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Is it possible to establish the photon horizon in the waveguide model of a black hole outside the field of gravity?

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Abstract. **On the basis of the fundamental provision of general relativity about the equality of inertial and gravitational masses and the equivalence of kinematic and gravitational acceleration, a negative answer is given to the question posed in the title.**

Keywords: *Lorentz transformations, waveguide model of a photon, finite observable photon rest mass, horizon in the waveguide model of a black hole, 'Einstein elevator'.*

1. Introduction

Diverse and interdependent properties of a cosmic black hole [1], which is fully within the competence of general relativity, are represented by its waveguide model [2, 3] only to a very limited extent. Thus, the gravitational field of the model is postulated by an extraneous gravitational potential Ψ, which differs significantly from a real situation with its own gravity of a space hole caused by its mass and size.

The main feature, reproducible by the waveguide model of a space black hole, is the establishment of the horizon H in the gravitational field during the propagation of a photon wave through a waveguide in the direction of increasing the potential Ψ while decreasing its propagation constants k and group velocity u from the initial values of k_0 and u_0 until their vanishing,

$$u = k/\omega = 0, \tag{1}$$

for the critical increment of the potential $\Delta\Psi > 0$. Here $u = u(\Delta\Psi)$; $k = k(\Delta\Psi)$; the potential $\Psi < 0$ is normalised to zero at infinity, $\Psi_\infty = 0$; $|\Psi| \ll c^2$; ω is the frequency; c is the speed of light; k_0 and u_0 are defined in some coordinate system, which in no way has advantages and is conditionally designated as a 'laboratory' one. The coordinate $z(\Delta\Psi)$, at which an increment $\Delta\Psi$ of an extraneous gravitational potential is achieved, determines the position of the horizon H insurmountable to photons [3, 4].

In this thought experiment, the reason for a change in the propagation constant k of the photon wave are the dependences (determined by general relativity) of two parameters on the potential Ψ, i.e., the speed of light $c \approx c_\infty(1 + 2\Psi/c^2)$ and the transverse dimension of the waveguide $r \approx r_\infty(1 + 2\Psi/c^2)$ that define the critical mode frequency $\omega_{\mu\nu}$ and the mass-like quantity, so-called finite *observable photon rest mass*

$$M_{\mu\nu} = \hbar\omega_{\mu\nu}/c^2 \approx M_{\mu\nu\infty}(1 - 3\Psi/c^2), \tag{2}$$

which has the actual physical (but not immanent) content [3].

Thus, the establishment of the photon horizon in the waveguide model is a consequence of some effects described in the framework of general relativity.

Meanwhile, it appears that the critical condition (1) can be formally satisfied without any gravitational field and without recourse to general relativity within the framework of special relativity through a simple application of the Lorentz transformation, leading in an alternative inertial coordinate system to a vanishing group velocity: $u = 0$ (1).

Therefore, the question posed in the title has a more general nature: the answer is designed to determine whether the waveguide model of a black hole belongs to the objects of special relativity, or its adequate description requires an indispensable reference to the foundations of general relativity.

In addition to this particular motivation, this methodological paper can add one more justifying example to the well-known long-standing debate about the real or only virtual nature of the fundamental effects of special relativity, reflected by Lorentz transformations [5], with the debate stemming from the classical Einstein's paper of 1905 [6].

2. Photon horizon in the waveguide model of a black hole in the presence or outside a gravitational field

The waveguide model of a photon [2, 3] is a potential well of infinite depth for photons with a complete field restriction over the transverse coordinates and with free wave propagation along the axis z. This proagation is determined by the special relativity rules of transformation of the main kinematic parameters of a photon wave in the waveguide [3, 7] in the transition to the alternative inertial coordinate system moving in the initial laboratory system at $c\beta = V_\beta$, namely the propagation constants

$$k_\beta = k_0(1 - c\beta/u_0)(1 - \beta^2)^{-1/2} \tag{3}$$

and the wave frequencies

$$\omega_\beta = \omega_0(1 - \beta u_0/c)(1 - \beta^2)^{-1/2}. \tag{4}$$

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It follows that the fulfilment of the critical condition (1), at first glance, does not require addressing general relativity, and, relying only on the Lorentz transformations and staying within the theory of special relativity, it is sufficient in the thought experiment to observe the behaviour of the photon in a waveguide in an alternative system that moves along the z axis with a velocity

$$V_\beta \equiv c\beta = u_0 \equiv k_0/\omega, \tag{5}$$

which, in accordance with (2), (3), leads to a stop of the waves and the appearance of the horizon H.

Here it is fundamentally important to refine the scenario of the thought experiment, pointing to its two radically different versions.

The prognostic version of the experiment (even mental) consists in a purely virtual possibility (without going beyond the scope of special relativity) to give theoretically perfect prediction of the results (3)–(5).

In the other version, for the experiment to be physically implemented, it is necessary to really introduce the object under study (i.e., the waveguide model) for observation in the alternative system, i.e., to increase the speed of the object from $V_0 = 0$ to $V_\beta = c\beta = u_0$.

This change in velocity occurs with a positive kinematic acceleration

$$a = V_\beta^2/(2\Delta z) > 0 \tag{6}$$

and movement of the object over a distance Δz, which means the loss of inertial properties and transition of the analysis from special relativity to the foundations of general relativity (for simplicity, at short intervals a is assumed constant).

It turns out that (in full accord with the classic thought experiment) an observer isolated in the 'Einstein elevator' is not able to distinguish between the kinematic acceleration a and the gravitational acceleration g, equivalent to each other up to sign:

$$a = -g. \tag{7}$$

Integration of general mathematical definition $g = -\mathrm{grad}\,\Psi = -\mathrm{d}\Psi/\mathrm{d}z$ leads to

$$\Delta\Psi = V_\beta^2/2 = a\Delta z, \tag{8}$$

where the positive increment $\Delta\Psi$ on the interval $\Delta z > 0$ is measured from the initial value of the gravitational potential $\Psi(z_0)$ at point z_0.

Thus, in accordance with the fundamental provision of general relativity (7), emergence of a model black hole occurs not outside gravity but in the gravitational field with the potential Ψ, and the coordinate, at which an increment $\Delta\Psi$ (8) is reached, is by definition the position of the horizon $H(\Delta\Psi)$.

3. Conclusions

The first result of the discussion is to establish the need for a more accurate wording of the question posed in the title.

If the question is of purely prognostic sense, i.e., limited only by reasonable prediction of the experimental results, but not by its physical implementation (even mental), the expected answer is *positive*, and all the analysis can be carried out within the framework of the theory of special relativity.

Of course, a *negative* answer follows even from an attempt of a thought experiment with the conditions inherent in the actual experiment taken into account. In particular, such an experiment consists in moving the model with finite acceleration a, i.e., the rejection of inertial properties and transition from special relativity to the foundations of general relativity. In accordance with the principle of equivalence $a = -g$ (7), it automatically leads to the appearance of a gravitational field with the potential Ψ, defined by the magnitude of the kinematic acceleration a. Thus, a real physical establishment of the horizon *H occurs* by all means *in a gravitational field*. In essence, a negative answer to the question posed in the title is a direct and comprehensive consequence of the fundamental principle of general relativity about the equality of inertial and gravitational masses, applied to the finite observable photon mass $M_{\nu\mu}$.

The analysis performed also adds another justifying example to the discussion mentioned in the Introduction [5], in which, despite its purely methodological nature (the term 'teaching' is even mentioned in [5]), H. Lorentz, M. Laue, W. Pauli, V. Weisskopf, I.E. Tamm, L.I. Mandel'shtam, L.D. Landau, E.L. Feinberg and others participated at various times, which testifies to the importance of the informal understanding of the essence of the problem.

An argument in favour of the reality (as opposed to virtuality) of changes in both sizes and time, as well as in forces acting on them in the case of real (not prognostic) implementation of the Lorentz transformation is quite obvious: accelerating movement of a body with a finite rest mass requires the application of some extraneous forces that cause corresponding changes of bodies, which was clear for Einstein, of course, as early as 1905 [5]. 'Mysterious' universal nature of these forces and the resulting changes in the accelerated bodies [5] is based on the absolute and fundamental universality of gravitational interaction (as compared, for example, with electric, magnetic, etc. [5]) of any physical bodies and on their only universal property – the finite rest mass.

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