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Exploring the Feasibility Space Travel using the Special Theory of Relativity

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ABSTRACT: Special relativity is a well-established concept which was first introduced by Albert Einstein in 1905. Since then, multiple science fiction movies have explored the theme of space or interstellar travel. This paper explores the idea of space travel and whether it is possible presently or in near future with the help of the concept of Special Relativity. It involves the derivation of the Lorentz factor with the help of light clocks, explores the time dilation and length contraction equations, includes calculations for a hypothetical interstellar journey, and finally evaluates the feasibility of the same.

KEYWORDS: Special Relativity, Relativity, Space travel.

I. INTRODUCTION

The speed of light is the absolute limit of speed which means that nothing can ever move faster than it (3×10^8 m/s). The nearest star from our planet is the Sun around which our Earth revolves. The second nearest star is Proxima Centauri which is approximately 4.2 light years away from Earth. This means that light takes approximately 4.2 years to travel from this star to our planet. Therefore, if someone were to travel to Proxima Centauri and return to Earth at the speed of light (c), it would take them 8.4 years to do the same, which does not seem like a very long time in comparison to a human's lifetime.

In June 1905, Einstein wrote a paper called "On the electrodynamics of moving bodies" [1]. In this, he proved a theory which is now known as the Special Theory of Relativity. He refuted some ideas of Newtonian physics and proved that at large velocities, the concept of simultaneity cannot be considered absolute. He also proved that at high velocities, there are certain relativistic effects that can be observed. These are the time dilation and length contraction effects. Due to these effects, theoretically, it is possible to travel to a star like Proxima Centauri and return within a lifetime. However, there are various challenges and paradoxes involved. This paper will explore some of these challenges.

II. RELATED WORK

The year 1905, also known as the miracle year, was when Albert Einstein published five of his career-changing papers. The first one was published in March 1905 which was based on light quantum. The next one was published in April 1905 which was about measuring the size of molecules. In the paper published in May 1905, he proved the existence of atoms (using the random movement of particles due to bombardment by other particles which is known as the Brownian motion [2]). In June 1905, he published one of his most significant papers of all time: the paper on electrodynamics of moving bodies or the Special Theory of Relativity which explained the unusual observations made when the speed of an object is close that of light. The last paper of the year was like an extension or addendum to his previous paper where he introduced the equation $E = mc^2$ and presented the relationship between mass and energy which Newton himself was not able to see.

III. ABOUT SPECIAL RELATIVITY

The two postulates of Special Relativity

There are only two postulates under the Special Theory of Relativity. The first one is the Principle of Relativity which states that the laws of physics are the same in all inertial frames of reference. An object is in an inertial frame of reference either when it is stationary or moving at a constant speed and "no inertial frame shall be distinguished from any other inertial frame by any property" [1]. For example, if a train is moving at constant velocity and if a ball is

dropped, it will fall down and the same will happen when it is dropped at a house that is stationary. The second postulate is the Principle of Light Constancy which states that the speed of light remains the same in all frames of references and “light is always propagated in empty space with a definite velocity c which is independent of the state of motion of the emitting body.” [1].

The Lorentz factor

The derivation of the Lorentz factor is fairly simple and can be done using a light clock. The light clock of a stationary object looks something like this:

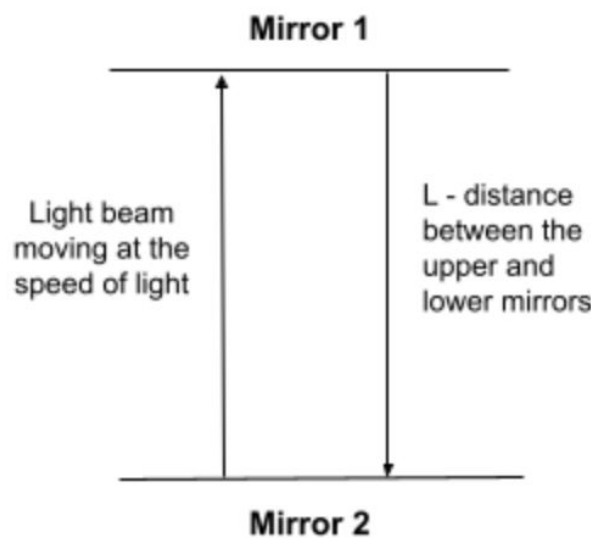


Figure 1. Light clock

The light clock of a moving object, on the other hand, looks like this:

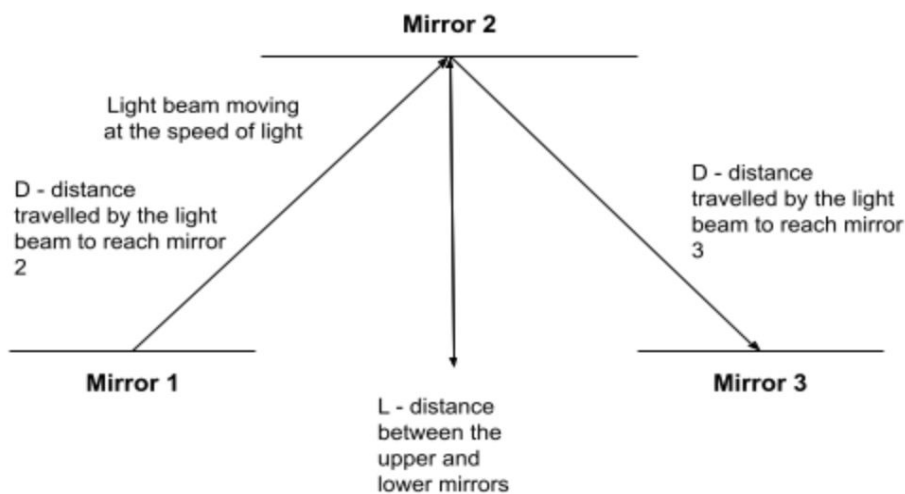


Figure 2. Light clock



Note: the distance L between the upper and the lower mirrors is the same in both the light clocks.

Since *total time = total distance/speed*, the time taken by light to travel in each of these objects can be measured.

$$\text{Stationary object} = \frac{2L}{c}$$

$$\text{Moving object} = \frac{2D}{c}$$

Since D is greater than L (L is perpendicular to the mirrors and hence, D is the hypotenuse of both the triangles in the second light clock), and both have the same denominator c , it can be said that the time taken by the light beam to travel in the light clock of the moving object is more than the time taken for the light beam to travel in the stationary object.

To find the Lorentz factor, the Pythagoras theorem can be used. Here, the distance between the two lower mirrors is the distance travelled by the moving object in the time $\frac{2D}{c}$. Let $\frac{2D}{c}$ be there and let the constant velocity of the moving object be v here. From this it can be concluded that the distance travelled (which is *time × speed*) is vt here. This gives us the value of the distance between the two lower mirrors.

$$\text{Finally, according to the Pythagoras theorem, } D^2 = L^2 + \left(\frac{vt}{2}\right)^2$$

To further solve this equation, let the time taken by the light beam to travel in the stationary object's light clock be t' .

Therefore, $t' = \frac{2L}{c}$ and from this, the value of L can be taken out in terms of t' and c .

$$L = \frac{t'c}{2}$$

Moreover, D can also be written as $\frac{ct}{2}$.

With all the substitutions, the Pythagoras theorem equation can be also written as:

$$\left(\frac{ct}{2}\right)^2 = \left(\frac{ct'}{2}\right)^2 + \left(\frac{vt}{2}\right)^2$$

$$\text{After simplifying the equation, the final answer is } t = \left(\left(\frac{1}{1-\frac{v^2}{c^2}}\right)^{\frac{1}{2}}\right) * t'$$

Here, the factor by which t' is getting multiplied is the Lorentz factor (also known as the gamma factor). It can also be written as:

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

The generic equation is $t_{\text{moving}} = \frac{1}{\gamma} * t_{\text{rest}}$.

This is the time dilation equation.

Time dilation and length contraction

The above mentioned information can be further explored through a simulation. The different variables in this situation are as follows:

1. Constant variables –
 - a. speed of light (c)
 - b. one frame of reference is stationary

- c. speed of the moving object/person is constant because there is no acceleration.
2. Independent variable – the speed of the moving person/object
3. Dependent variable – time of the moving person/object (can be observed by the time it takes for the ball (represents light here) to reach the top of the light clock and back)

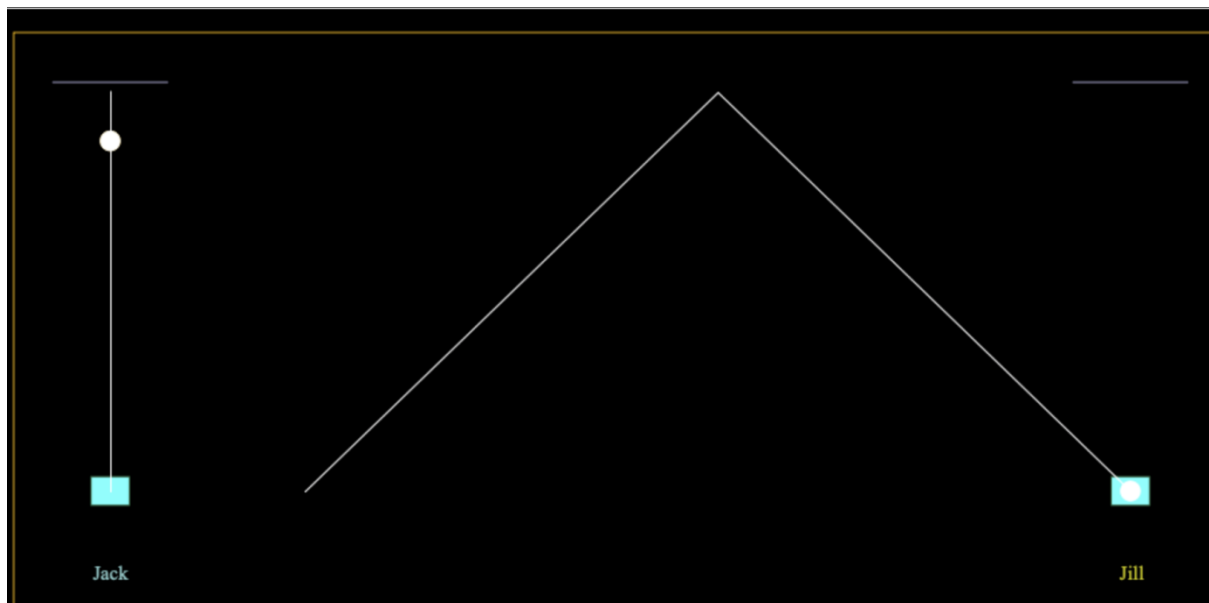


Figure 3. Simulation [3]

In this image from the simulation it can be seen that the ball that is ejected from the moving object takes more time to come back to its original position as compared to ball from the stationary object. This is figure is just like the light clock images in the previous section.

The time is slower by a factor of gamma and therefore, the time dilation equation can be written as-

$$t' = t\sqrt{1 - v^2 / c^2}$$

Here, t' = dilated time (of a moving object), v = velocity of the moving object, c = constant for the speed of light and t = time in a stationary frame of reference. Since, this equation has the value of the gamma factor, it can also be written as:

$$t' = \frac{1}{\gamma} t$$

Similarly, the length contraction equation is:

$$L = L_0 \sqrt{1 - v^2 / c^2}$$

which can be written as

$$L = \frac{1}{\gamma} L_0$$

To notice the effect of time dilation, atomic clocks (which are extremely accurate) have been put on airplanes and carried around the planet. The time measured on these clocks has been compared with the time on the clocks in an observatory. The clocks were inconsistent which proves the existence of relativistic effects.

Travelling to the Proxima Centauri: A hypothetical situation

To understand the relativistic effects in work, a hypothetical situation can be considered.

Note the following variables:

Distance between Earth and Proxima Centauri (up to 1 d.p.) = 4.2 light years

Speed of the spaceship (hypothetical) = $0.943c$

Lorentz factor = γ

There are two frames of reference here:

- 1) Earth observer's frame of reference: For them, the Earth is stationary and the rocket is moving.
- 2) Rocket observer's frame of reference: For them, the rocket is stationary and Earth is moving.

Earth observer	Rocket observer
Travel time = $\frac{4.2 \text{ light years}}{0.943c}$ Since $c = 1$ light year per year, travel time = 4.45 years	For the rocket observer, the distance between Earth and Proxima Centauri has contracted. Therefore, for the rocket observer, the distance would be <u>proper length</u> $\frac{4.2}{\gamma}$ (proper length is defined as 'the distance between two points measured by an observer who is at rest relative to both of the points.' [4]) Hence, distance for the rocket observer = $\frac{4.2}{\gamma} = 1.4 \text{ light years}$ ($L = \frac{1}{\gamma} L_0$). Therefore, the rocket observer sees the distance between the Earth and Proxima Centauri as 1.4 light years.
Since the rocket is moving, the rocket's time from the Earth observer's frame of reference would be $t_{\text{moving}} = \frac{1}{\gamma} * t_{\text{rest}}$. Time passed on the rocket from the Earth's frame = $\frac{4.45}{\gamma} = 1.48 \text{ years}$.	From the rocket's frame of reference, it is stationary and the star is moving towards the rocket. Hence, the time for the star to reach the rocket observer = $\frac{\text{distance}}{\text{speed}} = \frac{1.4 \text{ light years}}{0.943c} = 1.48 \text{ years}$ (which is the same as the time passed on the rocket from the Earth observer's frame of reference.

Table 1. Frames of references [5]

This means that when the astronaut reaches Proxima Centauri, for him, only 1.48 years would have passed but for people on Earth, 4.45 years would have passed. Another important point to note is that from the rocket observer's frame of reference, the *elapsed time on Earth* = $\frac{1.48}{\gamma} = 0.49$ years because from their perspective, Earth is moving away from them and time is passing more slowly on Earth.

What we can understand from this is that time is relative and there is no absolute frame of reference. Therefore, theoretically, it is possible to visit a nearby star and come back in a lifetime because according to the concept of time dilation, as an object's speed moves closer to the speed of light, time passes at a slower rate for that object. This means that travelling at relativistic speeds would ensure that an astronaut's return to their planet within a lifetime.

Energy problem

It is obvious that for a trip like this to take place, the speed of the spaceship needs to be close to that of light. However, for a spaceship to travel at such speeds, a massive amount of energy is required. This is because the energy required to



move large objects with high value of masses like spaceships is tremendous. This is why, presently, it is only possible to move subatomic particles at relativistic speeds inside particle accelerators.

The only fuel that would be efficient enough to do interstellar travel can be generated through the interaction between matter and anti-matter. This would result in a 100% release of energy, unlike nuclear fusion or fission that are not very efficient. However, another problem that arises here is that the mass of this fuel would be added on to the mass of the spaceship itself. This puts us in a vicious cycle as more the mass of the fuel, the more the fuel required to run the spaceship. Moreover, if the rocket moves at a constant acceleration, it would get harder and harder to maintain the level of acceleration as the speed of the rocket gets closer to that of light.

IV. CONCLUSION

Hence, the theory of relativity allows us, with the relevant calculations, to prove that it is possible for a person to travel to a nearby star and return in a lifetime. However, this is not a feasible thing to do yet. Many science-fiction novels and movies have explored the concept of manipulation of the space-time curvature or other methods for space travel but something like this has not been explored in the real world. Only particles with negligible or very less mass can travel at relativistic speeds inside particle accelerators today.

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