Black Hole Firewalls and Quantum Gravity

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Abstract

A correct theory of quantum gravity cannot ignore the zero point vacuum energy because it has to be cut off at the Planck energy, leading to a preferred reference system in which this energy is at rest, with a violation of Lorentz invariance at high energies. In approaching and crossing the event horizon at the velocity of light in the preferred reference system, an elliptic differential equation holding matter in a stable equilibrium goes over a transluminal Euler-Tricomi equation into a hyperbolic differential equation where there is no such equilibrium, with all matter disintegrating into gamma rays without the loss of information and violation of unitarity.

1. Introduction

A recent paper by Almheiri, Marolf, Polchinski and Sully [1], has raised the following question: "If a black hole is highly entangled with its surrounding, does a freely falling observer who crosses the event horizon burn up at the horizon?" These authors must have been unaware of a previously published paper, entitled "Gamma-Ray Bursters and Lorentzian Relativity" [2]. What has been called Lorentzian relativity refers to the pre-Einstein theory of relativity by Lorentz and Poincaré. It still assumed the existence of an ether, found by Einstein superfluous with his postulates. But through quantum mechanics and its zero point vacuum energy, a "transmogrified" ether had to be reintroduced into physics.* It is Lorentz-invariant for energies small compared to the Planck energy, but because of Einstein's general theory of relativity has to be cut off at this energy, resulting in a "firewall" at the event horizon of a Schwarzschild black hole. It is the purpose of this communication to elaborate on this previously obtained conclusion.

2. The Minkowski Space-Time as a Consequence of Quantum Mechanics

According to quantum mechanics each mode of the electromagnetic field with the frequency ω has the zero point energy

$$\varepsilon_0 = \frac{1}{2}\hbar\omega \tag{1}$$

From there one obtains the frequency spectrum $f(\omega)$ of the quantum mechanical zero point vacuum energy by multiplying (1) with the volume element in frequency space $4\pi\omega^2 d\omega$:

$$f(\omega)d\omega = \text{const}\ \omega^3 d\omega \tag{2}$$

With $c = \omega/k$ one has

$$f(\omega)d\omega = \text{const}\ d\omega^4 \tag{3}$$

or in wave number space $\boldsymbol{k} = k_1, k_2, k_3, k_4,$ where $k_4 = i\omega/c,$

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* That the zero point vacuum energy is a kind of an ether was first recognized by Nernst, and it can replace the ether in the Lorentz-Poincaré pre-Einstein theory of relativity.

$$f(k)dk = \text{const}\, dk^4 \tag{4}$$

where $dk^4 = dk_1, dk_2, dk_3, dk_4$ is the Lorentz invariant volume element in four-dimensional momentum space. It thus follows that (2) is Lorentz invariant. Not only is it Lorentz invariant, but also "frictionless," by which is meant that a charged particle moving with the velocity v through a zero point field with the frequency spectrum given by (2) does not lose energy. This latter result follows from the equation by Einstein and Hopf [3]

$$F = \text{const}\left[f(\omega) - \frac{\omega}{3}\frac{df(\omega)}{d\omega} \right] v \tag{5}$$

where F is the friction force, which for $f(\omega) = \text{const}\cdot\omega^3$ is equal to zero.

The importance of this result is that quantum theory through its zero point vacuum energy "generates" from the three dimensions of space and one dimension of time the Minkowski space-time and by implication the special theory of relativity.

3. The Zero Point Energy and Quantum Gravity

With the zero point energy cut off at the Planck length $l = \sqrt{\hbar G/c^3} \sim 10^{-33}$ cm, that is, at the Planck energy $E_p = \sqrt{\hbar c^5/G} \sim 10^{19}$ GeV, Lorentz invariance is violated, establishing a preferred reference system in which this energy is at rest. What happens at the event horizon of a Schwarzschild black hole can be obtained by solving Einstein's gravitational field equation in the preferred reference system. This solution remains a very good approximation for black holes moving with non-relativistic velocities against the (absolute) preferred reference system, but the event horizon of a black hole cannot be transformed away by a transformation of the solution to a reference system not a rest with the preferred reference system, for example by a transformation to a reference system at rest with a body falling into the black hole.

The argument that the space curvature at the event horizon is small and that for this reason quantum gravity can there be ignored is not valid with the zero point vacuum energy cut off at the Planck energy, because at 10^{19} GeV in the preferred reference system, an elementary particle is subject to the space curvature at the Planck length, regardless whether the particle is accelerated by falling into a black hole or by other means. A black hole is the supreme particle accelerator, reaching in the system at rest with the zero point vacuum energy particle energies 15 orders of magnitude larger compared to the 10^4 GeV reached by the Large Hadron Collider (LHC), with the microscopic dimension of the particle determined by the Landau pole at an energy much larger than the Planck energy.

4. The Disintegration of Elementary Particles reaching the Planck Energy in the Preferred Reference System

In the standard model (SM) the mass of the elementary particles comes from the Higgs field, which has never been directly observed. In the alternative theory preferred by the author, elementary particles are made up of very large positive and negative masses gravitationally bound to each other, with the positive gravitational field mass of the mass dipole providing the observed positive mass [4, 5]. Without counting the gravitational field mass, a positive-negative mass dipole would have a vanishing rest mass, as in the standard model in the absence of the Higgs field.

In the pre-Einstein theory of relativity by Lorentz and Poincaré for velocities below the velocity of light in the preferred reference system, particles are held together in a static equilibrium by electrostatic forces (or forces acting like them) as a solution of an elliptic differential equation derived from Maxwell's equations or other gauge field equations. In approaching the velocity of light the differential equation goes over into a hyperbolic differential equation, analogous to the transition from subsonic to supersonic flow in gas dynamics, by a transluminal Euler-Tricomi equation.

In the Lorentz-Poincaré ether theory of relativity, Maxwell's equations are only valid in the ether rest frame, where the electrostatic potential Φ obeys the inhomogeneous wave equation:

$$-\frac{1}{c^2}\frac{\partial^2\Phi}{\partial t^2}+\nabla^2\Phi=-4\pi Q(r,t) \tag{6}$$

where $Q(r, t)$ is the electric charge density. For a solid body at rest in the ether and in static equilibrium, one has

$$\nabla^2\Phi=-4\pi Q(r) \tag{7}$$

$Q(r)$ is here the microscopic distribution of the positive and the negative electrical charges within the body, holding the body together.

If set into absolute motion along the x-axis with the velocity v, the coordinates at rest with the moving body are obtained by the Galilei-transformation

$$x'=x-vt,\quad y'=y,\ \ z'=z,\ \ t'=t \tag{8}$$

whereby (6) is transformed into

$$-\frac{1}{c^2}\frac{\partial^2\Phi'}{\partial t'^2}+\frac{2v}{c^2}\frac{\partial^2\Phi'}{\partial x'\partial t'}+\left(1-\frac{v^2}{c^2}\right)\frac{\partial^2\Phi'}{\partial x'^2}+\frac{\partial^2\Phi'}{\partial y'^2}+\frac{\partial^2\Phi'}{\partial z'^2}=-4\pi Q'(r',t') \tag{9}$$

After the body has settled into a new equilibrium one has $\partial/\partial t'=0,$ and hence

$$\left(1-\frac{v^2}{c^2}\right)\frac{\partial^2\Phi'}{\partial x'^2}+\frac{\partial^2\Phi'}{\partial y^2}+\frac{\partial^2\Phi'}{\partial z^2}=-4\pi Q'(x',y,z) \tag{10}$$

Comparing (10) with (7) one sees that the l.h.s. of (10) is the same as (7) if one sets $\Phi'=\Phi,$ and $dx'=dx\sqrt{1-v^2/c^2}$. Clocks made up of solid matter must then go slower by the same factor. It thus follows that Lorentz invariance is here seen as a dynamic effect caused by true contractions of objects in absolute motion, with the four-dimensional Minkowski space-time an illusion caused by these contractions. For $v > c$ there is no potential function Φ as for $v < c$, and there is no equilibrium. The same is true if elementary particles are made up of positive and negative masses held together by gravitational forces. The disintegration of elementary particles in approaching the event horizon takes place by this mechanism.

5. Schwarzschild's Exterior and Interior Solutions

In Einstein's gravitational field theory the metric surrounding a spherical mass M is given by Schwarzschild's line element in spherical polar coordinates r, θ, φ (G Newton's constant, c velocity of light):

$$ds^2 = \frac{dr^2}{1-2GM/c^2 r} + r^2(d\theta^2 + \sin^2\theta d\varphi^2) - c^2(1-2GM/c^2 r)dt^2 \tag{11}$$

The same can be obtained with Newton's theory of gravity in conjunction with the theory by Lorentz. According to Newtonian mechanics the velocity v of a body falling from infinity into the gravitational field of a mass M is

$$v = \sqrt{2GM/r} \tag{12}$$

In the Lorentzian ether theory this velocity leads to a contraction of the body in its radial direction given by

$$dr = dr'\sqrt{1-v^2/c^2} = dr'\sqrt{1-2GM/c^2 r} \tag{13}$$

and a likewise clock retardation

$$dt = \frac{dt'}{\sqrt{1-v^2/c^2}} = \frac{dt'}{\sqrt{1-2GM/c^2 r}} \tag{14}$$

Inserting (13) and (14) into $ds^2 = dr'^2 = c^2 dt'^2$ one obtains (11).

In approaching the Schwarzschild radius $R_s = 2GM/c^2$ at the event horizon, an infalling body approaches the velocity of light. But seen by an observer infinitely far away this velocity is

$$v = \frac{dr}{dt} = -c\left(1-\frac{R_s}{r}\right) < c \tag{15}$$

approaching $v \to o$ for $r \to R_s$, but if measured in a local inertial reference system, at rest relative to the collapsing body, the infalling particle approaches there $v = c$.
From (15) one has

$$-ct = \int \frac{dr}{1-R_s/r} \approx R_s \int \frac{dr}{r-R_s} \tag{16}$$

and hence

$$r - R_s = \text{const}\, e^{-ct/R_s} \tag{17}$$

If at $t = 0$, $r = (a + 1)R_s$, $a >> 1$, it follows that

$$\frac{r - R_s}{R_s} = a e^{-ct/R_s} \tag{18}$$

To reach the Planck energy $m_p c^2 \sim 10^{19}$ GeV, where $m_p \sim 10^{-5}$ g is the Planck mass, one must have for an elementary particle mass m:

$$m/m_p = \sqrt{1 - v^2/c^2} = \sqrt{1 - R_s/r} \tag{19}$$

hence

$$\frac{r - R_s}{R_s} = \left(\frac{m}{m_p}\right)^2 \tag{20}$$

Inserting (20) into (18) and solving for $t = t_0$, the time needed to reach the distance r where the kinetic energy of the infalling particle becomes equal to the Planck energy, one finds

$$t_0 = \frac{R_s}{c} \log\left[a\left(\frac{m_p}{m}\right)^2\right] \tag{21}$$

In the limit $m_p \to \infty$, $t_0 \to \infty$, as in general relativity where v can come arbitrarily close to c. For a finite value of m_p this is not the case. For an electron of mass m one has $m_p/m \sim 10^{22}$ and $\log(m_p/m) \sim 10^2$, making the collapse time about 100 times longer than the Newtonian collapse time $t_N \sim R_s/c$. For baryons the collapse time t_0 is not significantly different. If $R_s \sim 1$ km (typical for a solar mass) one has $t_N \sim 3\times10^{-6}$ sec, and $t_0 \sim 3\times10^{-4}$ sec.

During the gravitational collapse, the location of the event horizon, defined as the position where $v = c$, develops from the "inside out," both in Newtonian and Einsteinian gravity. Assuming a spherical body of radius R and constant density ρ, the Newtonian potential inside and outside the body is

$$\begin{aligned} \phi_{in} &= -\frac{GM}{2R}\left[3 - \left(\frac{r}{R}\right)^2\right] \qquad r < R \\ \phi_{out} &= -\frac{GM}{r} \qquad\qquad\qquad\quad r > R \end{aligned} \tag{22}$$

An infalling test particle would reach at $r = 0$ the maximum velocity v, given by

$$\frac{v^2}{2} = -\phi_{in}(0) = \frac{3}{2}\frac{GM}{R} \tag{23}$$

Therefore, it could reach the velocity of light if the sphere has contracted to the radius

$$R_1 = 3GM/c^2 = (3/2)R_s \tag{24}$$

Accordingly, the disintegration of the matter inside the sphere begins at its center after the sphere has collapsed to (3/2) the Schwarzschild radius.

A similar result is obtained from general relativity by taking the Schwarzschild interior solution for an incompressible fluid [6]. The event horizon begins there to develop at $r = 0$, in the moment the sphere has contracted to the radius

$$R_1 = (9/8)R_s \tag{25}$$

According to Schwarzschild's interior solution the event horizon where $v = c$ moves from the center of the collapsing body radially outwards, with the time needed to convert an entire solar mass into energy of the same order of magnitude as t_0.

If a mass of 50 solar masses ~ 10^{35} g is converted into radiation, an energy of ~ 10^{56} erg would be set free. An energy output of this magnitude has been observed in one gamma ray burster. In the process of the conversion into energy, baryons (together with the charge-neutralizing electrons) would be converted into GeV gamma ray photons.

But it must not always lead to a fast gamma ray burst. It was Eddington who noticed that there is a flow of hydrogen coming from the center of the galaxy. This might be caused by a very large black hole but of low density. There infalling matter reaching the event horizon decays into gamma rays, which by their radiation pressure can accelerate hydrogen out of the center of the galaxy.

What happens in approaching the event horizon of a black hole should also happen at the event horizon of the expanding universe. It could there explain the cosmic microwave background radiation as the firewall radiation. And it would explain why the temperature of this radiation is uniform, which has been explained by inflationary expansion.

6. Firewalls or No Drama*

A firewall at the event horizon of a black hole, predicted by the author about 12 years ago [2], has with the recent publication of the paper by Almheiri, Marolf, Polchinski and Sully [1], led to a hot debate that if it is true, then at least one of three cherished notions in theoretical physics must be wrong:

1. The equivalence principle of general relativity;
2. The unitarity of quantum mechanics;
3. The normalcy of physics far away from a black hole as in the absence of gravity.

I claim it is the existence of a preferred reference system which resolves this paradox. To 1: The equivalence principle of general relativity is sustained for small space-time curvatures, but in approaching the Planck energy in the preferred reference system the space-time curvature cannot be ignored, where it becomes of the order $1/l^2 \sim 10^{66}$ cm^2 ($l \sim 10^{-33}$ cm). To 2: Infalling elementary particle reach at the event horizon the Planck energy where they decay in gamma rays, resulting in a gamma ray burst preserving unitary. To 3: The assumption that far away from the event horizon of a black hole physics works as in the absence of gravity is only approximately true. Because even in the absence of gravity, elementary particles can in the preferred reference system reach the Planck energy, where the space-time curvature in the small is large and of the order $1/l^2$. According to (19) this is going to happen for $\gamma = (1 - v^2/c^2)^{-1/2} = m_p/m \sim 10^{22}$, or where $v/c = \sqrt{1-(m/m_p)^2} \sim 1 - 10^{-44}$. It thus follows that

* The name "Drama" was in the ongoing conversation given to the black hole firewall.

special and general relativity remain extremely good approximations except in the vicinity of an event horizon.

The space-time curvature near the Planck length requires a more detailed analysis. The widely accepted assumption that at the Planck length space-time is a kind of turbulent space-time foam [7], is likely wrong. As it was first noticed by Sakharov [8], this assumption implies a huge cosmological constant about 120 orders of magnitude larger than what is observed. Because of it Sakharov proposed the hypothesis that the vacuum of space is occupied by an equal number of Planck mass particles ("maximons") and compensating "ghost" particles, which must be negative mass Planck mass particles. A vacuum filled with positive Planck mass particles only, would also be unstable [9]. Following Sakharov's proposal, the author had made the hypothesis that the vacuum of space is a kind of plasma made up of positive and negative Planck mass particles in equal numbers [10], and it was shown by Redington [11], that such a configuration leads to stable solutions of Einstein's gravitational field equations, describing a literal rippling of space-time. This hypothesis also satisfies the average null energy condition of general relativity, with all particles composed of positive and negative masses, with the gravitational field mass providing their observed positive mass [4].

Conclusion

The black hole firewall paradox has all the making to go down in the history of physics as unique, as was the Michelson-Morley experiment for the theory of relativity, and the blackbody radiation for quantum theory. My paper tries to make a modest contribution to the black hole firewall debate, pointing out that it is quantum theory and without any input from the special theory of relativity, which leads to the Minkowski space-time and Lorentz invariance, but through gravity and Einstein's gravitational field equations of general relativity, ironically also to a Lorentz invariance-violating preferred reference system at ultrahigh energies. This means that quantum gravity can become important even if space curvature in the large is small, as it is the case at the event horizon of a black hole. There the energy of an infalling particle can reach the Planck energy and the space curvature in the small is large. By reaching the Planck energy at the event horizon, where matter becomes unstable and decays into gamma radiation, unitarity is sustained, and with no crossing of the event horizon there will be no weak Hawking radiation, but rather intense gamma ray bursts as they have been observed in other galaxies. Most recently the existence of a black hole firewall as it was proposed by the author to exist 12 years ago [2], has received additional support in a lengthy study by Almheiri, Marolf, Polchinkski, Stanford and Sully [12].

Appendix: The Euler-Tricomi Equation at the Event Horizon

Setting in eq.(10) $x' = x + R_s = r$, such that for $x = 0, r = R_s$, one obtains:

$$(1-\frac{R_s}{r})\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial y^2}+\frac{\partial^2\phi}{\partial z^2}=-4\pi Q \tag{A.1}$$

For $|x| << R_s$ it becomes the Euler-Tricomi equation:

$$\frac{x}{R_s}\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial y^2}+\frac{\partial^2\phi}{\partial z^2}=-4\pi Q \tag{A.2}$$

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