Black Holes and Gravitational Quantum Reflection — Introduction in popular terms

Falling into black holes

Black holes are commonly described an object with gravity so strong that even light cannot escape. The common description goes on to describe a black hole as a singularity where an enormous amount of matter have collapsed into an infinitely small point, this point being surrounded by an event horizon from which nothing can escape. The fact that spacetime at the event horizon is stretched to the extreme have also created the idea that a black hole might be just one end of a worm hole connecting two distant places in the universe, potentially serving as shortcuts across immense distances enabling fantastic stories in sci-fi novels.

The idea that black holes have central singularities has dominated the scientific community for the last 50 years, and especially since the ground breaking work of Stephen Hawking and Robert Penrose. The idea is however just a postulate, and one that have create a number of theoretical problems. The most famous of which is the information problem: Black hole singularities are the only place in the universe where information is destroyed.

It is relatively easy to calculate that a person, Bob, falling directly into a black hole will reach the event horizon in a finite time, seen from his own perspective, but from the perspective of somebody at a safe distance, Alice, the person will never reach the event horizon. So, who is right, Bob or Alice?

The traditional point of view is that Bob somehow passes the event horizon anyway, either by tunneling, or by all in-falling objects somehow passing the event horizon all at once. There is however no well-founded theory that can explain how Bob will pass the event horizon!

Another point of view, held by a smaller group of researchers, is that Bob will never reach the event horizon, but simply freeze in time, and since nothing ever passes the event horizon no central singularity will ever form. The point is that, in physics, all observers are right! The mathematics clearly show that Bob freezes in time, but at a distance extremely close to the event horizon, and this is a potential problem with this view. The distance from Bob to the event horizon is smaller than any other distances found in physics! This also hints that maybe it is not so fun being Bob…

The work of the article

The work of the article below supports the second point of view, Bob will not pass the event horizon, but with a twist: At the event horizon the gravitational pull becomes infinite (seen by the local observer), and infinite acceleration will make all particles reflect back. In quantum physics all particles are also waves, and the reflection of waves is a well-known process, from ocean waves hitting a harbor pier to light waves hitting a window.

The idea that waves can also reflect back from gravity is new, but it is well accepted and commonly observed for all other types of forces.

If nothing can pass the event horizon, then a central singularity cannot form, and neither can the event horizon. So, a black hole is an object which is very close to forming an event horizon, but doesn't due to gravitational reflection and the slowing of the pace of time.

This gravitational quantum reflection can explain how Bob avoids being frozen in time at an extremely small distance to the event horizon, although the alternative is not very pleasant: The particles in Bob will reflect back out one at the time, so Bob will effectively dissolve in the extreme acceleration near the surface of the black hole. Although the term "surface" is somewhat misleading when you are talking about a boiling soup of plasma.

Gravitational quantum reflection is not limited to black holes. The theory below proposes that gravitational quantum reflection will even happen on Earth, although it will be a very weak effect that will be difficult if not impossible to measure.

Where does this leave a black hole?

Black holes are warping spacetime to the extreme, space gets stretched to the point where only light going almost perpendicular from the surface will be able to escape, for all other directions, light will simply bend back to the black hole. The pace of time is slowed down the extent that light escaping will be redshifted to the extreme. This red shifting happens because, what seems like a very fast oscillating UV light photon at the surface will seem like a very slow oscillating infrared photon to the distant observer due to the difference in the pace of time. This all means that a black hole will be a very dark object when seen from the distance. Indeed, as a distant observer you might well say that black holes are extremely cold.

But, if you placed a camera at the "surface" of the black hole, you would see a hot boiling soup of particles, bouncing off the spacetime curvature, leaving the surface just to bend down again for another impact. The surface is not black at all!

If you point the camera upwards, then you will notice that the horizon is very high in the sky, it looks almost as if the surface of the black hole curves upwards to almost reach the zenith of the sky. It is only when you point the camera straight up, that you will see stars in the sky. This small round area is however full of stars, all of the stars you would normally expect to see in the sky are crammed into this small round window. The light from the stars being very hot and appearing ultraviolet due to the pace of time at the surface, and everything in the sky seem to move very fast.

Again, in physics, all observers are right. Both the distant observer seeing a very cold black hole and the local observer seeing an extremely hot and violent black hole, including Bob, who is by now part of the boiling particle soup.

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On the possibility of gravitational quantum reflection in the vicinity of black holes

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Abstract: Quantum reflection and spacetime curvature are usually considered to be on two very different scales, but near black holes the space time curvature is extreme enough for quantum reflection to be a theoretical possibility. This paper explores the possibility of such gravitational quantum reflections, and shows that potentially all incoming particles will be reflected before passing the black hole event horizon. This would make gravitational quantum reflection a phenomenon preventing gravitational collapse from forming a central singularity.

Keywords: Black Holes, Models of Quantum Gravity

Contents

1 The Schwarzschild metric and locally observed acceleration

The starting point of this paper is the Schwarzschild metric, which describes spacetime around a spherical or point like non-rotating mass and is traditionally used for describing black holes [1–4]:

$$ds^2 = c^2\left(1-\frac{r_s}{r}\right)dt^2 - \left(1-\frac{r_s}{r}\right)^{-1}dr^2 - r^2\left(d\theta^2 + d\phi^2 sin^2\left(\theta\right)\right), \tag{1.1}$$

where $r_s = \frac{2GM}{c^2}$.

The coordinate t is time as observed by a distant stationary observer, while r is circumferential radius, and represents the sphere with centre at the centre of mass and a circumference of $2\pi r$. This paper only considers the spacetime outside and focus on the region close to the event horizon, $r \geq r_s$ and $r_s \gg (r_s - r)$.

This is a region where it is important to apply the radial distance x instead of r in analysis of events, and this paper will define the radial distance x as the proper distance to the event horizon (the distance as measured by a stationary observer). Consider the case where $r - r_s = 1\,\text{mm}$ for a solar mass black hole ($M = 1.989110^{30}\,\text{kg}$, $r_s = 3\,\text{km}$) the actual distance x to the event horizon is $3.4\,\text{m}$, and for $r - r_s = 1\,\text{nm}$ the distance x is $3.4\,\text{mm}$.

The term $(1 - r_s/r)^{-1}\,dr^2$ is the square of the physical distance dx that a stationary observer (relative to the centre of mass) at location r will measure between two close points dr apart, hence $dx = \left(1/\sqrt{1-\frac{r_s}{r}}\right)dr$. Likewise the same observer will experience $dT = \left(\sqrt{1-\frac{r_s}{r}}\right)dt$ time pass between two events where a very distant stationary observer experiences dt time passing between the same events (e.g. time between two light pulses). The expression $\frac{\partial T}{\partial t} = \sqrt{1-\frac{r_s}{r}}$ is also called the time dilation experienced by the local observer, and is simply the effect that time progresses more slowly for an observer in a gravitational field.

The distance x can be found analytically:

$$x = \int_{r_s}^{r} \frac{1}{\sqrt{1 - r_s/r}} dr \tag{1.2a}$$

$$= r\sqrt{1 - r_s/r} + r_s \tanh^{-1} \sqrt{1 - r_s/r} \tag{1.2b}$$

$$= 2\sqrt{r_s (r - r_s)} \left(1 + \frac{1}{6}\frac{r - r_s}{r_s} - o\left((\frac{r - r_s}{r_s})^2\right)\right). \tag{1.2c}$$

In the vicinity of the event horizon $r_s \gg (r_s - r)$ and then x is very close to $2\sqrt{r_s (r - r_s)}$ also known as Flamm's paraboloid [3]. To illustrate, if $r_s = 3\,\text{km}$ and $x = 1\,\text{m}$, then the difference between x and $2\sqrt{r_s (r - r_s)}$ is just below $5\,\text{nm}$, and for $x = 10\,\text{cm}$ the difference will be just below $1\,\text{pm} = 10^{-12}\,\text{m}$. The approximation $x \approx 2\sqrt{r_s (r - r_s)}$ can be used to rewrite (1.1) to form a local metric:

$$ds^2 = c^2 \frac{x^2}{4r_s^2} dt^2 - dx^2 - dy^2 - dz^2, \tag{1.3}$$

where $r_s = \frac{2GM}{c^2}$.

The only non-vanishing Christoffel symbols of this metric are $\Gamma^t_{tx} = \Gamma^t_{xt} = \frac{1}{x}$ and $\Gamma^x_{tt} = \frac{c^2 x}{4r_s^2}$, and applying the geodesic equation for the x coordinate using the local time T of a test particle yields:

$$\frac{d^2x}{dT^2} + \Gamma^x_{tt} \left(\frac{dt}{dT}\right)^2 = 0. \tag{1.4}$$

The acceleration in local time can be found by applying that $dT^2 = \frac{x^2}{4r_s^2} dt^2$:

$$\frac{d^2x}{dT^2} = -\Gamma^x_{tt} \left(\frac{dt}{dT}\right)^2 = -\frac{c^2 x}{4r_s^2}\frac{4r_s^2}{x^2} = -\frac{c^2}{x}. \tag{1.5}$$

As an example, at 1 mm from the event horizon the acceleration experienced by a stationary observer will be $-(3 \times 10^8\,\text{m/s})^2/(10^{-3}\,\text{m}) = -9 \times 10^{19}\,\text{m/s}^2$. Interestingly this result is independent of the mass of the black hole as long as $r_s \gg (r_s - r)$.

Note that $\frac{d^2x}{dT^2} = -\frac{c^2}{x}$ will appear to the local observer as an infinitely deep energy well, and the energy E of an inbound particle can be found through integration to be proportional to $1/x$.

Traditionally particles are treated as point like when analysing trajectories near the event horizon. However, wave like particles near the event horizon will observe changes in acceleration at small enough geometries to experience different accelerations along the wave function of the particle. For all other types of fields, this would cause quantum reflection, and this author suggests that since the acceleration is approaching infinity for wave like particles approaching the event horizon, there will be perfect gravitational quantum reflection at the event horizon.

This local metric was only presented to give to an introduction to this topic and will not be further explored in this paper, instead the analysis of gravitational quantum reflection will take the wave equation combined with the Schwarzschild Metric as the starting point.

2 Gravitational quantum reflection

This author proposes to use the term gravitational quantum reflection for quantum reflection of particles due to the gravitation field.

The starting point for analysing gravitational quantum reflection is the x-component of the wave function of a particle traveling towards the event horizon using the local coordinates x and T, note that $p < 0$ due to the direction of travel:

$$\Psi = A(x)e^{i(px+ET)}. \tag{2.1}$$

This can be rewritten in terms of the global coordinates r and t:

$$\Psi = A(r)e^{i\left(p\int_{r_0}^{r} a^{-1}dr+Eat\right)}, \tag{2.2}$$

where $a = \sqrt{1 + r_s/r}$.

The analysis will start with considering an infinitesimal step Δr, and reflection is analysed as a traditional potential energy step at r_0, and then letting $\Delta r \to 0$ to reach an analytically solvable differential equation.

The particle moving from r_0 towards $r_0 - \Delta r$, with the energy as seen by a local observer changing from $a(r_0)E(r_0)$ to $a(r_0 - \Delta r)E(r_0 - \Delta r)$, gives the wave equations:

$$\text{For } r \geq r_0\text{: } \Psi(r,t) = A(r_0)e^{i\left(p(r_0)\int_{r_0}^{r} a^{-1}dr+E(r_0)a(r_0)t\right)} + B(r_0)e^{i\left(-p(r_0)\int_{r_0}^{r} a^{-1}dr+E(r_0)a(r_0)t\right)} \tag{2.3a}$$

$$\text{For } r < r_0\text{: } \Psi(r,t) = A(r_0 - \Delta r)e^{i\left(p(r_0-\Delta r)\int_{r_0}^{r} a^{-1}dr+E(r_0-\Delta r)a(r_0-\Delta r)t\right)} \tag{2.3b}$$

where $B(x)$ represents the reflected wave.

Demanding continuity of the wave function and the derivatives with respect to r and t at $r = r_0$ and $t = 0$:

$$A(r_0) + B(r_0) = A(r_0 - \Delta x), \tag{2.4a}$$

$$p(r_0)\left(A(r_0) - B(r_0)\right) = p(r_0 - \Delta r_0)A(r_0 - \Delta r_0), \tag{2.4b}$$

$$\left(A(r_0) + B(r_0)\right)E(r_0)a(r_0) = A(r_0 - \Delta r_0)E(r_0 - \Delta r_0)a(r_0 - \Delta r). \tag{2.4c}$$

Notice that equations (2.4a) and (2.4b) are the traditional equations for analysing reflection from a potential energy step (e.g. [5]), while (2.4c) follows from requiring continuity in the time direction.

Combining equations (2.4a) and (2.4c), applying Taylor expansion around r_0, and apply it too all $r = r_0 > r_s$:

$$aE = \left(E - \frac{dE}{dr}\Delta r\right)\left(a - \frac{da}{dr}\Delta r\right). \tag{2.5}$$

Expanding the equation, dividing with Δr, and letting $\Delta r \to 0$:

$$a\frac{dE}{dr} = -E\frac{da}{dr}. \tag{2.6}$$

This implies $\frac{d}{dr}(aE) = 0$ and has the solution:

$$E = \frac{E_0}{a} = \frac{E_0}{\sqrt{1 - \frac{r_s}{r}}}, \tag{2.7}$$

where E_0 is an integration constant and can be interpreted as the energy at large distances from the black hole. Close to the event horizon this can be simplified to $E = E_0 r_s/x$, in agreement with the previous observation that the energy of an inbound particle, seen by a local observer, will be proportional to $1/x$.

Combining equations (2.4a) and (2.4b) results in (a variation of the classical equation for transmission [5]):

$$A(r_0 - \Delta r) = A(r_0) - \frac{p(r_0 - \Delta r) - p(r_0)}{p(r_0 - \Delta r) + p(r_0)} A(r_0). \tag{2.8}$$

Applying Taylor expansion around r_0, dividing with Δr, and letting $\Delta r \to 0$, and apply it too all $r = r_0 > r_s$:

$$\frac{\partial A}{\partial r} = -\frac{A}{2p}\frac{\partial p}{\partial r}. \tag{2.9}$$

Since $E^2 = p^2c^2 + m^2c^4$, $p < 0$ and $\frac{\partial p}{\partial r} > 0$, we can apply the relation $-\frac{\partial p}{\partial r}/p \geq -\frac{\partial E}{\partial r}/E$:

$$\frac{\partial A}{\partial r} = -\frac{A}{2p}\frac{\partial p}{\partial r} \geq -\frac{A}{2}\frac{\partial E}{\partial r}\bigg/ E. \tag{2.10}$$

With the solution

$$A^2 \leq A_0^2 \sqrt{1 - \frac{r_s}{r}}. \tag{2.11}$$

In the vicinity of the event horizon this can be simplified to:

$$A \leq k\sqrt{x}. \tag{2.12}$$

This implies that the probability density function for particles with zero rest mass traveling towards the event horizon is $P(r,t) = \Psi^*\Psi = A^2 \propto \sqrt{r - r_s} \propto x$ and for other particles the probability density function decays faster as $r \to 0$. This is equivalent to total reflection for all particles approaching the event horizon of black holes.

The reflection arising in weak gravitational field will be miniscule. As an illustration, a photon traveling from interstellar space to the surface of the earth will have a probability of reflection in the order of 10^{-9}, with the probability of reflection over the last 1 m being 10^{-16}. This will be very difficult if not impossible to measure.

3 Implications

The implication of total quantum reflection in the vicinity of the event horizon of black holes is that nothing can pass the event horizon, and therefore no singularity will be created. Although the formation of a singularity has commonly been assumed especially after the works of Penrose [6] and Hawkings [7, 8], this paper supports the position of Mitra [9, 10], Crothers [11] and Burghardt [12] that no singularity is formed.

Black holes will, however, still be black, because the only directions allowing even light to escape from the vicinity of the event horizon are almost perpendicular to the event horizon leaving most outgoing light and matter curving back onto the event horizon. In addition the time dilation causes an extreme redshift, making whatever escapes from near the event horizon difficult to observe, a "black star" [12].

Although this theory does not offer a central singularity, this author proposes to keep the term "black hole" to cover objects where the primary force preventing further collapse is gravitational quantum reflection.

4 Conclusion

In this paper it is shown that both acceleration and potential energy observed by a local observer in the vicinity of the event horizon of a black hole are inversely proportional to the distance to the event horizon.

It is suggested that this infinite energy well will lead to total reflection due to gravitational quantum reflection, and this in turn leads to black holes without singularities, where the primary force preventing further collapse is gravitational quantum reflection.

Gravitational waves from colliding black holes might offer an opportunity to probe the structure of these objects to support or reject gravitational quantum reflection. Likewise, the study of light pulses in deep vacuum might offer an experimental approach to proving or disproving the theory put forward in this paper.

If gravitational quantum reflection occurs, a number of interesting questions arise, for instance, is gravitational reflection possible to measure (or falsify) in earths gravitational field? How close are black holes to what this author proposes to call the "Schwarzschild limit": $M_s = \frac{rc^2}{2G}$? What are the properties of a state of matter governed by gravitational quantum reflection? Does gravitational quantum reflection play a role in other astrophysical problems, for instance in the description of the Big Bang?

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