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A Review on Penrose Process

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Abstract: ***Penrose process provides one of the possible explanation for astronomically observed phenomena like gamma ray bursts and active galactic nuclei. In this process the rotational energy of a rotating blackhole is extracted. After the proposal of BSW mechanism the Penrose process attracted physicists to study the efficiency of the process. The efficiency of the Penrose process is always moderate even though the centre of mass energy may diverge near the horizon.***

Keywords: Penrose process, BSW mechanism

1. Kerr Blackhole

Blackholes are the most beautiful predictions of Einstein's theory of gravitation. A black hole can be characterized by its mass, angular momentum and charge according to 'no-hair' theorem. The geometry of a rotating, axially symmetric object (uncharged) is described by the Kerr metric. This solution is obtained by Roy Kerr in 1963. In Boyer-Lindquist coordinates (t, r, θ, φ) it reads [5],

$$ds^2=-\left[1-\frac{2mr}{\Sigma}\right]dt^2-\frac{4amr\sin^2(\theta)}{\Sigma}dtd\phi$$

$$+\frac{\Sigma}{\Delta}dr^2+\Sigma d\theta^2+\left[r^2+a^2+\frac{2a^2mr\sin^2(\theta)}{\Sigma}\sin(\theta)d\phi^2\right]$$

where

$$\Sigma=r^2+a^2\cos^2(\theta)$$

$$\Delta=r^2+a^2-2mr$$

where a and m are the angular momentum per unit mass and the mass, respectively, of the blackhole. The metric has two Killing vectors $\xi^a=\partial_t^a$ and $\eta^a=\partial_\phi^a$ which corresponds to the conserved quantities, energy and angular momentum of the particle moving in Kerr spacetime, respectively. The Kerr metric has coordinate singularity at $\Delta=0$, i.e., at $r=m\pm\sqrt{m^2-a^2}$, which corresponds to the event horizon and cauchy horizon. If both these horizons coincide then the black hole is called extremal. Neither signals nor particle can escape from the region inside the event horizon. In addition to these there is another surface defined by the condition $g_{tt}=0$ known as the static limit surface which makes Kerr black hole more interesting one. The side view of the horizon structure of Kerr black hole is shown in (fig 1) [4].

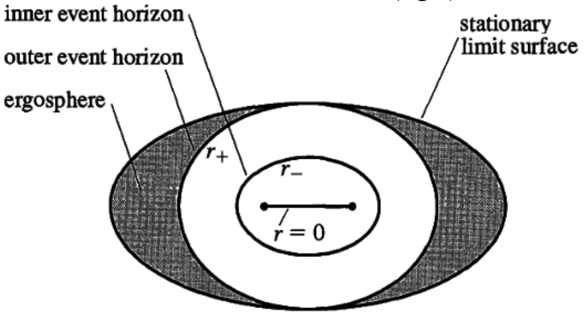

Figure 1: The horizon structure of Kerr black hole

2. Ergo Region

The region between the event horizon and the static limit surface is known as ergo region or ergosphere. It is possible for a particle to enter and leave the ergo region, but not to remain stationary. The space time within the ergo region is dragged in the rotational direction of black hole, known as frame dragging, so that a particle crosses the static limit surface won't be static in the ergo region. The possibility of having a timelike or null trajectory with negative energy within the ergoshere makes it possible to visualize Penrose process in a rotating black hole.

3. Penrose Process

An interesting feature of the Kerr mertic is that the rotational energy of the blackhole can be extracted through what is known as Penrose process [7]. In the original Penrose process a particle which falls into the black hole disintegrated into two particles in the ergo region, one with negative energy plunged into black hole, and the other with energy greater than the incident particle escapes to infinity. Since the outgoing particle has more energy than that of incident particle the energy of the black hole is extracted in this process. As a consequence the rotational energy of the black hole decreases. However the inefficiency of this single particle Penrose process soon led to the proposal of collisional Penrose process [9].

4. BSW Mechanism

Penrose process attracted many physicists after the proposal of the BSW mechanism[1] , in which the Kerr black hole acts as a particle accelerator. BSW mechanism says that the centre of mass energy will diverge near the horizon of Kerr black hole for particle collision. The range of the angular momentum per unit mass (l) of the particle falling into the black hole is $-2(1+\sqrt{1+a})\leq l\leq 2(1+\sqrt{1-a})$. The results for the centre of mass energies for two colliding particles of same mass given in [1] which can be obtained using the equation,

$$E_{C.M}=m_0\sqrt{2}\sqrt{1-g_{\mu\nu}u_1^\mu u_2^\nu}$$

where u_1^μ and u_2^ν are the 4-velocities of the particles.

5. Collisional Penrose Process

In this revised scenario, two particles are colliding in the ergo region of the Kerr black hole which leads to Penrose process under suitable initial conditions. The efficiency of the collisional Penrose process is more than the original Penrose process. The different aspects of this problems are studied by many people [2] [8] [3] where the preliminary emphasis was put on the efficiency of the mechanism, with different physical situations. The original Penrose process and its some variants are depicted in (fig. 2) [6].

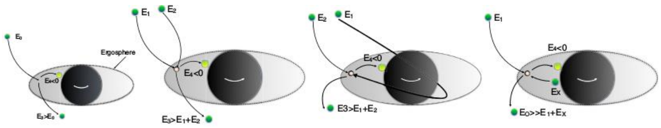

Figure 2: First figure represents the original Penrose process. The second one for collisional Penrose process. In the third diagram the incident particle collides with a particle which is rotating around the black hole. In the last figure the collision is between an ingoing and an outgoing particles, sometimes known as super Penrose process. The efficiencies of this processes are in increasing order from left to right side.

The study of the dynamics of a particle moving in a Kerr geometry which is essential for the understanding of collisional Penrose process. The allowed region of impact parameter for the particle (the simplest case, a photon), created in the ergo region after the collision, to escape to infinity is shown below (fig. 3). This analysis is important because the particle will escape to infinity only under certain conditions even though the centre of mass energy may diverge near the horizon. The outgoing particle has finite energy so that the efficiency of the Penrose process is always moderate.

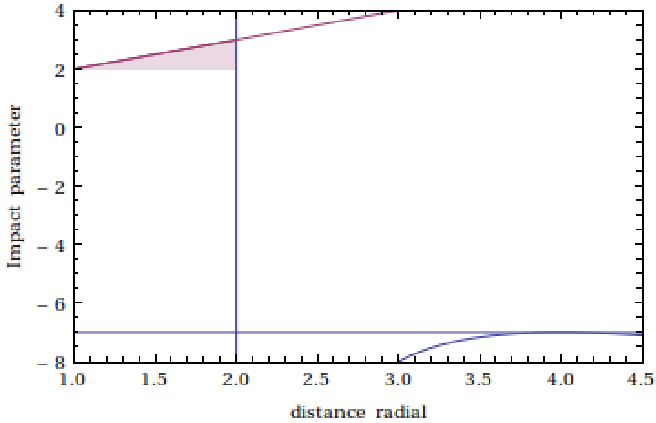

Figure 3: The shaded region represents the initial conditions of a photon that can escape to infinity. i.e., $2 \leq b \leq r + 1$.

The study of Penrose process is important in understanding the gamma ray bursts and Active galactic nuclei in galaxy. Apart from the speculations that a post modern civilization may use rotating black holes as energy power houses, the study of Penrose process in different spacetime geometries will shed light on astrophysical applications.

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