for such a strong negative attitude of some science leaders, including the founders of general relativity, to black holes? Apparently, the main reason was the surprising properties of the nonmaterial boundary of a black hole mentioned above, which we now call the event horizon. These unusual properties led to an emotional refutal of the very possibility of the event horizon arising in a vacuum. We quote several arguments, some of which may sound fantastic.

"There is a magic circle which no measures can bring us inside. It is not unnatural that we should picture something obstructing our closer approach, and say that a particle of matter is filling up the interior" (Eddington [5], 1920).

"*Every gravitating particle has a ring-fence around it, which no other body can penetrate*." (Whittaker [6], 1949).

"The 'Schwarzschild singularity' does not appear for the reason that matter cannot be concentrated arbitrarily. And this is due to the fact that otherwise the constituting particles would reach the velocity of light" (Einstein [7], 1939).

With time, the situation with the prediction of black holes gradually changed. Misconceptions related to erroneous interpretations of some solutions of GR equations were clarified. Finally, in the 1960s, black holes became a subject of serious studies. It was understood that black holes open the window into a new, very broad field of the physical world.

Black holes were discovered in the Universe by astrophysical observations, and since then they have been intensively studied both theoretically and experimentally. Further theoretical research discovered a range of new properties of black holes, which turn out to be as strange as the initially formulated ones. We consider some of them. As stressed above, black holes have no material surface. Their event horizon is a conventional boundary in space–time, separating the region from which radiation and bodies can escape to infinity and the region where this is impossible. Nevertheless, this empty boundary in many cases behaves like a material surface endowed with mechanical, electromagnetic, and thermal properties (see [8]).

We start with electrodynamics. Under certain conditions, a black hole can behave like a dynamo machine. We imagine a metal sphere, electrically neutral as a whole, in empty space, without any black holes. What if this sphere is placed in a magnetic field between poles of a magnet and rotates around the axis parallel to the magnetic field lines? When the sphere rotates, free electrons on the surface of the sphere move under the action of the Lorentz force and, depending on the rotation direction, run to the poles or to the equator. In other places, an excessive positive charge arises. As a result of such a polarization, a quadrupole electric field appears. If a pole and the equator are now connected by a wire, an electric current flows. This is the well-known unipolar inductor operating as a dynamo machine.

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We now return to black holes and suppose that there is a rotating black hole immersed in a regular magnetic field, for example, in a space between two gas clouds. For simplicity, we assume that the black hole spins around the axis parallel to the magnetic field lines. The solution of the Einstein equations jointly with the Maxwell electromagnetic equations yields the following result. At first, the rotating black hole drags the regions of space adjacent to the event horizon in coaxial rotation. Thus, the magnetic field lines become entrained in the same circular motion to induce a quadrupole electric field similar to that around a metal sphere rotating in a magnetic field. As a result, in the conductor connecting the pole and equator, an electric current appears. Rotating black holes work like a dynamo machine, similarly to a rotating tangible metal sphere. Rarefied astrophysical plasma can serve as a conductor. It cannot be ruled out that a similar mechanism actually operates in active galactic nuclei containing black holes and causes the observed effects in the nuclei of such galaxies [2, 8, 9].

We next discuss the black hole thermodynamics. We first recall some quantum properties of space–time in the absence of black holes. If a rigid reference frame moves with acceleration in empty space, there is a spacetime region from which no signals can be received by observers in this frame. The boundary of this region can be called the horizon. Quantum physics asserts that due to the partial loss of information by these observers, thermal radiation arises with the temperature

$$T = \frac{\hbar a}{2\pi k c} = 10^{-42} \left(a[\mathrm{sm\,s^{-2}}]\right) [\mathrm{K}]\,, \qquad (1)$$

where a is the acceleration, $\hbar$ is the Planck constant, k is the Boltzmann constant, and c is the speed of light.

At the same time, an observer in the inertial frame does not see any radiation. She observes ordinary quantum fluctuations with the creation and annihilation of pairs of particles and antiparticles.

Returning to black holes, there is also a horizon — the event horizon. In 1974, Hawking [10] showed that because of this an observer who is at rest relative to the black hole must see a thermal atmosphere near the horizon with the temperature depending on the distance above the horizon Z:

$$T = \frac{\hbar c}{2\pi k Z} = 10^{-7}\,\frac{M_\odot}{M}\left(\frac{r_{\mathrm{g}}}{Z}\right) [\mathrm{K}]\,, \qquad (2)$$

where M is the mass of the black hole and $M_\odot$ is the solar mass. Most of the particles of the atmosphere are kept by gravity and fall back on the horizon, and new particles are created instead of them. A tiny fraction of the particles escapes to infinity. This is the famous Hawking radiation, which can be observed in principle. The power of the radiation is

$$P = 10^{-20}\left(\frac{M}{M_\odot}\right)^{-2} [\mathrm{erg\,s^{-1}}]\,. \qquad (3)$$

A freely falling observer does not see the thermal atmosphere. She observes the usual quantum fluctuations of virtual particles. The thermal atmosphere of a black hole can be used to extract the energy of the black hole. We imagine a container with mirror walls and a lid, which can be hung close to the black hole horizon. We plunge the box with the lid open almost down to the horizon, where it is filled with hot radiation, close the cover, pull up the box, and remove it a large distance from the black hole. The hot radiation inside the box can then be used

We now turn to the second discovery made shortly after the formulation of GR, the hypothetical possibility of the existence of wormholes. This discovery was made by the Austrian physicist Flamm [11]. The simplest wormhole can be perceived as follows. There are two entries (mouths) to a wormhole, each of which externally looks like a black hole. However, they have no event horizons and are connected by a corridor (throat). This corridor lies outside our spacetime in superspace. The distance between the entries in the external space can be arbitrarily large. The corridor can also be arbitrarily long. Wormholes can connect remote regions in our Universe through the corridor. If a wormhole is empty, the corridor rapidly collapses into a singularity due to gravity. These are impenetrable wormholes. Penetrability can be provided by introducing so-called exotic matter with a huge negative pressure into the wormhole. Such matter creates antigravity, stabilizing the wormhole. Matter and radiation can flow through penetrable wormholes in both directions.

While the formation of black holes is understood, and they were discovered in the Universe long ago, the origin of wormholes and the possibility of their existence remain questionable. Nevertheless, we have hypothesized that wormholes do exist. For example, it is possible that some galactic nuclei are not supermassive black holes but entries to wormholes.

We reiterate that the external parts of wormholes are very similar to black holes. Therefore, processes in the external space are very similar for both classes of objects. In this connection, we stress that the recent discovery of gravitational waves, which is interpreted in terms of the coalescence of two black holes, would look similarly for the coalescence of a wormhole and a black hole. Consequently, we should be cautious with definite interpretations of such events.

Of the many interesting properties of wormholes, the following should be noted.

A special topology of the space of a wormhole permits the existence of an unusual steady-state magnetic field configuration: the magnetic field lines radially enter one mouth of the wormhole, pass through the throat, and exit radially from the other mouth. The field near each entry has a monopole character. This is impossible in the case of black holes.

Finally, we note the hypothetical existence of many universes (the multiverse). It is then possible that wormholes connect different universes, and matter, radiation, and information can flow from other universes into our Universe. Furthermore, there can be more complicated structures of wormholes, for example, wormholes connecting our Universe with other universes in the future or in the past. In this case, motion through the corridor is possible only in one direction. Such wormholes can have branching corridors. Clearly, the search for wormholes in the Universe is very important. The proof of the possibility of the existence of other universes would have an enormous ontological impact.

The search for wormholes in the Universe is stipulated by the scientific program of the ongoing Radioastron project and the future Millimetron space project [12].

We now turn to the third hypothesis stemming from GR, the fundamental possibility of the existence of a time machine. Einstein wrote that immediately after the creation of GR he understood that the curvature of spacetime can lead to the formation of closed timelike geodesics, and hence to the existence of a time machine enabling travel from the future to the past, and this possibility worried him a lot. At first glance, such a possibility can violate the causality principle, because, by returning to the past, it is possible to change the initial conditions and make evolution follow a totally different scenario contradicting the original path. However, this is not so. As shown in [13], there is a self-consistency principle. If time loops exist, the future acts on the past from the very beginning by the time loop, thus enabling fully self-consistent evolution along the entire loop. That is, the future influences the past from the very beginning, but nothing can be altered in the past. The past depends on the future and is fully consistent with it. Physics becomes more complicated (and more intriguing!), but no contradictions arise. As proved in [14, 15], the self-consistency principle is a direct consequence of the least action principle, a basic physical principle.

In [2], specific examples of time machines are presented. The reality of such constructions has been questioned many times, for example, due to quantum processes that can possibly occur. However, thus far, no rigorous proof forbidding time machines has been found. The general opinion is that the final answer can be obtained only after the construction of quantum gravity.

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