

Black holes and quark-gluon plasma.

Bezverkhniy Volodymyr Dmytrovych, Bezverkhniy Vitaliy Volodymyrovich.

Ukraine, e-mail: bezvold@ukr.net

Abstract: It is shown that in black holes, baryonic matter is converted into quark-gluon plasma. A black hole consists of a small core (“drop” from QGP) and a large gravitational radius. In small black holes, the radius of the core of the quark-gluon plasma will be equal to the gravitational radius. In large black holes, the radius of the QGP core will be much less than the gravitational radius. Therefore, Hawking radiation should be sought near small black holes. The minimum mass of a black hole, and its minimum radius, will vary over a wide range of values depending on the state of the QGP inside the black hole. It is also obvious that such a binary structure of black holes explains the existence of supermassive black holes, since it forbids the decrease in the mass of most black holes.

Keywords: black hole, quark-gluon plasma, phase diagram of hadronic matter, gravitational radius, minimum black hole mass, Hawking radiation.

INTRODUCTION.

A black hole is an object whose gravitational attraction is so great that even a photon cannot leave it [1]. That is, the second cosmic velocity for a classical black hole will always be greater than the speed of light in vacuum. The boundary of this region is called the black hole event horizon, which is characterized by the Schwarzschild radius [2]. Naturally, at this boundary the second cosmic velocity is equal to the speed of light. Such objects in outer space will be invisible, since photons cannot leave them. Black holes can be detected by their gravitational effects.

Consider the Schwarzschild formula [2]:

$$R_s = (2 * G * M) / c^2$$

where, R_s - is the Schwarzschild radius (gravitational radius),

M - is the mass of the black hole,

c - is the speed of light in vacuum,

G - is the gravitational constant.

Obviously, any material object that has a certain mass and radius can be converted into a black hole. To do this, need to change either its radius or its mass. This fact can be demonstrated

even for the mass of the proton. This was well known after I. Newton. In 1784, John Michell [3] sent a letter to the Royal Society. In a letter, he showed that for a body with a radius of 500 solar radii, and with a density of the Sun, the second cosmic velocity will be equal to the speed of light (on its surface). That is, the light cannot leave this body. Michell suggested that many such invisible bodies can exist in space. In 1796, Pierre-Simon Laplace [4] included a discussion of this idea in his work "Exposition du Systeme du Monde". But, black holes became popular only in the 20th century. Since their existence follows from some exact solutions of Einstein's equations. The first such decision was received by Karl Schwarzschild in 1915. The popularity of black holes in our time is due to the fact that from A. Einstein's general relativity it follows that a black hole is a region of space-time that has specific and fantastic properties (deceleration, actually stopping time, strong curvature of space-time, croton burrows, gravitational waves, a portal to another Universe, etc.). In fact, black holes have become a tool for checking Einstein's general relativity.

In this review, we will return to the origins, in the days of Michell and Laplace. And we will try to understand what a black hole is using modern knowledge about the structure of the nucleus of atoms and elementary particles. That is, we will apply quantum mechanics to the solution of this problem, and not the theory of gravity.

RESULTS AND DISCUSSION.

To begin with, we recall that the atomic nucleus consists of positively charged protons and neutrons (neutral). Protons and neutrons are interconnected due to the strong interaction, which at distances of the order of 10^{-15} meters, completely prevails over other fundamental interactions. It is interesting to note that the interaction of protons and neutrons in the nucleus is not an "elementary" interaction. That is, the interaction between nucleons of the nucleus is an inevitable consequence of the presence of a strong interaction between the quarks that form these nucleons [5]. There is a complete analogy with Van der Waals forces (interaction between molecules), which are a consequence of the existence of covalent chemical bonds. The fact of the "secondary nature" of the interaction between nucleons is an essential point in understanding nuclear forces.

The radius of the nucleus can be determined by the approximate formula [6]:

$$R = 1.23 * 10^{-15} * A^{(1/3)}$$

where A - is the number of nucleons.

We also note that the calculation of the momentum of nucleons in the nucleus shows that nucleons move with relativistic velocities. The average nucleon speed in the nucleus can be calculated based on the Fermi gas model [7]. As a result of the calculation, the nucleon velocity in the nucleus is $c/4$

[8]. That is, the speed of nucleons in the nucleus is exactly four times less than the speed of light in a vacuum. This is a very amazing fact! Since the volume of the nucleus of atoms (not the lightest), it is only 2 – 3 times larger than the volume of nucleons that make up this nucleus. Therefore, the numerous drawings of atomic nuclei that depict tightly adjacent nucleons in the nucleus, strictly speaking, are not accurate. The collision of nucleons in the nucleus is not correctly represented as a collision of billiard balls. The classic picture is not applicable here. Since nucleons are composed of three quarks. And quarks are structureless point particles in which the radius tends to zero $r \rightarrow 0$ [9].

It is well known that all elementary particles (electron, quark, photon, etc.) are structureless point particles. As the experiment shows, such particles are indeed point particles. And therefore, it is not possible to experimentally determine their radius. Moreover, if they are really point and elementary, then it will be impossible to determine their radius at any level of development of experimental equipment. This is obvious, since their radius tends to zero $r \rightarrow 0$, in our reference frame. Considering A. Einstein's STR, it can be argued that the microparticle's own frame of reference moves relative to external frames of reference, with the speed of light in vacuum. This is possible only if the own reference frame describes the internal motion of a given elementary particle (spin, or, for example, de Broglie oscillations).

We also recall that in 1935, the Japanese physicist Hideki Yukawa [10] constructed the first quantitative theory of nucleon interaction. According to H. Yukawa, nuclear forces arise when nucleons are attracted to each other through the exchange of pi-mesons (or pions, experimentally discovered in 1947). The attraction or repulsion of two nucleons is described as the emission of a pion by one nucleon and its absorption by another nucleon. In this case, nucleons turn into each other (proton \leftrightarrow neutron). This theory has also successfully described collisions between nucleons. The consequence of this description is the presence in the nuclear forces, an exchange component. That is why a collision between nucleons cannot be considered as a simple collision of billiard balls. Everything is a little more complicated.

Now we can return to our question: What is a black hole?

Theoretically, a black hole is an object that is formed by gravitational compression of a star of a certain mass. Or in the general case, compression of baryonic matter. Moreover, under the given conditions, gravitational compression is practically unlimited. Therefore, in order to understand what a black hole is, it is necessary to analyze the process of compression of baryonic matter. We proceed to this analysis.

Obviously, with some compression of the nucleus, the nucleons will be placed almost close

to each other. Now recall the confinement (captivity) of quarks. As you know, confinement is the inability to remove quarks from each other, at a distance of more than 10^{-15} meters. When you try to separate the quarks, these quarks are attracted the more, the further they are from each other. Therefore, it is not possible to “take out” the quark from the nucleon [11].

Confinement is a consequence of the strong interaction between quarks, which are exchanged among themselves by gluons (quanta of a special field). Moreover, in this case, asymptotic freedom arises: quarks flying at very small distances from each other can be considered, to a first approximation, noninteracting. That is, in some approximation, the "quark gas" is like an ideal gas.

“...Confinement is inherent in quarks and gluons only in “ordinary” conditions... and in some special conditions it may not exist. The physical meaning of these "special conditions" is the same: at low temperatures (formally at $T = 0$ °K), as the heavy nucleus contracts, its individual nucleons begin to "overlap" each other (in the language of quantum mechanics, their wave functions overlap). As a result, quarks and gluons belonging to individual nucleons under ordinary intranuclear conditions lose their “owners”, become free (and then “their” and neighboring nucleons become indistinguishable for them), and begin to move freely within the entire volume of the compressed nucleus. Of course, they are still subject to confinement, but the size of the "prison cell" is becoming much larger. And if N cores are compressed in this way, the volume increases by N times. With a sufficiently large number of nuclei, it can become quite macroscopic, and even huge. And inside this whole volume, quarks and gluons will move like ordinary free particles (like gas molecules inside the volume they occupy). The confinement property is not only lost, it just becomes empty, which is especially obvious if $N \rightarrow \infty$: deconfinement of quarks and gluons occurs. This state of matter is called quark-gluon plasma. It is very likely realized in the bowels of neutron stars.

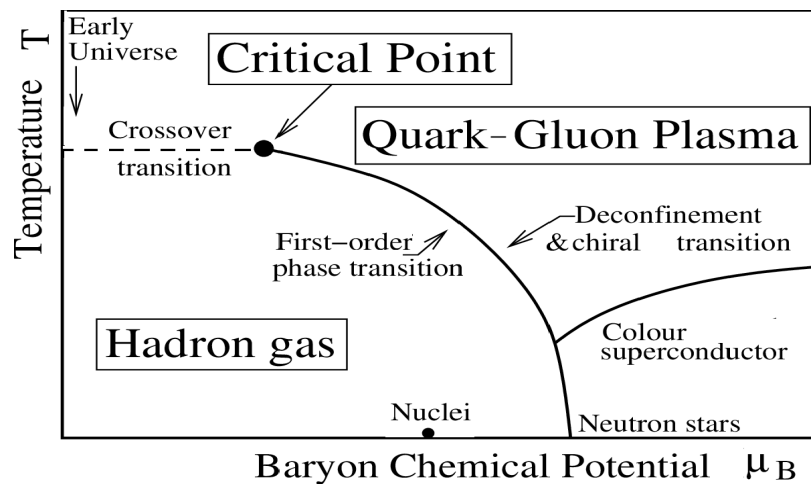
It is not difficult to evaluate the degree of compression at which ordinary nuclear matter should turn into a quark-gluon plasma. It is well known that the volume of a nucleus (from among the not lightest ones) is approximately two to three times larger than the total volume of all nucleons forming it. Therefore, in order to press the nucleons to each other, it is enough to reduce the core volume by only two to three times. And if we reduce it, say, four times, then the wave functions of the nucleons overlap so much that the boundaries between the individual nucleons will be almost completely destroyed...

The described example illustrates the transition to quark-gluon plasma, by means of compression alone, without increasing temperature. With increasing temperature, the same effect can be achieved... due to the thermal production of particles in collisions... Thus, a quark-gluon

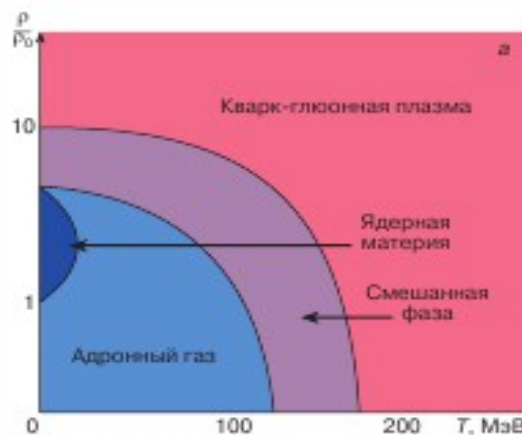
plasma can also exist at a low... baryon charge density, but this requires a fair amount of heat, about 10^{12} °K, in comparison with which the temperature in the bowels of the Sun (10^7 °K) is an unimaginable cold..." [12].

Quark-gluon plasma (QGP, quark soup) is an aggregate state of a substance in which the hadron substance goes into a state where there are only quarks, antiquarks and gluons [13].

QGP phase diagram [14]:



Using the phase diagram of hadron matter, we determine the pressure in a black hole, which is guaranteed to turn nucleons of atomic nuclei, into a quark-gluon plasma [15]. Consider the phase diagram given by the author in this work.



Note to the chart.

1. The red color determines the region of existence of the quark-gluon plasma.
2. The dark blue color determines the region of existence of nuclear matter.
3. Light blue color determines the region of hadron gas existence.
4. The violet color determines the region of existence of the mixed phase.

5. The temperature, in MeV, is plotted on the abscissa axis.
6. Density ratios ρ/ρ_0 are plotted along the ordinate axis, where ρ_0 is the density of baryons in atomic nuclei.

For the convenience of further calculations, we pass from the ratio of densities (ρ/ρ_0) to the ratio of the corresponding pressures. We consider the process when we have one nucleon and press another nucleon into it. Or, when we have one nucleon, and push four more nucleons into it (additionally). Obviously, in this case, the ratio of densities and volumes will be inversely proportional to:

$$\rho/\rho_0 = V_0/V$$

To move from the ratio of densities to the ratio of pressures, we need to take into account a certain transition coefficient.

We will take this process of compression of baryonic matter as an adiabatic process, since our system does not exchange heat with the surrounding space [16, 17]. Then, for calculating the coefficient, we will use the Poisson's adiabatic equation:

$$P * V^k = \text{const}$$

where P - is the pressure,

V - is the volume,

k - is an adiabatic exponent.

The adiabatic exponent (k) for a nonrelativistic nondegenerate monatomic ideal gas is $5/3$. Obviously, the motion of quarks can be regarded as a kind of monatomic ideal gas (recall the asymptotic freedom!). But, the movement of quarks is likely to be relativistic. And therefore, the magnitude of the adiabatic index will be greater. We do not have reasonable algorithms for calculating the adiabatic exponent for quarks; therefore, we will assume that this coefficient is two ($k = 2$). Strictly speaking, we can take the value of this indicator equal to 3 or more. But, as will be further seen from the calculation algorithm, this will not be decisive for the final result. The values will be slightly different, but the order of magnitude will be the same. Moreover, this will not affect the calculation algorithm in any way, which will give us the opportunity to understand the physical meaning of the processes under consideration.

Given that $\rho/\rho_0 = V_0/V = 10$, as well as the Poisson's adiabatic equation, it is easy to show that the pressure ratio can be expressed through the relation:

$$P/P_0 = (\rho/\rho_0)^k$$

Where do we get that when the density ratio is 10 ($k = 2$), the pressure ratio will be 100.

$$P/P_0 = (\rho/\rho_0)^k = 10^2 = 100$$

But, for further calculations, we will use the pressure at the center of the proton (P_0) as the initial value. That is, we assume that in the initial position, the nucleons are tightly adjacent to each other. Therefore, we must take into account the ratio of the density of the nucleus to the density of the nucleon (proton).

The density of the atomic nucleus is $0.15 \text{ baryons/fm}^3$ [15]. When recounting, we obtain the value:

$$\rho(\text{cores}) = 2.509 * 10^{(17)} \text{ kg/m}^3$$

The proton radius is $0.831 * 10^{(-15)} \text{ m}$ [18]. Given the weight of the proton, we get the density value:

$$\rho(\text{proton}) = 6.958 * 10^{(17)} \text{ kg/m}^3$$

That is, the proton density is 2.773 times greater than the density of the nucleus:

$$\rho(\text{proton}) / \rho(\text{nucleus}) = 6.958 * 10^{(17)} / 2.509 * 10^{(17)} = 2.773$$

Therefore, when calculating through the density, the earlier obtained value of the pressure ratio should be slightly adjusted ($P/P_0 = (\rho/\rho_0)^k = 10^2 = 100$). This means that if we take the proton pressure as P_0 , then the ratio P/P_0 will be equal to:

$$P/P_0 = (\rho/(2.773 * \rho_0))^k = 10^2 / 7.690 = 13.00$$

It is clearly seen from the figure of the phase diagram of hadron matter that at a density ratio $\rho/\rho_0 = 10$, a quark-gluon plasma is formed at any temperature. As the initial pressure (P_0), we use the pressure at the center of the proton, which was experimentally measured by physicists bombarding protons with beams of accelerated electrons [19].

The measured pressure at the center of the proton turned out to be 10^{35} Pa , that is, higher than the pressure inside the neutron stars. Above, we have already recalculated the pressure ratio (P/P_0), depending on the corresponding densities, and obtained a value equal to 13 ($P/P_0 = 13$). Therefore, in order to obtain a quark – gluon plasma (according to the phase diagram), it is enough to increase the density by a factor of 10, which is equivalent to a pressure increase of 13 times (compared with the pressure at the center of the proton). That is, the pressure value (on nuclei, or nucleons) should be $1.3 * 10^{36} \text{ pascals}$, and more. And then, we are guaranteed to get a quark-gluon plasma.

Moreover, it does not matter what the temperature in the quark-gluon plasma formed will be. It can be seen from the phase diagram that at a density ratio of 10 or more (or at a pressure of $1.3 * 10^{36}$ Pa or more), a quark-gluon plasma is formed at any temperature.

There is no doubt that such pressure is easily achievable in a black hole. Since, in black holes, the pressure is not numerically limited. Therefore, based on the phase diagram of hadron matter, it can be argued that in black holes baryonic matter is processed into a quark-gluon plasma. Next, we will try to determine some characteristics of black holes (mass, radius, etc.). For further calculations, we will use the drip model of the kernel [20 – 22]. According to this theory, the atomic nucleus is a spherical drop of nuclear matter, which has an incompressibility and resembles a liquid. This model has been successfully used to describe various properties of nuclei.

We, however, will use this model to describe the properties of compressed baryonic matter. The properties of our “drop” will differ from the standard drop core. This is clear, since the density of our drop is at least 10 times greater than the density of nuclear matter. That is, we will represent the quark-gluon plasma formed by gravitational compression in a black hole as a spherical drop of a certain radius. And based on this model, we determine the characteristics of the black hole. This is a physically justified model, since the real quark-gluon plasma is a liquid that is almost perfect and highly opaque [23]. And this is an experimental fact [13].

Obviously, the “drop – quark–gluon plasma” model is ideal for calculating the gravitational pressure inside such a drop. Since the “drop” model is a drop of a homogeneous incompressible fluid. And as was shown earlier, we already know the pressure in the center of a black hole (consisting of a quark-gluon plasma). This pressure is $1.3 * 10^{36}$ Pa. Therefore, to calculate the characteristics of a black hole, we just need to apply the appropriate formulas. But, it must be remembered that our incompressible "drop-liquid" consists of a real quark-gluon plasma. Therefore, quarks inside the entire volume of the liquid will move like ordinary free particles, that is, like molecules of an ideal gas. In quark-gluon plasma, deconfinement of quarks and gluons occurs. That is why the pressure in the center of such a drop will be equal to the pressure at any point of the drop. In fact, in a quark-gluon plasma we have an “ideal quark gas”, that is, the pressure throughout the drop will be uniform.

The pressure at the center of a drop in an incompressible fluid model is determined by the formula [24]:

$$P = (3 / (8 * \pi)) * G * (M^2 / R^4)$$

where P - is the pressure in the center of a liquid drop,

G - is the gravitational constant,

M - is the mass of the drop,

R - is the radius of the drop.

Where do we get:

$$M = ((8 * \pi * P) / (3 * G))^{0.5} * R^2$$

This formula allows you to calculate the mass of a black hole (consisting of a quark-gluon plasma) through its radius, or vice versa. But, we can calculate the mass of the black hole through the gravitational radius, according to the well-known formula (Schwarzschild radius):

$$M = (R_s * c^2) / (2 * G)$$

where M - is the mass of the black hole,

R_s - is the gravitational radius (or Schwarzschild radius),

G - is the gravitational constant,

c - is the speed of light in vacuum.

If we equalize the masses of the two formulas $M_1 = M_2$, then we get a black hole, which consists of a quark-gluon plasma, and whose radius is equal to the gravitational radius.

$$M_1 = ((8 * \pi * P) / (3 * G))^{0.5} * R^2$$

$$M_2 = (R_s * c^2) / (2 * G)$$

$$M_1 = M_2$$

$$((8 * \pi * P) / (3 * G))^{0.5} * R^2 = (R * c^2) / (2 * G)$$

$$R = (c^2 / (2 * G)) * ((3 * G) / (8 * \pi * P))^{0.5}$$

$$R^2 = (3 * c^4) / (32 * \pi * P * G)$$

Express the radius of the black hole through pressure:

$$R = (3 / (32 * \pi * G))^{0.5} * c^2 * 1/P^{0.5}$$

The speed of light and the gravitational constant are equal to:

$$(3 / (32 * \pi * G))^{0.5} = 21.14536 * 10^3$$

Therefore, we get the final formula:

$$R = 21.14536 * 10^3 * 9 * 10^{16} * 1/P^{0.5}$$

$$R = 1.903 * 10^{21} * 1/P^{0.5}$$

Given the numerical value of the pressure ($P = 1.3 * 10^{36}$ Pa), we obtain the minimum radius of the black hole, consisting of a quark-gluon plasma. Moreover, this radius is exactly equal to the gravitational radius.

$$R = 1.903 * 10^{21} * 1/P^{0.5} = 1.903 * 10^{21} * 1/(1.3 * 10^{36})^{0.5}$$

$$R = 1.903 * 10^{21} * 0.877058 * 10^{(-18)} = 1.669 * 10^3 \text{ m}$$

$$R_{\min} = 1.669 * 10^3 \text{ m} = 1.67 \text{ km}$$

That is, the minimum radius of a black hole consisting of a quark-gluon plasma is equal to 1.67 kilometers. The mass of such a black hole can be calculated by the formula:

$$M = ((8 * \pi * P) / (3 * G))^{0.5} * R^2$$

$$P = 1.3 * 10^{36} \text{ Pa}$$

$$((8 * \pi * P) / (3 * G))^{0.5} = 4.040 * 10^{23}$$

$$M = 4.040 * 10^{23} * R^2$$

The minimum radius of the black hole is $R_{\min} = 1.669 * 10^3$ m, so the minimum mass of the black hole will be:

$$M = 4.040 * 10^{23} * R^2 = 4.040 * 10^{23} * (1.669 * 10^3)^2 = 1.125 * 10^{30} \text{ kg}$$

$$M_{\min} = 1.125 * 10^{30} \text{ kg}$$

The mass of the Sun is $1.989 * 10^{30}$ kg [25]. That is, the minimum mass of a black hole is half the mass of our Sun (56.58 %). This is not a big black hole (by mass). It is the existence of such small black holes that present theoretical difficulties for classical theory. Since, classical models give the minimum mass of a black hole equal to 2.5 to 5.6 of the mass of the Sun. We have a black hole mass equal to 0.5 of the mass of the Sun will be easy and logical.

From the above formulas it is obvious (see below) that with increasing mass of the black hole, the gravitational radius will be greater than the true radius of the black hole. Since, the true radius of the black hole is the radius of the “drop” from the quark-gluon plasma.

The gravitational radius is:

$$R_s = (2 * M * G) / c^2 = 1.4831 * 10^{(-27)} * M$$

$$R_s = 1.4831 * 10^{(-27)} * M$$

The radius of the "drop" from the quark-gluon plasma:

$$M = 4.040 * 10^{23} * R^2$$

$$R = (M / (4.040 * 10^{23}))^{0.5} = 1.5733 * 10^{(-12)} * M^{0.5}$$

$$R \text{ (liquid drop model)} = 1.5733 * 10^{(-12)} * M^{0.5}$$

For this reason, Hawking radiation [26] must be sought near small black holes. That is, near black holes in which the gravitational radius is equal to the radius of the "drop". The mass of such black holes is approximately half the mass of our Sun. Theoretically, it is on such black holes that you can experimentally record Hawking radiation. On black holes of greater mass this cannot be done in principle. Since the radius of the nucleus of the "drop" from the quark-gluon plasma will be much smaller than the gravitational radius. And therefore, if photons leave the "drop", then they will not be able to overcome the gravitational radius. And the larger the mass of the black hole, the more impossible the process of registering Hawking radiation, since the gravitational radius will be much larger than the radius of the "drop" (hundreds and thousands of times). We demonstrate this by calculations.

We increase the minimum mass of the black hole ($M_{\min} = 1.125 * 10^{30}$ kg) by 1000 times, and calculate the radius of the "drop" and the gravitational radius.

So, we have a mass of black hole:

$$M = 1.125 * 10^{33} \text{ kg}$$

We calculate the radius of the "drop" of the QGP, as well as the gravitational radius.

$$R_s = 1.4831 * 10^{(-27)} * M = 1.4831 * 10^{(-27)} * 1.125 * 10^{33} = 1.66849 * 10^6 \text{ m}$$

$$R_s = 1668.49 \text{ km}$$

$$R(\text{liquid drop}) = 1.5733 * 10^{(-12)} * M^{0.5}$$

$$R(\text{liquid drop}) = 1.5733 * 10^{(-12)} * (1.125 * 10^{33})^{0.5}$$

$$R(\text{liquid drop}) = 5.2770 * 10^4 \text{ m}$$

$$R(\text{liquid drop}) = 52.77 \text{ km}$$

That is, the gravitational radius will be greater than the radius of the "drop" by almost 32 times.

$$N = R_s / R(\text{liquid drop}) = 1668.49 / 52.77 = 31.618$$

Naturally, with an even greater increase in the mass of the black hole, the ratio of the radii will only increase. Therefore, large black holes, and especially supermassive black holes [27], that is, holes

with a mass of $10^5 - 10^{11}$ solar masses, will have a gravitational radius in thousand times (and more) more of the radius of the “drop” from the quark-gluon plasma. Such giant holes will consist of a small nucleus of a quark-gluon plasma, and a giant gravitational radius. This explains well why, in classical calculations, the density of large black holes is equal to the density of water or air. In fact, the real density of black holes is gigantic ($\rho = 2.509 * 10^{18}$ kg/m³ and more), because this is the density of a quark-gluon plasma. But, since the gravitational radius is much larger than the real radius of the “drop”, in classical calculations the density value becomes equal to the density of water or air, which of course is incorrect.

Moreover, such a double structure of black holes (a small core from a QGP “drop” and a large gravitational radius) actually prohibits a decrease in the mass of black holes. Therefore, most black holes will only increase their mass (due to the fall of matter on them), which explains the presence of supermassive black holes.

Note that if the pressure inside the black hole is greater than the calculated one ($P = 1.3 * 10^{36}$ Pa), then, according to the above formula, the minimum radius of the black hole will decrease. See the formula.

$$R = 1.903 * 10^{21} * 1/P^{0.5}$$

Therefore, both the minimum radius and the minimum mass of the black hole can change depending on the pressure inside the black hole. Recall that for the calculations we used the minimum necessary pressure (or more precisely, the minimum density ratio), which guaranteed translates the baryonic substance into the quark-gluon plasma. But, in real black holes, the pressure can be great. And will be! However, the formulas presented make it possible to calculate new values of quantities at any pressure (and density). And it is quite obvious that the radii and masses of black holes will vary over a wide range of values (depending on pressure, or in the general case, on the state of a quark-gluon plasma).

CONCLUSION.

Confirmation of the above, that there is a quark-gluon plasma in a black hole, there is a scientific article [28], which practically proved the presence of a quark nucleus in a neutron star. Researchers at the University of Helsinki claim that neutron stars have “practically confirmed” nuclei consisting of quarks. Quarks can make up more than half of the mass of the neutron star itself (the mass of the star is equal to two masses of the Sun). Naturally, in a black hole, the pressure will be higher than in a neutron star, and therefore, in a black hole, all baryonic matter will pass into the quark-gluon plasma. That is, the above described is fully confirmed. Here is the abstract of this

work [28]:

"The theory governing the strong nuclear force—quantum chromodynamics—predicts that at sufficiently high energy densities, hadronic nuclear matter undergoes a deconfinement transition to a new phase of quarks and gluons (ref. 1). Although this has been observed in ultrarelativistic heavy-ion collisions (2, 3), it is currently an open question whether quark matter exists inside neutron stars (4). By combining astrophysical observations and theoretical ab initio calculations in a model-independent way, we find that the inferred properties of matter in the cores of neutron stars with mass corresponding to 1.4 solar masses (M_{\odot}) are compatible with nuclear model calculations. However, the matter in the interior of maximally massive stable neutron stars exhibits characteristics of the deconfined phase, which we interpret as evidence for the presence of quark-matter cores. For the heaviest reliably observed neutron stars (5, 6) with mass $M \approx 2M_{\odot}$, the presence of quark matter is found to be linked to the behaviour of the speed of sound $c(s)$ in strongly interacting matter. If the conformal bound $c(s)^2 \leq 1/3$ (ref. 7) is not strongly violated, massive neutron stars are predicted to have sizable quark-matter cores. This finding has important implications for the phenomenology of neutron stars and affects the dynamics of neutron star mergers with at least one sufficiently massive participant".

REFERENCES.

1. Robert M. Wald. General Relativity. University of Chicago Press, 1984. ISBN 978-0-226-87033-5. <https://books.google.com/books?id=9S-hzg6-moYC&printsec=frontcover>
2. Marc L. Kutner. Astronomy: A Physical Perspective. Cambridge University Press, 2003, p. 148. ISBN 9780521529273. <https://archive.org/details/astronomyphysica00kutn>
3. John Michell. Wikipedia. https://en.wikipedia.org/wiki/John_Michell
4. Pierre-Simon Laplace. Wikipedia. https://en.wikipedia.org/wiki/Pierre-Simon_Laplace
5. Strong interaction. Wikipedia. https://en.wikipedia.org/wiki/Strong_interaction
6. Atomic nucleus. Wikipedia. https://en.wikipedia.org/wiki/Atomic_nucleus
7. Fermi gas. Wikipedia. https://en.wikipedia.org/wiki/Fermi_gas
8. Schwierz N., Wiedenheover I., Volya A. Parameterization of the Woods-Saxon Potential for Shell-Model Calculations (2008). https://arxiv.org/PS_cache/arxiv/pdf/0709/0709.3525v1.pdf
9. Quark. Wikipedia. <https://en.wikipedia.org/wiki/Quark>

10. Hideki Yukawa. Wikipedia. https://en.wikipedia.org/wiki/Hideki_Yukawa
11. Greensite J. (2011). An introduction to the confinement problem. Lecture Notes in Physics. 821. Springer. Doi:10.1007/978-3-642-14382-3. ISBN 978-3-642-14381-6. <https://doi.org/10.1007%2F978-3-642-14382-3>
12. Roisen I. Quark-gluon plasma. Science and life. 2001, No. 3. <https://www.nkj.ru/archive/articles/7754/>
13. Quark–gluon plasma. Wikipedia. https://en.wikipedia.org/wiki/Quark_%E2%80%93gluon_plasma
14. Bhalerao R. S., Rajeev S. (2014). Relativistic heavy-ion collisions. In Mulders, M.; Kawagoe, K. (eds.). 1st Asia-Europe-Pacific School of High-Energy Physics. CERN Yellow Reports: School Proceedings. CERN-2014-001; KEK-Proceedings-2013–8. Geneva: CERN. pp. 219 – 239. <http://cds.cern.ch/record/1443909>
15. Saleev V. A. Quark-gluon plasma - a new state of matter. Soros Educational Journal. 2000, Vol. 6, No. 5. http://nuclphys.sinp.msu.ru/mirrors/2000_5.pdf
16. Carathéodory C. (1909). Untersuchungen über die Grundlagen der Thermodynamik. Mathematische Annalen. 67 (3): 355–386. doi:10.1007/BF01450409. http://neo-classical-physics.info/uploads/3/0/6/5/3065888/caratheodory_-_thermodynamics.pdf
17. Bailyn M. (1994). A Survey of Thermodynamics. New York, NY: American Institute of Physics Press. p. 21. ISBN 0-88318-797-3.
18. Xiong W., Gasparian A., [...], Zhao Z. W. A small proton charge radius from an electron – proton scattering experiment. Nature. Vol. 575, pp. 147 - 150 (2019). <https://www.nature.com/articles/s41586-019-1721-2>
19. Burkert V. D., Elouadrhiri L., Girod F. X. The pressure distribution inside the proton. Nature. Vol. 557, pp. 396 - 399 (2018). <https://www.nature.com/articles/s41586-018-0060-z>
20. Gamow G. (1930). Mass Defect Curve and Nuclear Constitution. Proceedings of the Royal Society A. 126 (803): 632–644. Doi: 10.1098/rspa.1930.0032. <https://royalsocietypublishing.org/doi/10.1098/rspa.1930.0032>
21. Weizsäcker C. F. (1935). Zur Theorie der Kernmassen. Zeitschrift für Physik (in German). 96 (7–8): 431–458. Doi: 10.1007/BF01337700. <https://link.springer.com/article/10.1007/BF01337700>

22. Semi-empirical mass formula. Wikipedia. https://en.wikipedia.org/wiki/Semi-empirical_mass_formula#cite_note-1
23. Aref'eva I. Ya. Holographic approach to quark—gluon plasma in heavy ion collisions. Phys. Usp. 57, 527 – 555 (2014); Doi: 10.3367/UFNr.0184.201406a.0569. <https://iopscience.iop.org/article/10.3367/UFNe.0184.201406a.0569>
24. Find the gravitational pressure inside the globe in the model of a homogeneous incompressible fluid. Solving problems in physics. <https://taskhelp.ru/zadachi/reshenie-zadachi-nayti-gravitacionnoe-davlenie-vnutri-zemnogo-shara-v-modeli-odnorodnoy>
25. Sun. Wikipedia. <https://en.wikipedia.org/wiki/Sun>
26. Hawking S. W. Black hole explosions? Nature 248, 30–31 (1974). Doi: 10.1038/248030a0. ISSN 1476-4687. <https://www.nature.com/articles/248030a0>
27. Supermassive black hole. Wikipedia. https://en.wikipedia.org/wiki/Supermassive_black_hole
28. Annala, E., Gorda, T., Kurkela, A. et al. Evidence for quark-matter cores in massive neutron stars. Nat. Phys. (2020). <https://doi.org/10.1038/s41567-020-0914-9>