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A quantum mechanical interpretation of gravitational redshift of electromagnetic wave

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ABSTRACT

It had been observed that electro-magnetic waves can undergo a frequency shift in a gravitational field. This effect is important for satellite communication and astrophysical measurements. Previously, this redshift phenomenon was interpreted exclusively as a relativistic effect. Here we found this effect can also be explained based on a quantum mechanical consideration. We propose that, due to the quantum nature of the photon, its effective mass is not zero. In a gravitational field, the total energy of the photon includes both its quantum energy and its gravitational energy. Then, the condition of energy conservation will require a frequency shift when the photon travels between two points with different gravitational potentials. This result suggests that the gravitational redshift effect of a photon is essentially a quantum phenomenon. This new understanding can be helpful for the future design of satellite navigation systems and other astrophysical applications.

1. Introduction

From experimental observations, it was known that electromagnetic waves can undergo a frequency shift in the presence of gravitational field [1–3]. This was called the “gravitational redshift effect” [3–6]. This effect was thought to be due to space-time distortion as predicted from general relativity (GR) [1,3–5,7,8]. Several groups had used the measurement of gravitational redshift as an experimental test of the GR theory [1,2,8]. In recent years, with the development of satellite navigation systems, such as the Global Positioning System (GPS), this effect becomes more important; it must be accounted for properly in order to precisely determine the position of a receiver on the Earth surface [4].

Because of the importance of the gravitational redshift effect, we would like to conduct a wider investigation of its physical basis. We know electro-magnetic wave can be quantized as a photon, which behaves as a particle in many ways. Such a particle will have certain effective mass. Could it be possible that such a particle behavior may demonstrate certain gravitational effect? We would like to examine such a possibility. This work has three specific aims: (1) *Uniqueness.* If one wants to use the gravitational redshift effect as a test of GR, one needs to make sure that there is no alternative interpretation for this effect. (2) *Simplicity*. The theory of GR is very complicated; we wonder if there can be a simpler explanation of the gravitational redshift effect based on more easily understood physical principles. (3) *Applications*. In astrophysical measurements, redshift of optical signals is an important part of the observed information. A better understanding of the physical basis of the gravitational redshift effect will allow us to use this effect to investigate the gravitational properties of an astrophysical system. To demonstrate such a potential, we will show that one can use the gravitational redshift effect to measure dark matter in a distant galaxy.

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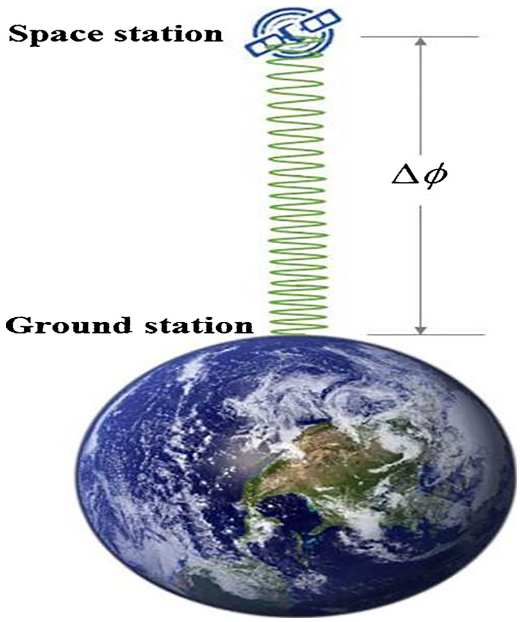

Fig. 1. Gravitational redshift of photon. When light is beamed up from a ground station at the Earth surface to a space station, its frequency undergoes a redshift. $\Delta\phi$ is the gravitational potential difference.

2. The interpretation of the gravitational redshift effect according to GR

Traditionally, the motion of astronomical objects is calculated based on Newton's theory of gravity. In 1916, Einstein proposed that gravity can be replaced with acceleration based on the principle of equivalence [9]. He argued that the space-time is curved by the presence of gravity and conjectured that the equation of motion should be described based on the theory of general relativity (GR). Although the Einstein's equation is much more complicated than Newton's gravitational theory, it has an advantage in explaining the gravitational effect on light. It is well known that light has no rest mass, and thus, according to Newton's gravitational law, light cannot interact with gravity. But according to GR, time can be affected by gravity; such a theory can provide a theoretical basis for explaining the gravitational redshift of light. Suppose a beam of laser light is transmitted from a ground station (point A) to a receiver in a space station (point B) orbiting above the Earth (See Fig. 1). According to GR, the light will experience a gravitational redshift [7]

$$\nu' = \nu\left(1+\frac{\Delta\phi}{c^2}\right), \tag{1}$$

where ν' is the frequency of light at point B, ν is the initial light frequency at point A, $\Delta\phi$ is the difference of the gravitational potential between point A and point B ($\Delta\phi = \phi_A - \phi_B$). The above equation can be rewritten as

$$\frac{\Delta\nu}{\nu} = -\frac{\Delta\phi}{c^2}. \tag{2}$$

where $\Delta\nu = \nu - \nu'$ is the change of frequency. This relation has been used in many experiments to test the validity of GR [1,2,8]. Such a relation is also used in satellite communication. In fact, it is now incorporated into many receiver systems designed for GPS [4].

3. Gravitational effects on photon due to its quantum mass

Because of the importance of the gravitational redshift effect, it would be interesting to examine whether it can be explained by alternative physical interpretations. In this work, we would like to investigate if such an effect can be explained based on the quantum properties of a photon. In the following, we will show that one can directly derive the gravitational redshift effect on electro-magnetic waves based on a few simple assumptions:

(1) *From the quantum properties of a photon, one can determine the effective mass of a photon in a gravitational field.*
(2) *The photon in a gravitational field should satisfy the principle of energy conservation.*

In the classical Newtonian theory, the "gravitational mass" is supposed to be identical to the "inertial mass" [10,11]. This identity is also assumed in GR [8]. In Newton's original theory, this mass was thought to be a constant. At the beginning of 20th century, it was discovered in experiments that the mass of a particle could vary with its speed (v) [12,13]. This speed-dependent mass is called