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THE NEW EQUATION OF THE LIGHT BEAM AND ITS EFFECT ON THE OPERATION OF GPS

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ABSTRACT

The motion of light in a weak gravitational field is discussed. It is explained that the experimentally verified decreasing the speed of light in a gravitational field, which is theoretically grounded in general relativity, applies only to its phase velocity. It is proved that the group velocity of an electromagnetic signal does not decrease but increases near massive objects, contrary to general relativity. The new light beam equation is derived. Calculations of how the speed of light decreases with altitude is presented. An estimation of this effect is made on the operation of the GPS.

Keywords: GPS, gravitation, general relativity, speed of light, photon energy, wavelength, refractive index, principle of least time.

INTRODUCTION

In 2016, just to the centenary of general relativity, an event occurred. Two LIGO laboratories discovered a signal that was interpreted as gravitational waves from the fusion of two black holes (Abbott *et al*., 2016).

It is worth noting that no single black hole has been reliably detected so far. There are many massive objects that are candidates for black holes. They are divided into two classes. The first class includes objects having a mass of several solar masses. They, as a rule, are in double stellar systems. The second class combines super massive black holes located in the centers of galaxies. Their masses are millions and even billions of solar masses. All these massive objects occupy a sufficiently small area of space, therefore, according to general relativity, they must be black holes.

The most distinctive feature of a black hole is an event horizon, near which some physical processes can be changed dramatically. Detection of an event horizon near a massive object would be a weighty confirmation that this object is a black hole. But so far no candidate for black holes has such an event horizon.

The reason is that an event horizon visible from the Earth has a very small size and it is beyond the limits of resolving power of telescopes. For example, the diameter of an event horizon in a giant black hole in the center of our Galaxy (4 million solar masses) is only 24 million km (Eckart, 1996). From Earth, such a size is visible at an angle of less than 20 angular microseconds. The resolving power of the Hubble Space Telescope is more than 20 angular milliseconds, that is, a thousand times lower. In addition, the black hole in the center of the Galaxy is hidden from us by dense clouds of dust and is not visible in the optical range.

Super massive black holes in other galaxies are at giant distances, so their visible diameters are even smaller. Sizes for stellar-mass black holes are several tens of kilometers. They cannot currently be observed.

How can we find out whether black hole candidates are really black holes? How do we learn whether these massive and compact objects have event horizons?

Another problem related to detecting gravitational waves is the problem of the speed of their propagation. According to general relativity, gravity propagates at the speed of light. Abbott *et al*. (2016) have claimed that they have experimentally verified that the gravitational waves propagate with the speed of light in a vacuum.

The famous physicist Leon Brillouin assumed that gravity can propagate slower than light (Brillouin, 1970). The French mathematician Pierre Laplace, investigating the motion of bodies in the Solar system, concluded that gravity must propagate millions of times faster than light, since otherwise violation of Newton's law of universal gravitation would be observed. Zakharenko has developed a model that allows for a complicated system consisting of electrical, magnetic, gravitational, and cogravitational subsystems to have an evaluated propagation speed many orders of magnitude higher than the speed of light (Zakharenko, 2016, 2017a, 2017b). And the evaluated limiting speed must be below 10^{27} m/s. This model also operates with the speed of light in a vacuum, with which

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an electromagnetic wave (system consisting of electrical and magnetic subsystems) and a gravitocogravitic wave (system consisting of gravitational and cogravitational subsystems, i.e. the gravitational wave) can propagate. That is, waves of a certain kind can almost instantly spread from one edge of the Universe to the other one. In 2004, a hypothesis was advanced about the nonlocal character of the gravitational interaction, according to which gravity instantly propagates (Yanchilin, 2004).

Unfortunately, the modern technical level of astrophysical observations does not allow us to verify all these hypotheses. On the other hand, laser technologies have undergone significant development over the last 20 years. Specialists in laser technology could solve some problems in the field of astrophysics and gravity. However, for this purpose it is necessary to formulate these problems in the language of modern experimental physics (Kryukov, 2015). In this connection, it is possible to mention the paper by Füzfa (2016). Füzfa has proposed a method for studying the interactions between the magnetic and gravitational subsystems under terrestrial conditions in a laboratory, but not in space at astronomical distances.

The author of this article proposes to conduct quite feasible laboratory experiments that will make it possible to determine whether there are event horizons for massive objects in the galaxies centers.

The phase velocity of light in the gravitational field

It is known that a light beam, passing near the Sun, deviates from the direct path. This effect was calculated by Einstein in general relativity. Here is the formula for the deflection angle β:

$$\beta = \frac{4GM}{\rho c^2} \tag{1}$$

Here, G is the gravitational constant, M is the mass of the Sun, ρ is the impact parameter, and c is the speed of light. Subsequently, this effect was verified in numerous experiments and was the first confirmation of general relativity.

From equation (1), we can conclude that the phase velocity of light decreases near the Sun and other massive objects. It was this interpretation of the effect that Einstein proposed in (Einstein, 1911). Shapiro suggested testing this effect experimentally by radaring Mercury during its passage behind the Sun (Shapiro, 1964). During the experiment, a radio beam passed near the Sun, its phase velocity decreased and the return signal came with a delay in phase. According to general relativity, the calculated signal delay was approximately 240 microseconds. Numerous experiments have confirmed these calculations. Therefore, it is now generally accepted that the speed of light slows down near the Sun and other massive objects.

Nevertheless, in radar experiments, not the signal delay, but the phase delay of the signal was measured. A detailed description of such experiments is in the textbook (Misner *et al*., 1973). So it can be concluded from the experiment that the phase velocity of light decreases near the Sun. As for the group velocity of the signal, it has not yet been measured experimentally. Nevertheless, according to general relativity, the group velocity of a light wave behaves exactly the same as the phase velocity. So according to general relativity, light slows down near the Sun and other massive objects.

I propose to study this question carefully, because the phase and group velocities, as a rule, behave differently. The phase velocity, by definition, is a cyclic frequency divided by the wave number, and the wave number is the reciprocal of the wavelength multiplied by 2π. But the group velocity is the derivative of the cyclic frequency with respect to the wave number. The subject of the connection between the group and phase velocities is discussed in (Zakharenko, 2005).

It is known that bodies and particles, accelerating near a massive object, turn in the direction where their speed is larger. On the other hand, according to quantum mechanics, particles have wave properties. And the wave always turns in the direction where its phase velocity is smaller. Accordingly, when an electron falls to the Earth, its velocity increases, and the phase velocity of its wave, on the contrary, decreases. A light wave is a stream of particles – photons. According to quantum mechanics, electrons, protons, photons and other particles behave identically (Feynman *et al*., 1963).

Therefore, we can expect that for photons, like other particles, the group velocity will be inversely proportional to the phase velocity. In this case, photons will not slow down, but will accelerate in a gravitational field in the same way as ordinary particles. Let's figure this out.

The speed of light in a weak gravitational field

The trajectory of a light beam is determined by the principle of the shortest optical path:

$$\int \frac{dl}{\lambda(l)} = \min \tag{2}$$

If the light wavelength λ does not change along the trajectory of the ray l, then it can be taken out from the sign of the integral. In this case, the light travels along the shortest path, that is, along a straight line. If the light deflects toward the Sun, it means that its wavelength decreases near the Sun. Knowing the deflection angle (1) we can calculate the effective refractive index $n(r)$ as a function of the distance r to the Sun center. These calculations are in many textbooks and monographs on general relativity (Fock, 1964; Bowler, 1976):

$$n(r) = 1 + \frac{2GM}{rc^2} \tag{3}$$

It follows from equation (2) that the effective refractive index is inversely proportional to the wavelength. Taking into account that $GM << rc^2$, we get:

$$\lambda(r) = \lambda_0 (1 - \frac{2GM}{rc^2}) \tag{4}$$

Here λ_0 is the photon's wavelength at a great distance from Sun, $\lambda(r)$ is the photon's wavelength at a distance r from Sun. Thus, when the photon approaches Sun, its wavelength decreases according to equation (4). Equation (4) is interpreted in general relativity as follows. The speed of light near Sun (or other massive object) decreases (Bowler, 1976):

$$c(r) = c_0 (1 - \frac{2GM}{rc^2}) \tag{5}$$

The light energy ε and its frequency ω do not change when the light propagates in a static gravitational field (Okun *et al*., 1999):

$$\varepsilon = \text{const} \tag{6}$$

$$\omega = \text{const} \tag{7}$$

The wavelength λ is proportional to the speed of light (5) multiplied by its frequency (7). As a result, we get equation (4). So far, we have been in the territory of general relativity. However, now we will leave this territory and pass to the quantum mechanics. The photon energy ε is equal to:

$$\varepsilon = \omega\hbar \tag{8}$$

If we do not rely on general relativity, then we cannot say how the photon frequency is changed as it approaches the Sun. We transform equation (8):

$$\varepsilon = \omega\hbar = 2\pi\nu\hbar = 2\pi \frac{c}{\lambda}\hbar = \frac{2\pi}{\lambda}\frac{e^2}{\alpha} \tag{9}$$

Here, ν is the linear frequency of the light wave, e is the electron charge, and α is the fine structure constant. The fine structure constant and the magnitude of the electron charge in a gravitational field do not change (Misner *et al*., 1973). Therefore, the photon energy varies inversely with its wavelength:

$$\varepsilon \propto \frac{1}{\lambda} \tag{10}$$

We obtain from equations (4) and (10):

$$\varepsilon(r) = \varepsilon_0 (1 + \frac{2GM}{rc^2}) \tag{11}$$

We came to the conclusion that the photon energy increases when approaching a massive object, contrary to general relativity (6).

A photon's energy is equal to its inert mass multiplied by the square of the speed of light. Therefore, we can conclude that the square of the speed of a photon (light) increases proportionally to its energy (11):

$$c^2(r) = c_0^2 (1 + \frac{2GM}{rc^2}) \tag{12}$$

If the speed of light is changed in a gravitational field, then the question arises. What is the value of the velocity in the denominator of equation (12)? In the case of a weak field, this does not matter, since the error will be of the second order of smallness. So we can write equation (12) in the form:

$$c^2(r) = c_0^2 (1 + \frac{2GM}{rc_0^2}) \tag{13}$$

or

$$\frac{c^2(r)}{2} = \frac{c_0^2}{2} + \frac{GM}{r} \tag{14}$$

Let us write a well-known equation for the velocity V of an ordinary particle, which moves slowly ($V << c$) in a field of mass M:

$$\frac{V^2(r)}{2} = \frac{V_0^2}{2} + \frac{GM}{r} \tag{15}$$

Here V_0 is the velocity of a particle at a great distance from the mass M, $V(r)$ is the velocity at a distance r from the center of mass M. Equations (14) and (15) are completely identical. We came to the interesting conclusion that the speed of light in a weak gravitational field (14) changes just as much as the velocity of an ordinary nonrelativistic particle (15). Take the square root of equation (13):

$$c(r) = c_0 (1 + \frac{GM}{rc_0^2}) \tag{16}$$

Let us calculate with which acceleration g_c light moves in a gravitational field. Let it move strictly in the direction of the mass M. In this case:

$$g_c(r) = \frac{dc(r)}{dt} = \frac{dc(r)}{dr}\frac{dr}{dt} = c\frac{dc(r)}{dr} = \frac{GM}{r^2} = g \tag{17}$$

We got a very interesting result: the photon falls in a gravitational field with gravitational acceleration *g*!

Let's sum up. We used the experimentally verified equation for the deflection angle of light (1) and the fundamental principle (2). As a result, we came to the conclusion that the wavelength of light decreases when it approaches massive objects (4). Before this point we were in the territory of general relativity. But then, based on the fundamental equation (9), we concluded that the photon energy increases (11) when it approaches a massive object, contrary to general relativity (6).

New equation of the light beam

The photon energy varies inversely with its wavelength (9). Therefore, equation (2) can be written in the form:

$$\int \varepsilon(r)dl = \min \tag{18}$$

Taking into account that the square of the photon velocity (12) varies in proportion to its energy (11), we obtain:

$$\int c^2 dl = \min \tag{19}$$

We have obtained a new equation for the motion of a light beam in a gravitational field. When an electromagnetic wave propagates in a conventional medium, its velocity decreases inversely with the refractive index. Therefore, it turns in the direction where its velocity is smaller. The electromagnetic wave moves in the medium so as to spend a minimum of time on its path. But when this wave moves in a gravitational field, the square of its velocity plays the role of an effective refractive index. In this case, the wave turns in the direction where its velocity is larger. In a gravitational field, an electromagnetic wave moves so as to spend a minimum of its own time on its path.

From a new point of view, photons behave in a gravitational field like other quantum particles. When they approach a massive object, their phase velocity decreases, but the group speed increases.

Equation (19) was first presented in the monograph (Yanchilin, 2003). But in that monograph, it was obtained on the basis of some assumptions, based on Mach's principle. In this paper, equation (19) is rigorously proved on the basis of equations (1) and (9).

Experimental verification of the new equation

It follows from equation (16) that the speed of light depends on the height *H* above the Earth's surface:

$$c(H) = c(0)(1 - \frac{gH}{c^2}) \tag{20}$$

Here, $c(0)$ is the speed of light at zero height, $c(H)$ is the speed of light at height *H*, and *g* is the acceleration of gravity.

It follows from equation (20) that when the height is 1 meter, the speed of light decreases by a relative value of 10^{-16}. With a rise of 100 meters, the relative decrease is 10^{-14}. This is within the accuracy of modern laser technology.

Therefore, the author hopes to use this publication to involve physicists in experimental verifying the equation (20).

The radii of the orbits of GPS navigation satellites are ~ 27,000 km. It follows from equation (16) that at such altitude the speed of light is smaller than on Earth:

$$\frac{c(r) - c_0}{c_0} = -\frac{GM}{Rc^2}(1 - \frac{R}{r}) \tag{21}$$

Here *r* is the distance from Earth's center, *R* is Earth's radius, c_0 is the speed of light on Earth's surface, $c(r)$ is the speed of light at a distance *r* from Earth's center.

We can calculate from equation (21), that at a great distance from the Earth the speed of light decreases by a relative value of 0.7×10^{-9}. This is approximately 21 cm/s. At the altitude of the GPS navigation satellites, the decrease in the speed of light is slightly less and is about 16 cm/s. This effect is insignificant and does not significantly affect the accuracy of the navigation system. Given that the flight time of the signal from the satellite to the receiver is about 70 milliseconds, the error in determining the coordinates will be of the order of 1 cm. Geodetic measurements are usually carried out with higher accuracy. So specialists in precision navigation measurements will be able to detect the effect of decreasing the speed of light with altitude. An experiment to measure the energy and frequency of a photon, when it moves up is discussed in (Yanchilin, 2017).

CONCLUSION

According to general relativity, the speed of light decreases near a large mass, and this statement has been repeatedly verified in radar experiments. However, even with a superficial acquaintance to these experiments it becomes clear that the phase velocity of light was measured in them. As for the group velocity of the light signal, it has not yet been measured. From the equation for the deflection angle of light, it follows that the wavelength of a photon decreases near a massive object. From the basic equation of quantum mechanics for photon energy, it follows that the photon energy is inversely proportional to the wavelength and therefore must increase in a gravitational field, contrary to general relativity. So the group velocity of light also increases. We can verify this effect measuring the transmission rate of a light signal as a function of altitude above Earth's surface. If this effect is confirmed, it will mean that even the most massive and compact objects have no event horizons, and they are not black holes. Thus, it is proposed to solve the problem of the existence of black holes in a laboratory experiment.

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