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A new concept of wormholes and the Multiverse

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Contents

Abstract. We review a new concept of wormholes. We classify the wormholes into three categories: static, space-like, and time-like, and discuss the properties of each category. The relation between wormholes and black holes is examined. The astrophysical properties of wormholes are investigated.

Keywords: wormholes, Einstein's general theory of relativity, Multiverse

1. Introduction

Wormholes were theoretically predicted by general relativity (GR) more than a hundred years ago in [1], shortly after its formulation. The simplest model of a wormhole proposed in [1] represents two entrances located in three-dimensional space and connected by a throat-bridge that lies outside our space–time. This bridge can be very short, while the distance between the entrances in the external space can be very long. Thus, these wormholes connect remote parts of our Universe by short bridges. Such models were thought to be static. Matter and light can pass through such a wormhole in both directions.

The first mathematical model of a wormhole constructed by Einstein and Rosen [2] consists of two pieces of the external space–time of a black hole (two Schwarzschild solutions) cut off at the gravitational radius (the horizon) and glued together. Thus, the model represents two asymptotically flat spaces connected by a throat-bridge. The authors thought that the construction, called the Einstein–Rosen bridge, should be static. Later such bridges started being referred to as wormholes. However, it became clear that the assumption of their static nature is incorrect. The gravity of the curved space–time very rapidly makes the throat of the bridge collapse into a singularity, an infinite space–time curvature. The collapse occurs so rapidly that even light has no time to pass through the wormhole from one part of space to another. Such wormholes were called nontraversable. An Einstein–Rosen bridge can be stabilized if it is filled with exotic matter [3], whose equation of state satisfies the inequality

$$\varepsilon + p_{\mathrm{r}} < 0\,, \tag{1}$$

where ε is the energy density and p_{r} is the radial pressure.

Exotic matter creates antigravity that balances gravity, which renders the bridge static. Typical examples of static wormholes are presented in [4–6]. Numerous studies of these wormholes have addressed their stability and the passage of matter through them (see, e.g., [7–12], as well as Section 2). These wormholes have also been used to construct models of the Multiverse [13, 14]. According to the Multiverse model, other universes exist besides our Universe. The wormholes serve as connecting tunnels between the universes. Static wormholes are definitely traversable in both directions. Dynamical wormholes can be nontraversable, like the Einstein–Rosen bridge (see, e.g., [15]). For a long time, solutions of the Einstein equations have been analyzed that can be also regarded as possible links between different universes, although they are qualitatively different from the wormholes considered above. A typical example is the maximum analytic expansion of the Reissner–Nordström solution, which is usually called an electrically (or magnetically) charged black hole (see, e.g., [6, 16–18]). We discuss this solution in more detail in Section 4. We stress that the Reissner–Nordström and similar solutions essentially represent models of the Multiverse with time-oriented wormholes.

That the maximally extended empty Reissner–Nordström solution (i.e., containing only gravitational and electromagnetic fields) enables traveling from one universe to another was first noted in [19] and later in [20, 21]. In this paper, we single out such solutions into a separate class of wormholes that play the main role in constructing models of the Multiverse.

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So far, we have considered spherically symmetric solutions of the Einstein equations, clearly because they can frequently be treated fully analytically. We also mainly address such solutions here. This is sufficient to study many principal issues. However, not all fundamental problems considered in this paper can be solved using only spherically symmetric models. In Sections 4 and 5, we analyze another exact model in the framework of GR, which is of fundamental importance for our topic, namely, the maximally extended Kerr solution [22] describing rotation. Clearly, the Kerr solution is a nonspherical stationary solution of the Einstein equations. Unlike the Reissner–Nordström solution, which includes an electromagnetic field, the Kerr solution describes totally empty space with only the gravitational field. This fact is important for the study of many fundamental issues (see Sections 4 and 5 for more details).[1]

In Section 5, we briefly discuss new possibilities offered by nonspherical solutions and consider fundamentally new situations arising in analyzing instability of the spherical solutions.

In studying the motion of matter in the Reissner–Nordström solution, we mainly deal with the evolution of spherical thin charged material shells — self-gravitating bubbles without internal tensions. This is because these solutions determine the evolution of the surface of spherical bodies made of pressureless matter, which are of special importance for us, and, in addition, there is no need to consider the evolution of matter inside the sphere. The evolution of thin spherical shells is considered in detail, for example, in [17] (see also [23, 24]).

Theoretically, wormholes were predicted as long ago as black holes were. These theoretical discoveries in the first decades after their formulation had similar fates. In the best case, nobody considered them seriously, and there were strong opinions arguing for their being mathematical artefacts of the Einstein equations. Only starting from the mid-1930s did serious theoretical studies of these topics start appearing. Later on, the fates of these discoveries became significantly different. Black holes have been discovered to reside in the Universe in binary star systems and in the center of many galaxies (see [25]). They have been studied in detail both theoretically and in astrophysical observations [26]. Black holes result from the natural evolution of some astrophysical objects. The status of wormholes is quite different: to date, they remain hypothetical theoretical objects. It is unclear whether wormholes can actually exist in the Universe. However, we note that there is no rigorous proof that they cannot exist. For example, their possible formation from quantum fluctuations — the quantum foam considered by J Wheeler to exist for extremely small scales — is discussed by Thorne [3, Ch. 14] "If quantum foam *does* exist, I hope there is a natural process by which some of its wormholes can spontaneously grow to human size or bigger and even did so during the extremely rapid 'inflationary' expansion of the universe, when the universe was very, very young." (see Section 5). Presently, wormholes are being intensively studied theoretically. In this paper, we review the topical problems, including the physics of wormholes and the hypothesis of the Multiverse, and consider new related ideas.

[1] We note that there is a generalization of the Kerr solution to the case where an electric or magnetic field is present (see [27]); however, it is of no importance here.

Thus, wormholes should be separated into three classes:

(1) static wormholes;

(2) space-like wormholes;

(3) time-like wormholes.

In Sections 2–4, we analyze the properties of each class separately. In Section 5, we consider the impact of these properties on astrophysical manifestations of wormholes.

2. Static wormholes

The model of a wormhole constructed by Einstein and Rosen (see [2] and Section 1) turned out to be nonstatic. An initial instantly static construction corresponding to this model starts evolving immediately (Fig. 1). The reference frame associated with this construction contracts. Event horizons appear that separate two asymptotically flat empty spaces, A and B, representing external solutions of the Schwarzschild metric, from the tunnels contracting in the T_- region. The contraction results in the formation of a space-like space–time singularity $r = 0$. Figure 1 shows null geodesics inclined by the angle 45°. The figure suggests that no signal propagating with a subluminal velocity can escape from region A into region B and vice versa. Its world line touches the singularity $r = 0$. Thus, the construction represents a tunnel rapidly contracting under the action of gravity, a nontraversable wormhole.

The construction can be made static by adding 'exotic matter', which creates antigravity equilibrating the curved space–time gravity.

As mentioned in Section 1, exotic matter has the equation of state satisfying condition (1). The simplest exotic matter is a massless scalar field Ψ (see [4]) with the negative energy density ε (see [4, 5]),

$$\varepsilon < 0 \,. \tag{2}$$

The Morris–Thorne (MT) model [4, 5, 28] is one of the simplest models of static wormholes. The corresponding linear element of such a wormhole is

$$\begin{aligned} ds^2 &= -dt^2 + dR^2 + r^2\,d\Omega^2\,, \\ r^2 &= Q^2 + R^2\,, \qquad d\Omega^2 = d\theta^2 + \sin^2\theta\,d\phi^2\,, \end{aligned} \tag{3}$$

where R ranges from $-\infty$ to $+\infty$, and Q is the strength of the exotic field Ψ supporting the static condition. Here and

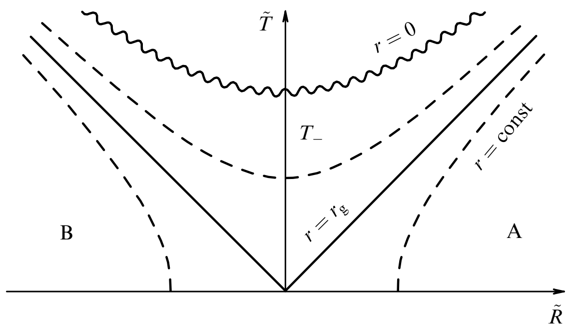

Figure 1. Einstein–Rosen bridge contraction. $\tilde{R}$ is the radial space coordinate, $\tilde{T}$ is the time coordinate, A and B are external asymptotically flat regions, r_g is the gravitational radius, and T_- is the contracting T region. The dashed curves show $r = \mathrm{const}$ lines; $r = 0$ is the space-like space–time singularity.

below, we set the speed of light $c = 1$. We note that the MT model has zero mass. For an observer at rest in reference frame (3), the gravitational force is absent at any point.

The nontrivial spatial topology of static wormholes leads to many interesting features. First, this topology enables matter, radiation, and information to leak through some regions of space into others or even from the space of one universe into another in the Multiverse model (see below). Second, this gives rise to peculiarities in the wormhole electrodynamics, as first noted by Wheeler [29, 30]. Later, these problems were addressed in many papers (see [31] and the references therein). The possibility of the existence of an electric field whose field lines go radially in 'our' space A, enter radially into the wormhole, and go out radially in space B is the most interesting. The field bears a monopole character near each entrance, although there is no source of the field. Wheeler called this solution 'charge without charge'. Of course, a similar solution is possible for the magnetic field as well. Other possible field configurations are presented in [31].

It is also of interest to consider processes arising when a narrow beam of radiation with positive energy is sent into the wormhole. This problem was considered in [10]. To solve the problem in the GR framework, it is necessary to consider the evolution of the wormhole space–time and of the physical fields: the massless exotic scalar field Ψ initially supporting the wormhole in static equilibrium and the massless field Φ describing the radiation flux through the wormhole. For simplicity, a massless scalar field Φ with a positive energy density ε was chosen. The joint solution of the Einstein equations and the Klein–Gordon equation for the fields Ψ and Φ yields the results presented below. The calculations can be most conveniently performed in double null coordinates u and v, in which the spherical linear element is given by

$$ds^2 = -2\exp\left(2b(u,v)\right)\,du\,dv + r^2(u,v)\,d\Omega^2\,, \tag{4}$$

where $b(u,v)$ and $r(u,v)$ are functions of the coordinates u, v.

We have considered the injection of a narrow Φ-field beam with the relative amplitude $A_\Phi = 0.01$ (relative to the initial amplitude of the supporting field Ψ) into an MT wormhole from 'our' space A (see [10]). The results of calculations are presented in Figs 2 and 3. Figure 2 shows the evolution of the space–time structure after the Φ-pulse injection. 'Our' A-space in (u,v) coordinates is shown in the bottom part of Fig. 2. After the pulse Φ enters the wormhole, the additional gravitation due to the Φ field first makes the wormhole contract. Event horizons emerge on each side of the space. Then the true space-like singularity $r = 0$ appears, as in the Schwarzschild metric. The narrow pulse of the Φ field propagates along the u-direction with the speed of light. The Φ field interacts with the space–time curvature and is partially scattered. It is seen from Figure 3 that despite the appearance of the singularity $r = 0$, the horizons, and scattering, most of the energy of the narrow Φ-field flux (the almost vertical lines in the left part of the figure) passes from 'our' space into another and carries information. If another signal is injected (along the v-coordinate) with the speed of light from our space considerably later than the first pulse, the corresponding world line hits the singularity $r = 0$ and is not able to traverse into another space. In Fig. 3, the critical value of the v coordinate is $v_c \approx 13.5$. In this sense, the MT wormhole is unstable. A small perturbation destroys it. However, it has

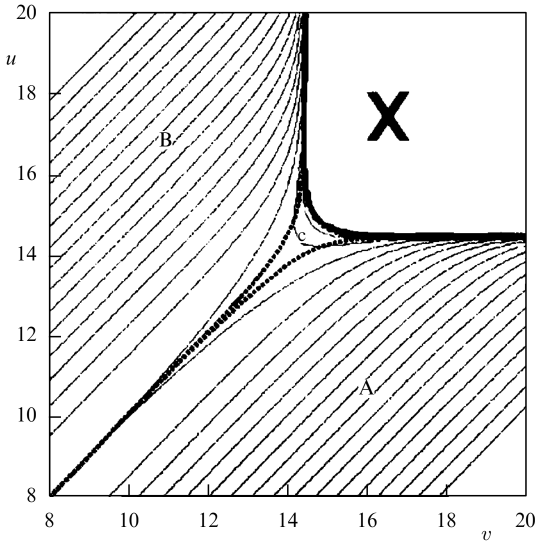

Figure 2. Evolution of an MT wormhole in the (u,v) coordinates after the Φ-pulse injection. A is our universe, B is another universe. The thick solid curve shows an $r = 0$ singularity arising due to the compression. The dashed lines show the emerging apparent horizons; thin solid lines show contours $r = \text{const}$; c is the emerging T_- region; the cross indicates the region outside the computation domain behind the $r = 0$ singularity.

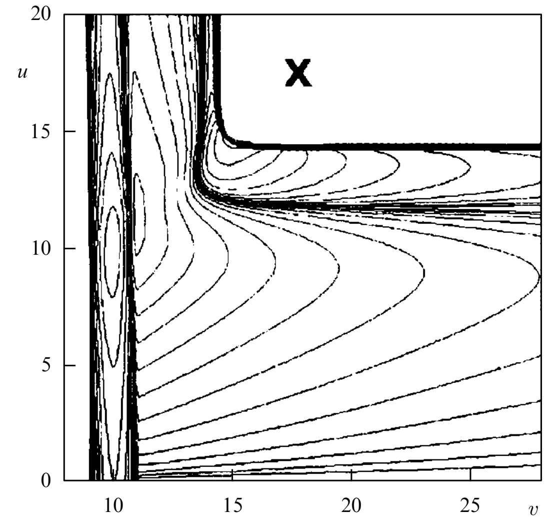

Figure 3. Passage of a narrow Φ pulse through an MT wormhole. The thin solid curves show the Φ-field scattering contours. The cross marks the region outside the computation domain. The thick solid line indicates $r = 0$.

time to pass the radiation and information from one space to another.

We note that there can be wormholes filled with special exotic matter, which are stable under small perturbations (see [11, 12, 32]).

In addition to the stability problems of static wormholes, there are other important issues related to their physical properties. First and foremost, this relates to properties of the exotic matter that must be filling static wormholes. Properties of exotic matter are peculiar, and far from all physicists agree upon them. There is no model of a static wormhole fully acceptable to all physicists as yet.

In this paper, we do not discuss in detail this aspect of the problem, which is beyond the scope of our task. In addition to

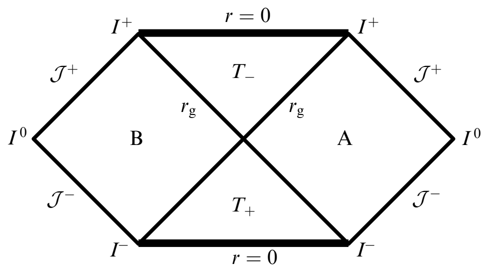

Figure 4. Penrose–Carter diagram for the Kruskal metric showing a multiverse consisting of two empty universes, A and B, connected by a nontraversable Einstein–Rosen bridge. I^0 is the spatial infinity, I^+ is the infinite time-like future, I^- is the infinite time-like past, $\mathcal{J}^+$ is the light future (future null-infinity), $\mathcal{J}^-$ is the light past (past null-infinity), T_+ is the expanding T region, T_- is the compressing T region, and $r = 0$ is the space–time singularity.

the above quotation from Thorne's book [3] on possible ways for wormholes to appear in the Universe, we quote another, more sceptical opinion from the same author: "If traversable wormholes are allowed by the laws of physics, I think it extremely unlikely they can exist naturally, in the real universe. I must confess, though, that this is little more than a speculation, not even an educated guess" [3, Ch. 14].

3. Models of the Multiverse with space-like wormholes

We now turn to space-like models of wormholes and to models of the Multiverse. The simplest model of the Multiverse is an MT wormhole connecting two asymptotically flat spaces — two universes with infinite proper lifetimes each, connected by a narrow throat. Of course, this model, as well as the two following ones, does not directly relate to our nonstatic Universe.

The Kruskal metric [26] — a maximum analytic extension of the Schwarzschild metric (Fig. 4) — is another simple model of the Multiverse. In Fig. 4 (as well as in the subsequent figures), three solutions are presented as the Penrose–Carter diagrams [26], in which special mathematical transformations are used to bring infinitely remote points to finite distances. In Fig. 4, there are also two spaces, asymptotically flat at infinity, existing for an infinitely long time. However, here, they are connected by a nontraversable dynamical wormhole, an Einstein–Rosen bridge. This model is often referred to as a 'black–white hole' or 'eternal black hole' (see, e.g., [26]). However, it is clear that this is not a hole in the commonly accepted sense because it does not result from the collapse of something. It is more accurate to treat the Kruskal metric as a model of the Multiverse.

Another exact model of the static Multiverse was constructed in [14]. This model includes matter of three types: a centrally symmetric electric (or magnetic) field, the cosmological Λ term, and an exotic dust with $\varepsilon < 0$. The dependence of the profile $r^2 \equiv g_{22}$ on the radial coordinate R is given by

$$r^2(R) = \frac{1 - \sqrt{1 - 4\Lambda q^2}\, \cos\left(2\sqrt{\Lambda} R\right)}{2\Lambda}\,. \tag{5}$$

The Multiverse is here represented by a sequence of static universes connected by static throats.

Finally, we consider a multiverse that can be related to the real world, including our Universe [33].

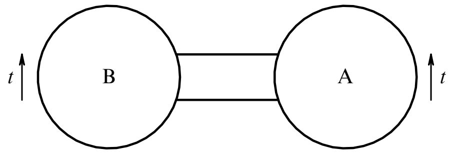

Figure 5. Two universes, A and B, connected by a space-like wormhole.

The model includes two almost closed (semi-closed) worlds [34–37] connected by a dynamical wormhole. Each of the semi-closed worlds/universes was calculated in [35, 36]. The unification of these two worlds into one Multiverse is presented in [33] as an exact solution of the Einstein equations. The same paper [33] shows that not only semi-closed Friedmann cosmological worlds can be connected in this way, but a semi-closed universe with open space can also be connected. Other combinations are also possible.

These models offer somewhat limited possibilities for sending a signal from one universe to another connected to it [say, from universe A to universe B (Fig. 5)]. The limitation is that in order that the signal be successfully sent from A to B, it must be sent from A at an early expansion stage, and in B it will be received quite late. It is possible to send a signal from B to A, but only if it leaves B sufficiently early.

In all cases, the dynamical wormhole connecting the universes represents a Kruskal space-like wormhole.

The simplest models of the Multiverse considered up to now are schematically shown in Fig. 5. They represent two worlds of different structures connected by a space-like wormhole (traversable or nontraversable). In this sense, they are similar to pipelines between neighboring apartments. Inside each world, time flows independently from minus infinity to plus infinity, as shown in Fig. 5.

4. Models of the Multiverse with time-like wormholes

A multiverse with time-like wormholes has a totally different structure. Figure 6 schematically shows such a model. Time inside each world flows as shown by arrows. These models can be typically represented by a maximal extension of the Reissner–Nordström metric, in which the chain of worlds continues without a bound from the past to the future (Fig. 7).

Each of the asymptotically flat worlds with an electric field, A and B, connected by a nontraversable Einstein–Rosen

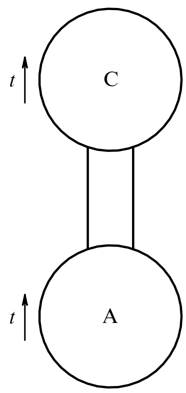

Figure 6. Two universes, A and C, connected by a time-like wormhole.

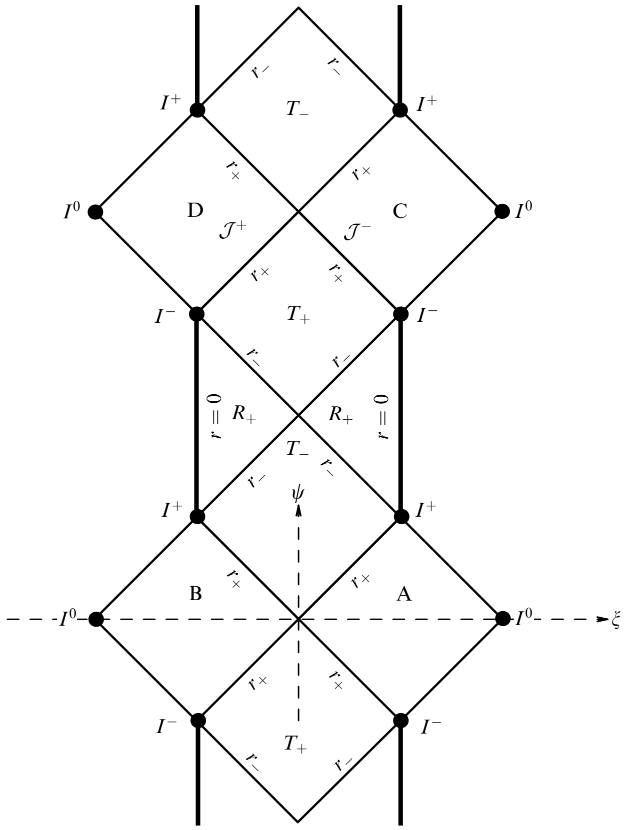

Figure 7. Reissner–Nordström metric. A, B, C, and D are asymptotically flat universes, ψ is the time coordinate, ξ is the space coordinate, I^0 is the spatial infinity, I^+ is the future time-like infinity, I^- is the past time-like infinity, T_+ is the expanding T region, T_- is the contracting T region, $r = 0$ is the space–time singularity, r_+ is the event horizon, and r_- is the Cauchy horizon.

bridge is connected with two analogous worlds, C and D, by time-like wormholes.

A trip, say, for A to C or D is possible, as mentioned in the Introduction, i.e., these are traversable time-like wormholes. These wormholes are nontraversable in the opposite direction: this would be the motion against the time direction.

As mentioned in the Introduction, a maximum extension of the Reissner–Nordström solution is often called an electrically (or magnetically) charged black hole (see, e.g., [6, p. 23], [10], [16, pp. 8, 12, 37, 115], [17, 26]). In fact, this is not, of course, a black hole, because this Reissner–Nordström solution describes not a collapse of something but a model of the Multiverse with an infinite number of individual worlds, each existing for an infinite proper time.

As stressed in Section 3, the everywhere empty Kruskal solution describes not a black hole (because this is not a result of the collapse of matter) but a model of the Multiverse with two empty worlds, in each of which time flows from minus infinity to plus infinity.[2]

If we want to consider the formation of a noncharged black hole, we should take only a part of the Kruskal metric and connect it to collapsing matter as shown in Fig. 8. The matter contracts to the true singularity $r = 0$, which is space-like. It cannot be viewed as the result of the compression of matter to zero size, because the space-like orientation of the singularity from the matter compression point would mean its motion with superluminal velocity. The singularity results from the evolution of the entire empty region T_-. There is a reference frame in which the singularity emerges simultaneously. The natural question arises as to what happens as a result of the gravitational collapse of charged spherical matter to under its gravitational radius (event horizon). Which object appears here? To investigate this and other problems below, we analyze the evolution of a charged sphere (shell) in the GR framework. Excluding inner matter of a spherical body simplifies the solution (see [17, 24]). We also consider a dust shell for simplicity. We consider a solution where the shell is empty and is described by the Minkowski space–time. The metric outside the bubble is described by the Reissner–Nordström solution and in the Schwarzschild coordinates has the form

$$ds^2 = -F^2\,dt^2 + F^{-2}\,dr^2 + r^2(d\theta^2 + \sin^2\theta\,d\phi^2)\,, \qquad (6)$$

where

$$F^2 = 1 - \frac{2m}{r} + \frac{Q^2}{r^2}\,,$$

with Q being the electric field strength and m the total mass of the system. We set $c = 1$ and $G = 1$. In the structure shown in Fig. 7, $m > |Q|$ is assumed.

The Einstein–Maxwell equations for this problem reduce to the following equation of motion of the shell:

$$m = M(1 + \dot{R}^2)^{1/2} - \frac{M^2 - Q^2}{2R}\,. \qquad (7)$$

Here, R is the radius of the shell at a proper time τ, $\dot{R}$ is the derivative of R with respect to τ, and M is the total proper

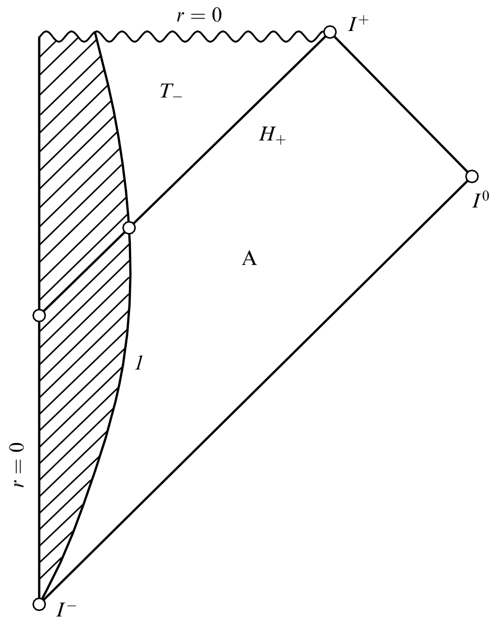

Figure 8. Collapse of an uncharged material ball into a black hole. A is 'our' universe, *1* is the world line of the ball's surface, H_+ is the event horizon of the black hole, I^0 is the spatial infinity, I^+ is the future time-like infinity, I^- is the past time-like infinity, the vertical line $r = 0$ shows the ball center, and the wavy line $r = 0$ shows the space–time singularity.

[2] We note, however, that both worlds A and B are related to the evolution of the initial singularity $r = 0$ and jointly generate the final singularity $r = 0$.

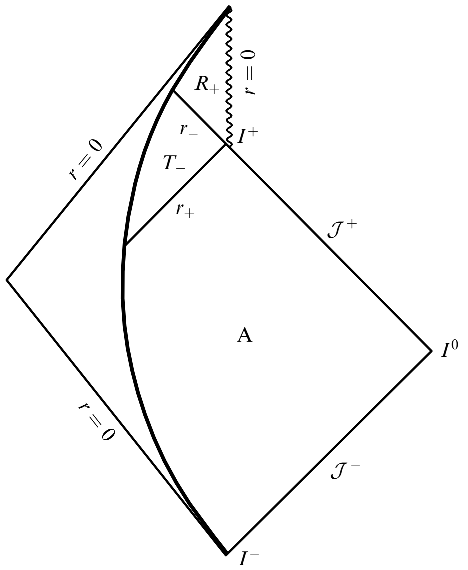

Figure 9. Collapse of a charged gravitating shell (solid thick curve). A is 'our' universe, r_+ is the event horizon, r_- is the Cauchy horizon, R_+ is the inner R-region, the solid line $r = 0$ is the ball center, the wavy line $r = 0$ is the space–time singularity, I^0 is the spatial infinity, I^+ is the future time-like infinity, I^- is the past time-like infinity, $\mathcal{J}^+$ is the future null-infinity, and $\mathcal{J}^-$ is the past null-infinity.

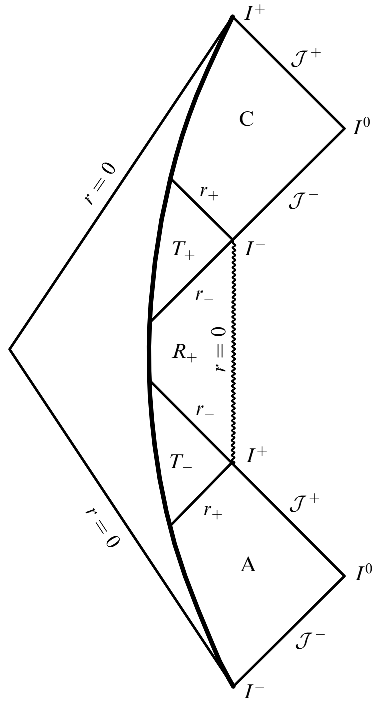

Figure 10. Passage of a charged shell from universe A into universe C (solid thick curve). I^0 is the spatial infinity, I^+ is the future time-like infinity, I^- is the past time-like infinity, $\mathcal{J}^+$ is the future null-infinity, $\mathcal{J}^-$ is the past null-infinity, r_+ is the event horizon, r_- is the Cauchy horizon, the solid line $r = 0$ is the ball center, and the wavy line $r = 0$ is the space–time singularity.

mass of the shell (i.e., the sum of the constituent dust grain masses).

The solution $R = R(\tau)$ depends on the constants M, m, and Q. A qualitative analysis of the solution is easy to perform. It is straightforward to see that for $Q^2 < M^2 < m^2$, the solution has the form shown in Fig. 9. Here, the trajectory $R(\tau)$ starts in 'our' universe A, crosses the event horizon r_+, which corresponds to the moment of collapse of the charged shell, plunges under its event horizon (see below about the horizon r_-), and approaches the true singularity $r = 0$. Qualitatively, everything occurs in the same way as during the collapse of electrically neutral dust, but the singularity $r = 0$ turns out to be time-like! The singularity is not a result of the evolution of collapsing charged matter to zero sizes and always exists in the proper time, as in an electrically empty Reissner–Nordström metric. Here, there are no universes in the future. Hence, it is not a wormhole but a collapse (see Fig. 9).

We now consider another solution of Eqn (7) for other values of the constants. Let $M^2 < Q^2 < m^2$. The evolution is qualitatively shown in Fig. 10. The part of the evolutionary curve lying in 'our' universe looks like the previous solution describing the collapse with the formation of a black hole. Later, however, there is no contraction to the zero size, and the contraction changes into expansion into another universe, C, lying in the absolute future with respect to 'our' universe. Hence, the solution in Fig. 10 is not a collapse but a wormhole between universes A and C.

Finally, note that for $Q^2 < m^2 < M^2$, the evolution, if we trace it starting from 'our' universe, occurs qualitatively as in the case $Q^2 < M^2 < m^2$. This is important from the standpoint of astrophysical appearances of time-like wormholes (see Section 5).

We also note the following important feature of the maximally extended Reissner–Nordström solution: it has inner horizons, the lines r_- in Fig. 7. They correspond to the smaller roots of the equation $F = 0$. These horizons, called Cauchy horizons, separate regions where the evolution is fully determined by the preceding evolution from the regions where the evolution is influenced by additional circumstances. For example, the horizon r_- (1) in Fig. 7 separates the region of the preceding evolution from the region R_+ in which additional influence, for example, from the singularity $r = 0$, should be taken into account.

The presence of the Cauchy horizons gives rise to the possibility of a significantly different future evolutions of two solutions with an absolutely identical past evolution in 'our' universe A. The Cauchy horizons separate the region in one universe, including the T_+ region (which is essentially related to the beginning of a wormhole), from regions R_+ already related to the wormhole proper, and the region T_-, which is its end, from other universes C and D lying in the absolute future of A and B. In these other universes, processes occur basically independently of A and B, except for some influence through the wormhole.

An example of an independent process in universe C is shown in Fig. 11, in which the evolution of a shell in universe C occurs mainly independently of universes A and B. Inside this shell, there is not empty space–time but the Kruskal metric (in the upper part of Fig. 11).

Figure 12 shows a process occurring in universe C that is significantly influenced by universe A through the wormhole. It represents a unification of the processes shown in Figs 10 and 11 and ends with the collision of the shells, although, in principle, there could be no shell starting the evolution in the region C (shell *1*). The beginning of its evolution is independent of A.

To conclude this section, we recall that the time-like Reissner–Nordström wormholes considered here are only

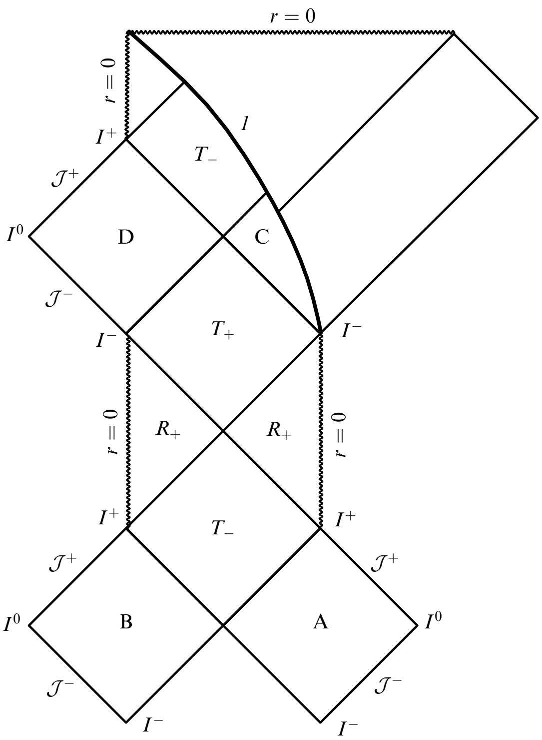

Figure 11. Evolution of shell *1* with the Kruskal metric inside universe C (the upper part of the figure). This evolution is not caused by events in universe A. The notation is the same as in the preceding figures.

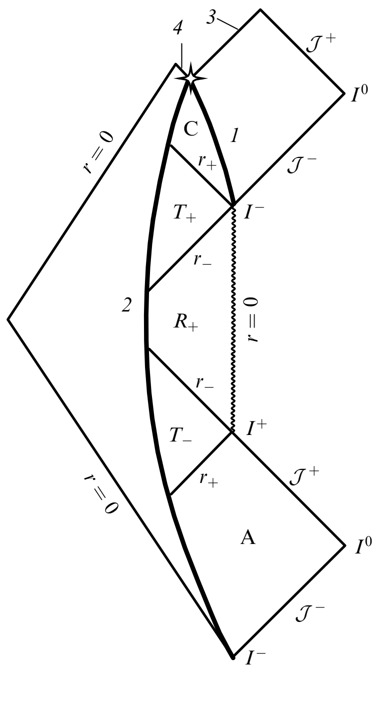

Figure 12. Evolutions of gravitating charged shells *1* and *2* with independent beginnings. The evolutions end with their collisions (shown by the star). *3* and *4* are the signals from the collisions propagating with the speed of light. Other notation is the same as in the preceding figures.

one possible type of wormholes of this class. There are many others. For example, another representative of this class is the maximally extended Kerr solution with rotation [22]. Many topological features of this solution are similar to those considered here. The main difference is more complicated structures of the transitional zone and of the singularity $r = 0$. We do not consider this here. Of course, Kerr wormholes with rotation are especially important from the astrophysical standpoint (see Section 5).

Another concluding remark relates to the peculiarity of the topological structure of a Reissner–Nordström wormhole. As seen from Fig. 7, there are two different entrances to the transitional region T_- from two different universes A and B, and two different exits from the region T_+ into two different universes C and D. Thus, it is possible to say that two tunnels from A and B merge into one in the R_+ region and then separate into two tunnels in the T_- region. Such is the 'fine structure' of this wormhole.

5. Discussion. Conclusion

We emphasize once again that wormholes remain hypothetical theoretical objects. There are different opinions about their possible existence in the real world. In addition to Thorne's opinion presented in Section 1, we can cite two other authoritative researchers.

For example, Visser writes [6, p. 374]:

"What are my personal choices? I think that all the possibilities discussed in this monograph should be investigated to some extent… . Tentatively my own views are:

• Topology change is bad.
• Traversable wormholes are good.
• Time travel is bad."

Another well-known specialist, including on the Multiverse hypothesis, Linde, wrote [38, p. 625] on the properties of wormholes after inflation: "A typical thickness of 'tubes' connecting mini-universes after inflation may become very large."

Thus, studies of wormholes are of theoretical and perhaps practical (from the astrophysical standpoint) importance [39].

As mentioned in Section 4, the Cauchy horizon plays the most important fundamental role in time-like wormholes. Numerous papers have investigated the structure of space–time near the Cauchy horizon where different perturbations interact in an intricate way [26, 40–43]. As a result, a true space–time singularity is likely to emerge there, albeit one very weak along most of its extension. A strong singularity (for example, $r = 0$ in the Schwarzschild solution) is one that tidally disrupts any infalling body. In a mild singularity we consider, the tidal forces also tend to infinity, but the integral of their action over the trajectory of a freely falling body remains finite, i.e., the body is not disrupted. Thus, the crossing of a mild singularity by an object can prove to be barely noticeable. The body can continue moving further. The final answer to the question of the singularity crossing can be obtained only after the creation of a theory of quantum gravity, because its effects must dominate when crossing the singularity. Here, we assume that the mild singularity is traversable. This opinion is shared by many specialists.

The feature of the mild singularity considered above has been understood mainly by investigating the stability of the Cauchy horizon in the Kerr solution (see [16]). This is because in contrast gravitational and electromagnetic fields whose perturbations must be taken into account in the analysis of the Reissner–Nordström solutions, there is only the gravitational field in the Kerr solution, and the problem is simplified in some sense. To summarize the situation, Burko and Ori write [16, p. 6]: "Moreover, nothing in our present understanding of the theory of gravity indicates to the impossibility of the extension of geometry beyond the inner horizon". They hence conclude that the Kerr type of causal structure (i.e., the gravitational rebound through a wormhole) cannot be ruled out.

We are interested in the space–time structure in the presence of a Cauchy horizon, and we disregard the possibility that it can prove to be singular. The authors of [40] conclude that the Cauchy horizon is preserved. However, this problem must be investigated further, which we postpone to future studies.

Here, we also omit the discussion of the obscure problem of the possible instability of exits from white holes (see [26]).

We note that Kerr black holes [26] and probably many other objects have topological properties similar to those discussed here, and we therefore consider our general conclusions without any further stipulations, taking into account that the most important of them we have already made. Therefore, the remarks on observational manifestations of Reissner–Nordström wormholes also relate to the general case of time-like wormholes.

We note that observational manifestations of static wormholes have been analyzed many times (see [44]). Most of these manifestations relate to the possibility of matter leakage through such wormholes in both directions and to the topological features of the structure of three-dimensional space inside these wormholes, which, for example, allow the magnetic field to have a specific monopole structure in their vicinity. However, for such static wormholes to exist, they must be filled with a special form of exotic matter. Therefore, it is clear that even if wormholes exist, most likely they should be dynamical space- and time-like configurations.

We consider the model of the Multiverse with time-like wormholes and similar objects discussed in Section 4. What should be their observational manifestations? The general property should be the asymmetry between the entrance to and exit from them. The entrance is in the universe existing in time earlier than the universe with the exit. Matter and radiation can only enter but not go out of the entrance. Otherwise, this would be motion against the time flow direction. We call such entrances black entrances. They can either exist independently of any matter, as is the case of the Reissner–Nordström metric, or arise from the collapse of a gravitating mass, either as the entrance into a black hole leading to the singularity (see Fig. 9) or the passage to another universe (see Fig. 10). We note that after crossing the Cauchy horizon, the evolution is determined not only by what is going on in the original universe but also by additional factors. Thus, the gravitational collapse of an object in our Universe can lead to a different subsequent evolution inside the arising black entrance.

We now consider exits from a wormhole, the white holes. They can exist in our Universe and can be exits from time-like wormholes going out from other universes (see Fig. 10), or can be related to processes in the past in the transitional zone, including ones with time-like singularities. It is the study of such throats — white holes — that is of the most observational interest, because they carry information about other worlds of the Multiverse. We recall that all the above relates not only to the solution with an electric or magnetic field inside relativistic objects (i.e., to the Reissner–Nordström solution) but also to the case of rotation, even without any electromagnetic field (i.e., to the Kerr metric). The latter case is especially important for astrophysics. Gravitational collapse of real rotating masses can lead not only to the appearance a black hole with an inner nontraversable singularity but also, possibly, to the passage through a wormhole into other universes.

We also note that time-like wormholes can connect space–time patches not only in different universes but also in one universe. Then they are simultaneously time machines [26]. In addition, the following combinations are possible: one wormhole connecting, say, universes A and C, and another wormhole connecting C and A in the opposite direction. In this case, a time-machine-like time loop also emerges.

The appearance of a time machine does not lead to any difficulty with the causality principle and is not any problem from this standpoint for the wormhole itself [26].

Of course, the search for such unusual objects by astrophysical methods is of extreme interest.

Observational tests of the possible existence of wormholes and hence the existence of the Multiverse is envisaged by the research program at the Astro Space Center of the Lebedev Physical Institute of RAS (space projects Radioastron and Millimetron).

The external parts of all wormholes considered here can be similar to black hole surroundings, and therefore the processes occurring in the external space around these objects can be similar. Therefore, the recently discovered emission of gravitational waves, which is interpreted as being due to the coalescence of two black holes, would occur similarly with the participation of wormholes, and hence a definitive interpretation should be considered with care.

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References

1. Flamm L *Phys. Z.* **17** 448 (1916)
2. Einstein A, Rosen N *Phys. Rev.* **48** 73 (1935)
3. Thorne K *The Science of Interstellar* (New York: W.W. Norton and Co., 2014); Translated into Russian: *Interstellar, Nauka za Kadrom* (Moscow: Mann, Ivanov i Ferber, 2015)
4. Armendáriz-Picón C *Phys. Rev. D* **65** 104010 (2002)
5. Morris M S, Thorne K S *Am. J. Phys.* **56** 395 (1988)
6. Visser M *Lorenzian Wormholes: From Einstein to Hawking* (New York: Springer-Verlag, 1996)
7. Shinkai H, Hayward S A *Phys. Rev. D* **66** 044005 (2002)
8. González J A, Guzmán F S, Sarbach O *Phys. Rev. D* **80** 024023 (2009)
9. Bronnikov K A, Grinyok S *Grav. Cosmology* **7** 297 (2001)
10. Doroshkevich A et al. *Int. J. Mod. Phys. D* **18** 1665 (2009)
11. Bronnikov K A et al. *Grav. Cosmology* **19** 269 (2013)
12. Novikov I D, Shatskiy A A *JETP* **114** 801 (2012); *Zh. Eksp. Teor. Fiz.* **141** 919 (2012)
13. Carr B (Ed.) *Universe or Multiverse*? (Cambridge: Cambridge Univ. Press, 2007)
14. Shatskii A A, Novikov I D, Kardashev N S *Phys. Usp.* **51** 457 (2008); *Usp. Fiz. Nauk* **178** 481 (2008)

15. Zeldovich Ya B, Novikov I D *Relyativistskaya Astrofizika* (Relativistic Astrophysics) (Moscow: Nauka, 1967)
16. Burko L M, Ori A (Eds) *Internal Structure of Black Holes and Spacetime Singularities* (Annuals of the Israel Physical Society Series, Vol. 13) (Bristol: IOP Publ., 1997)
17. Berezin V, Dokuchaev V *Global Geometry of Space-Times with Shells* (New York: Nova Science Publ., 2014); Translated from Russian: Berezin V A, Dokuchaev V I *Global'naya Geometriya Prostranstva-Vremeni s Zaryazhennoi Obolochkoi* (Moscow: IYaI RAN, 2013)
18. Doroshkevich A et al. *Phys. Rev. D* **81** 124011 (2010)
19. Novikov I D *JETP Lett.* **3** 142 (1966); *Pis'ma Zh. Eksp. Teor. Fiz.* **3** 223 (1966)
20. De la Cruz V, Israel W *Nuovo Cimento A* **51** 744 (1967)
21. Bardeen J M *Bull. Am. Phys. Soc.* **13** 41 (1968)
22. Kerr R P *Phys. Rev. Lett.* **11** 273 (1963)
23. Israel W *Phys. Rev.* **153** 1388 (1967)
24. Boulware D G *Phys. Rev. D* 2363 (1973)
25. Cherepashchuk A M *Phys. Usp.* **39** 759 (1996); *Usp. Fiz. Nauk* **166** 809 (1996)
26. Frolov V P, Novikov I D *Black Hole Physics, Basic Concepts and New Developments* (Dordrecht: Kluwer Acad. Publ., 1998)
27. Novikov I D, Frolov V P *Fizika Chernykh Dyr* (Black Hole Physics) (Moscow: Nauka, 1986)
28. Ellis H G *J. Math. Phys.* **14** 104 (1973)
29. Wheeler J A *Phys. Rev.* **97** 511 (1955)
30. Wheeler J A *Geometrodynamics* (New York: Academic Press, 1962)
31. Beskin V S et al. *Astron. Rep.* **55** 753 (2011); *Astron. Zh.* **88** 819 (2011)
32. Garcia N M, Lobo F S N, Visser M *Phys. Rev. D* **86** 044026 (2012); arXiv:1112.2057
33. Novikov I D, Shatskiy A A, Novikov D I *Astron. Rep.* **59** 339 (2015); *Astron. Zh.* **92** 379 (2015)
34. Klein O, in *Werner Heisenberg und die Physik unserer Zeit* (Eds G Beck et al.) (Braunschweig: F. Vieweg, 1961) p. 58
35. Novikov I D *Sov. Astron. Rep.* **7** 587 (1964); *Astron. Zh.* **40** 772 (1963)
36. Zel'dovich Ya B *Sov. Phys. JETP* **16** 732 (1963); *Zh. Eksp. Teor. Fiz.* **43** 1037 (1962)
37. Harrison B K et al. *Gravitation Theory and Gravitational Collapse* (Chicago: Univ. of Chicago Press, 1965)
38. Linde A, in *Three Hundred Years of Gravitation* (Eds S W Howking, W Israel) (Cambridge: Cambridge Univ. Press, 1987) p. 625
39. Novikov I D *Phys. Usp.* **59** 713 (2016); *Usp. Fiz. Nauk* **186** 790 (2016)
40. Ori A *Phys. Rev. Lett.* **67** 789 (1991)
41. Bonanno A et al. *Proc. R. Soc. Lond. A* **450** 553 (1995)
42. Marolf D, Ori A *Phys. Rev. D* **86** 124026 (2012)
43. Scheel M A, Thorne K S *Phys. Usp.* **57** 342 (2014); *Usp. Fiz. Nauk* **184** 367 (2014)
44. Kardashev N S, Novikov I D, Shatskiy A A *Int. J. Mod. Phys. D* **16** 909 (2007)