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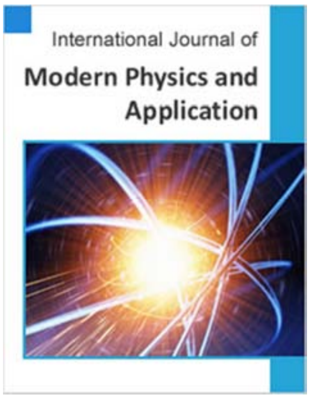

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Energy of the Particle Falling onto the Surface of the Gravastar

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Abstract
The particle falling onto the surface of the gravastar is considered. It is studied the problem of convertation of the liberated gravitational binding energy of the particle into radiated photon and the problem of the decay of the proton. It is shown that the heat energy (gravitational binding energy) of the particle is balanced by the gravitational energy of the particle, and the energy of the particle is equal to the rest mass of the particle. The particle has not energy to radiate the photon. The probability of the decay of the proton is negligible. A toy model of the particle with the split energy (high and low level modes) is considered. The energy of the proton in the high level mode is rather large to ensure the efficient decay of the proton. The electron in the high level mode can convert half the liberated gravitational binding energy into radiated photon.

1 Introduction

The theory of general relativity [1] predicts that a sufficiently compact mass can form a black hole from which no escape of particles and electromagnetic radiation is possible. The boundary of the black hole, the so called event horizon, looks like an ideal black body, as it reflects no light. As an alternative to black hole, the model of the gravastar was proposed [2, 3] which removes the formation of event horizon at the endpoint of gravitational collapse. The model contains a vacuum in the interior and, instead of event horizon, a thin layer of stiff matter. To this end, the problem of gravitational collapse was addressed by many authors within the classical theories and several solutions to avoid the development of black hole event horizon have been discussed, e.g. [4] and references therein.

The event horizon of the black hole is able to hide the kinetic and thermal energy of accreting matter gained during infall. The accreting matter hitting the surface of the gravastar may radiate the kinetic and thermal energy. This fact was used [5-7] to test for the presence of event horizon in the radio source Sgr A* in the centre of the Galaxy interpreted as a supermassive black hole, with a mass of $4.1 \div 4.5 \times 10^6 m_S$ in the units of the mass of the sun m_S [8, 9]. The conclusion is that the gravitational binding energy liberated into radiation and kinetic outflow during accretion onto the putative surface of the gravastar is not seen in the observations of Sgr A*. The contrary view [10] is that the gravastar possesses a large thermal capacity so the thermal radiation generated by accretion will in general be unobservable.

The liberated gravitational binding energy may ensure the efficient decay of the proton falling onto the surface of the gravastar, as it was considered [3] within the $SU(5)$ theory of grand unification [11], with the dominant mode of proton decay $p \rightarrow e^+\pi^0$ where the end products are positron and photons. An excess of 511 keV radiation from positron annihilation from the centre of the Galaxy [12] was explained [13] by the decay of the protons under their falling onto Sgr A* while interpreting Sgr A* as a gravastar. This explanation was shown [14] to be consistent with the accretion rate onto Sgr A* but to predict too high luminosity of Sgr A* in comparison with the observed one. The explanation [13] of the excess of 511 keV radiation may work if the protons decay into some particles like neutrinos which do not give contribution to the luminosity of Sgr A*. The mode of the decay of proton at the Planck scale into positron and hypothetical Planck neutrinos, $p \to e^+ 4\nu_{Pl}$, was proposed in [15]. Planck neutrino may be considered as a dark matter candidate [16].

So, it is expected that the liberated gravitational binding energy of the particle falling onto the surface of the gravastar can be seen at infinity as the radiated photon. Also, the liberated gravitational binding energy may ensure the efficient decay of the proton. In the description of the processes going at the surface of the gravastar, along with the liberated gravitational binding energy one should take into account the gravitational energy. In the present paper, the problem of the energy radiated by the particle at the surface of the gravastar and the problem of the decay of the proton at the surface of the gravastar will be studied, taking into account the gravitational energy of the particle.

2. The Energy Radiated by the Particle and the Decay of the Proton at the Surface of the Gravastar

Consider the particle falling from infinity onto the surface of the gravastar. In general relativity, the transformation of the energy is defined by the metric component g_{00}. At infinity, the initial energy of the particle is equal to the rest mass of the particle, $E_i = m$. At the surface of the gravastar, the final energy of the particle is

$$E_f = \frac{m}{(g_{00})^{1/2}} = \frac{m}{(1-2GM/Rc^2)^{1/2}} \tag{1}$$

where G is the Newton constant, c is the velocity of light, M and R are the mass and radius of the gravastar respectively. The liberated gravitational binding energy is

$$E_g = E_f - E_i = \frac{m}{(1-2GM/Rc^2)^{1/2}} - m. \tag{2}$$

This energy is converted into the kinetic energy of the particle toward the gravastar

$$E_k = \frac{m}{(1-v^2/c^2)^{1/2}} - m = \frac{m}{(1-2GM/Rc^2)^{1/2}} - m \tag{3}$$

where v is the velocity of the particle. After the collision of the particle with the surface of the gravastar, the energy is converted into the heat energy of the particle.

Let the particle radiate the photon, and the heat energy (liberated gravitational binding energy) of the particle is converted into the energy of the photon. As measured at infinity, the energy of the photon is

$$E_\gamma = E_g (g_{00})^{1/2} = m[1-(1-2GM/Rc^2)^{1/2}]. \tag{4}$$

In the weak field $2GM/Rc^2 << 1$, the energy of the photon is $E_\gamma \approx GMm/R$. In the strong field $2GM/Rc^2 \approx 1$, the energy of the photon is $E_\gamma \approx m$. The latter case corresponds to the conditions at the surface of the gravastar. Then, the liberated gravitational binding energy of the particle, as measured at infinity, is $E_\gamma \approx m$. This value was used [5-7] to test for the presence of event horizon in Sgr A*.

Consider the problem of the energy radiated by the particle at the surface of the gravastar. The particle has the heat energy (liberated gravitational binding energy) which may be converted into the energy of the photon. One can think of the heat motion of the particle as an oscillation inward and outward the gravastar. For the purpose of the present study, the heat motion of the particle outward the gravastar will be considered. Therefore, the heat energy of the particle will be treated as the kinetic energy of the particle outward the gravastar. The total energy of the particle includes the gravitational energy. The kinetic energy of the particle and the gravitational energy of the particle are of the same magnitude but acting in the opposite directions. The kinetic energy of the particle is balanced by the gravitational energy of the particle, and the total energy of the particle is equal zero

$$E_k + E_g = 0. \tag{5}$$

The relativistic conservation law of the particle is given by

$$E = \frac{m(g_{00})^{1/2}}{(1-v^2/c^2)^{1/2}} = m. \tag{6}$$

Thus, the energy of the particle at the surface of the gravastar is equal to the rest mass of the particle. This is the same value as that measured at infinity. The reference frame at the surface of the gravastar defined by eq. (6) is equivalent to that at infinity, with no transformation between the frames.

In view of eq. (6), the particle has not energy to radiate the photon. The gravitational field of the gravastar prevents convertation of the liberated gravitational binding energy of the particle into the energy of the radiated photon. Therefore, the liberated gravitational binding energy of the particle cannot be seen at infinity. This is in contrast to the value of the liberated gravitational binding energy of the particle seen at infinity eq. (4) which was used in [5-7]. In view of the present study, the constraints [5-7] cannot be used to distinguish the event horizon of the black hole and the surface of the gravastar.

Consider the problem of the decay of the particle falling onto the gravastar. The decay of the proton falling onto the gravastar was considered [3] within the $SU(5)$ theory of grand unification [11]. The gravitational binding energy released at the surface of the gravastar can be sufficiently high to ensure the efficient decay of the proton. The energy released in the decay of the proton is equal to the energy of the proton, neglecting the mass of the positron. When taking into account the gravitational energy, the energy of the proton is equal to the rest mass of the proton eq. (4). In this case, the probability of the decay of the proton is negligible.

3. Toy Model of the Particle with the Split Energy

Consider a toy model of the particle with the split energy. The reference frame at the surface of the gravastar defined by eq. (6) will be used which is equivalent to that at infinity. Therefore, the results obtained in the frame defined by eq. (6) will be valid for the frame at infinity. The energy of the particle at the surface of the gravastar, including mass and heat energy, is given by

$$E' = \frac{m}{(1-v^2/c^2)^{1/2}} = \frac{m}{(1-2GM/Rc^2)^{1/2}}. \qquad (7)$$

Here, v is the velocity of the particle outward the gravastar. Assume that the energy is split into two modes, $E' = (E'_+ E'_-)^{1/2}$, with the high level mode

$$E'_+ = \frac{m}{(1-2GM/Rc^2)^{3/4}} \qquad (8)$$

and the low level mode

$$E'_- = \frac{m}{(1-2GM/Rc^2)^{1/4}}. \qquad (9)$$

When taking into account the gravitational energy, the energy of the particle is split into two modes, $E = E'(g_{00})^{1/2} = (E_+ E_-)^{1/2}$, with the high level mode

$$E_+ = E'_+(g_{00})^{1/2} = \frac{m}{(1-2GM/Rc^2)^{1/4}} \qquad (10)$$

and the low level mode

$$E_- = E'_-(g_{00})^{1/2} = m(1-2GM/Rc^2)^{1/4}. \qquad (11)$$

The particle in the high level mode can overcome the gravitational field of the gravastar.

Apply the foregoing model to the proton at the surface of the gravastar. The accreting protons are divided into two equal parts with the energies E_+ and E_-. The energy of the proton E_+ is rather large to ensure the efficient decay of the proton. Assume that the accreting protons with the energy E_+ decay and those with the energy E_- retain at the surface of the gravastar. Locally in its own frame, the kinetic energy of the proton in the mode E_- is given by

$$E_{k-} = \frac{m_p v^2}{2} = \frac{GMm_p}{2R} \qquad (12)$$

where m_p is the mass of proton. The energy may be associated with the heat motion of the proton over the surface of the gravastar. This gives the centrifugal acceleration of the proton

$$a_{cf} = \frac{v^2}{R} = \frac{GM}{R^2} \qquad (13)$$

which balances the gravity of the gravastar. Thus, the proton in the mode E_- is in equilibrium with the gravity of the gravastar.

Consider the problem of the energy radiated by the proton in the mode E_+. In the $SU(5)$ theory of grand unification [11], the dominant mode of proton decay is $p \rightarrow e^+\pi^0$ where the end products are positron and photons. Observational constraints [14] rule out photons as proton decay products and favour dark radiation consisting of the particles which do not take part in the electromagnetic interaction like hypothetical Planck neutrinos proposed in [15]. It is reasonable to think that the gravitational binding energy of the proton is converted into dark radiation while the energy of the positron remains non-relativistic. In this case, the energy of the photon radiated by the proton in the mode E_+ is negligible.

Apply the foregoing model to the electron at the surface of the gravastar. The accreting electrons are divided into two equal parts with the energies E_+ and E_-. The heat energy of the electron in the mode E_+ can be converted into radiated photon. Locally in the frame of the electron, the heat energy of the electron in the mode E_+ is given by

$$E_{k+} = \frac{m_e v^2}{2} = \frac{GMm_e}{2R} \qquad (14)$$

where m_e is the mass of electron. At the surface of the gravastar, $2GM/Rc^2 \approx 1$. One can estimate the heat energy (gravitational binding energy) of the electron converted into radiated photon as $\approx m_e c^2/4$. That is, around half the liberated gravitational binding energy of the electron in the mode E_+ can be converted into radiated photon.

Consider observational constraints on the liberated gravitational binding energy of the electrons falling onto Sgr A* while interpreting Sgr A* as a gravastar, following the analysis [14] of the observational constraints on the decay of the protons falling onto Sgr A*. An excess of 511 keV radiation from positron annihilation from the centre of the Galaxy [12] was explained [13] by the decay of the protons falling onto Sgr A* while interpreting Sgr A* as a gravastar. The observed flux of 511 keV radiation implies a power of

$\approx 10^{37}$ erg s^{-1}. Assume that half the power is given by the positrons from the decayed protons in the mode E_+ and the other half the power is given by the electrons in the mode E_+ after liberation of the gravitational binding energy into radiated photons. From this, the flux of the electrons in the mode E_+ is $\approx 5\times10^{36}$ erg s^{-1}. As was shown above, the liberated gravitational binding energy of the electron in the mode E_+ can be estimated as $\approx m_e c^2 / 4$. Then, the luminosity due to the liberated gravitational binding energy of the electrons falling onto Sgr A* can be estimated as $\approx 1.25\times10^{36}$ erg s^{-1}. This is consistent with the bolometric luminosity of Sgr A*, $\approx 10^{36}$ erg s^{-1}, e.g. [17]. Thus, the bolometric luminosity of Sgr A* can be explained by the liberated gravitational binding energy of the electrons falling onto Sgr A*.

4. Conclusion

The particle falling onto the surface of the gravastar has been considered. The problem of convertation of the liberated gravitational binding energy of the particle into radiated photon and the problem of the decay of the proton have been studied. It is expected that the liberated gravitational binding energy of the particle can be converted into radiated photon. Also, the liberated gravitational binding energy of the particle may ensure the efficient decay of the proton. The previous studies of these problems did not take into account the gravitational energy of the particle. In the present study, it has been shown that the gravitational energy of the particle balances the liberated gravitational binding energy of the particle that prevents its convertation into radiated photon. The probability of the decay of the proton is negligible.

A toy model of the particle with the split energy (high and low level modes) has been considered. In the model, the protons accreting onto the gravastar are divided into two equal parts with the high and low energies. The energy of the proton in the high level mode is rather large to ensure the efficient decay of the proton. The accreting protons in the high level mode decay and those in the low level mode retain at the surface of the gravastar. Observational constraints favour the decay of proton into positron and dark radiation. It is reasonable to think that the gravitational binding energy of the proton is converted into dark radiation while the energy of the positron remains non-relativistic. In this case, the energy of the photon radiated by the proton in the high level mode is negligible.

The electrons accreting onto the gravastar are divided into two equal parts with the high and low energies. Around half the liberated gravitational binding energy of the electron in the high level mode can be converted into radiated photon. Observational constraints on the liberated gravitational binding energy of the electrons falling onto Sgr A* have been considered while interpreting Sgr A* as a gravastar. The bolometric luminosity of Sgr A* can be explained by the liberated gravitational binding energy of the electrons falling onto Sgr A*.

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