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Unified Quantification of Energy Dynamics in Stellar-Mass Black Holes

Author: Mauurya Desai

E-mail: mauuryadesai@gmail.com

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ABSTRACT:

This study aims to provide a comprehensive analysis of energy dynamics within a stellar-mass black hole, focusing on the quantification of energy using a single variable. This research examines the processes of mass intake, photon behaviour, antimatter creation, and energy quantification in a black hole. Additionally, the process of accretion is explored, which details how celestial objects fragment into elementary particles due to intense gravitational forces. Gravitational lensing and red-shift effects on photons are analyzed to further provide a detailed foundation for the research while demonstrating the feasibility of anti-matter production through high-velocity quark collisions in the singularity's vicinity. It quantifies the energy produced by matter-antimatter collisions, thus contributing to the black hole's mass. Significant challenges which may hinder the scope of this research are also addressed, such as defining density at the singularity. Such a unified framework offers a fluid approach to understanding the black hole's energy dynamics, providing a novel basis for future research.

1. INTRODUCTION:

Due to their energetic and extremely complex environments, black holes have persisted as one of the greatest fascinations in physics. The black hole referred to in this paper is a stellar-mass black hole, formed by the gravitational collapse of a planetary star, observed as a hypernova explosion. This paper focuses on describing and quantifying the energy in the stellar-mass black hole, ultimately proving and quantifying the singularity as pure energy.

This study integrates classical general relativity with quantum gravity theories to offer a comprehensive analysis of the energy intake and one variable quantification process within black holes. The following sections will explore the processes of mass intake, photon behaviour, antimatter creation and quantification, and their effect on black hole mass and density.

Effectively using studies not limited to the ones mentioned in the Literature Review as the basis for the following research, this paper explores a unified approach to energy quantification at the singularity while cementing the prominent possibility of the demonstrated phenomena in the black hole's vicinity.

Research Question:

"How can energy dynamics in stellar-mass black holes be quantified using a single-variable approach?"

2. LITERATURE REVIEW:

Understanding the energy dynamics within the black holes commands the integration of principles from general relativity, quantum mechanics, and particle physics.

3.1 Accretion Process and Mass Intake

The process of mass intake in black holes has been thoroughly studied through various experiments and observations. Shapiro and Teukolsky (1983) describe the fragmentation of celestial objects due to intense gravitational forces and friction within the accretion disk, whereas Frank, King, and Raine (2002) elaborate on the angular momentum transfer facilitated by viscous forces and magnetic torques.

3.2 Photon Behaviour and Gravitational Effects

The behavioural changes of photons near black holes have been extensively researched by Bardeen (1973) and Cunningham and Bardeen (1973), which detail how photons are trapped in orbits near the event horizon and how they spiral into singularity. These findings are supported by Beckwith and Done (2005), who observed similar gravitational lensing effects in astronomical observations.

3.3 Antimatter creation

Antimatter as a product of high-energy particle collision near black holes was ascertained by Moskalenko and Strong (1998), who explained the creation of particle-antiparticle pairs through quantum chromodynamics (QCD), while Blandford and Znajek (1977) and Penrose (1969) provided theoretical models for electromagnetic energy extraction in such extreme environments.

Effectively using studies not limited to the ones mentioned in this review as the basis for the following research, this paper explores a unified approach to energy quantification at the singularity while cementing the prominent possibility of the demonstrated phenomena in the black hole's vicinity.

4. Detailed Analysis and Quantification of Energy Dynamics in a Stellar-Mass Black Hole:

4.1 Process of mass intake in a black hole:

A celestial object approaching the gravitational field of a black hole is attracted towards its singularity, first interacting with the accretion disk. The accretion disk is a structure of diffused material in rapid orbital motion around the black hole. The object loses momentum due to the black hole's intensifying gravitational force, thus falling inward. While traversing to the singularity, the body collides with other material around the disk. It breaks down into smaller particles due to the intense friction and tidal forces within the accretion disk. (Shapiro & Teukolsky, 1983; Frank, King, & Raine, 2002)

Now, the tinier particles spiral inwards towards the singularity, aided by the angular momentum transfer, facilitated by viscous forces and magnetic torques (Misner, Thorne, & Wheeler, 1973). These particles approach the event horizon, where the escape velocity is equal (or nearly equal) to light. The mass gets stretched, shredded, and fragmented into its respective elementary particles due to immense tidal forces and the fine curvature of the space-time horizon (Chandrasekhar, 1983). These particles are then pulled towards the singularity by the intensified and overpowering gravitational force.

4.2 The case of photons:

Photons are primary particles in a light wave. The light waves approaching the gravitational field of the black hole are curved due to the black hole's gravitational attraction (Bardeen, 1973; Cunningham & Bardeen, 1973). When these light waves near the event horizon of a black hole, it becomes nearly impossible for them to escape as the geodesic curvature of space-time is extremely fine, thus causing light to rotate around the black hole and be pulled towards the singularity (Beckwith & Done, 2005). This phenomenon, as observed in various astronomical observations and experiments, is called gravitational lensing.

The light waves' wavelengths are stretched as they spin around the event horizon, causing a shift of light colour towards the red spectrum (redshift). This phenomenon increases the light waves' entropy as they move towards the singularity, as the system of disorder of the light wavelength keeps growing due to increasing elongation (Hawking & Ellis, 1973).

The entropy (S) of a system can be calculated using the formula:

$$S = k_B \, l_n \, W$$

Where:

k_B=Boltzmann's constant (1.380649×10^{-23} joule per kelvin (K))

l_n=Natural Logarithm($\log_e(x)$) [e= 2.718281…]

W=Number of all possible configurations(x)

This detailed understanding of photon behaviour in intense gravitational fields near black holes gives merit to the concept that photons significantly contribute to a black hole's energy dynamics.

4.3 Antimatter:

Antimatter consists of all elementary particles, whose charge is opposite to the corresponding matter particles. They are created due to high-velocity collision between certain pairs of quarks, which are the fundamental particles of protons/neutrons. These collisions produce particles/anti-particle pairs i.e. electrons and positrons (Amaldi & Lari, 2010).

According to quantum chromodynamics (QCD), quarks are bound together by the carriers of strong force, gluons. When these particles collide at high velocities, the energy involved can create conditions similar to the aftermath of the Big Bang. Under such settings, the energy of this collision can be converted into mass-having quark-antiquark pairs (Moskalenko & Strong, 1998).

Theoretical models, such as the ones proposed by Blandford and Znajek (1977) (describing the electromagnetic extraction of energy from Kerr black holes) and Penrose (1969) (describing energy extraction from rotating black holes), support the notion that antimatter can be created in extreme environments, such as near black holes, where high-energy photon collisions can lead to the production of matter-antimatter pairs.

4.4 The case of antimatter in a blackhole:

The revolution of light particles around a black hole is due to the velocity of light and the centripetal force of gravity in the black hole. Thus, the direction of the revolution of light around a black hole is dependent on the direction of tangential interception of the light with the event horizon (the direction in which the light interacts with the gravitational field of the black hole). The light waves disintegrate into their photons towards the inner regions of the event horizon. However, these photons revolve around the horizon in both clockwise and anticlockwise directions, resulting in high-velocity collisions (Cunningham & Bardeen, 1973).

As described in quantum electrodynamics (QED), such high-speed photon collision can cause the creation of matter-antimatter pairs: electron-positron pairs are a documented result of photon-photon high-energy interactions (Breit & Wheeler, 1934). The conditions for such a reaction to materialise involve high photon densities and energies, both of which are found in the vicinity of a black hole's event horizon.

The feasibility of antimatter production near a black hole can be demonstrated and calculated using the Breit-Wheeler process, describing the production of electron-positron pairs from the collision of two photons:

The energy threshold is equal to the combined rest mass energy of electron and positron,

$E_{threshold} = 2 \times 0.511\text{MeV} = 1.022 \text{ MeV}$

Assuming two photons with energy E = 1.022 MeV collide, the total available energy is

$E_{total} = 2 \times 1.022 \text{ MeV} = 2.044 \text{ MeV}$

The cross-sectional area for this collision is

$\sigma_{\gamma\gamma} \approx 1.25 \times 10^{-30} \text{ cm}^2$

Considering the extreme gravitational lensing and high energy density near a black hole, such dense physical environments can warrant photon densities of up to 10^{20} photons/ cm^3 (Meszaros, 2006; Svensson, 1984). Thus, let's assume this upper limit to be the photon density n_γ.

The number of electron-positron pairs N_{e+e-} produced per second can be estimated using photon flux Φ_γ and an assumed interaction volume V of 1 cm^3, assuming relative velocity $v \approx c$:

$N_{e+e-} = \Phi_\gamma \times \sigma_{\gamma\gamma} \times V$

$N_{e+e-} = n_\gamma \times \text{c} \times \sigma_{\gamma\gamma} \times V$

$N_{e+e-} = 10^{20} \text{ photons/ cm}^3 \times 3 \times 10^{10} \text{ cm/s} \times 1.25 \times 10^{-30} \text{ cm}^2 \times 1 \text{ cm}^3$

$N_{e+e-} = 3.75 \text{ pairs/s}$

Thus, under such extreme conditions, electron-positron pairs of significant value can be produced near the black hole's event horizon. Additionally, the extreme gravitational fields and high-energy photon collisions provide the required conditions for this phenomenon, significantly contributing to the energy dynamics within the blackhole (Penrose, 1969).

4.5 Quantifying energy at the singularity:

The contents moving towards a black hole after passing the event horizon, consist of matter particles and antimatter particles, the creation of which has been explained above. These contents move towards the singularity while they keep rotating in tighter spaces. However, before entering the singularity, these contents may collide with each other due to displacement caused by tidal waves of gravity, and/or particles colliding just before entering the singularity due to finite radii in a space of volume 0. 00000..1. The particles annihilate each other to produce pure energy, which reaches the singularity. Annihilation converts equal masses of antimatter and matter particles to energy for which 1 gram is 9×10^{13} joules. In a black hole, this energy is generally high-energy gamma radiation (Hawking, 1975).

The emitted gamma rays are subjected to extreme gravitational redshift, which causes them to lose energy as they move towards the singularity, thus eventually contributing to the black hole's overall energy (Bardeen, Press, & Teukolsky, 1972). The extreme curvature of spacetime near the singularity forces the gamma rays to significantly bend, essentially trapping and guiding them towards the singularity (Wald, 1984). Moreover, the extremely high energy density at the event horizon prevents such high-energy photons from escaping, thus reinforcing the energy increase in the singularity (Misner, Thorne, & Wheeler, 1973).

Assuming 1 gram of matter and antimatter collide,

Using Einstein's equation of general relativity $E = mc^2$,

$E = 0.001\text{kg} \times (3 \times 10^8\ \text{m/s})^2$

$E = 9 \times 10^{13}\ \text{J}$

Thus, for x grams of matter-antimatter collision, the energy produced is:

$E = 9x \times 10^{13}\ \text{J}$

In extreme environments, alternate energy forms such as neutrinos and kinetic energy of secondary particles may manifest (Ginzburg & Syrovatskii, 1964).

4.6 Quantifying mass and density:

4.6.1 Defining density

At the singularity, the Schwarzschild solution to Einstein's field equations describes a non-rotating black hole with a singularity which has a radius of zero and a density theoretically infinite:

$$\rho = \frac{M}{V}$$

Since volume is 0 as radius is 0, density is infinite. This method, however, does not consider the quantum effects which gain immense significance at extremely small scales, specifically at the Planck scale. At Planck Scale:

- Plank length: $l_P \approx 1.6 \times 10^{-35} m$
- Plank mass: $m_P \approx 2.2 \times 10^{-35} m$

At this scale, the classical concepts of singularities are replaced by the likes of loop quantum gravity, which suggests that spacetime is quantized. This potentially prevents infinite density (Rovelli, 1998).

4.6.2 Defining mass at singularity

Using Einstein's equation of General Relativity:

$E=mc^2$

The mass of a black hole can be defined using the aforementioned values to substitute in the equation,

$(9x) \times 10^{13}\ \text{J} = M \times (3 \text{ x } 10^8)^2$

$M = (x \times 10^{13}) \times 10^{-16}$

$M = x \times 10^{-3}$ kg

Therefore, the energy produced (E) contributes to the black hole's mass (M) through the above formulae derived, in the context of matter-antimatter pairs (x).

5. CONCLUSION

This study provides a comprehensive analysis of energy dynamics within a stellar-mass black hole by integrating principles from classical general relativity and quantum gravity theories. Focusing on the quantification of energy using one variable, the process of mass intake, photon behaviour, creation of antimatter, and overall dynamics in black holes have been examined.

By demonstrating the feasibility of significant antimatter production near black holes, supported by theoretical models and empirical data, a framework for understanding matter-antimatter interactions in these extreme environments has been provided. The energy produced from those collisions was quantified as well, thus contributing significantly to the mass and energy of a black hole.

The findings of this study highlight the importance of considering quantum effects in black hole physics and offer new insights into the processes of black hole energy dynamics. Such a unified framework provides a robust foundation for future research. Future studies should possibly aim to refine photon behaviour and antimatter creation models near black holes and explore their implications in other extreme astrophysical environments. Bridging the gap between classical and quantum theories is a definite requirement to further our understanding of these cosmic enigmas.

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