A theoretical study of OAM light beams under gravity

Calin Vasilescu
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Abstract

Here I study the behaviour of internal orbital angular momentum OAM light beams in a gravitational field. According to this study, such a beam should behave like a particle with rest mass, therefore the wavefront should slow down if the beam is pointed against the gravitational field and it will accelerate if pointed in the same direction as the gravitational field. This study is conducted in a classical context, intentionally ignoring Lorentz factors. However, the relativistic effects associated with these helical structures will emerge naturally. The paper will focus on a single relativistic phenomenon – naturally occurring velocity limitation of a spin ½ particle concept which poses a rest mass. However, this rest mass is also a redefined concept. It is interesting that if a beam is pointed against a gravitational field, the step length of the helical structure reduces which acts on increasing the detected frequency of the incoming beam (considering a stationary detector above the source and the gravitational filed direction pointing downward), but since the speed of the wavefront reduces, it acts as a reducing factor for the frequency that the detector will read. In other words, although the wavelength of the beam reduces as the wave-front advances, the speed of the wavefront reduces as well, resulting in a decreasing frequency. When the front-wave velocity tends to zero, this frequency tends to a positive number.

It is clear that if the wavefront speed reduces under a gravitational field, it will eventually stop and reverse the direction, falling towards the source of the field. This behaviour is similar to a particle with rest mass. However, if photons don't have mass, then, my suggestion is that particles are helical structures that have similar construction to OAM $|m| = 1$ and therefore, we could say they don't have mass either.

1. Introduction

The paper contains a theoretical study of a particular behaviour of OAM helical mode $|m|=1$ light beams in certain conditions.

One property of the electromagnetic waves that has recently been explored, is the ability produce beams that carry orbital angular momentum (OAM). These beams have a unique helical phase front. The OAM relates to the special phase profile rather than the state of polarization of the wave which is associated with the spin angular momentum (SAM). In the case of the SAM the electrical field rotates along the beam axis and this is also known as circularly polarised EM waves. The wave carries OAM if it spirals around the beam axis, leading to a helical phase front. In the case of OAM $|m| = 1$ beams the helical phase-front is related to a phase term of $exp\ (i\theta)$ in the transverse plane, where θ is the angular coordinate. Although the SAM and OAM of EM waves can be coupled to each other under certain circumstances, they can be clearly distinguished from paraxial EM beams. Therefore, OAM and SAM can be considered as two independent properties of EM beams.

One particular property that I am interested in analysing in this paper is the behaviour of these waves under a gravitational field. There is a popular expression which says that gravity bends light. It is known that, according to General Relativity it is more precise to say that light follows the curvature of space, however, I will use the concept of a gravitational field to analyse these waves. My particular interest is what happens to these helical structures in a gravitational field.

2. The wavefront speed of an internal orbital angular momentum (OAM) light beam

If we look at an OAM helical mode $m=0$ beam of light, the propagation speed of the wave front is the maximum and it is equal to the speed given by the permittivity and permeability of the medium ($\mu_0\varepsilon_0$). In this case, all local momentum vectors follow a straight line. This corresponds to an integer spin particle like simple photons *($m=0$).*

For a beam of light of internal OAM helical mode $|m|=1$ or greater, there is experimental evidence that the wave-front speed is always lower than the speed of light c [4]. The local momentum vectors follow helix trajectories, instead of following a straight trajectory. The local momentum vectors have the same velocity, c. However, the front-wave velocity will be slower.

3. Defining a classical model for a photon and a particle for the purpose of explaining this concept

For this concept, to make an analogy with the particles in The Standard Model, I will define the term particle, in a classical way, ignoring the quantum behaviour. I will study the behaviour of this particle in a flat space Euclidean space ignoring Lorentz transformations. What is also important to note is that, since we cannot use Lorentz transformations and Minkowski spacetime concept, gravity will be considered as a consequence of a gravitational field rather than a space-time curvature. In my other paper [1], I have presented a hypothesis that shows gravity as a consequence of electromagnetic interference, but that statement needs to be considered very carefully. I will show below that, gravity doesn't modify the energy of the particle model described this paper. Thus, the concept of gravity can be reconsidered.

For in this concept, I will define a photon is a classical electromagnetic wave as a packet of a **fixed number of oscillations** (Fig. 1), and a fixed amplitude. I will refer to this model as *pulse photon (P photon)*. I will also consider the arrangement of classical local momentum vectors to describe a spin 1 (P photon) and spin ½ for a helical mode $|m| = 1$. For the latter, I will use the name *omega particle (Ω particle).*

In the figure 1, the energy density across the *pulse #1* is greater than the energy density of the *pulse #2*, therefore, the total energy of a pulse can be written as:

$$E=E_0\,n \qquad [1]$$

where, k is proportional to the amplitude which here is constant, and n is the number of oscillations.

Since the helical mode is $m=0$, the wave-front velocity is constant (c) and it is equal to the propagation speed of light in a vacuum, therefore we can define the velocity of the *P photon* as c. For the helical mode 1, the velocity of the wavefront will be defined as the velocity of the Ω *particle*. When calculating the frequency of the particle we need to be careful, as the frequency seen by a stationary observer will be f = v/λ, therefore the velocity of the wavefront will have a critical significance.

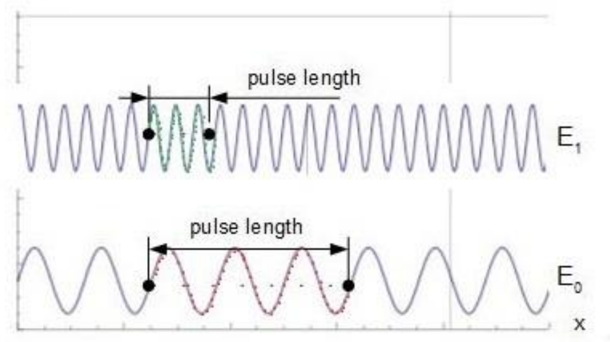

Fig.1. A representation of a classical wave packet, helical mode $m=0$, on a spatial x axis having linear polarisation. Only the electric field is depicted here. The energy of the whole packet (pulse) E_1 is equal to E_0., however, the energy density is greater for *pulse* #1.

When sending a pulse in the direction of a gravitational field, it is known that the frequency of the wave increases. However, there is no reason for the number of oscillations to increase, therefore, if the energy density increases and the total energy of the pulse (P photon), remains constant. This behaviour seems surprising because, according to General Relativity the frequency of a photon should increase, hence, when we use $E_\gamma=h\nu_\gamma$ formula for the energy of a photon, the energy should increase when falling in a gravitational field. It is clear that this classical photon model looks very different from the quantum mechanical model.

A more careful analysis of the structure, tells us that when we scan across the whole helical structure of the particle and choose a section plane perpendicular to the direction of travel, the *local wavefront* velocity will obviously vary across the helical structure. Therefore, as a whole, the Ω particle never has a definite velocity like a simple object, but since here is defined as the velocity of the front end (wave front) of the particle, we can use it as a reference. Even if the wavefront at an instant of time stops, the structure of the particle will continue to propagate following it.

4. Analysing an OAM light beam under a gravitational field

According to my hypothesis, such a beam would behave like a particle with rest mass, therefore the wavefront should slow down and the frequency should reduce if the beam is pointed against the gravitational field and it will accelerate and increase its frequency if pointed in the same direction as the gravitational field.

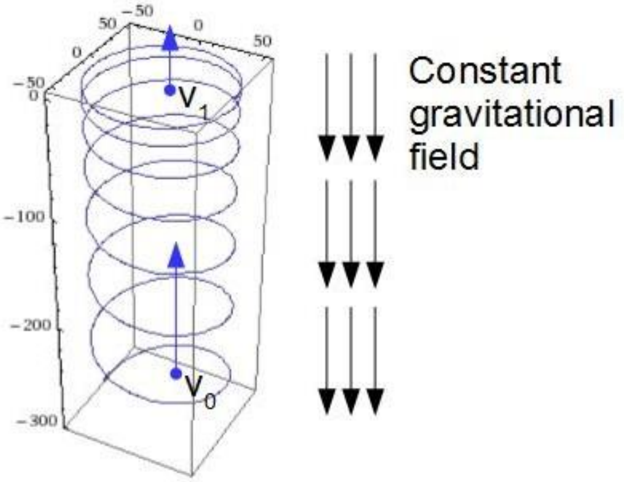

Fig.2. An OAM $|m| = 1$ wave-front decelerating in a constant gravitational field. The blue plot represents the maximum intensity of the helical structure.

In figure 2, the wavefront is decelerating as it travels upward and the frequency of the waves that compose the OAM beam reduces. The wavefront velocity will eventually reach zero at some point and then it will reverse the direction of travel and the beam will fall down towards the source.

Although I have used my hypothesis [1] that is in contradiction (it suggests the relativistic effects occur from the helical geometry rather than imposing a speed limit using Lorentz factor) with *The Theory General Relativity* for predicting this behaviour, strictly this phenomenon doesn't necessarily contradict the theory. That is because the local momentum directions have an azimuthal component as opposed to a normal beam (m=0). Even though I cannot use the Minkowsky space-time concept, it has been demonstrated experimentally that a gravitational field can act on light as well. Hence, gravity will act the local momentum beams trajectories reducing the angle between the trajectories and the plane that is perpendicular to the direction of motion of the helical structure and will make the wavefront velocity to reduce.

5. A particle model that indicates the existence of helical structures [1]

Although in the Dynamic Wave Geometry Concept I have used a particle model that is similar to an OAM *mode 1* photon, that model doesn't correctly describe a critical characteristic of an OAM beam. The paper only launches a hypothesis about what happens to particles when travelling at various velocities. The explanation didn't take into account that the step length of the helix of the particle model described in the paper is equal to the wavelength of the beam and assumed there is an additional oscillation.

I will use an Ω *particle* described in chapter 3 which says that this particle has a helical structure.

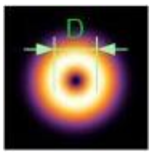

Fig.3

If we consider the diameter (D) of the centre of the projected maximum intensity ring (fig.3) of the helical structure, after calculating the helix geometry, we obtain the following wavelength of the particle:

$$\lambda_P = \frac{D_v}{c} \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{D_v}{c} \gamma \qquad [2]$$

where, v is the absolute speed of the Ω *particle* wavefront and γ is a factor that happens to coincide with the Lorentz factor. However, this is not a simple coincidence. I will have to mention that in my hypothetical concept [1], I have used a Euclidean space and linear time dimension and the γ factor that appears in the equation 2, demonstrates that the geometry of the particles automatically generates a relativistic effect. Here, the equations are the same as if defining a reference frame with the observer at rest, because either the observer or the emitter will be at rest in the absolute space.

At infinitesimal velocity, the wavelength tends to zero. However, it is interesting that the frequency of the particle, since it depends on v, is not infinite.

$$f = \frac{c}{D\gamma} \qquad [3]$$

For $v = 0$ we obtain $f = c/D$ and $\gamma = 1$.

We can write the total energy of the particle:

$$E = nE_0 = n\, m_0 c^2 \qquad [4]$$

$$m_0 = \frac{E}{nc^2} \qquad [5]$$

Here, m_0 becomes the rest mass of the particle. This formula is similar for a P photon, except that the wavefront velocity is not zero.

We can see the rest mass as proportional to the energy stored in the electromagnetic field. If we consider the particle to be a neutrino for example, this mass will correspond to the rest mass from the Standard Model.

In chapter 3, I have shown that the energy of a P photon does not change if accelerated. This is also obviously true for an **Ω** particle. Therefore, the mass of the particle does not change either. Instead, the mass density increases. This way mass always remains proportional to energy and becomes redundant. The reason for which the energy and the mass of an **Ω** particle at rest is clear. The propagation of the wave continues and the helical structure becomes a circular structure.

In a gravitational field this particle will have at a height h_1, a wavelength λ_1. If it travels towards the object that generates gravity (we consider a uniform constant gravitational field), at a height h_0, the wavelength will increase to λ_2.

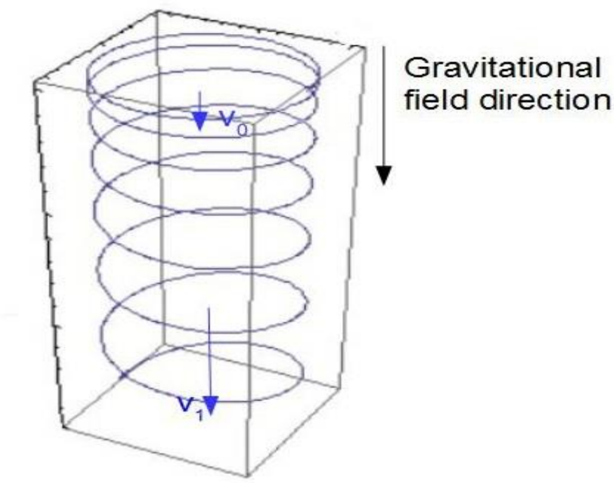

Fig.4. An OAM, |m|=1 photons descending in a constant gravitational field. The blue line represents the trajectory of a maximum intensity of the helical structure. The plot is on a length dimension axis and although the wavelength increases, because the wave-front speed also increases, the frequency increases given by the equation 2.

Since the $E_{p0} = E_{p1}$ and m ("rest"mass) is constant, then the only term that changes is Υ. A higher Υ corresponds to a higher wave front speed of the particle. This means that a particle wave front accelerates as it descends in a gravitational field. If the wave is *OAM m=0* then the particle wave-front cannot increase and it only blue shifts its frequency.

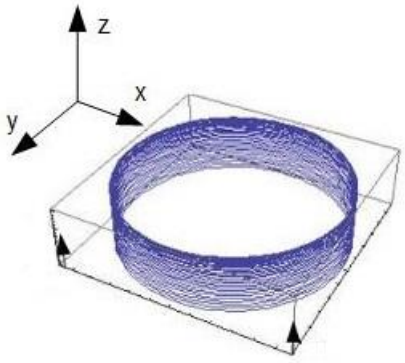

Fig.5. An internal OAM light beam m=1 slowing down to ininitesimal velocity. The black arrows represent the initial velocity of the wavefront (z=0, on z axis). At z=0, v = 0 but the local beams (only the maximum intensity is depicted here) vectors still propagate at the speed of light (c).

6. Discussion

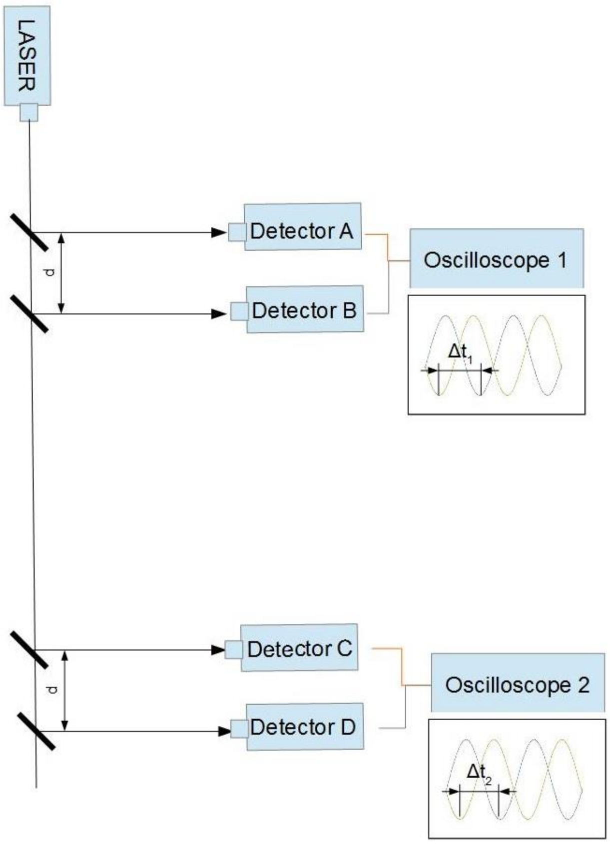

Fig. 6. An experimental setup for determining the speed change of a OAM light beam under gravity. The laser is a source of OAM m=1 light The setup for the oscilloscope 1 is at a higher altitude..

In figure 6, the oscilloscope 1 measures the time difference between the detection at *detector A* and *detector B*. Because the wavefront will accelerate under gravity, Δt_1 will be higher than Δt_2.

Although I have attempted to write some equations, that indicate the consequences of such a model, the immediate purpose of this paper is, however, to show how an OAM light beam reacts to gravity and not necessarily to define the rest mass / energy concept.

Although I wasn't able to find any experimental evidence for the behaviour of these beams, the setup for such an experiment should be easy to prepare considering the technologies available.

If the mechanism presented here proves to be correct, it will probably have a significant impact on current theories.

By considering a photon as a pulse of a fixed number of oscillations of the electromagnetic field, we can analyse the photoelectric effect from this perspective. It becomes clear that the energy density is important, not the total energy of the pulse.

It is important to mention the wavefront velocity of a **Ω** *particle,* in my opinion, can never reach zero velocity. That is because a more careful analysis of the structure, tells us that when we scan across the whole helical structure of the particle and choose a section plane perpendicular to the direction of travel, the local wavefront velocity will obviously vary across the helical structure. Therefore, the **Ω** *particle* never has a definite velocity across the whole structure.

Although not the purpose of this paper, I can briefly mention that, this concept strongly suggests that all particles are constructs similar to OAM photons, and therefore the local beams that compose the particles always travel at a constant speed, but the wave fronts can have any speed between 0 and c.

The concept is supporting the anisotropy of light generating the fundamental relativistic phenomena, that is in agreement with the experimental evidence that is currently debatable.

When we look at the **Ω** *particle* described here, we can also ask what happens to its length as a function of velocity. According SR, objects would experience a length contraction. However, after evaluating the shape helix equation, this model shows that the opposite happens, according to the following equation:

$$x' = x\sqrt{\frac{1}{1-\frac{v^2}{c^2}}} \qquad [6]$$

Notice that the velocity *v* is in absolute space.

Another reason for using absolute space is because it is known that the vacuum has the μ_0 and ε_0 properties in respect to the electromagnetic field. Since these properties are physical, I think it is natural to assume that the vacuum is an electromagnetic medium. This medium cannot be attributed a definite position or velocity, but we can refer the frame of reference where it is at rest. In the equation 6, *v* can be seen as the velocity relative to this frame, and *x* a physical object in this frame.

The electromagnetic medium is clearly supported by this concept. However, this statement remains questionable at the moment and it hasn't been accepted by the mainstream opinion.

Analysing the behaviour of a simple *P photon* defined in this paper, under gravity, reveals a new perspective on the energy conservation principle and indicates that gravity could be a simple interaction of the electromagnetic field waves.

8. Conclusions

I have presented the reasons why, a wave-front velocity of an internal OAM helical mode $|m| = 1$ beam of light should vary in a gravitational field, depending on the direction of travel. This beam seems to behave like a stream of particles that have a rest mass greater than zero, suggesting that ½ spin particles have a very similar construction. This concept demonstrates a natural relativistic effect associated with the helical structures, in a Euclidean space and linear time dimension.

Acknowledgments

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