PREDICTING THE EXTENT OF TIME TRAVELING DONE AT DIFFERENT SPEEDS USING THE THEORY OF RELATIVITY

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ABSTRACT: Our understanding of the universe has changed widely since Einstein's explanation of time as an axis. In this paper, we aim to study the effect of traveling at speeds beyond the limit assigned by Einstein in his theory of relativity. Using his very equations for time dilation, we will show that it is not only possible to break down the barriers of time, but also to predict with certainty about the effects that a body will undergo if it travels beyond the limit of the speed of light. This article deals with the mathematical proof of time travelling and the derivation of a general formula that is applicable for all speeds greater than, the speed of light. The extent of time dilation will also be under discussion. This article concludes the variation in the dilation of time with concluding help of exemplary questions and the extended articles used in the relativity equations. The methods and the conclusion of our paper conclude the result in favor of relative extension of time.

Objectives: To study the influence of different speeds greater than light on the rest or proper time using Einstein's equation of time dilation from the special theory of relativity. To study the relativity equation related to the dilation of time. The possibilities of the time dilation regarding the various masses in case of exceeding the speed of light.

Keywords: time dilation; special theory of relativity; time travelling; speed of light; particle physics; neutrinos; energy; dimensions.

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INTRODUCTION

The most influential and revolutionary article ever published in the physics history was of Einstein in 1905 (Einstein, 1905). The theory of special relativity caused great changes in the world of physics and stirred even more hypotheses that led to the gradual but complete change of our perception of the universe and how it works. The theory itself has two postulates:

1. Every Newton's law is used and can be applicable in the inertial time frames.
2. As we knew the speed of light c is always same.

According to Einstein, Albert. "Relativity: The Special and General Theory". (1920) page no. 1 to 65.

Einstein proved mathematically that for objects travelling at the speed of light or by a factor of c/10 astonishing consequences are to be observed. The mass of the object becomes massive (mass variation), so much so that it becomes impossible for it to be moved. The object shortens (length contraction). The famous mass-energy equation is also one of the results of this theory. But the most fascinating result is, indeed, time dilation. As explained by Albert Einstein in 'the electrodynamic of the moving bodies' (published on 30^{th} June 1905).

$\mathbf{E = mc^2}$

One of the maximum best portions of instructional literature ever produced in physics history is Einstein`s unique concept of relativity. The concept of unique relativity explains how space impacts on mass & time. Small quantities of mass may be changed with big quantities of electricity , as described via way of means of the traditional equation E = mc2, in line with the concept, which gives a method for the rate of mild to outline the hyperlink among electricity and matter.

"**energy is equal to mass times the speed of light squared.**"

However, they are not easily interchanged. Due to the light speed is already a huge figure, and the derivation requires it to be multiplied 2 times (or squared) to get more bigger, a minute quantity of mass contains a massive pottential of energy. As PBS Nova described in an example, "If you could convert every atom in a paper clip into pure energy, leaving no mass behind, the paper clip would produce [the equivalent energy of] 18 kilotons of TNT. That's about the size of the bomb that annihilated Hiroshima in 1945."

The most remarkable effects of theory of special relativity in dilatation of time. As Jefeminko in 1996 explained the Time dilation, according to this theory, there is the difference in elapsed time between two events as measured by observers who are really moving relative to one another or moving differently depending on their proximity to a gravitational mass. It basically states that the faster we go, the more time we forfeit by Rindler in 1970

An interesting question arises at this point: Does time exist? The answer is simple: yes. It definitely does (Horwich, 1978). Because only such a thing can be controlled or governed that is an entity. Anything that does not even exist cannot be controlled. Travelling at speed of light controls time. (Einstein, 1905; Hawking, 1988). The Newtonian concept that time is merely our perception of the sequence of events and all the talk about the 'arrow of time' is thus defied. Time does have an existence.

A similar phenomenon was discussed by Stephen Hawking. He explains the existence of light 'cones' at the location of events (Hawking, 1988). According to Hawking, any event taking place in the universe has a past light cone, a future light cone, and the place where they both meet (the present). Entering any of these two light cones actually means entering the past or future of a particular event. Hence, time was considered a separate dimension. It brought the total to four (Manning, 1914). Now, we have 3 dimensions of space (x, y, z axis) and one dimension of time. Today, however, we believe in 5 dimensions including gravity; whereas, the String Theory proposes up to 26 dimensions. (Frank D. and Smith Jr.: 'Physical Interpretation of the 26 Dimensions of Bosonic String Theory') 2001.

Time dilates when one travels at the speed of light. This effect is even visible at $3 \times 10^7\ \text{ms}^{-1}$. The same equations can also be used to predict just how much one can travel in past and future, if one crosses the limit of the speed of light set up by Einstein himself.

The astronaut began work on a deep space journey at 95% the speed of light. The astronaut's clock had measured ten years when he returned, so he had aged ten years. When the astronaut reunites with his earthbound twin, he discovers that the twin has aged 32 years! This is explained by the fact that the astronaut's twin is travelling at relativistic speeds, which slows down his "clock."

TIME DILATON EQUATION:

$$\mathbf{t = t_0/(1-v^2/c^2)^{1/2}}$$

t is the time rewiwed in the differ reference frames.

t0 = is the time in frame of reference of the observer.

v = the moving object's speed

c = the vacuum speed of light

we'll set v = 0.95c, t0 = 10 years. Solve it for earthbound twins refrence.

$t = 10/(1- (.95c)^2/c^2)^{1/2}$

$t = 10/(1- .95^2)^{1/2}$

t = 10/ .312

t= 32 years

SAMPLE PROBLEMS RELATED TO TIME DILATION:

1) Tanya boards a spaceship and travels at 0.800 times the speed of light past Earth. Tara, her twin sister, remains on Earth. They both start timers the moment Tanya's ship passes Earth. Tanya watches her timer and stops it when 60.0 seconds have passed. How much time has Tara's timer indicated has passed at that point?

Ans :

$$\Delta t = \frac{\Delta t_0}{\sqrt{1-\left(\frac{v}{c}\right)^2}}$$

$$\Delta t = \frac{60.0\ s}{\sqrt{1-\left(\frac{0.800c}{c}\right)^2}}$$

$$\Delta t = \frac{60.0\ s}{\sqrt{1-(0.800)^2}}$$

$$\Delta t = \frac{60.0\ s}{\sqrt{1-0.640}}$$

$$\Delta t = \frac{60.0\ s}{\sqrt{0.360}}$$

$$\Delta t = \frac{60.0\ s}{0.600}$$

$$\Delta t = 100\ s$$

2) An observer notices that a muon has formed and observes that it reaches the surface after 20.0 x 10-6 seconds. Observers also note that the muon he was traveling at 2.97 x 108 m/s. How much time passed in the muon's coordinate system from the time the muon formed to the time it reached the surface?

Answer:

$$\Delta t = \frac{\Delta t_0}{\sqrt{1-\left(\frac{v}{c}\right)^2}} \rightarrow \Delta t_0 = \Delta t\sqrt{1-\left(\frac{v}{c}\right)^2}$$

$$\Delta t_0 = \Delta t\sqrt{1-\left(\frac{v}{c}\right)^2}$$

$$\Delta t_0 = (20.0 \times 10^{-6}\ s)\sqrt{1-\left(\frac{2.97 \times 10^8\ m/s}{3.0 \times 10^8\ m/s}\right)^2}$$

$$\Delta t_0 = (20.0 \times 10^{-6}\ s)\sqrt{1-(0.990)^2}$$

$$\Delta t_0 = (20.0 \times 10^{-6}\ s)\sqrt{1-0.9801}$$

$$\Delta t_0 = (20.0 \times 10^{-6}\ s)\sqrt{0.0199}$$

$$\Delta t_0 \cong (20.0 \times 10^{-6}\ s)(0.141)$$

$$\Delta t_0 \cong 2.82 \times 10^{-6}\ s$$

The laws of physics forbid matter to attain a speed equal to or greater than the speed of light. The reason is again explained by Einstein. He famous equation $E = mc^2$ is all about this. This equation is explained next. As an object (initially at rest) gains more and more speed, more and more energy is required to move at this high speed. Thus, the object consumes greater energy. Now as the same object approaches speed close to the speed of light, the kinetic energy possessed by the body converts into mass and adds to the original mass of the body. Such that the object becomes so heavy that it is difficult to move the object until at last, a stage is reached where the speed of the object becomes so high that an infinite amount of energy is required to move it any further. Such an amount obviously cannot be provided and so it is said that any object can never exceed the speed of light (Einstein, 1905; Hawking, 1988).

Then, how can light itself travel at a pace which is forbidden by the laws of nature? To put it simply, Einstein's famous mass-energy relation suggests that any object traveling with the speed of light will have its mass increased to such an extent, that it would be impossible to move the object, unless or until one is able to provide an infinite amount of energy, which is of course beyond the scope of our world. Hence, no object can move at this speed (Weinstock, 1965). Then, why light it-self can do so? Light itself has mass (photons: a term suggested by Einstein) as explained by Max Planck's Quantum Theory. (*As* explained *by Badino, M. in 'The Bumpy Road: Max Planck from Radiation Theory to the Quantum'. Springer International Publishing, 2015.)* Why does its mass not become infinite at such an exceptional speed?

The answer was given by de- Broglie. According to him, light is the purest form of matter. It does not obey the laws of relativity. Ordinary rules of physics break at the discussion of light. Light, being the purest form of matter, is the only matter that can pass through another matter without disturbing it whatsoever (Broglie, 1924). Hence, being the superior form of matter, light is not affected even at the maximum speed of the universe.

Another piece of evidence regarding the mass of photons can be the phenomenon of pair production (Blackett and Occhialini, 1933). In this phenomenon, a gamma ray, which is, in fact, a photon, enters the electric field of an atomic nucleus and splits up into its composite particles i.e. an electron and a positron (antielectron). Since the electron has a mass of 9.1×10^{-31} kg, and the positron has the same negative mass; therefore, as a whole, the mass of the photon appears to be zero. Just as an atom is quasi-neutral (charged but on the whole neutral), so is a photon. It can be said to have a *quasi-mass.*

As a matter of fact, it is now being considered that the speed of light is *not* the limit of the speeds of the universe after all. The neutrinos in dark matter travel at speeds greater than the speed of light (Aquino, 2014). Moreover, the hypothetical existence of tachyons and the practical production of Cherenkov radiations also violate the speed limit. Hence, we shall consider various speeds, all of them greater than that of light, and observe the influence these speeds have on our perception of time. In other words, we shall explore the phenomenon of time traveling supported by math.

General relativity holds this feature (local motion at velocities less than the speed of light) as the observer moves along a time-like path. However, the curvature of spacetime opens up the possibility of distorting the global geometry to allow for so-called "closed time-like curves", orbits that intersect in the past. Finding solutions to Einstein's equations with closed time-like curves is easy. As a simple example, take an empty Minkowski space, identify each point in the space at time t1 with the corresponding point at time t2, and create a cylindrical spacetime in which stationary particles move like a time loop. gain. Concepts of curves, such as closed time in the real world, are difficult to reconcile with our intuitive understanding of causality. Perhaps we can find a global solution to general relativity involving closed time-like curves. These are definitely time machines. However, it may not be possible to build such systems in local regions of the universe. Theorems along these lines were proved by Frank Tipler in the 1970s. Tipler assumed that the energy density can never be negative and showed that closed time-like curves can never occur in local regions without producing singularities. This was promising because he could have expected both singularities and closed time-like curves to be hidden behind the event horizon (not part of the evidence).

Interest in time travel was revived a decade or so ago with the discovery of a new space-time with a closed time-like curve. Wormhole solutions discovered by Michael Morris, Kip Thorne, Ulvi Urtzever, and J. Richard Gott. The wormhole spacetime requires a negative energy density, whereas the closed time-like curve in the cosmic string spacetime does not originate from a local region. model has spurred research into the possibilities of time travel under more general conditions.

A. EINSTEIN

GENERAL THEORY OF RELATIVITY

Einstein presented it in 1916. Gravity is the theme of general relativity. General relativity describes large-scale physical phenomena, while gravity defines macroscopic behavioural patterns. General relativity is based on Einstein's principle of equivalence: it is impossible to distinguish between physical effects caused by gravity and those caused by acceleration at the microscopic level. Gravity is regarded as a geometric phenomenon caused by the curvature of space and time. The solution of the field equations that describe general relativity can provide answers to questions about planetary dynamics, star birth and death, black holes, and the evolution of the universe.

SPECIAL THEORY OF RELATIVITY

It was presented by Einstein in 1905 in one of his famous papers. The theory of relativity is a theory that deals with motion of objects close to speed of light and even with super luminous motion (greater than speed of light: $c=3\times10^{8}$m/sec). It turns out that Newton's second law ceases to be correct as speeds of objects approach the speed of light; only Einstein's relativistic mechanics are applicable for such cases. We will use this theory in our upcoming discussions.

METHOD

With the help of the following method, we can find the extent of time traveling done in case a body exceeds the speed of light. For this purpose, we shall use Einstein's equations from the special theory of relativity.

Consider 't_o' as the rest or proper time. Then consider 't' as the dilated time. Moreover 'c' is the speed of light while 'v' is the velocity of the moving body. If the negative sign with time is considered as a time in the past (since time is an axis), exceptional results are obtained. Similarly, a positive sign can be considered as the future.

- For an object travelling at twice the speed of light, the proper time will seem to be square root three times in the past.

For v= 2c:

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

$$t = \frac{t_o}{\sqrt{1-\frac{(2c)^2}{c^2}}}$$

$$t = \frac{t_o}{\sqrt{1-\frac{4c^2}{c^2}}}$$

$$t = \frac{t_o}{\sqrt{1-4}}$$

$$t = \frac{t_o}{\sqrt{-3}}$$

$$t_o = \sqrt{-3}\, t$$

- For an object travelling at thrice the speed of light, we can go square root of 8 times in the past.

For v = 3c:

$$t = \frac{t_o}{\sqrt{\left(1-\frac{v^2}{c^2}\right)}}$$

$$t = \frac{t_o}{\sqrt{\left(1-\frac{(3c)^2}{c^2}\right)}}$$

$$t = \frac{t_o}{\sqrt{(1-9)}}$$

$$t = \frac{t_o}{\sqrt{(-8)}}$$

$$t_o = \sqrt{-8}\, t$$

- For four times the speed of light, the proper time will seem to be square root of 15 times in the past.

For 4c:

$$t = \frac{t_o}{\sqrt{\left(1-\frac{v^2}{c^2}\right)}}$$

$$t = \frac{t_o}{\sqrt{\left(1-\frac{v^2}{c^2}\right)}}$$

$$t = \frac{t_o}{\sqrt{\left(1-\frac{16c^2}{c^2}\right)}}$$

$$t = \frac{t_o}{\sqrt{(1-16)}}$$

$$t = \frac{t_o}{\sqrt{-15}}$$

$$t_o = \sqrt{-15}\, t$$

- For five times the speed of light, we can go square root of 24 times in the past, with respect to the proper time.

For 5c:

$$t = \frac{t_o}{\sqrt{\left(1-\frac{v^2}{c^2}\right)}}$$

$$t = \frac{t_o}{\sqrt{\left(1-\frac{(5c)^2}{c^2}\right)}}$$

$$t = \frac{t_o}{\sqrt{\left(1-\frac{25c^2}{c^2}\right)}}$$

$$t = \frac{t_o}{\sqrt{(1-25)}}$$

$$t = \frac{t_o}{\sqrt{-24}}$$

$$t_o = \sqrt{(-24)}\, t$$

- For ten times the speed of light, we can go square root of 99 times in the past, with respect to the proper time.

For 10c:

$$t = \frac{t_o}{\sqrt{\left(1-\frac{v^2}{c^2}\right)}}$$

$$t = \frac{t_o}{\sqrt{\left(1-\frac{(10c)^2}{c^2}\right)}}$$

$$t = \frac{t_o}{\sqrt{\left(1-\frac{100c^2}{c^2}\right)}}$$

$$t = \frac{t_o}{\sqrt{(1-100)}}$$

$$t = \frac{t_o}{\sqrt{-99}}$$

$$t_o = \sqrt{(-99)}\, t$$

- Ultimately, for infinite speeds, time becomes zero, as shown below:

$$t = \frac{t_o}{\sqrt{\left(1-\frac{v^2}{c^2}\right)}}$$

$$t = \frac{t_o}{\sqrt{\left(1-\frac{\infty^2}{c^2}\right)}}$$

$$t = \frac{t_o}{\sqrt{\left(1-\frac{\infty}{c^2}\right)}}$$

$$t = \frac{t_o}{\sqrt{(1-\infty)}}$$

$$t = \frac{t_o}{\sqrt{(-\infty)}}$$

$$t = \frac{t_o}{\sqrt{(\infty)}\, i}$$

$$t = \frac{t_o}{\infty\, i}$$

$$t = 0$$

RESULT

The above mathematics has already proven that time travelling is not only possible but also predictable.

Let the coefficient of the speed of light be ‘n’. Then, in accordance with the above discussion:

$$t_o = \sqrt{(1-n^2)}\, t$$

where the factor of “ $\sqrt{(1-n^2)}$ ” is a constant quantity for a particular speed called “Moaaz constant”.

If we only consider the magnitude (ignore the negative sign), then we will achieve a range of time travelling. As time is an axis, therefore in the example in which an object moves at twice the speed of light, the result shows that we may move either 3 times in the future or even anywhere in between these two extremes on the time axis. But to attain any value beyond this range will not be possible at this speed.

DISCUSSION

Thus, it can be concluded that different speeds that cross the limit assigned by Einstein, allow one to travel in different eras of past, present and future.

To simplify the above discussion, a generalized formula has been derived:

$$t_o = \sqrt{(1-n^2)}\, t$$

The above discussion may be supported by the fact that we, knowingly or unknowingly, observe time dilation in our routine lives, the biggest example of which is the Global Positioning System (GPS). The 77 satellites (of which only 31 are in orbit around earth) have a speed of about 3.9 kilometers per second and can go around the earth twice a day. The result is that the time on these satellites and the time on earth differ by about 38 microseconds which is corrected by highly accurate atomic clocks. If left unchecked, these can cause navigational errors of about 11.4 kilometers per day. (Gift, 2020). Thus, time dilation is indeed a real effect and affects our lives to a great extent.

This can be explained by the “twin paradox”, which is a thought experiment (Dray, 1990). According to this experiment, one of the two twins are sent onto a spaceship travelling at or near the speed of light. Upon returning, the twins compare themselves with each other and come to know that the one who has travelled on the spaceship is younger than the other one. Moreover, the twin from space is bulkier and shorter than before as well. These observations can only be explained by the special theory of relativity. For the twin on the spaceship, travelling at speed of light caused time dilation, length contraction and mass variation simultaneously. Thus, time dilation also slows down the aging process in humans, which further supports the fact that this is a real phenomenon.

Today, some physicists believe that wormholes, predicted by the Einstein field equations, may be the source of traveling forward in time. Teleportation and time traveling might be possible through these wormholes (Al-Khalili, 2011).

In addition, it has been widely believed for a long time that black holes might just turn out to be time machines (Novikov, 2016). In fact, the gravity of a black hole is so strong and so intense that nothing, including light, can escape from it (except Hawking radiations, as were discovered by Stephen Hawking in the year 1974). Even time is bent near a black hole. This is due to the extreme curvature of the space-time fabric around a black hole (Thorne, 1995).

As mentioned above, Stephen Hawking (1974) discovered Hawking radiations (Hawking, 1988). According to him, a black hole has the ability enough to emit thermal radiation from its event horizon. He called this ‘positive energy’, which leaks out from a black hole. But to conserve energy, there must be a ‘negative energy’ that flows into the black hole simultaneously. Similarly, if positive energy is engulfed by a black hole that increases its mass, then negative energy is emitted that decreases the mass of the black hole. This obeys the law of conservation of energy (Almheiri *et al*., 2021).

This phenomenon can be applied to the above discussion. In order to conserve the total matter and energy of the universe, only positive energy of a body can travel to the future whereas if a body travels back in time, only its negative energy will be able to do so. Shortly, the same body may coexist in the past with its younger version, or it may coexist in the future with its older version, without violating the laws of conservation of matter or energy. This also solves the problem that during time travel, if a body goes into the past, there will be two of them at the same time. As for the conservation of mass, it is already evident that we have both matter and antimatter in the universe. For every single particle, there exists an antiparticle. Hence, matter, on the whole remains constant. Moreover, a body wishing to travel across time changes into energy as soon as it approaches the speed of light; therefore, only energy can undergo time travel.

NO.	SPEED (v)	EFFECT ON TIME	RANGE OF TIME TRAVEL POSSIBLE
1.	2c	Square root of 3 times in the past	$t_o = \sqrt{-3}\, t$
2.	3c	Square root of 8 times in the past	$t_o = \sqrt{-8}\, t$
3.	4c	Square root of 15 times in the past	$t_o = \sqrt{-15}\, t$
4.	5c	Square root of 24 times in the past	$t_o = \sqrt{(-24)}\, t$
5.	10c	Square root of 99 times in the past	$t_o = \sqrt{(-99)}\, t$
6.	∞	Time becomes zero	$t = 0$

Conclusion: To put it precisely, the generalized formula gives an explanation of the duration of time in control of a body if it travels at a speed greater than that of light. The mathematics even shows that if, hypothetically, a body does reach an infinite speed, then time for that body becomes zero. Thus, it becomes *timeless.* This timelessness brings it out of the influence of the time axis, and such a body can then truly coexist in the past, present and future.

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REFERENCES

Einstein, Albert (1905). On the Electrodynamics of Moving Bodies, Annalen der Physik.

Augustyn, Adam. (2018). The Encyclopedia of Brittanica.

Strominger, Andrew (2017). Lectures on the Infrared Structure of Gravity and Gauge Theory.

Ashby, N. (2003). Relativity in the Global Positioning System.

Greene, Brian (2015). The Theory of Relativity, then and now.

Penrose, R (2006). Encyclopedia of Mathematical Physics.

M. Dalarsson, N. Dalarsson (2015). Tensors, Relativity and Cosmology.

John B. Kogut (20118). Special Relativity, Electrodynamics and General Relativity.

John C. Morrison (2010). Modern Physics.

'The Physics' (March 26, 2015). ATLAS experiment at CERN.

'LHC The Guide FAQ'. Cds.cern.ch. (2017)

Hawking, Stephen. (1988). A Brief History of Time.

Buzzo, Daniel (2014). Time Travel: Time dilation. University of the West of England. (2014)

Will, Clifford. (1986). Was Einstein Right?

Parkinson, Spilker. (1996). The global positioning system.

Joseph A. Spencer and James T. Wheeler. (2011). The Existence of Time. International Journal of Geometric Methods in Modern Physics: Vol. 08, No. 2, pp. 273-301.

Obregon, Carlos (2015). Existence and Time: Philosophical and Scientific Inquiry.

Gunn, Alastair. Does Time Exist in Space? BBC Science Focus Magazine.

Greene, Brian (2000). The Elegant Universe: Superstrings, Hidden Dimensions, and the Quest for the Ultimate Theory. American Journal of Physics 68 (2), 199-200.

T. banks (2003). A Critique of Pure String Theory: Heterodox Opinions of Diverse Dimensions. SCIPP- 03/06, RUNHETC-2003-16.

Bultheel, Adhemar (2014). The Shape of Inner Space. String Theory and the Geometry of the Universe's Hidden Dimensions. Bulletin of the Belgian Mathematical Society- Simon Steven 21 (3), 273-274.

Wolfenstein, Lincoln (2018). Neutrino Oscillations in Matter. Solar neutrinos, 294-299.

Zuber, Kai (2020). Neutrino Physics.

Campbell, John et al., (2011). Vector Boson Pair Production at the LHC. Journal of High Energy Physics, article no. 18.

Nikishov, A. (1970). Pair Production by a Constant External Field. JETP 30 (4), 660.

Dai, D. and Stojkovic, Dejan (2019). Observing a Wormhole.

Almheiri. A. et alt., (2021). The Entropy of Hawking Radiation. Rev. Mod. Phys. 93, 035002.

Horowitz, G. and Brill, Dieter (1991). Negative Energy in String Theory. Physics Letters B 262 (4), 437-443.

Treptow, R. (1986). Conservation of Mass: Fact or Fiction? Journal of Chemical Education 63 (2), 103.

Deutsch, David and Lockwood, Michael. (2016). The Quantum Physics of Time Travel. Science Fiction and Philosophy: From Time Travel to Superintelligence'. 370-383.

Al-Khalili, Jim. (2011). 'Black holes, Wormholes and Time Machines'. CRC Press.

Gardner, M. (2020). Time Travel and other Mathematical Bewilderments. American Mathematical Soc.

Cvetic, Mirjam and alt. (2005). Rotating Black Holes in Gauged Supergravities; Thermodynamics, Supersymmetric Limits, Topological Solitons and Time Machines.

Arntzenius, Frank and Maudlin, Tim (2002). Time Travel and Modern Physics. Royal Institute of Philosophy Supplements 50, 169-200.

Gott, J. (2002). Time Travel in Einstein's Universe: The Physical Possibilities of Travel through Time. Houghton Mifflin Harcourt.

Rodrigo, Enrico (2010). The Physics of Stargates: Parallel universes, Time Travel, and the Enigma of Wormhole Physics. Eridanus Press.

Marquet, Patrick (2022). Godel Time Travel with Warp Drive Propulsion. Progress in Physics 18.

Campbell, John et al., (2011). Vector Boson Pair Production at the LHC. Journal of High Energy Physics, article no. 18.

Nikishov, A. (1970). Pair Production by a Constant External Field. JETP 30 (4), 660.

Dai, D. and Stojkovic, Dejan (2019). Observing a Wormhole.

Almheiri. A. et alt., (2021). The Entropy of Hawking Radiation. Rev. Mod. Phys. 93, 035002.

Bridgman PW. The Logic of Modern Physics. Oxford: Macmillan; 1927.]

Peres A. Measurement of time by quantum clocks. Am. J. Phys. 1980;48:552–557. doi: 10.1119/1.12061

Helstrom, C. W. Quantum Detection and Estimation Theory, Vol. 123 of Mathematics in Science and Engineering (Academic Press, New York, 1976).

Holevo, A. S. Probabilistic and Statistical Aspects of Quantum Theory, Vol. 1 of Statistics and Probability (North-Holland, Amsterdam, 1982).

Braunstein SL, Caves CM. Statistical distance and the geometry of quantum states. Phys. Rev. Lett. 1994;72:3439–3443. doi: 10.1103/PhysRevLett.72.3439.

Braunstein SL, Caves CM, Milburn GJ. Generalized uncertainty relations: theory, examples, and Lorentz invariance. Ann. Phys. 1996;247:135–173. doi: 10.1006/aphy.1996.0040.

Busch, P., Grabowski, M. & Lahti, P. J. Operational Quantum Physics, Vol. 31 of Lecture Notes in Physics Monographs (Springer, Berlin, 1997).

Busch, P., Lahti, P. J., Pellonpää, J.-P. & Ylinen, K. Quantum Measurement: Theoretical and Mathematical Physics (Springer, New York, 2016).

Wiseman HM, Milburn GJ. Quantum Measurement and Control. Cambridge: Cambridge University Press; 2010.

Pauli W. General Principles of Quantum Mechanics. Berlin: Springer; 1980.

Busch P, Grabowski M, Lahti PJ. Time observables in quantum theory. Phys. Lett. A. 1994;191:357–361. doi: 10.1016/0375-9601(94)90785-4.

Brunetti R, Fredenhagen K, Hoge M. Time in quantum physics: from an external parameter to an intrinsic observable. Found. Phys. 2010;40:1368–1378. doi: 10.1007/s10701-009-9400-z.

Smith ARH, Ahmadi M. Quantizing time: interacting clocks and systems. Quantum. 2019;3:160. doi: 10.22331/q-2019-07-08-160.

Loveridge L, Miyadera T, Busch P. Symmetry, reference frames, and relational quantities in quantum mechanics. Found. Phys. 2018;48:135–198. doi: 10.1007/s10701-018-0138-3

Höhn, P. A., Smith, A. R. H. & Lock, M. P. E. The trinity of relational quantum dynamics. Preprint

Höhn, P. A., Smith, A. R. H. & Lock, M. P. E. Equivalence of approaches to relational quantum dynamics in relativistic settings.

Zych M, Costa F, Pikovski I, Brukner Č. Quantum interferometric visibility as a witness of general relativistic proper time. Nat. Commun. 2011;2:505. doi: 10.1038/ncomms1498.

Zych M, Rudnicki Ł, Pikovski I. Gravitational mass of composite systems. Phys. Rev. D. 2019;99:104029. doi: 10.1103/PhysRevD.99.104029.

Paige AJ, Plato ADK, Kim MS. Classical and nonclassical time dilation for Quantum clocks. Phys. Rev. Lett. 2020;124:160602. doi: 10.1103/PhysRevLett.124.160602

Lock MPE, Fuentes I. Quantum and classical effects in a light-clock falling in Schwarzschild geometry. Class. Quantum Grav. 2019;36:175007. doi: 10.1088/1361-6382/ab32b1.

Khandelwal, S., Lock, M. P. E. & Woods, M. P. Universal quantum modifications to general relativistic time dilation in delocalised clocks. Quantum**4**, 309 (2020).

Höhn PA. Switching internal times and a new perspective on the 'wave function of the universe' Universe. 2019;5:116. doi: 10.3390/universe5050116

Castro-Ruiz E, Giacomini F, Belenchia A, Brukner Č. Quantum clocks and the temporal localisability of events in the presence of gravitating quantum systems. Nat. Commun. 2020;11:2672. doi: 10.1038/s41467-020-16013-1.

Page DN, Wootters WK. Evolution without evolution: dynamics described by stationary observables. Phys. Rev. D. 1983;27:2885. doi: 10.1103/PhysRevD.27.2885.

Sorli, Amrit (2022). Time Invariant Space, TimeTravel, and Hawking Chronology Protection. OSF Preprints.

Saathoff, Guido et alt., (2003). Improved Test of Time Dilation in Special Relativity. Physical Review Letters 91, (19), 190403.

Augustyn, Adam and alt. (2021). Time Dilation. Britannica.
Malleshappa, Kiran (2014). Time Dilation. International Journal of Scientific and Research Publications, Volume 4, Issue 9, September, 2014.
Wang, Xinghong (2021). A Discussion on Time Dilation based on Special Relativity. International Journal of Scientific Research and Modern Education. Volume 6, Issue 1, 2021.
Smith, Alexander and Ahmadi, Mehdi (2020). Quantum Clocks Observe Classical and Quantum Time Dilation. Nature Communications 11, 5360.
Sarkar, Ansh (2018). A New Dimension to Time Dilation. International Journal of Innovative Science and Research Technology'. Volume 3, Issue 7.
Wong, Bertrand (2019). Existence of Tachyons and their Detection. Research and Reviews: Journal of Physics, Volume 8, Issue 2.
Leiro, Alejandro (2016). Tachyons and other Things Fast: A Study of Superluminal Motion. Worcester Polytechnic Institute.
Time Travel in Einstein's Universe: The Physical Possibilities of Travel through Time J. Richard Gott III Houghton Mifflin, New York, 2001.
Einstein's On the Electrodynamics of Moving Bodies is based on the English translation of his original 1905 German-language paper (published as Zur Elektrodynamik bewegter K¨orper, in Annalen der Physik. 17:891, 1905) which appeared in the book The Principle of Relativity, published in 1923 by Methuen and Company, Ltd. of London.
Einstein's Does the Inertia of a Body Depend upon its Energy-Content is based on the English translation of his original 1905 Germanlanguage paper (published as Ist die Tr¨agheit eines K¨orpers von seinem Energiegehalt abh¨angig?, in Annalen der Physik. 18:639, 1905) which appeared in the book The Principle of Relativity, published in 1923 by Methuen and Company, Ltd. of London.
Albert Einstein, (1920). Relativity: The Special and General Theory.
Enrico (2010). The Physics of Stargates: Parallel universes, Time Travel, and the Wormhole Physics. Eridanus Press.
A. Einstein, Den Speciella Och den Allmänna Relativitetsteorin, (Daidalos, Gothenburg, 2006), (The Special and General Theory of Relativity) (Swedish).
A. Einstein, Relativity: The Special and the General Theory, 100th anniversary ed. (Princeton University Press, Princeton, NJ, 2015).
J. Slowak, Mathematics shows that the Lorentz transformations are not self-consistent (Physics Essays, Vol. 33 No. 1, 2020).
J. Slowak, Special Relativity is Nonsense, 2nd ed. (Books on Demand, Stockholm, 2020).
A, SARKA (2018). A New Dimension to Time Dilation. International Journal of Innovative Science and Research Technology'. Volume 3, Issue 7.
Wong, Bertrand (2019). Existence of Tachyons and their Detection. Research and Reviews: Journal of Physics, Volume 8, Issue 2.