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Introduction to Black Hole Information Paradox

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Abstract

In this work, we consider the analogy between the physical laws of black holes and Thermodynamics ordinary laws. In this context, we studied Hawking Radiation and hence the evaporation and information loss in black holes. Finally, we concluded the information loss does not violate fundamental physics if we consider the semiclassical model, therefore, an information paradox is not viable. The unitarity breaking by the singularity, which has been studied by AdS (Anti-de Sitter) model, is one of the discussions that has motivated the inclusion of Information Paradox as an unsolved problem in contemporary Physics..

Key Words: General Relativity, Black Hole, Information Paradox.

Introduction

Black holes are objects predicted by General Relativity and constitute a singularity enclosed by an event horizon.

The analogy between black holes and Thermodynamics laws came with some results, which are presented in this work, that showed black hole surface area could be related to entropy. Moreover, the Carter-Israel conjecture emphasized this analysis with the concept of black hole stationary states.

When Hawking radiation was calculated and hence the prediction that black holes evaporate, the discussion about information loss started to be relevant. After all, if black holes evaporate what does it happen with the stored information during its life? This phenomenon introduced the semiclassical model of Black Holes Thermodynamics. Considering this formalism the information loss is effective, but it does not violate fundamental physics in this process.

However if we describe the system using Quantum Mechanics we will see the singularity opens the quantum system in a way to perform a non unitary evolution, which violates fundamental physics during the process. This is the Black Hole Information Paradox and the AdS/CFT (Anti-de Sitter/Conformal Field Theory) model has most of the studies about this issue to develop a solution of the loss information in black holes.

The work at all proposed to understand the thermodynamics analysis of black holes, the description of black holes entropy formula and the effects of Hawking Radiation. Understanding the information loss and the respective paradox are the main objectives of this research.

Black Holes and Thermodynamics

The studies of Black Hole Thermodynamics started with some important results of General Relativity, namely, Carter-Israel Conjecture, Area Theorem, Penrose Process and the Irreducible Mass. All of them have as assumption the uniqueness theorems.

- Kerr-Newmann Uniqueness Theorem: The Kerr-Newmann family solutions exhausts the set of solutions describing asymptotically flat, stationary axially symmetric electrovacuum black holes.

$$ds^2 = -dt^2 + dr^2 + 2a sin^2\theta dr d\phi + (r^2 + a^2) sin^2\theta d\phi + \Sigma d\theta^2 + \frac{2Mr}{\Sigma}(dr + a sin^2\theta d\phi + dt^2)^2 \quad (1)$$

- Carter-Israel Conjecture: If an absolute event horizon develops in an asymptotically flat space-time, then the solution exterior to this horizon approaches a Kerr-Newmann solution asymptotically with time [1].
- Hawking Area Theorem: $8\pi m_2[m_2 + \sqrt{m_2^2 - a_2^2}\,] > 8\pi m_1[m_1 + \sqrt{m_1^2 - a_1^2}\,]$ [2].
- Penrose Process: The variation of the black hole event horizon surface increases even though its mass can decrease. [3]
- Irreducible mass: There is no process, reversible or irreversible, which will decrease the irreducible mass. [4]

These results open the possibility to interpret black hole not only as equilibrium states, but also a relation between horizon area surface as entropy. We could formulate the Four Laws of Black Hole Mechanics [5].

First Law: It is the differential of Generalized Smarr Law and we interpret as a state equation of a stationary black hole.

$$\delta M = \frac{\kappa}{2\pi}\delta A + \Omega_H \delta J_H \int \Omega \delta dJ + \int \bar{\mu} \delta dN + \int \bar{\theta} \delta dS \quad (2)$$

Second Law: It is basically the Hawking Area Theorem statement. The horizon area A of each black hole never decreases with time.

$$\delta A \geq 0 \quad (3)$$

Hawking Radiation

The Hawking Radiation introduced the semiclassical model and the concept of Black Hole Thermodynamics. To understand this phenomenon we had to work with creation and annihilation particle operators in gravitational fields [6]. For a curved space-time there is no unique choice of set of normal solutions, particularly, in asymptotically flat in the past and in the future space-time, we can express φ as (5).

$$\Box\varphi + m^2\varphi + \xi R\varphi = 0 \quad (4)$$

$$\varphi = \sum_j (a_j f_j + a_j^{\dagger} f_j^{*}) = \sum_j (b_j F_j + b_j^{\dagger} F_j^{*}) \quad (5)$$

- Bogolubov Transformations: $a_j = \sum_k(\alpha_{jk}^* b_k - \beta_{jk}^* b_k^{\dagger})$; $b_j = \sum_j(\alpha_{jk} a_j + \beta_{jk}^* a_j^{\dagger})$
- Expectation value of particles in the future region:

$$\langle N_k \rangle = {}_{\mathrm{i}}\langle 0|b_k b_k^{\dagger}|0\rangle_{\mathrm{i}} = \sum_j |\beta_{kj}|^2 \quad (6)$$

For a Schwarzschild black hole and considering high frequencies, we found that the expectation value of particles obeys a Planck spectra, i.é., a thermal radiation.

$$|\alpha_{\omega'\omega lm}| = e^{4\pi M\omega}|\beta_{\omega'\omega lm}|$$

$$N_{\omega lm} = \sum_{\omega'} |\beta_{\omega'\omega lm}|^2 = \frac{1}{e^{\omega/T_H} - 1} \quad (7)$$

where $T_H = \frac{1}{8\pi M}$ is the Hawking temperature.

First Law: $dS_{BH} = \frac{dM}{T_H}$.

Second Law: $S_T = S_{BH} + S_{ord} \geq 0$

Information Loss

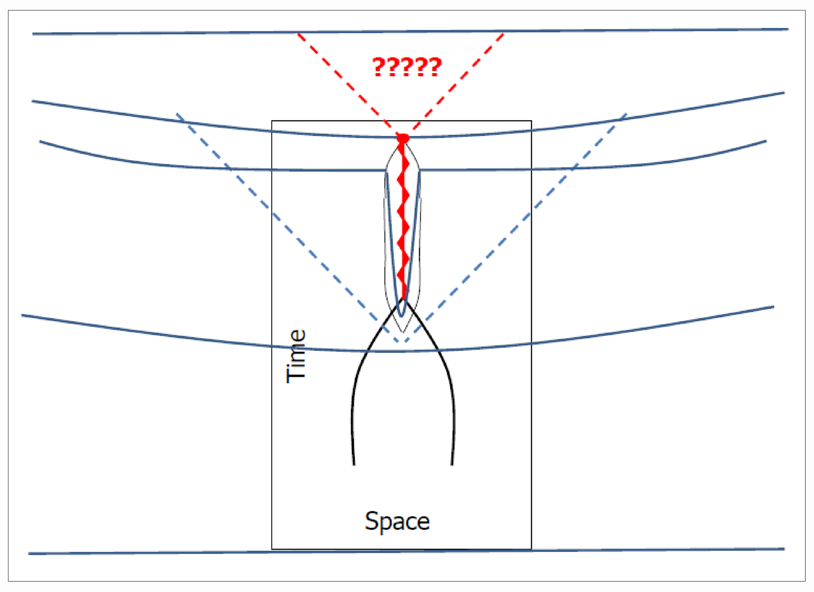

Figure 1: Evolution of a black hole evaporation process [7].

Conclusions

This work made an intensive bibliographic research, including a historical approach. We formulated the Four Laws of Black Hole Mechanics and studied an introduction to the semiclassical model for Thermodynamics of black holes. We concluded at the end of evaporation, the singularity opens the system perfoming a non unitary evolution. According to semiclassical model, this process does not violate any fundamental physics and the information inside black hole is lost. But a non unitary evolution violates the formalism of Quantum Mechanics we know. For this reason, a model of quantum gravity is necessary to eliminate both information loss and non unitary evolution. This is the Black Hole Information Paradox.

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